BACKGROUND MATERIALS FOR IMPLEMENTATION OF DECISION-MAKING REGARDING MAINTENANCE STRATEGIES

IM-SAFE.EU

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Preface

This report is part of the H2020 CSA IM-SAFE project results and is the outcome of WP3 (Data-informed safety evaluation and maintenance strategies) Task 3.2 (Decision-making concerning maintenance strategies) activities, listed as delivery D 3.2. It constructs a part of the technical background for the formulation of the proposal for the mandate to CEN for a further amendment to the existing EU standards on the implementation of maintenance and monitoring strategies in asset management.

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WP3 contributes to the identification of the normative gaps with regard to current decision-making processes for maintenance activities based on review of the current state-of-the-art as represented by standards, guidelines, other regulations as well as current practice and research. The particular focus of Task 3.2 is on maintenance and control plans of infrastructures.

This report includes the review of Quality Control Plans and maintenance strategies and tactics adopted by the CoP members in the different European countries, including the analysis of the guaranteed minimum maintenance levels, a comparison between various methods of condition survey, assessing the capital and the operating costs of different solutions, the description of a decision-making framework that summarizes the aspects covered in tasks T3.1 and T3.2, which aims at a sustainable and efficient management of both single bridges and a network of bridges, and the showcase of examples of practical applications of the decision-making process to a real-case scenario under ongoing monitoring performed by a Consortium partner on TEN-T corridors and regional transport networks. Lastly, the creation of an interactive map with information of how/where the different methods are used in different countries in Europe is described.

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Table of Content

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Table of Figures

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Table of Tables

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1 Problem statement

1.1 Introduction

Bridges and tunnels in Europe are vulnerable elements of the transport infrastructure, due to higher traffic loads than expected at the time of design, progressive ageing and deterioration of materials, insufficient quality control during construction, weak diagnostics of structures, suboptimal maintenance strategies, and additional risks originating from climate change, new man-made hazards and limited resources for renovation and replacement. Maintenance deficiency accelerates the structural deterioration and the safety risk of infrastructure: an optimized utilisation of the narrow resources for conservation and care should be put in place through an efficient asset management process to significantly slow down or contain the consequences of such deterioration. This urgent issue is not just European: for instance, in the USA, Federal Highway Administration (FHWA) has rated almost 200,000 bridges (one-third of all bridges) as structurally deficient or functionally obsolete. There is a clear need of sound procedures for integrating and adopting the latest technologies, techniques, and methodologies to account for monitoring in safety assessment, risk evaluation and decision making, necessary to radically improve asset management and to guarantee safety and resilience of transport infrastructure.

Appropriate maintenance strategy shall be selected for the management of the infrastructure, with suitable maintenance tactics (e.g. time-based, condition-based or risk-based maintenance) being chosen for implementation. A proactive/predictive maintenance strategy is desirable as it enables early identification of problems and possible risk issues following from the condition of the structure, potentially enabling early preventive actions to be taken to minimise the overall cost of ownership. In the current practice, proactive maintenance strategies are increasingly used. However, current decision-making processes with respect to maintenance activities are lacking a solid rational basis, and thus, often taken ad-hoc without duly considering the condition data and the outcome of safety and risk evaluations. Therefore, there is an evident urgency for providing consistent and harmonised basis for decision-making concerning the implementation of maintenance strategies in asset management. Accurate information from monitoring of structures is crucial to take the right decisions on maintenance and safety; unfortunately, there are gaps in the existing European standards and the monitoring practice at national level. Structural monitoring is not adequately addressed in the current Eurocodes (CEN/TC-250, 2020), and the existing standards on monitoring are not consistently interpreted and implemented in different European countries due to a lack of coherent policies and the gaps in knowhow. The current standards do not embed the full extent of knowledge on the analytics of extensive measurement and monitoring data to provide input for optimal maintenance strategies and safe operation of the infrastructure, and the adoption of digital technologies beyond the conventional inspection methods.

For maximal safety, availability and cost-effectiveness of transport infrastructure, IM-SAFE envisions a paradigm shift from the time-based/corrective maintenance towards risk-based/predictive maintenance through data-informed decision-making enabled by a new and harmonised European standard for monitoring, including a standardised digitalisation approach. IM-SAFE envisions that risk-based maintenance strategies will be embedded in infrastructure management systems to ensure safety over the infrastructure assets' lifetime. Assessment of the structural condition will be based on the integration of inspections, monitoring and testing. The main advantage of such integrated approach is that the information gathered from the structures enables timely and cost-effective decision-making on repairs, strengthening and renovations. The gathered data will be used for assessing the actual safety and the risk levels of the structure as well as for predicting the future safety and risks. This is currently possible by using the latest digital innovations that integrate structural

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models, predictive degradation models and data analytics techniques. The combined human expert and artificial intelligence will result in the transformation of measured data into knowledge about the performance and safety of the structure. This will provide input for predictive maintenance, which in turn will guarantee the achievement of the required safety levels and will support the planning of an optimal maintenance for the assets. IM-SAFE through the research activities in the scope of Work Package 3 (WP3) has the purpose to enable this vision by filling-in the gaps in the current standards and translate them into practice. IM-SAFE will lead to new European standards for monitoring and maintenance of the structures, and the rules in the structural design codes (Eurocodes).

1.2 Challenge of standardisation of a proposal for a practical decision-making process for asset owners and operators to facilitate proactive maintenance

Development and adoption of new European standards involve complex processes that require multi-level dialogues, consensus and commitment from political and industrial stakeholders to move forward from legacy procedures. The need for robust standardisation is generally acknowledged by public authorities and industrial stakeholders; however, developing new European standards based on national state-of-the-art is challenging as there are only a few existing national standards in this field with shortcomings in their coverage and technical depth. The lack of European standards in monitoring and maintenance results in the difficulties to secure political support and public funding for appropriate monitoring and maintenance.

The high diversity of transport infrastructure assets and their environments add to the complexity for standardised monitoring. Getting a broad acceptance for the new standards will also be difficult, especially if changes in the existing procedures and agreements on monitoring and maintenance are implied. There are diverse points of view with regards to how maintenance and risk management of transport infrastructures should be carried out along with ongoing discussion on responsibilities and liabilities. Standardisation, thus, requires dialogues and discussions about responsibilities, liabilities and accountabilities among the policy-makers, public clients, design and engineering consultants, and construction firms – the key stakeholders in the currently fragmented value-chain in construction.

There is still a dominance of the legacy procedures/systems or known approaches for regular manual/visual inspections, damage assessment and corrective maintenance; preventive and condition-based maintenance are only used occasionally. As a result, 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 this context, the advantages of performance monitoring will be fully exploited and compared to the conventional approaches based on visual inspections and non-destructive testing (NDT). In order to shift the maintenance paradigm towards a condition-based one, the ageing challenges and resilience threats have to be assessed and addressed. Occurrences of Loss-of-Performance (LoP) events and their risks should be analysed in terms of the sources of hazards and the consequences. Therefore, IM-SAFE will deal with the key factors of resilience-oriented maintenance and risk management based on the “4R”: Robustness, Redundancy, Resourcefulness and Rapid response.

To enable the transition from corrective/time-based maintenance to risk-based maintenance of the transport infrastructure, the integrated technical concept of IM-SAFE is founded on three pillars:

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1. **Smart integration of multi-scale technologies for monitoring** the structures, which is substantially more effective compared to the conventional approach that solely relies on inspections. Using integrated technologies enables more in-depth knowledge about the actual demands, responses, and capacities of the structures. The gain in knowledge leads to an improved assessment of the actual safety level and improves the rationalization of decision-making concerning measures or interventions on the transport infrastructure assets.
2. **Digitalization to enable real-time data acquisition and data-informed safety assessment**. Digital technologies are prerequisite for such improvement of the monitoring practice. It is widely recognized that digitalization will play a major role in the near future with respect to the collection and exploitation of large amounts of data that will be used as basis for decision-making throughout the lifetime of assets. Therefore, the new European standard for monitoring needs to address digitalization, including 3D and Big Data acquisition, open interoperability between different data sources and data models, data analytics technologies including Artificial Intelligence (AI), and open data platforms. The currently used safety and risk assessment methods need to be re-evaluated and broadened in order to take advantage of the information gathered by using surveying technologies and digitalization. Meaningful data gathered from the inspections, structural monitoring and testing are necessary to identify and evaluate deterioration and systemic deficiencies of the key structural elements and materials, which –in combination with increased loads and resilient threats– make the structures vulnerable to catastrophic consequences of major failures or collapses.
3. **Data-informed risk and safety assessment** for decision-making on asset management. Acquiring and analysing monitoring data with support of big data science will enable structural designers and engineers to resolve the complex relationships between loads and behaviour and to improve the knowledge on the development of materials degradation. This knowledge will lead to new structural models, which can improve the design, maintenance and retrofitting. It will reduce uncertainties on the actual loads on the asset, extent of deterioration and deviations from design assumptions, and thus avoiding over-dimensioning of the structure in the design. Infrastructures of the same road network will be evaluated based on their Condition State Classification, ranging between fully operational (new), good (operational/satisfactory), reasonable (operational/needs minor interventions), bad (operational/needs major intervention), poor (non-operational). Safety assessments and maintenance decision-making process will take into consideration the implications of the Condition State Classification of the structures as part of the structural diagnosis process. Maintenance strategies on road networks will be based on the single road infrastructure condition analysis, identifying Damage Indicators (DIs) and Performance Indicators (PI).

1.3 Objectives of the deliverable

This report forms the technical background for the formulation of the proposal for the mandate to CEN for a further amendment to the existing EU standards on data-informed safety assessment considering inspections, monitoring and testing and for a new standard for preventive maintenance of transport infrastructure, with specific focus on road and railway bridges and extension of some of the main considerations to tunnels. Within this context, the objectives of T3.2 are:

- To propose a **practical decision-making process** for asset owners and operators to facilitate proactive maintenance, that overcomes the current barriers (see results of IM-SAFE WP1) and reflects on the most recent developments of condition survey technologies and structural diagnostics (see results of IM-SAFE WP2 and WP4), with the aim to reduce the risks of sudden collapse and to minimise the lifecycle cost of asset management while ensuring the required service level and quality of the infrastructures are achieved. The decision-making process will be differentiated based on the infrastructure Condition State Classification (see results of IM-SAFE WP2) and

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will take into consideration the strategic role of each infrastructure within the road network. This objective will be achieved in cooperation with the CoP (see results of IM-SAFE WP6).

- To **develop background information and practical guidance material** as rationale for the mandate for new standards (CEN) for maintenance and control of large infrastructures, such as bridges and tunnels. This objective facilitates the preparation of recommendations for standardisation (see results of IM-SAFE WP5).
- To **showcase the application of the decision-making process** in relevant a real-case scenarios on the TEN-T corridors or regional transport networks. The results will feed into IM-SAFE WP5.

1.4 Report contents

Chapter 1 of this report explains the context, the approach and the aim of the of the activities carried on in Task 3.2 of WP3 of the IM-SAFE project. Chapter 2 provides an overview of the principles of through-life management and maintenance of infrastructures, with attention to the main maintenance strategies, conservation processes and investigations, evaluations and decision-making for maintenance activities.

In Chapter 3 principles of maintenance of infrastructure are given, as well as a risk-based framework for maintenance management, a classification of the common typologies of maintenance strategy, in terms of acceptance of risk, the trigger for maintenance and the activities required in the strategy, and principles for the selection of maintenance strategies.

In Chapter 4 the Condition-based Maintenance approach specifically for bridges is described, providing an overview of the maintenance strategies commonly used for asset management adopted by the CoP in the different European countries. Chapter 5 focuses on Quality Management (QM) as part of the wider framework of the Asset Management, which aims to ensure that the resulting built structure satisfies the assumptions adopted in the design, emphasizing its application to all levels, processes and activities of an organization. Asset management is a very broad area and includes a lot of processes that are associated with quality management. For the reason of emphasizing QM, QM was primarily highlighted.

In Chapter 6 principles of Information Management are given, focusing on information collected in the maintenance and monitoring phase of an infrastructure. A classification for the relevant information for infrastructures is also provided.

In Chapter 7 the impact of costs of information on decision-making is presented, together with an analysis of the Value-of-information based decision-making for investigations activities. A proposal for a practical decision-making process for asset owners and operators that overcomes the current barriers (see results of IM-SAFE WP1) and reflects on the actual developments in monitoring, damage detection, and digital technologies (see results of IM-SAFE WP2 and WP4) is outlined in Chapter 8. This proposal, that presents the concept of proactive maintenance plan, with the aim to reduce the risks of further structural deterioration, to minimize costs, and simultaneously to ensure the quality of the transport infrastructure performance, has been developed together with the CoP direct involvement (see results of IM-SAFE WP6). An Interactive Map (wiki-like) containing information of how different countries in Europe deal with KPIs and Risk management method complements the project results (see Appendix of this report). Evaluation of the application of the decision-making process to 6 relevant real-case scenario under ongoing monitoring performed by a Consortium partner on TEN-T corridors and regional transport networks is shown in Chapter 9 (these results feed the IM-SAFE WP5). Finally, in Chapter 10 an appraisal with regards to standardization is given: a review of current frameworks for Quality Control Plans, a proposal of framework for Preventive Maintenance Procedures and a proposal of framework for data-informed decision-making for

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safety and risk management of the European transport infrastructures, aiming at a sustainable and efficient management of both single bridges and a network of bridges, are given.

Summary and conclusions of the report are given in Chapter 11, which is followed by the list of References (Chapter 12), Appendix 1 with the additional detail information on online IM-SAFE Wiki on maintenance methods in the EU and the description of Case Studies implemented in the online IM-SAFE Knowledge Base (see https://imsafe.wikixl.nl/ maintenance_management_information). To set the basis for a common understanding of the glossary within Europe and to respond to the need of resolving conflicting definitions that may cause misleading interpretation the IM-SAFE terminology proposal is include in IM-SAFE online Knowledge Base, https://imsafe.wikixl.nl/.

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2 Principles of life cycle management of infrastructure

2.1 Life cycle management concept

The life cycle management of infrastructure is a process adopted during the whole lifetime of infrastructure assets to ensure the continued safe service of an individual assets or of a network of interconnected assets (fib MC2020, 2022), (fib MC2010, 2013). The life cycle management is the overall approach to be used in managing infrastructure assets through their life-cycle, particularly during its operation phase. The life cycle management strategy should be developed from (predetermined) performance requirements set for new, existing or altered assets. Performance requirements that are to be dealt with in the life cycle management process shall be set for the primary function(s) of an asset and may be expressed by the Key Performance Requirements with the associated performance criteria.

Given the need for sustainable development of built environment, for the infrastructure networks and infrastructure under consideration the Key Performance Requirements shall be derived from the objectives of the three pillars of sustainability (social responsibility, environmental impact and economic efficiency) and give attention to the key factors of resilience: robustness, redundancy, resourcefulness and rapid response. The life cycle management of the assets should contribute to achieving an acceptable balance between these objectives. The RAMS (or RAMSSHE€P) analysis approach can be used to develop appropriate criteria for the 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 the reports of (COST TU1406) and in IM-SAFE report D3.2 (Bigaj-van Vliet, et al., 2022) . 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 report considering that in the context of the problem statement the main focus in on the life cycle management of the reliability of infrastructure assets (in particular with reliability with regard to structural safety).

Due to limitations in the available resources or conflicting requirements, life cycle management usually requires compromises and judgement about the action to be taken by asset managers during each life cycle stage (of planning, design, execution, operation including through-life interventions, and decommissioning). Implementation of asset management principles shall provide input to in all those stages to aid decision-making in compromising and judging options and alternatives for through-life interventions. In this context, through-life interventions refer to both structural and operational interventions (further discussed in section 2.2) and may include e.g. inspection, monitoring, maintenance as well as rehabilitation, repair or upgrading required for adaptation to changed performance requirements, including those associated with improving the performance of structures in-service or extending the useful life.

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. Therefore, the risk of performance degradation of the asset during the whole life cycle, as well as the impact of the asset on the environment and economy, shall be considered during the formulation of the life cycle management concept. For this reason, a fully integrated approach to life cycle management is very complex and optimisation of maintenance activities involves making trade-offs between competing objectives, with due consideration of interactions and interdependencies between a wide range of factors, including risk, operational interferences, quality, climatic impact and costs. Therefore, a rational management necessitates performing a rational risk assessment for the whole life cycle of the asset, a realistic life-cycle cost (LCC) calculations and life-cycle analysis (LCA) of the environmental impacts and benefits associated. In this context it is

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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 systems considered. Accordingly, the process of making life-cycle evaluations should be approached with caution. Moreover, during the service life, the life cycle management scenarios shall be appropriately updated to take account of the influence of actual or anticipated changes in risk, operational interferences, quality, cost and environmental impacts and benefits (fib MC2020, 2022).

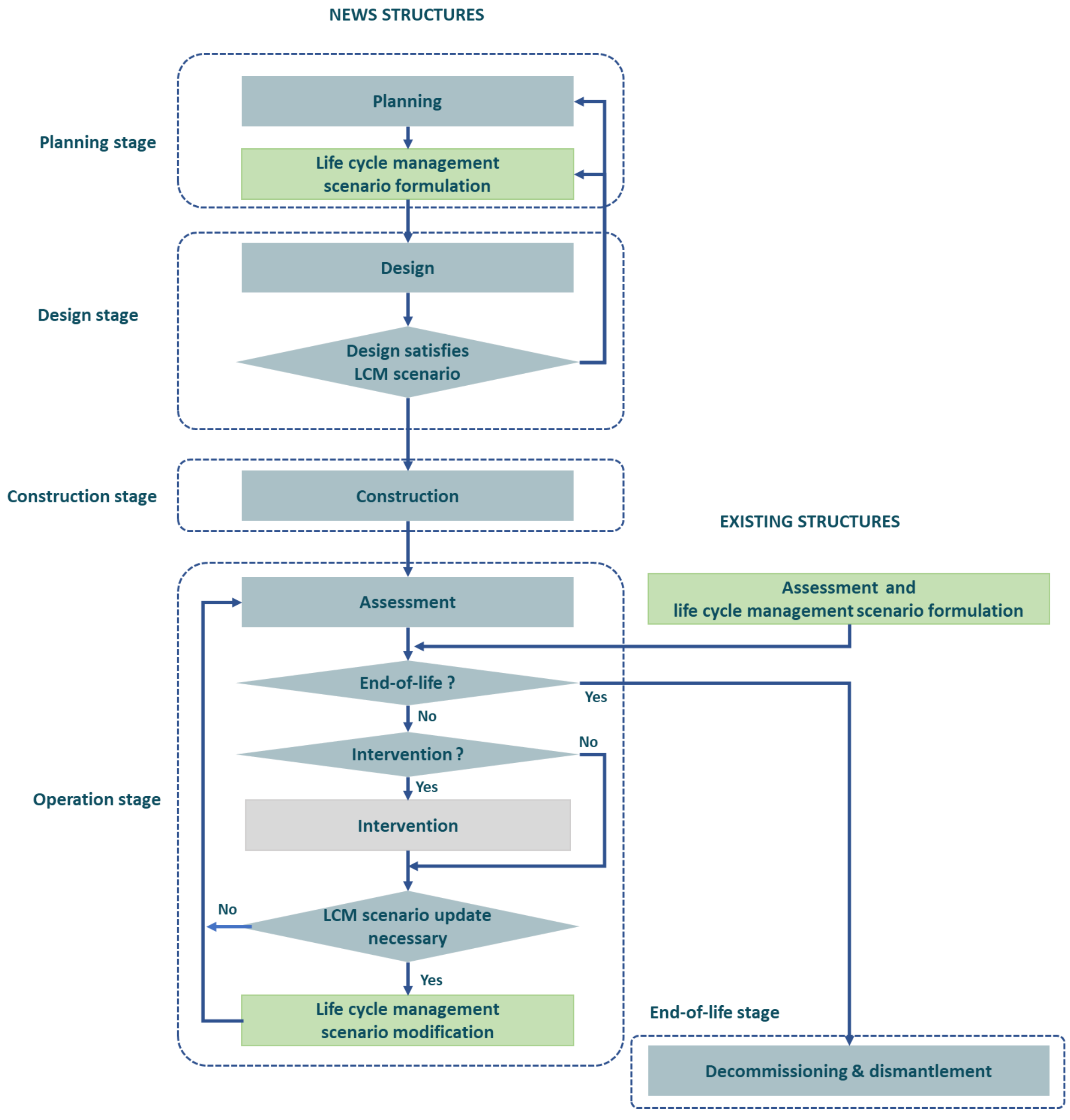

Figure 2.1 – Indicative process flow for life cycle management (LCM) for new and existing structures, based on (ISO 22040, 2021)

Figure 2.1 presents a schematised process flow for life cycle management for new and existing structures and illustrates how the life cycle management scenario(s) can be modified during the design /assessment stage, the execution stage, and the use stage of a structure, if necessary. When the scenario is modified, the management process reverts to the previous stage (ISO 22040, 2021). For new structure the basic life cycle management scenario shall be formulated at the planning stage of the structure. Design work shall be carried out to satisfy the plan and the scenario. When the design outputs do not satisfy the initially formulated life

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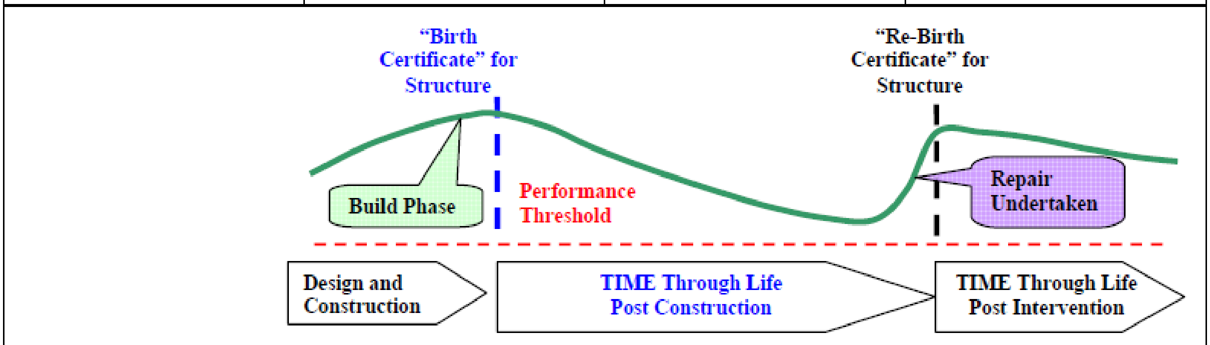
cycle management, the LCM scenario shall be modified to be consistent with design outputs or the plan and/or design shall be carried out again. After commissioning and completion of the construction work, initial assessment shall be carried out to check the state of the structure. When any defect is found from the initial assessment, appropriate intervention shall be taken as required. Then, it shall be assessed whether the basic life cycle management scenario is suitable for the subsequent life cycle of the structure. If modification is deemed necessary, the life cycle management scenario shall be updated. At the following assessment, the conditions of the structure shall be re-assessed, and the life cycle management scenario shall be updated as necessary. If the sustainability evaluation shows that the condition defining end-of-life have been reached and no interventions are to be decided upon in order to keep the structure in pronged use, the structure shall go to the end-of-life stage and undergo decommissioning and dismantlement, followed by reuse or recycling of the materials. For an existing structure that has not been managed so far but is decided to be managed based on the cycle management concept, the cycle management shall start with the first assessment of its performance at the operation stage. The basic cycle management scenario shall be formulated by using all available assessment data and design and execution documents. If the assessment results indicate that no remedial measures are necessary, the structure shall go to the end-of-life stage. Otherwise, the same procedure as that for a new structure shall be followed. When the basic cycle management scenario is updated, subsequent management shall be carried out according to the updated scenario.

2.2 Life cycle management activities

Figure 2.2 schematically illustrates the positioning of the main activities of the life cycle management within the perspective of a life cycle of the asset (fib Bulletin 44, 2008).

Phase in life of an asset	**Planning & Design** and **Construction**	Post-construction service life **Operation**	Post-remedial intervention service life **Extended Use**



Through-life activities			
Life cycle management			
Condition survey & evaluation			
Performance assessment			
Decision-making for interventions			
Execution of interventions			
Information management			

Figure 2.2 – Main activities of the through-life management, schematised according to (fib Bulletin 44, 2008).

During all phases of the life cycle, decisions regarding maintenance activities are made, however their objectives and the information required to support such decisions are changing

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as follows:

- **Planning and Design**: Planning and Design stages includes the concept phase, when the owner's basic requirements and needs are established, and the design phase (usually involving preliminary and detailed design phases), when the performance requirements are defined along with the structural forms, materials and dimensional details so that the performance requirements are satisfied for the design working life at the chosen target level. During project planning and design the foreseen approach to maintenance management shall be defined, followed by the preliminary selection of the maintenance strategies. Information acquired during these stages 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 is essential in the life cycle management activities, and, therefore it shall be recorded, transferred to and reflected upon during the Construction and Operation stages for as-design information, as it constitutes the pertinent basis for decision-making during these stages of the life cycle.

- **Construction:** Construction stage includes processes whereby the asset is constructed so as to fully achieve the performance level set at the design stage. Information acquired during the execution stage, including materials, construction methods, and quality control records, which are necessary for future life cycle management activities, shall be recorded and transferred to the use stage for as-built information (see chapter. 4 for further details). During construction stage, the choice of the maintenance management approach and choice of the maintenance strategy must be confirmed (and adequately revised if needed) making use of the outcomes of the condition survey and evaluation performed after construction of the structure, and then continued into the operation phase. For similar reasons as in for the previous phases, the as-built information shall be considered pertinent for recording.

- **Operation:** During Operation stage the life cycle performance of an asset and its functionality must be guaranteed via appropriate implementation of the maintenance management and maintenance strategy (incl. selection and execution of interventions performed during post-construction service and post-intervention service and taking into consideration the past, present and future development of the condition and performance of the asset). 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 evaluation and performance assessment executed during operation and use stage. 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. Information acquired from condition survey and performance assessment during the Operation and Use stage, information related to applied interventions, and information on performance recovery after interventions shall be recorded and transferred to the party responsible for life cycle management of the asset and utilised in development of subsequent asset management scenarios (see chapter 3 for further details).

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- **End-of-life:** End-of-life stage concerns the process by which the asset is decommissioned and removed; being either dismantled, with the components being re-used as far as possible, or demolished and the materials recycled. 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. The objective of life cycle management is to reduce the amount of waste and promoting the reuse members / recycling of construction materials, which needs to be adequately managed and documented. 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.

2.3 Life cycle management activities during operation stage

The life cycle management activities for an existing asset during operation stage (i.e. during post-construction service life and post-intervention service life in Figure 2.2) related to maintaining its structural performance involve:

- condition survey,
- structural performance assessment.
- interventions on existing structures incl. decision-making for interventions and execution of interventions (including maintenance)
- information management.

Ad1

- **Condition survey** is the process of acquiring information related to the current condition of a structure, conducted with the aim of recognizing important limitations, defects and deterioration relevant for the ability of a structure to meet specified performance requirements (e.g. appearance, functionality and structural performance requirements). Condition survey involves gathering information on the current condition and factors relevant to the development of that condition. Condition survey should also seek to gain an understanding of the (previous) circumstances which have led to the development of that state, together with the associated mechanisms causing damage or deterioration. Condition survey might involve investigations such as document search (e.g. the Birth Certificate search), inspections (e.g. initial inspections, detailed inspections, extraordinary inspections), testing and monitoring. Condition **survey** is essential part of condition control, which is the overall process for safeguarding the condition of a structure during its lifetime, performed as a part of the life cycle management.

Ad2

- **Structural performance assessment** is a total set of activities performed in order to verify the reliability of an existing structure for future use, including:
    - **Structural performance analysis**, which comprises set of activities including structural analysis allowing a prognosis to be made of current and future performance, taking account of relevant deterioration mechanisms and, if appropriate, predictions of potential future damage. Performance analysis involves i**dentification of deterioration and damage mechanisms** and prediction of the degree and rate of deterioration and damage. Performance analysis involves analysing the available data to establish current performance, and to make a prognosis of future performance for management of the asset, taking into

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consideration future implications of the deterioration and damage mechanisms, as well as the need for, timing of and nature of any interventions required.
- **Structural performance evaluation**, which is the process undertaken after to performance analysis, that is concerned with evaluating need for, timing of and nature of any interventions required to meet the specified performance requirements (original or revised) and allow the structure to remain in service during the specific period of time.

Depending on the assessment findings, the structure or a structural part can, within the scope of the assessment (CEN-EN-1990):
- achieve the reliability required, assuming adequate inspection and maintenance during the remaining service life;
- achieve the reliability required at the time of the assessment, but not for the complete period of time during which the existing structure is intended to remain operational, taking into account the anticipated development of its condition and the planned level of maintenance;
- fail to achieve the reliability required;
- require immediate correction of the existing condition by means of immediate interventions.

Ad3

- **Decision-making for interventions** is the process concerned evaluating potential intervention options, selecting appropriate intervention options and setting the timing of intervention activities and works. Decision-making for interventions is based on establishing the technical, societal, environmental and economic implications of interventions upon the life cycle management of an asset. The choice of intervention option depends on various factors that are to be assessed for a network or an object that is the subject of life cycle management activities. In particular, the type, technique and extent of the intervention should be selected and developed taking into account, if relevant, the aspects such as (CEN-EN-1990):
  - the type and importance of the structure;
  - the specific requirement(s) that is/are not met (i.e. safety, serviceability, durability, robustness);
  - the specific requirement(s) to be improved;
  - sustainability objectives;
  - architectural, functional and aesthetic considerations and restrictions (e.g. intervention principles in heritage structures);
  - cost considerations;
  - disruption of use and duration of the works.
  - structural behaviour;
  - presence and extent of damage, defect or deterioration;
  - type of actions and influences;
  - expected consequences of failure;
  - remaining service life of the structure
  - possible cause and mode of attaining a limit state;
  - previously applied interventions;
  - options for interventions that are available (e.g. materials and technologies to be used for the intervention)
  - compatibility of retained structural parts of the existing structure and the new structural parts, including their materials.

Ad4

- Documenting should include recording of all information from operation stage required for life cycle management of the asset. Information management is further discussed in Chapter 5.

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2.4 Interventions on existing structures

As a part of life cycle management activities on existing structures, interventions should be undertaken. In context of life cycle management, interventions are defined as actions or series of activities taken to preserve or modify the performance and future serviceability of a structure, its components and/or elements in order to maintain or achieve an adequate level of reliability with respect to performance requirements applicable to the structure under consideration.

Typically, three different objectives of intervention are distinguished:
- enabling networks and/or objects to meet all performance requirements in the specified period of time, as envisaged at the time of design;
- extending the planned period of time during which all the performance requirements have to be met; or
- enabling networks and/or objects to meet revised performance requirements (e.g. to deal with enhanced loading or changed functionality needs).

Assessment of existing structures may result in identifying need for interventions and the intervention options are in general be classified as follows (see Figure 2.3, according to (ISO-13822, 2010)):

- **structural interventions**: (also referred to as constructional interventions), incl.:
    - maintenance,
    - rehabilitation
        - repair
        - upgrading
    - demolition,
- **operational interventions**, incl.:
    - inspection,
    - maintenance,
    - monitoring
    - change of use.

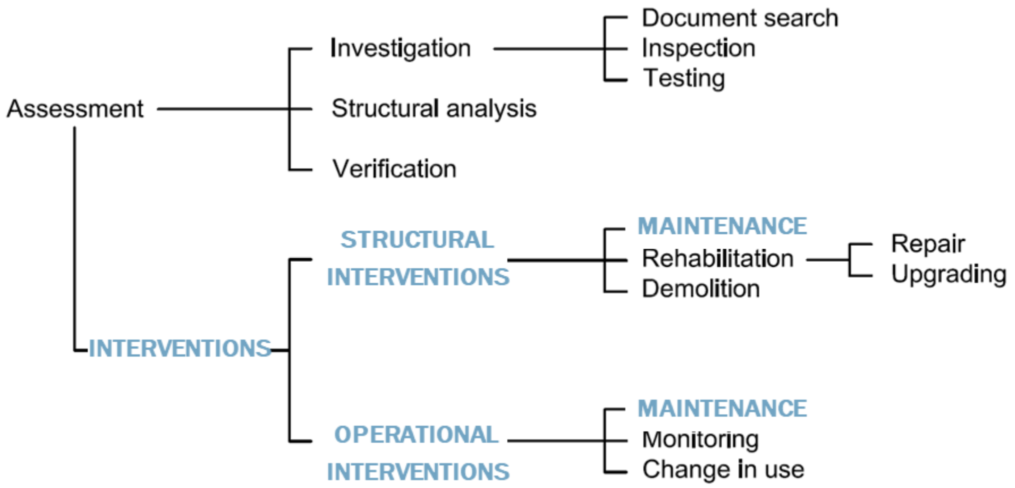

Figure 2.3 – Hierarchy of terms and positioning of maintenance in context of the assessment of existing structures, according to (ISO-13822, 2010)

Based on the approach to change in the condition or performance of the structure, interventions on existing structures may also be classified as:

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- **corrective/remedial** (or reactive), when actions are taken after unsatisfactory condition or performance have been observed (e.g. after damage of the structural members has become visible).
- **preventive** (or proactive), when some form of treatment is applied or action is taken to ensure that the condition of a structure remains within satisfactory bounds or that an unsatisfactory condition or performance is not reached, or does not occur.

Based on the timetabling of interventions, they may also be classified as:
- **planned,** when timing of the intervention works is known in advance, or
- **unplanned**, when intervention works is unexpectedly necessary and therefore the timing thereof cannot be known in advance.

Within the unplanned interventions, **immediate interventions** to restore safety can be distinguished i.e. measures that are aimed to mitigate the risk which are carried out without a delay when during the assessment process the structure appears to be in a situation that instigate an unacceptable level of risk.

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3 Principles of maintenance of infrastructure

3.1 Maintenance objectives

Maintenance is one of the intervention options to be considered for life cycle management of structures (see Figure 2.3) 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 service life of the structure in order to 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 aim of this chapter is to indicate the importance of risk and criticality analyses in determining appropriate maintenance approaches, what kind of maintenance strategies exist and how they compare to each other, and how to develop and improve maintenance plans through insights gained from the risk and critically analysis.

3.2 Risk-based framework for maintenance management

3.2.1 General framework

Risk-based maintenance of infrastructure assets combines the choice of 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 (CUR Report 190, 1997), 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. Risk-based maintenance management 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. 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 the 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 maintenance 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 inf needed revised) on the basis of 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 risk-based 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 outcome of the current condition evaluation and re-assessment of the (often revised during operation) performance requirements.

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In the particular case of revised performance requirements for existing structures, 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. and must be confirmed (and in needed revised) during the re-design stage on the basis of the outcome of the current condition evaluation.

Risk-based maintenance management process is a systematic approach which is used to plan and implement maintenance activities in order to avoid, reduce or control hazards and the risks arising from them. The goal of risk-based maintenance management is to help protect owners, users and society more generally from various undesired social impacts (such as reduced safety of humans and operations), economic losses and impairment of the environment. The flow of the risk-based maintenance management processes is illustrated in Figure 3.1. The process of setting out the risk-based maintenance framework for maintenance management, developed based on (fib Bulletin 44, 2008), indicating positioning of main components :

- risk & criticality assessment development of risk- & criticality- based data-collection strategy for inspection and monitoring
- formulation of maintenance programs and maintenance planning.

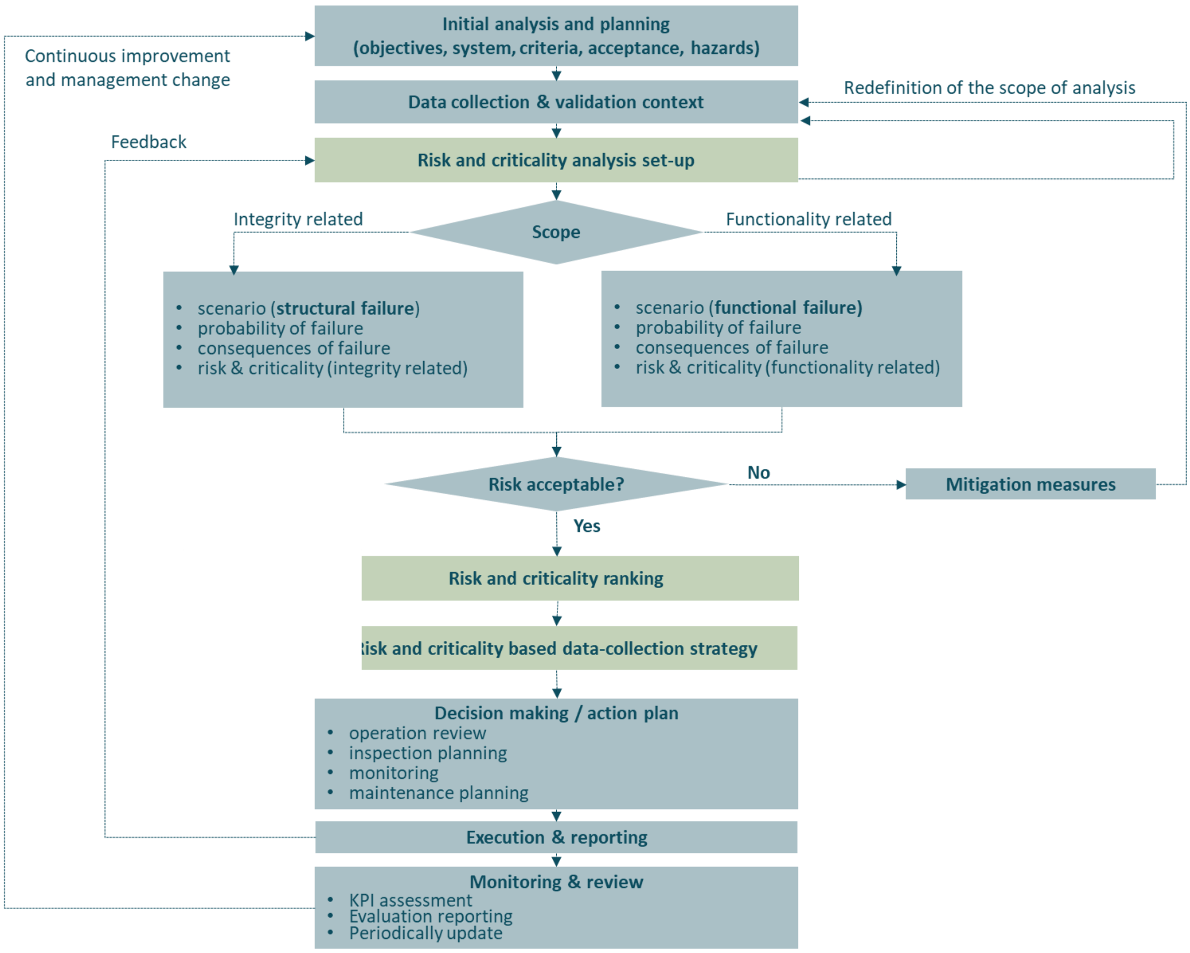

Figure 3.1 – The risk-based maintenance framework for maintenance management, based on (fib Bulletin 44, 2008), and modified based (Omenzetter, Bush, & Mccarten, 2015) to incorporate criticality assessment.

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3.2.2 Risk and criticality assessment

Assets vary in importance as a result of the different roles they can play in the functioning of networks. Moreover, assets have varying characteristics and conditions and thus the (degree) of risk per asset may vary too. This is recognised in practice, where some assets require other, e.g. more advanced, asset management approaches. This differentiation can be rationally motivated by using a risk- and criticality assessment. The outcome from risk and criticality assessment processes should provide sufficient detail to determine appropriate approaches in e.g. inspection regimes, data collection, monitoring and maintenance. For example, the outcomes should help in classifying or ranking infrastructure assets in order to determine what resources and activities should be allocated to monitoring and maintaining those assets. It is, however, first important to understand the differences and overlaps between risk and criticality.

Risk and criticality are very closely related terms. Criticality refers to the importance of the asset, and is usually indicated as the degree of consequences or impacts that failure of an asset may have on the operation or functionality of a system or network. In other words, the more severe the impact of asset failure is, the higher its criticality. High critical assets are assets that are of high importance to the functioning of a higher system such as a road network. Risk is the product of the probability of failure and the consequence of that failure. Accounting for the probability of failure is what is typically making the distinction between risk and criticality. Furthermore, critically is typically attributed to an asset while risks are more other attributed to failure modes. In practise we typically talk about critical assets and failure modes with high risk levels. Due to the close relation between risk and criticality, it should be noted that the terminology is sometimes uses interchangeably and in some approached even mean the same thing. For example, in a Failure Mode, Effect and Criticality Analysis (FMECA) the critically analysis refers to the quantification of risks through multiplying probabilities and consequences. And generally speaking, high critical assets can be associated with higher levels of risk.

However, both the assessment of criticality and the assessment of risks are important to asset management organisations in determining appropriate approaches for monitoring and maintenance of their assets. By understanding which assets are the most important through a criticality assessment, organisations can determine how to effectively schedule maintenance activities of the right components/objects at the right time to reduce risk over the whole object/network. The criticality assessment asks for defined criteria that enable to classify the potential consequences so that they can be objectively evaluated, categorized and prioritized There are several ways to conduct a criticality analysis. Which approach to use depends on 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. For the extensive discussion of criticality concept, a proposal for criticality analysis method for bridges and practical examples, reference is made to (Omenzetter, Bush, & Mccarten, 2015). For the extensive discussion of risk concept and overview of the methods applicable for performing risk analysis of transport infrastructures, reference is made to (Bigaj-van Vliet, et al., 2022).

3.2.3 Risk and criticality-based data collection strategy

The process for collecting and monitoring data for transport infrastructure asset management shall be based on risk and criticality rating of the assets: consistent with their risk and criticality assessment results, all assets shall be assigned an appropriate regime for specific data to be collected. The type, accuracy, quality, frequency and collection techniques for each regime shall be adequately chosen. In (Omenzetter, Bush, & Mccarten, 2015), a proposal is formulated for differentiation of a data collection regime (i.e. core, intermediate, advanced data collection level), which provides a means for relative ranking of the asset population based on risk and criticality score evaluated via a risk and criticality plot. (see Figure 3.2).

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Once the risk and criticality boundaries have been set, a review of should be undertaken to decide whether an asset or type of assets requires further assessment, ensuring that:

- no asset is out of context when compared to other assets of its type or similar assets in the same network
- assets on strategic or critical life-line routes are rated appropriately and have a level of consistency in their risk and criticality ratings
- the risk or criticality is not considered too high requiring further, more detailed investigation to better understand specific risk

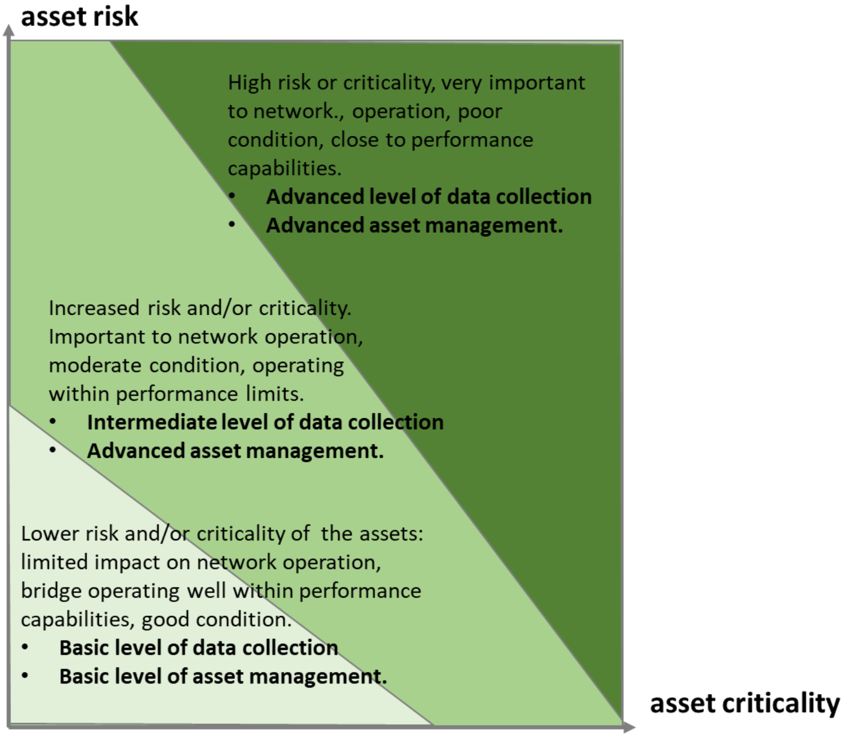

Figure 3.2 – Correspondence between data collection regimes and risk and criticality for bridges, evaluated via a risk and criticality plot aimed at differentiation of data collection regime (Omenzetter, Bush, & Mccarten, 2015)

3.3 Maintenance classes

Requirements for maintenance strategies for an asset, or its component parts, should be defined at the time of design (for new structures) or re-design (for existing structures) and may include allocation of the asset to a classification (i.e. meaning a specific regime of inspection, monitoring and maintenance is applied or aimed for). This should be done on the basis of a number of factors, such as the social and economic importance of the structure, its function, the nature of its design and that of its components, design service life, potential hazards incl. the environmental conditions to which it is exposed, the possible mechanisms of deterioration, the ease of undertaking inspections and maintenance works, together with considerations of cost and impact on third parties and environment. (fib Bulletin 44, 2008)

3.4 Development of risk-based maintenance programs and maintenance panning

It can be observed in practice that asset management organizations are increasing efforts to integrate the concepts of risks and criticality in their life cycle maintenance programs. This is seen as an enabler for better decision making, and thus assuring more value, and/or more value for money is obtained. For example but having more insight in risks and critically, asset

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management organisations are better equipped for determining appropriate monitoring and maintenance approaches which should lead to either better asset performance and/or cost reductions. Thus, the main principle for the development of the risk-based maintenance programs for the infrastructure networks is increasingly more often to minimise the total risk over the network or asset portfolio. Rational optimization 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 (CUR Report 190, 1997). Simply said, assets with greater risk and/or higher criticality will likely be subjected to more monitoring and maintenance efforts than assets with lower risk and/or criticality.

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.

More risk-based maintenance planning takes place within the context of the chosen (preventative or corrective) maintenance strategies and includes allocating maintenance resources, sourcing materials and properly training staff. Emergency management circumvents the planning process, but all other maintenance should be planned. The maintenance plans, i.e. the instructions for maintenance specific to the structure considered, should be developed on the basis of the design assumptions and a prognosis for the behaviour under the envisaged conditions of use during the specified service life, considering all performance requirements that need to be met. In order to prioritise work orders for risk-based maintenance planning, a work order priority matrix can be used ((REBOK, 2018) (fib MC2020, 2022)).

It is important to keep the maintenance plans flexible and develop it through a dynamic process of collecting information on operating conditions and revisiting the frequency of inspection and testing. The maintenance plan should state the types of inspection, testing and condition monitoring that have to take place, what components of the structure are to be inspected / monitored, what the frequency of the inspections should be and so on.

The provision for planned activities within the conservation plan must address the significant deterioration and damaging processes that are relevant to a structure during its service life. The maintenance plan may include:

- specification of the regime for inspection, testing and condition / structural health monitoring activities
- identification of deterioration and damage mechanisms, plus methods of estimating the degree and rate of progression;
- methods of evaluating structural and other performances against the performance requirements (criteria to be met);
- impact on the environment and the climate;
- decision-making, including selecting and implementing the LCM activities required to manage the structure, as well as undertaking any interventions which may be required to remedy non-conformity with the performance requirements;
- organisation]
- (financial) resources
- through-life management activities and the execution of maintenance works and other interventions;
- methods of documenting through-life management activities including maintenance works and other interventions.

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3.5 Classification of main maintenance strategies

A maintenance strategy indicates the approach taken in maintaining 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).

The table below provides an overview of commonly used maintenance strategies, based on (ISO-13822, 2010). The common strategies are further explained in this paragraph.

Table 3.1 – Typology of maintenance strategies (adapted from (ISO-13822, 2010))

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

3.5.1 Corrective maintenance strategy

A **corrective maintenance strategy** is also referred to as, reactive maintenance, failure-based maintenance, or as a strategy of ‘run to failure’. The measures and interventions are aimed at arresting currently active processes which are causing deterioration or damage. Typically, remedial interventions involve some form of treatment or the taking of measures after damage has become apparent, presumably involving visual indications (e.g. cracking or spalling of concrete). Such actions may be required immediately (e.g. emergency repair) or may be deferred to a suitable moment later in time (when acceptable). A corrective maintenance strategy means the asset or component is used to its maximal potential (i.e. the full life time is used) and maintenance is done only when failure demands it. This can be reviewed as a default strategy, but may not be appropriate if failure is associated with unacceptable consequences or non-optimal expenditure of means (e.g. budget).

3.5.2 Preventive maintenance strategies

Preventive maintenance strategies cover a range of maintenance strategies. Contrary to corrective maintenance, **preventive maintenance strategies** aim at taking (maintenance) action prior to failure occurring, thus avoiding the consequences of that failure. For infrastructure assets, a preventive approach to maintenance is desirable as it enables early identification of issues affecting the condition of the objects, potentially enabling early preventative action being taken to minimize the negative effect on the performance of the infrastructure and, consequently, the overall cost of ownership. A preventive maintenance strategy should be applied to objects and components thereof where it is necessary or desirable that the performance be kept above a specified minimum performance requirement. This would typically apply to cases where high levels or risks are found, and/or cases where the asset is deemed to be of critical importance. Logically, this requires knowledge on the probability of failure over time and/or use in order to determine when such (maintenance) actions are required. This is where a further distinction in maintenance strategies can be observed (fib MC2020, 2022).

In so-called **predetermined maintenance strategies** (sometimes also referred to as prescriptive maintenance), an a priori estimate is made within what timeframe or after what use failure becomes likely. Accordingly, activities set for predetermined maintenance are carried out in accordance with established intervals of time or number of units of use but

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without previous condition investigation. Intervals of times or number of units of use may be established from knowledge of the failure mechanisms of the item. Such estimates are based on databased, experience, etc. Based on this, a suitable moment for maintenance is picked (maximal use time within accepted risk levels). Maintenance interventions are thus planned accordingly.

In some cases, the probability of failure over time is hard to predict (accurately) a priori. For example, when practice shows that there can be a large spread in recorded failure rates. This hinders an effective predetermined maintenance strategy as no appropriate maintenance interval can be chosen. The time-based maintenance strategy involves the use of a time-based norm to estimate a proper timing of the measures of preventive interventions or the time period between such interventions. The main challenge is to estimate an appropriate time period (life span) as a time-based norm is such a way that it corresponds to a sufficiently low probability of failure/non-compliance for the actions being considered, typically taking them as a random variable over the period of time in question. Different preventative interventions could be undertaken at different times / frequencies i.e. based on norm set specific for a certain type of preventative intervention. A use-based maintenance strategy involves the use of a use-based norm to define when a preventative intervention should be undertaken. Implementation of the use-based norm usually requires registration of the actions which cause deterioration. An example of the use-based maintenance strategy is an approach based on monitoring of the number of load or action cycles applied to a structure. Interventions are undertaken after the registration of a certain number of load units (i.e. after registering an extreme action or after registering a predetermined measure of cumulative actions). Thus, the application of a load-dependent maintenance strategy involves a load unit norm. Similar criteria might be applied for other types of actions. The criteria and threshold values for the use-based norm are to be established beforehand as a part of setting the maintenance strategy during the design of new structures or re-design of existing structures (fib MC2020, 2022).

Condition-based maintenance strategies rely on (condition) information being obtained during use of the asset with the aim to better estimate when failure might occur, and when maintenance is required. In practice, a difference may be observed in how the information obtained during the use of the assets is used. For example, the observed condition can be compared to a set of e.g. criteria, thresholds, or limits. These criteria are determined based on the likely progression of condition or performance over time. If the observed condition is within acceptable bounds, no maintenance is performed. If the condition is not within acceptable bounds, this means maintenance is required and should be planned accordingly. This may be referred to as non-predictive condition-based maintenance, as making a case specific prediction is not being made. Predictive condition-based maintenance would then refer to a strategy where information obtained through the life cycle is used to make or update a prediction of the future condition or performance. Appropriate moments for maintenance actions are based on that prediction. The predictive condition-based maintenance is an expansion of the non-predictive condition-based maintenance. The predictive condition-based maintenance entails prescribed criteria related to one (or more) condition thresholds to enable decisions about interventions based on a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item. One of the main differences between non-predictive and predictive condition-based maintenance lies in the data being analysed. While the predictive maintenance strategy relies on combination of condition monitoring and/or inspection and/or testing and analyses the past and actual condition data to estimate future condition development, the non-predictive maintenance strategy relies on historical experience, averages, and life expectancy statistics to predict when maintenance activities will be required. The predictive condition-based maintenance strategy therefore looks for physical evidence that a failure is occurring or is about to occur. It is important to realize that this maintenance strategy is aimed at intervening before the failure occurs, on the premise that this is more economical and should have less of an impact on availability. The predictive maintenance approaches need to be underpinned by

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sound reliability principles and understanding of the phenomena. Furthermore, it should be mentioned that 'condition' may be interpreted broadly in this sense as it may include various type of information including condition, performance, properties of the asset, use, etc.

Overall, a variety of maintenance strategies can be observed that vary in the degree in which the risk event occurring is acceptable and the basis on which maintenance is determined (e.g. based on time, use, condition). What can also be observed is that the activities associated with the strategy vary. Where a corrective (failure based) strategy only entails the maintenance after failure has occurred, a condition based (predictive) strategy entails condition monitoring and prediction activities as well. Consequently, an appropriate maintenance strategy has to be chosen that provides best value for money. In a maintenance plan, it is likely that multiple strategies are in place simultaneously to cover the variety in risks and type of failure mechanisms. So as such, asset owners and managers will likely employ all these strategies in one way or another.

3.6 Principles of maintenance strategies selection

For new structures, the maintenance strategy required for the life cycle management and maintenance of infrastructure shall be considered when designing the structure. For existing structures, before taking the structure into the life cycle management and maintenance regime the maintenance strategy shall be developed on the basis of basis of the knowledge of the current structural condition of the structure and with due consideration of the prognosis for future performance. Similarly, when re-designing the structure to extend its service life or to accommodate revised performance requirements, the maintenance strategy should be developed on the basis of knowledge of the current condition of the structure, a prognosis for future behaviour and recognizing the implications of the revised performance requirements (Bigaj-van Vliet, et al., 2022).

The choice of maintenance strategy depends on various factors (and thus data and information regarding those factors) including risk level, changes of risks over time, predictability of failure, detectability of failure and costs:

- **Criticality**. The asset critically indicates the importance of an asset within a higher system (e.g. an infrastructure network). As such, it also provides an indication on the degree in which risk is accepted. In general, a risk is less acceptable where the asset is considered to be very important, thus requiring preventive action to be taken.
- **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 in risk 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 the 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 effective 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, condition-based maintenance strategy may prove useful.

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- **Feasibility of monitoring and maintenance**. The feasibility of measures should be taken into account as this may limit implementation of certain strategies. Difficulties in implementation can also be part of the feasibility, or can be expressed as additional costs.
- **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 above criteria are also shown in the flowchart below, which offers asset managers a basic structure for determining an appropriate maintenance strategy. The best choice of 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, and decreasing costs of e.g. censoring, and increasing knowledge on failure mechanisms make that (predictive) condition based maintenance strategies will likely become more a suitable strategy in the years to come. It should be noted that in some cases, no satisfying maintenance strategy may be found, in which case criteria should be reconsidered, or it may be considered useful to explore other options such as asset modification (redesign). For example, modifying an asset to become more robust, or to ensure redundancies are in place, can provide an interesting alternative in mitigating risk.

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 tailored maintenance strategies for an asset. In practice, it is usually considered effective to combine 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 an element, asset, portfolio, and network level.

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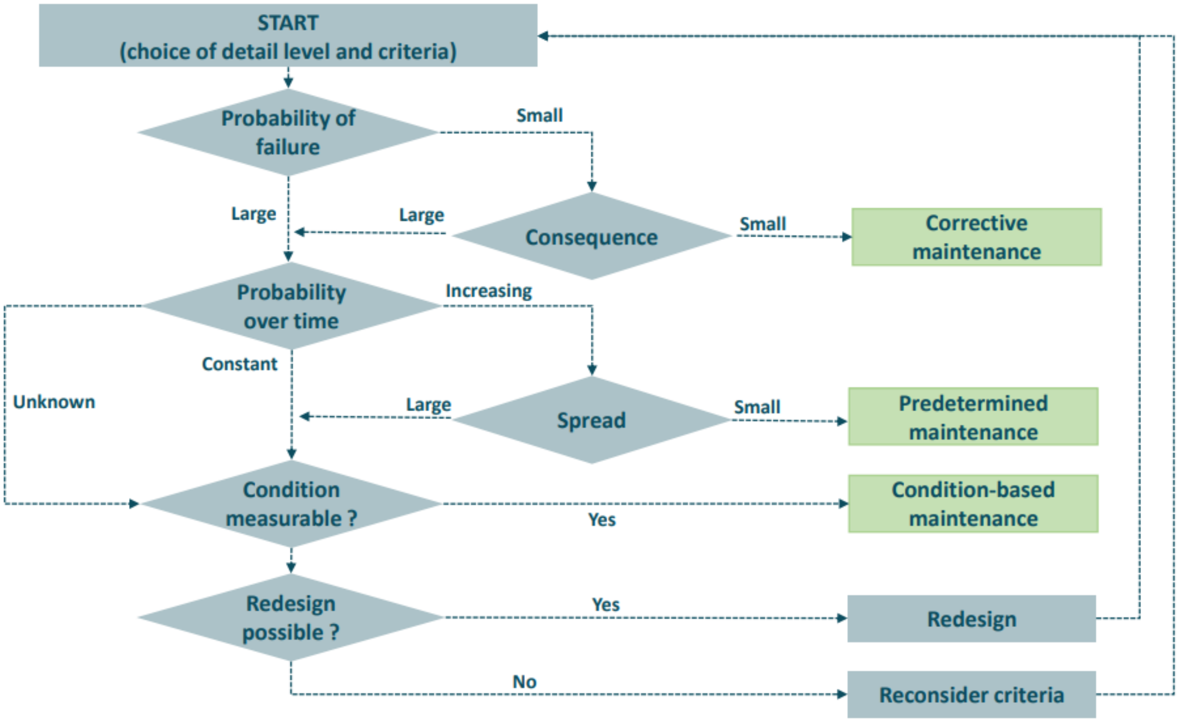

Figure 3.3 – General process of maintenance strategies selection

In context of selecting maintenance strategies, it should be kept in mind that there are situations where maintenance activities are not feasible. Such circumstances apply e.g. to parts of structures where inspection and the application of conservation measures is very difficult or not practical, or where it would be economically and/or technically difficult to undertake preventative or remedial measures (e.g. in case of foundations, where it may not be feasible to undertake inspections or conservation 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. Before this approach is adopted an appropriate review and judgment should be made of the consequences of failure and the feasibility, cost and environmental impacts of undertaking maintenance works / performing interventions in this manner. Should significant damage or deterioration occur (and be detected), a potentially difficult and expensive reactive / remedial intervention could be required. In addition to cost, such major works are also likely to have significant implications in terms of environmental impact.

If the changes over time in the performance of the structure after the intervention during its remaining service life due to actions and environmental influences cannot be predicted, the corresponding uncertainties may be mitigated by appropriate measures such as:

- select materials, structural specifications and construction methods for the intervention such that there will not be an unacceptable decline in the performance of the structure over time.
- select materials, structural specifications and construction methods for the intervention such that the decline in performance will only be to the extent predictable with existing technologies/intervention methods.
- devise measures to conduct inspections, maintenance or monitoring during the remaining service life after the intervention to ensure that the performance will not go below performance requirements.

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4 Maintenance Strategies and Limits

4.1 General

Infrastructures and structures are assessed mainly based on condition classification, which ranges from fully functional (new), good (functional/satisfactory), adequate (functional-/requiring minor intervention), poor (functional/requiring major intervention), and deficient (non-functional). The safety assessment and maintenance decision process will consider the impact of the condition rating of the structures as part of the structural diagnosis process.

In addition, life cycle analysis methods are used to evaluate new and existing structures and for maintenance strategies. Management systems that capture various degradation processes are very often used in conjunction with such life cycle analyses.

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. 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 at deterministic and probabilistic levels.

Each construction, during its life cycle, will face with deterioration 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, several design procedures based on the prediction of deterioration that will likely act on the structure need to be characterised and defined for instance using of performance indicators for the present and future structural conditions on deterministic and probabilistic level. It is known that management systems are supported in Quality Controls (QC) (see chapter 5) plans which in turn are supported by performance indicators. Therefore, it is extremely important to analyse such indicators in terms of used assessment frameworks (e.g. what kind of equipment and software is being used), and in terms of procedures and thresholds for the condition state classification.

Therefore, maintenance concepts have been introduced and applied by almost all countries worldwide to capture the condition of important infrastructures or structures. However, the strategies used differ in many aspects, such as the time intervals, the minimum maintenance limits, the use of performance indicators or key performance indicators, etc.

In this section, the aim is to show in the first part the maintenance strategies, their positive aspects and their limitations. In a further step, the strategies used in today's practice and their characteristics are presented and in a third part the predictive methods that already exist in practice but have not yet been fully implemented.

It should be noted that this Chapter 4 mainly refers to bridges, although some parallels to tunnels are also valid.

4.2 Basic considerations for maintenance strategies and limits

When the condition performance or reliability level is in a deteriorated state, the maintenance options need to be considered for each structure below the threshold. Usually three main options are considered, from do nothing, to minor repair and finally major repair or reconstruction.

The chosen maintenance strategy will have direct and indirect impacts, such as direct costs related to the maintenance activity and indirect costs caused by maintenance activities and borne by the society, such as user delay and environment impacts. The direct impacts are

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regularly calculated as owners' cost and will represent economy performance aspects of the structure. Other impacts are in categorized as availability and environmental aspects. Traffic safety is also one of the other performance aspects, which can be quantified at two periods, one during the regular operation and the other during maintenance activities. Related to these maintenance aspects, Figure 4.1 provides an overview between multiple performance goals/thresholds, indicators and maintenance planning.

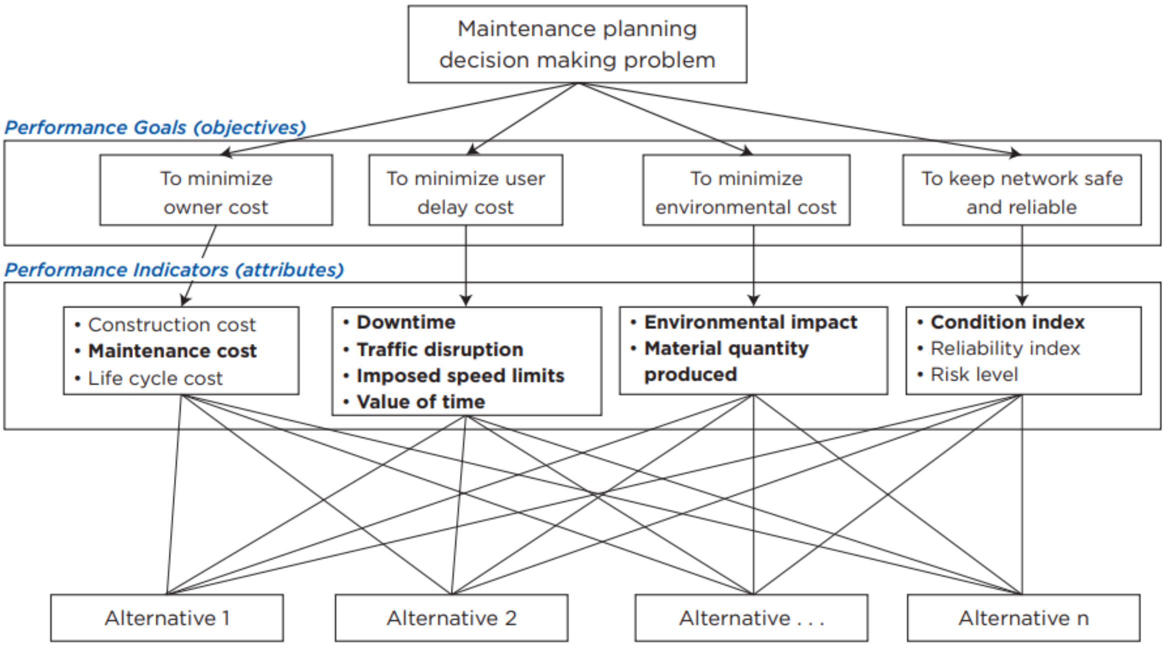

Figure 4.1 – Linking multiple performance goals (called multiple objective) to performance indicators, (adapted from (Rashidi & Lemass, 2011))

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 maintenance strategies. Moreover, in some European countries preventive maintenance uses both condition-based and predetermined 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. The minimum condition requirements associated with maintenance thresholds are frequently not clear or are variable over time.

Maintenance strategies have already been discussed in detail in Chapter 3. This section provides a brief overview of the completeness of the strategies and how they fit together.

Figure 4.2 shows a rough overview of the maintenance strategies commonly used in engineering, such as Corrective Maintenance, Preventive Maintenance, and Predictive Maintenance. Further maintenance processes can be distinguished in the individual strategies, as can be seen in this figure. In general, a distinction can be made in:

- Corrective maintenance
- Preventive maintenance
- Condition based maintenance
- Predictive maintenance.

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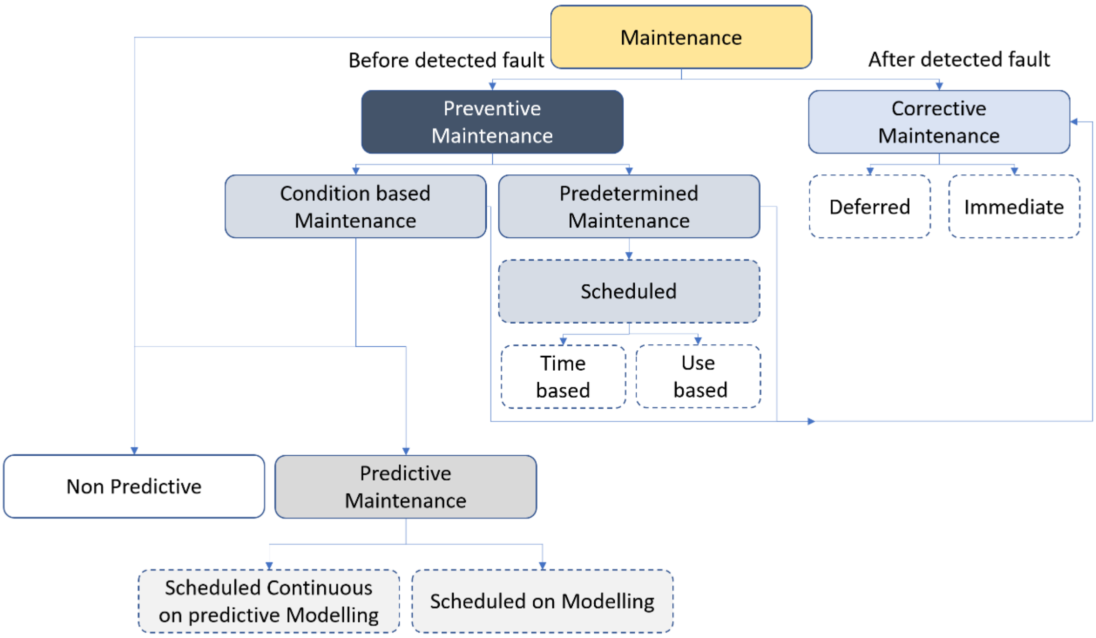

Figure 4.2 – Maintenance strategies applied in engineering practice

4.2.1 Maintenance Strategies

As shown in Figure 4.2, a distinction can be made at the top level between preventive maintenance and corrective maintenance strategies. In addition, in the branch of Preventive Maintenance, a distinction can be made between Condition Base Maintenance and Predetermined Maintenance. Furthermore, a condition-based maintenance can be extended with a Predictive Maintenance concept, as shown in Figure 4.2 on the right bottom side.

Details of the strategies and their *pros* and *cons* have already been discussed in chapter 3. The selection of the most appropriate maintenance strategy (or multiple strategies for each associated risk scenario) can be performed according to a reliability and/or risk-based approach. The reliability centred and risk centred maintenance selection, will be examined in more detail as a further consequence here.

4.2.2 Reliability centred maintenance

Details associated with this strategy and its elements can be found in Chapters 3, 7, 8 of Im-SAFE report D3.1 (Bigaj-van Vliet, et al., 2022). The following is a summary showing the important aspects.

Reliability centred maintenance (RCM) is a system maintenance strategy (e.g. using the reliability level of a system) that is implemented to optimize the maintenance program of a e.g. infrastructure owner or its structures. The final result of an RCM program is the implementation of a specific maintenance strategy focusing on the failure modes of the assets. The maintenance strategies are optimized e.g. with respect to intervals of inspections, maintenance tasks, reactive/proactive maintenance etc. so that the productivity of the infrastructure is maintained using cost-effective maintenance techniques. There are four principles that are critical for a reliability centred maintenance program:

- Preserve system function (as primary objective)
- Identify failure modes that can affect the system function
- Prioritize the failure modes

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- Select applicable and effective tasks to control the failure modes

An effective reliability centred maintenance implementation examines the structure as a series of functional systems, each of which has inputs and outputs contributing to the success of the facility. It is the reliability, rather than the functionality, of these systems that are considered. The questions that need to be asked for each asset are:

- What are the functions and desired performance standards of each asset?
- How can each asset fail to fulfil its functions?
- What are the failure modes for each functional failure?
- What causes each of the failure modes?
- What are the consequences of each failure?
- What can and/or should be done to predict or prevent each failure?
- What should be done if a suitable proactive task cannot be determined?

Reliability centred maintenance identifies the zones of the structure that are most critical and then seeks to optimize their maintenance strategies to minimize system failures and ultimately increase reliability and availability. The most critical zones are those that are likely to fail often or have large consequences of failure. With this maintenance strategy, possible failure modes and their consequences are identified; all while the function of the structure is considered. Cost-effective maintenance techniques that minimize the possibility of failure can then be determined. The most effective techniques are then adopted to improve the reliability of the facility as a whole.

Advantages of reliability centred maintenance:
Implementing RCM increases equipment availability and reduces maintenance and resource costs.

Disadvantages of reliability centred maintenance:
RCM does not readily consider the total cost of owning and maintaining an asset. Additional costs of ownership, like those considered during maintenance, are not considered, and are therefore not factored into the maintenance considerations.

Implementing reliability centred maintenance
There are several different methods for implementing reliability centred maintenance that are recommended, summarized in the following 7 steps.

Step 1: Selection of structures for RCM analysis
The first step is to select the component of structure for reliability centred maintenance analysis. The component/structure selected should be critical in terms of its effect on operations, its previous costs of repair, and previous costs of preventive maintenance.

Step 2: Define the boundaries and function of the systems that contain the selected component/structures. The component/structure belongs to a system that performs a crucial function. The system can be large or small, but the function of the system, and its inputs and outputs, should be known.

Step 3: Define the ways in which the system can fail (failure modes). In step 3 the objective is to list all of the ways that the function of the system can fail.

Step 4: Identify the root causes of the failure modes
With the help of operators, experienced technicians, RCM experts and structural experts, the root causes of each of the failure modes can be identified.

Step 5: Assess the effects and the fragility of the various failure modes

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In this step, the effects of each failure mode are considered. Component/structural failures may affect safety, operations, and other equipment. The criticality of each of these failure modes can also be considered.
There are various recommended techniques that are used to give this step a systematic approach. These include:

- Failure modes and effects analysis (FMEA)
- Failure, mode, effect and criticality analysis (FMECA)
- Hazard and operability studies (HAZOPS)
- Fault tree analysis (FTA)
- Risk-based inspection (RBI)

The most important failure modes will be determined at the conclusion of this systematic analysis. Importantly, the failure modes that are retained include only those that have a real probability of occurring under realistic operating conditions.

Step 6: Select a maintenance and monitoring tactic for each failure mode
At this step, the most appropriate maintenance tactic for each failure mode is determined. The maintenance tactic that is selected must be technically and economically feasible.

- Condition-based maintenance is selected when it is technically and economically feasible to detect the onset of the failure mode.
- Time or usage-based preventive maintenance is selected when it is technically and economically feasible to reduce the risk of failure using this method.
- For failure modes that do not have satisfactory condition-based maintenance or preventive maintenance options, then a redesign of the system to eliminate or modify the failure mode should be considered.
- Failure modes that were not identified as being critical in Step 6 may, at this stage, be identified as good candidates for a run-to-failure maintenance schedule.

Step 7: Implement and then regularly review the maintenance and monitoring tactic selected. Importantly, the RCM methodology will only be useful if its maintenance recommendations are put into practice. When that has been done, it is important that the recommendations are constantly reviewed and renewed as additional information is found.

The impact of reliability centred maintenance
Since the end product of a well-executed RCM analysis is that an appropriate maintenance strategy will be selected for each component of a structure, the impact is an overall improvement of reliability. RCM aims to reduce costs, improve safety, and eliminate maintenance tasks that are not effective or appropriate for a given component of a structure. Implementing RCM processes allows to avoid a one-size-fits-all mindset that could waste valuable time and resources.

4.2.3 Risk centred maintenance

Risk centred maintenance (RiCM) is also a corporate-level maintenance strategy that is also implemented to optimize the maintenance program of a e.g. infrastructure owner or its structures. The final result of an RiCM program is also like for the RCM the implementation of a specific maintenance strategy on each of the assets of the facility. The maintenance strategies are optimized so that the productivity of the infrastructure is maintained using cost-effective and risk reduced maintenance techniques.

More detailed information associated with this strategy and its elements can be found in Chapters 3, 7, 8 of IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

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4.3 Maintenance in Engineering Practice

The aim of this section is to show the maintenance strategies/routines/limits 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.

4.3.1 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.

Maintenance strategy and limits: 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 survey.

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:

- Unusual changes to the structure,
- Damage to the road surface including lateral beams,
- Damage to equipment such as transition structures, railings, guard rails, noise protection devices, snow and spray protection devices,
- Damage to drainage facilities,
- Damage to embankments,
- 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.

Time intervals: As shown in Figure 4.3, routine monitoring is performed every 2 to 12 months according to the (COST TU1406) surveys. These intervals were determined according to the (COST TU1406) information 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.

4.3.2 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, 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.

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Maintenance strategy and limits: 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 and Annex 2 of IM-SAFE project report D1.3 (Hoff, et al., 2021).

Time intervals: 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 4.4. 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 4.4, are more or less closely related to the routine monitoring considerations and the associated time intervals are determined according to the information from the (COST TU1406) surveys and the information based on the occurring damages, climatic conditions, traffic load and winter maintenance, the available budget and manpower (see Annex 2 of IM-SAFE project report D1.3 (Hoff, et al., 2021)).

Based on the result of the inspection, the following is in general documented:

- Condition of the object compared with the last finding,
- Usability of the traffic route in the previous scope depending on the condition of the object,
- Newly detected defects/damage,
- Immediate measures based on the detected defects/damage,
- Arrangement of an inspection, if defects/damage cannot be assessed in the course of the inspection,
- Special instructions for the next inspection/testing,
- Year of next inspection.

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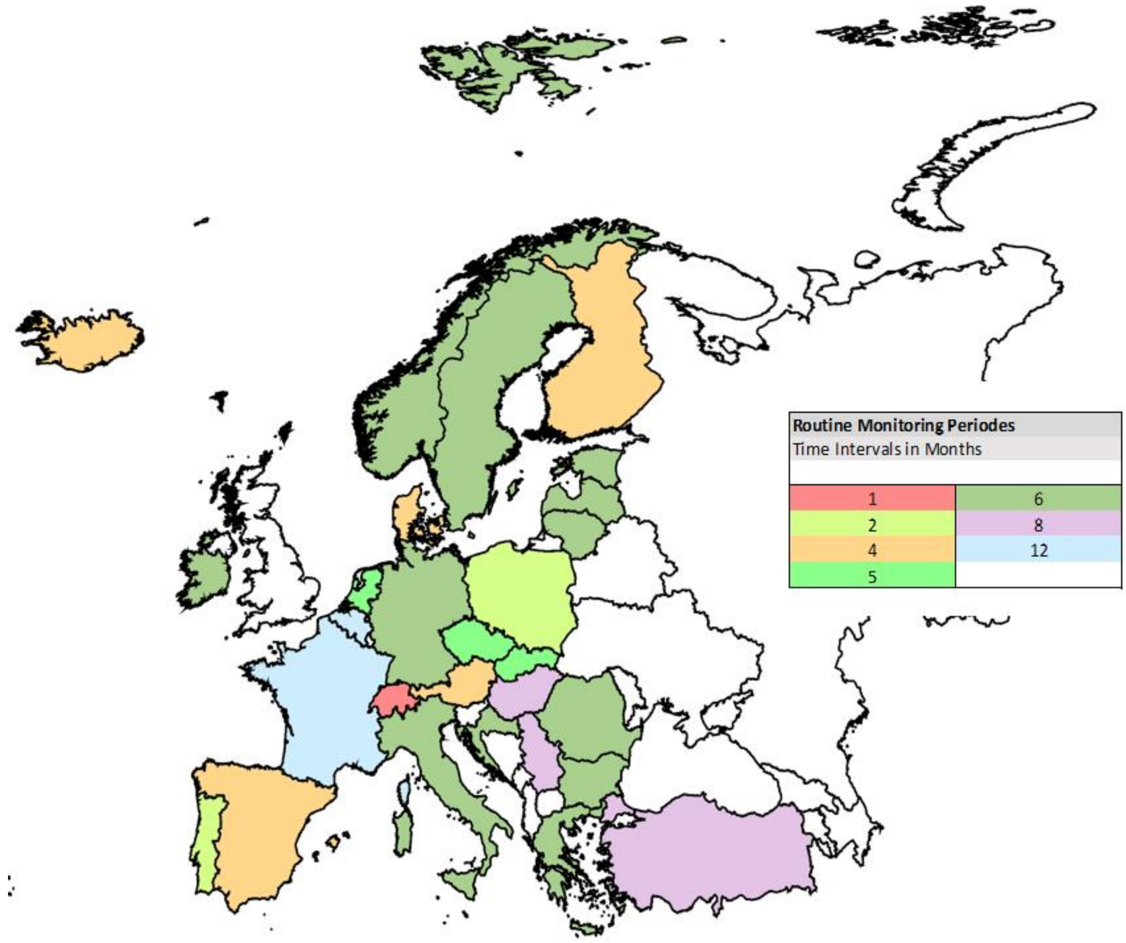

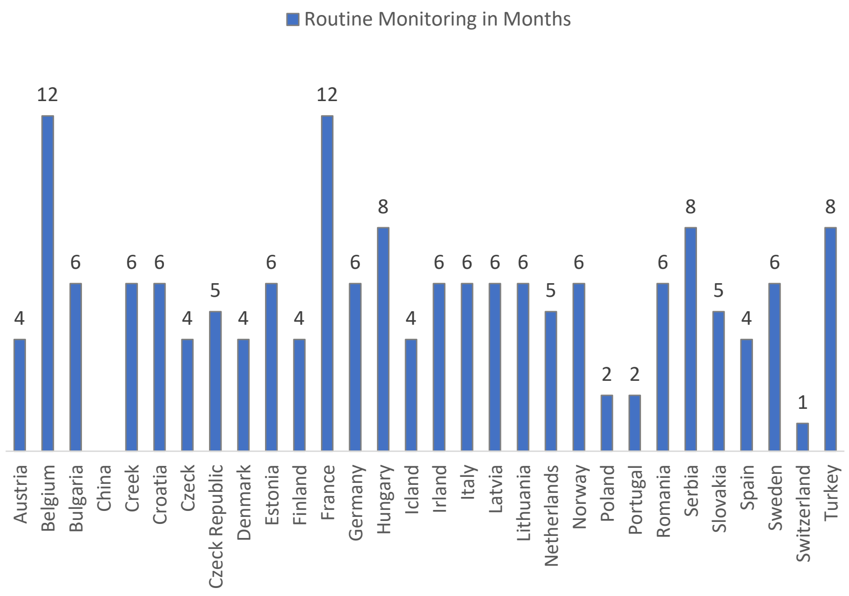

Figure 4.3 – Time intervals between routine monitoring according to the surveys in (COST TU1406) and Annex 2 of IM-SAFE project report D1.3 (Hoff, et al., 2021) (routine monitoring in the sense of detection of gross damage and conspicuous changes, as far as they are visible from a vehicle when driving over infrastructures)

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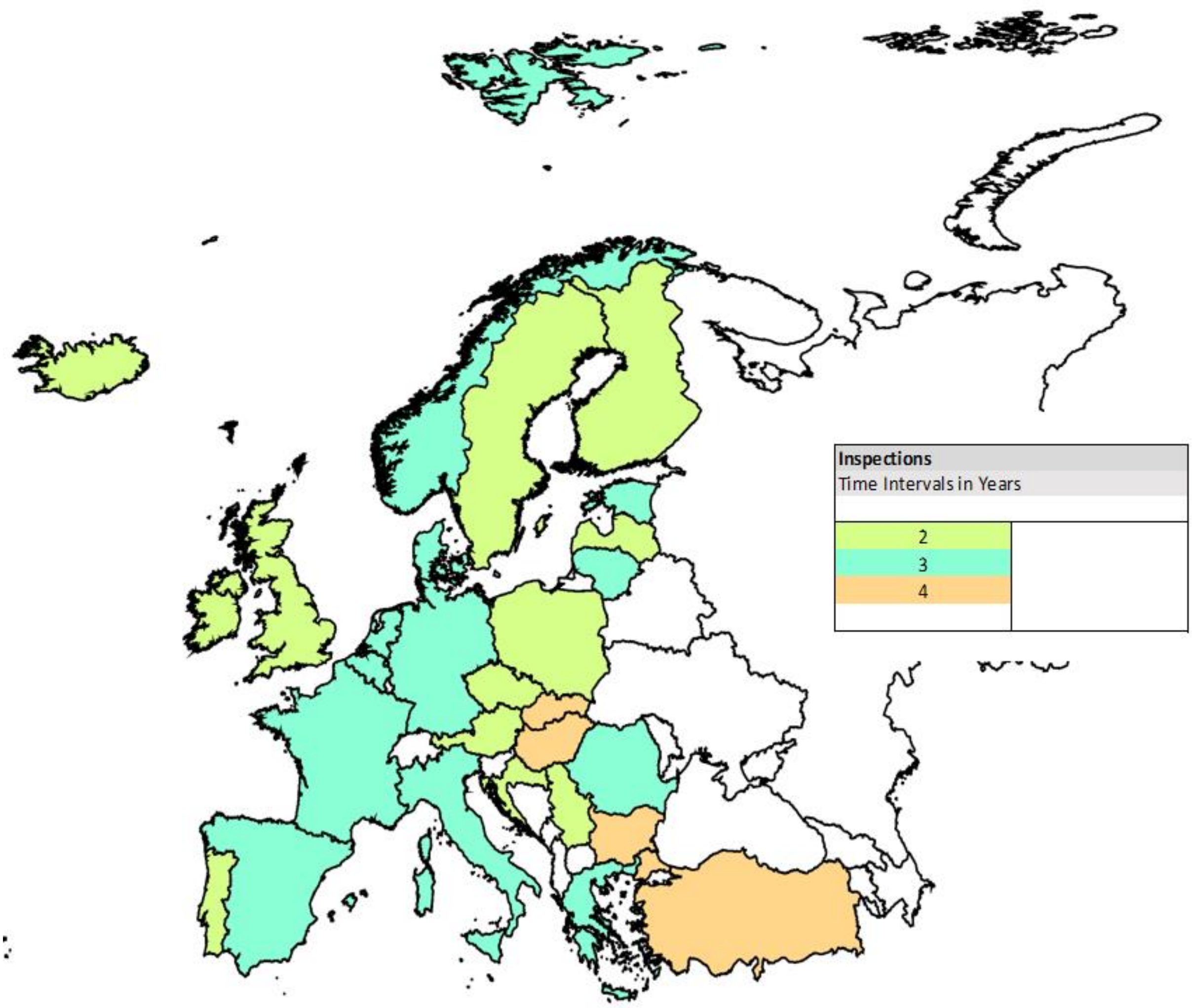

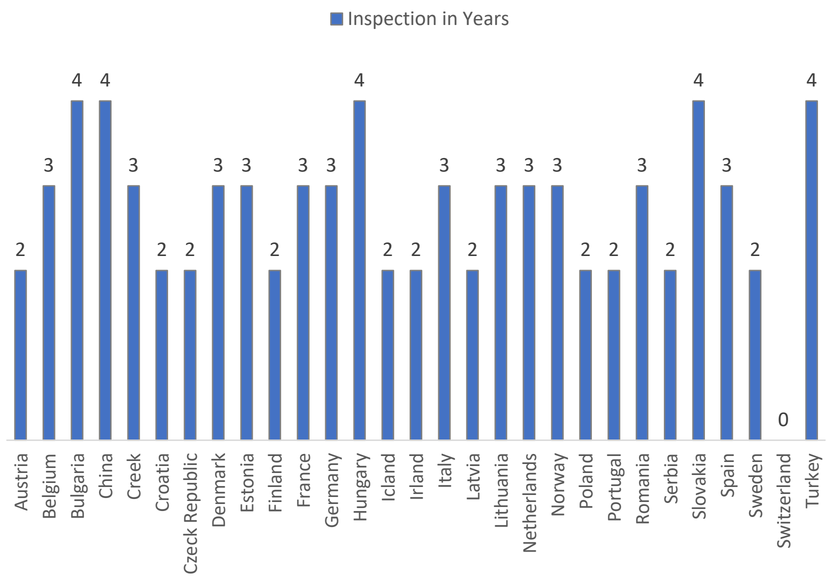

Figure 4.4 – Time intervals between inspections according to the surveys in (COST TU1406) and Annex 2 of IM-SAFE project report D1.3 (Hoff, et al., 2021)

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4.3.3 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.

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.

Maintenance strategy and limits: 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 (COST TU1406)WP1.

Time intervals: Structures such as bridges are usually inspected at intervals of about six years, see Figure 4.5, 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 4.5 displays the outcome of the inspection interval studies from the (COST TU1406) surveys and Annex 2 of IM-SAFE report D1.3 (Hoff, et al., 2021). The reasoning behind the interval determinations is similar to that given in section 4.3.1 and section 4.3.2.

Condition Classes: The number of condition classes of the CBM strategies handled in each individual countries are shown in Figure 4.6. More details on the condition classes and the meaning can be found in Annex 2 of IM-SAFE report D1.3 (Hoff, et al., 2021) and in section 4.3.4 of this report.

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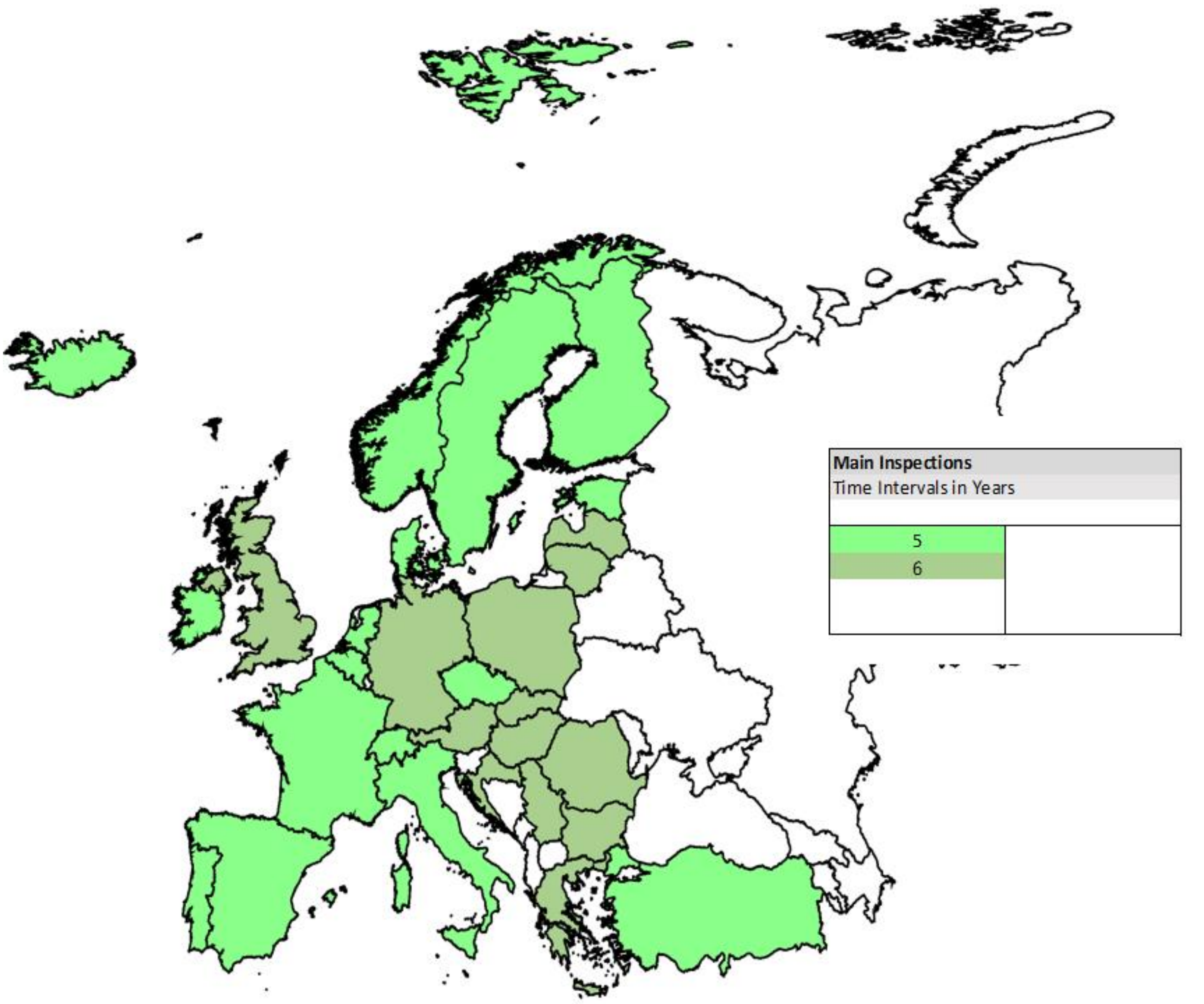

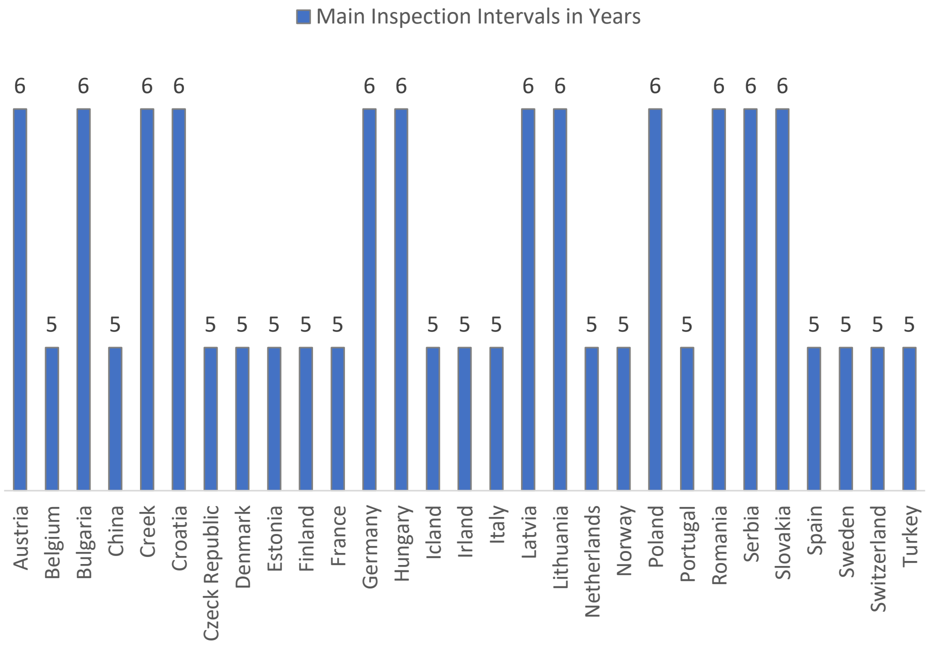

Figure 4.5 – Time intervals between main inspections according to the surveys in (COST TU1406) and Annex 2 of IM-SAFE report D1.3 (Hoff, et al., 2021)

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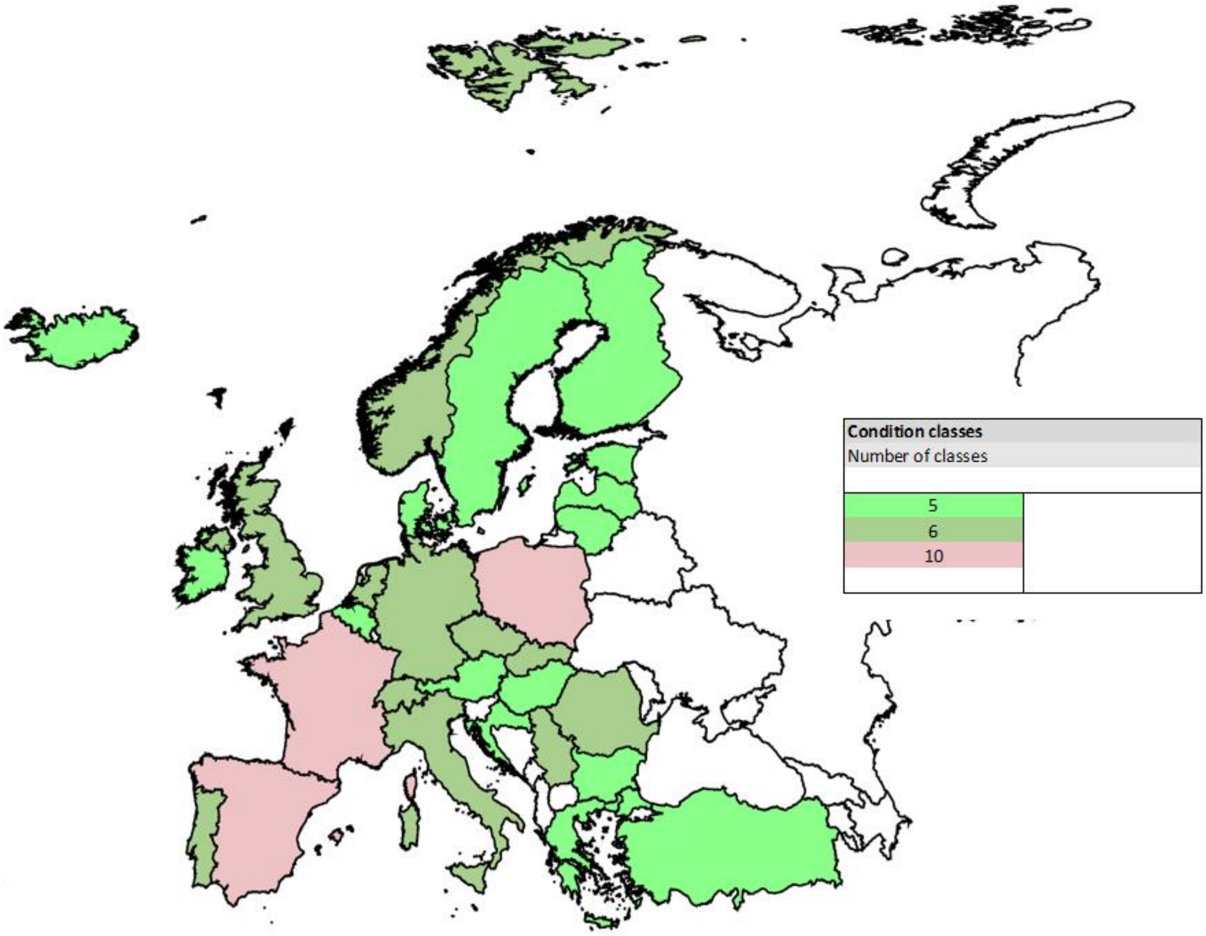

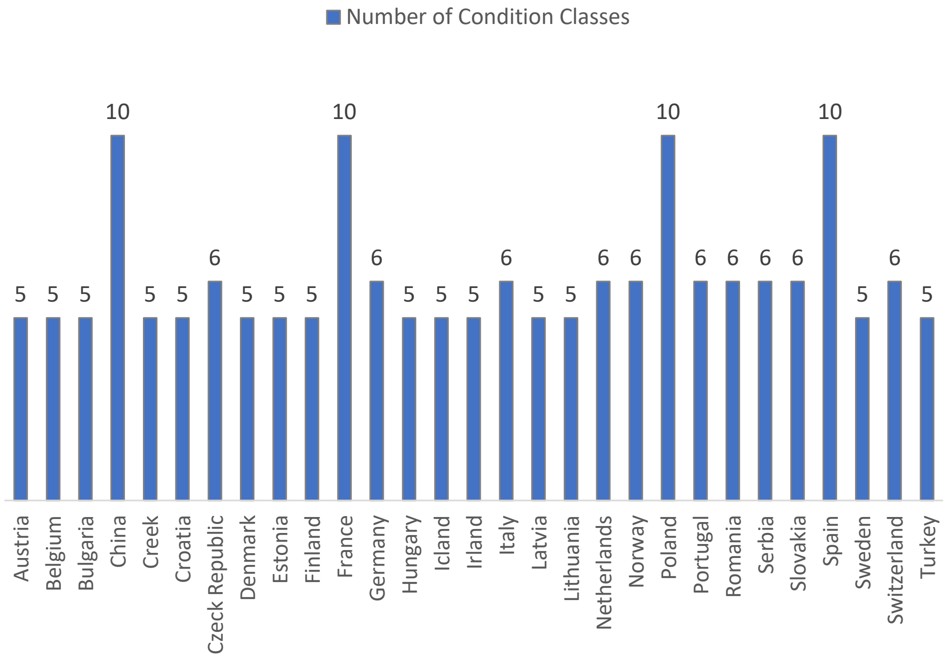

Figure 4.6 – Number of Condition Classes of CBM strategies according to the surveys in *(COST TU1406)* and *Annex 2 of IM-SAFE report D1.3 (Hoff, et al., 2021)*

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4.3.4 CBM Countries Excerpt

The following trends, shown in Fig 4.7, applied in Europe have been identified by relevant stakeholders during local and Pan-European workshops of the established Community of Practice (CoP).
Austria has been chosen as a representative example from Europe in Figure 4.6. These surveys conducted in D1.1-Annex 2 allow a quantitative evaluation.
The surveys show that the preventive maintenance strategy (condition-based (non-predictive) and predetermined time-based maintenance strategy, see [4.4] to [4.5]) in the European countries are predominantly used in the good condition classes. The corrective maintenance strategy is solely used in the bad condition classes and for structures at the end of their service life. The usage based preventive maintenance is partly used for wear parts such as expansion joints.

A predictive maintenance strategy is only used in exceptional cases for special structures or significant buildings and decision processes. Nevertheless, as presented above, the risk centred strategy was defined as trend predictive maintenance by the CoPs. Which should also be in the sense of the owners after D1.1.

Overview condition survey intervals

Country	Checking	Inspection	Assessment
Austria	4 Months	2 Years	6 Years (12)
Germany	6 Months	3 Years	6 Years
Switzerland	ongoing	As needed	5 Years
USA	6 Months	2 Years	5 Years
Japan	laufend	2 Years	5 Years
France	12 Months	3 Years	6 Years
England	As needed	2 Years	6 Years
Sweden	6 Months	3 Years	6 Years
South Africa	12 Months	As needed	5 Years

Guidelines bridge survey in Austria (*

	Checking	Inspection	Assessment
Monitoring	4 months	2 years	6 years (12)
Goals	Operational reliability & user safety	Changes in condition since last assessment	Extensive visual survey & measurement
Methods	Check for visual defects & changes	Visual survey with standard form	Extensive documentation
Responsi-bility	Road staff (operator)	Experienced engineers (operator)	Licensed civil engineer (extern)
Results	Short report major defects	Documentation of condition changes	Report on reliability & safety

*) Not for all Assets

Different survey types in Austria

Checking: Visual checking regarding obvious changes in bridge condition (check-list) at least e.g. every 4 months in Austria by road operators

Inspection: Visual assessment regarding bridge and bridge element condition with comprehensive check-list and photos at e.g. least every 2 years in Austria by bridge inspection people from operator

Assessment: Accurate determination and rating of bridge condition with time horizon for necessary maintenance and rehab works at least e.g. every 6 years in Austria by external certified civil engineers with report (four eyes principle)

Classification in Austria

Grading	Restriction	Damages	Measures
5 - very poor	Structural or functional damage	Extreme severe defects	Immediate repair/rehab
4 – poor	Reduced performance or substantial defects	Severe defects	Short term repair/rehab required < 3a
3 – fair	Reduced functional performance	Moderate defects	Medium term repair action required < 6a
2 - good	No restrictions	Minor defects	Maintenance
1 - very good	No restrictions	No defects	No action

Figure 4.7 – CBM countries excerpt in current practice

Daily practice
The surveys according to D1.1 and the elaborations in this chapter show the following daily practice:

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- In the European countries, condition-based and predetermined time-based preventive maintenance strategies are predominantly used. These preventive strategies are applied in the classes characterizing good and average structural conditions.
- The corrective maintenance strategy is applied mainly in the classes characterizing the bad conditions but also for structures in the last range of service life.
- The predetermined use-based preventive maintenance is partially applied for wearing parts such as for roadway expansion joints, bridge equipment or bearings.
- Predictive maintenance strategy so far is used only in exceptional cases for special structures or significant structures and decision processes.

Recommendations for maintenance strategies
The established practice in European countries is the combination of preventive maintenance strategies, which are applied in good to medium conditions, with corrective maintenance, which is applied in poor conditions and at the end of the service life. This can be considered as a very good basis.

The extension of this combination with the Reliability Centred Maintenance strategies, explained in the following sections, allows on the one hand a further systematization and optimization of maintenance and on the other hand also the direct integration of the Data based Assessment methods, see D3.2 Ch 8. Furthermore, the Reliability Centred Maintenance strategies allow an effective integration and application of the Predictive Maintenance strategies.

4.4 Maintenance- Assessment phases

In (Bigaj-van Vliet, et al., 2022) [9.2], a proposal was made for the implementation of performance indicators and key performance indicators in assessment phases. According to section 9.2 of (Bigaj-van Vliet, et al., 2022) breaking down the performance assessment of a structure or any other facility into a minimum of three phases is reasonable. Figure 4.8 presents these phases in a flow chart. This approach can be put into context with the maintenance strategies.

4.4.1 Phases

Ad. Phase I: *Preliminary assessment* (*Condition assessment - Visual inspection*)
The purpose of 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 Indexes (KPRs) for the strategic asset management and budget allocation. The performance evaluation shown in Figure 4.8 is based on anomaly detection and leads to the KPR level or, in case of an insufficient condition, to phase II. In this Phase I, the following maintenance strategies are generally used, as outlined in Chapter 3.

- 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)

Ad. Phase II: *Detailed investigations* (*Detailed Inspection, testing and monitoring*)
Structural investigations and updating of information are typical of Phase II – it comprises detailed inspection, testing and monitoring among others. 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. Performance indicators or observations in these phases are

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mainly received from detailed inspection, testing and monitoring, see Figure 4.8. In this Phase II, the following maintenance strategies are generally used, as outlined in Chapter 3.

- 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)

Ad. Phase III: *Assessment and prediction by advanced analysis* (*Structural Health Monitoring (SHM) und 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 (see Figure 4.8) 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 this phase, 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 this Phase III, the following maintenance strategies are generally used, as outlined in Chapter 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)

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Table 4.1 - Maintenance Strategies used in Phase I based on the surveys in (COST TU1406) and IM-SAFE project report report D1.3 (Hoff, et al., 2021).

	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 States	+	+	o
				Poland	o	+	o				

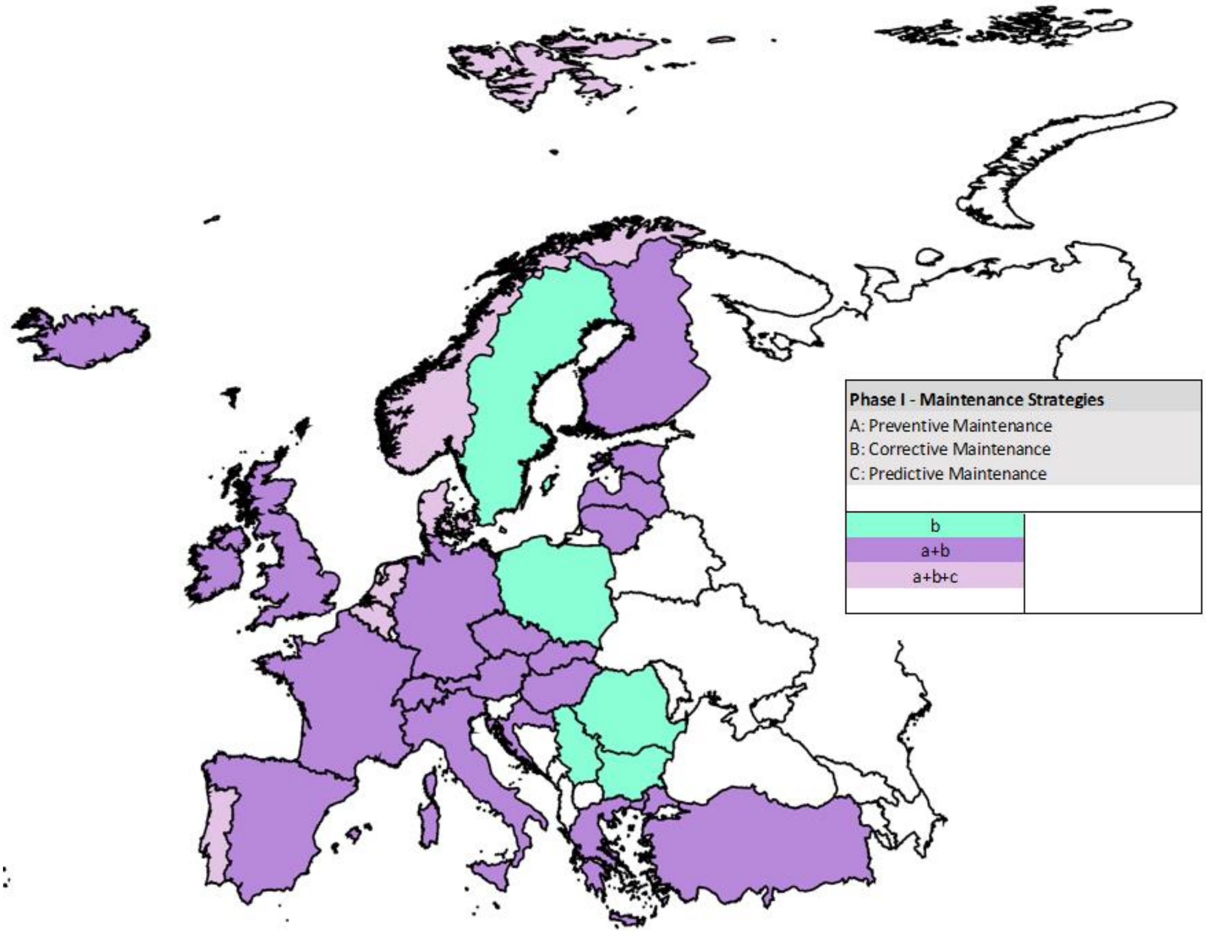

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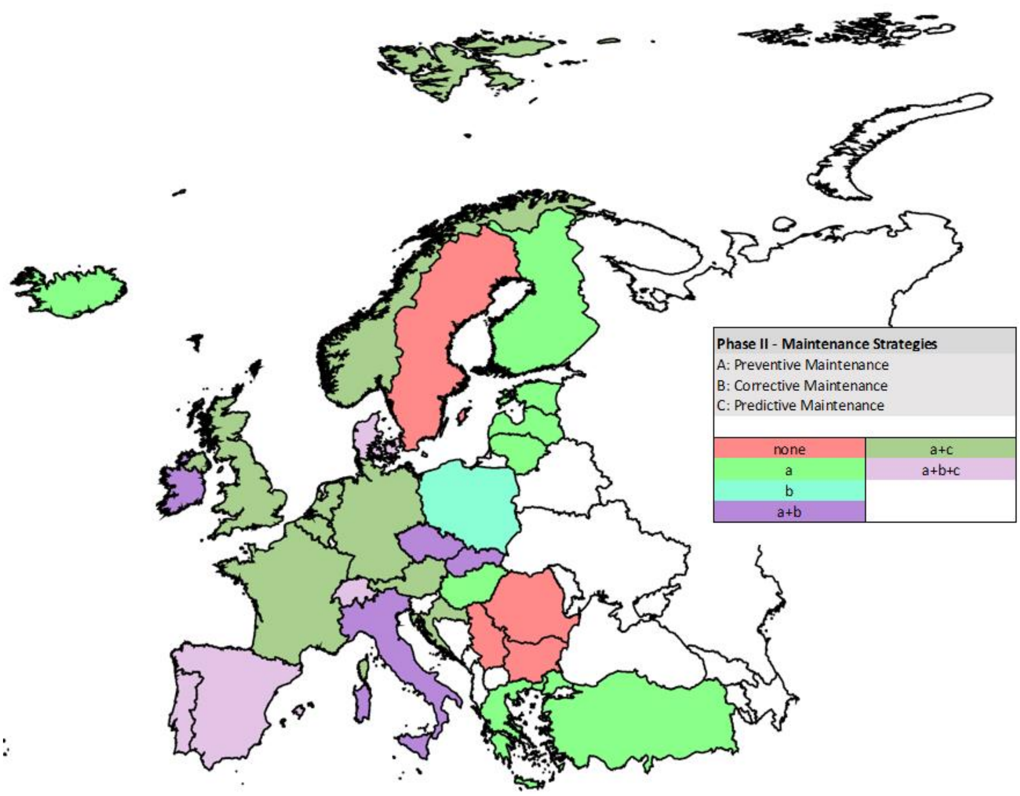
Table 4.2 – Maintenance Strategies used in Phase II based on the surveys in (COST TU1406) and IM-SAFE project report D1.3 (Hoff, et al., 2021).

	Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M
Austria	+	0	+	France	+	0	+	Portugal	+	+	+
Belgium	+	0	+	Germany	+	0	+	Romania	o	0	o
Bulgaria	o	0	0	Hungary	+	0	0	Serbia	o	0	0
China	+	0	0	Icland	+	0	0	Slovakia	+	+	0
Creek	+	0	0	Irland	+	+	0	Spain	+	+	+
Croatia	+	0	+	Italy	+	+	0	Sweden	o	0	0
Czeck Republic	+	+	0	Latvia	+	0	0	Switzerland	+	+	+
Denmark	+	+	+	Lithuania	+	0	o	Turkey	+	0	o
Estonia	+	0	0	Netherlands	+	0	+	United Kingd	+	0	+
Finland	+	0	0	Norway	+	0	+	United State:	+	0	+
				Poland	o	+	0				



4.4.2 Thresholds

With regard to structural performances, in context of limit state design, performance criteria are the threshold values that describe for each limit state the conditions to be fulfilled; in the reliability-based approach the performance criteria are established by limit state functions with associated reliability targets for the defined reference period.

In fact, IM-SAFE project defines “threshold” as a boundary set to compare with different measurable characteristic of a structural components and/or structural members, corresponds to the probability that the component and/or structural members will not meet specific performance requirements within a specific period of time. Hence, threshold values should be consistent with the ultimate or serviceability requirements and, additionally, consider the continuously increasing loss of function due to the damage response characteristics of the structures. In this respect, single events which can result in considerable damage at the structure, such as those due to traffic loads (e.g. heavy traffic, accidental impact, etc.) or environmental actions (e.g. storm, floods, earthquakes), should be recorded and analysed in order to identify possible damage and set threshold values. The acceptable threshold limits,

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however, should consider both economic and sustainability costs related to the loss of functionality.

In order to maintain a prescribed performance level, it is possible to distinguish between:

- Attention thresholds
- Alarm thresholds

Their exceedance may be considered as a trigger for decisions regarding:

- evaluation of residual service life
- assessment of the actual structural safety based on the reliability index β
- implementation of maintenance plans based on the actual condition of the structure.

Hence, based on the actual reliability level of the structure, maintenance and/or monitoring actions to be taken are to be scheduled, for instance the repetition of inspections and analysis of monitoring data, or an increase in their frequency.

Generally, threshold values may be gathered from applied codes and guidelines or may be determined based on experience, measurements, or calculations. When deciding about the maintenance, though, there is no uniform and generally adopted European approach to define and rate 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 constantly increasing number of European countries preventive maintenance strategies 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.

In case of monitoring, the measured values should be compared to threshold values which are to be set based on experience or on specific predictive models.

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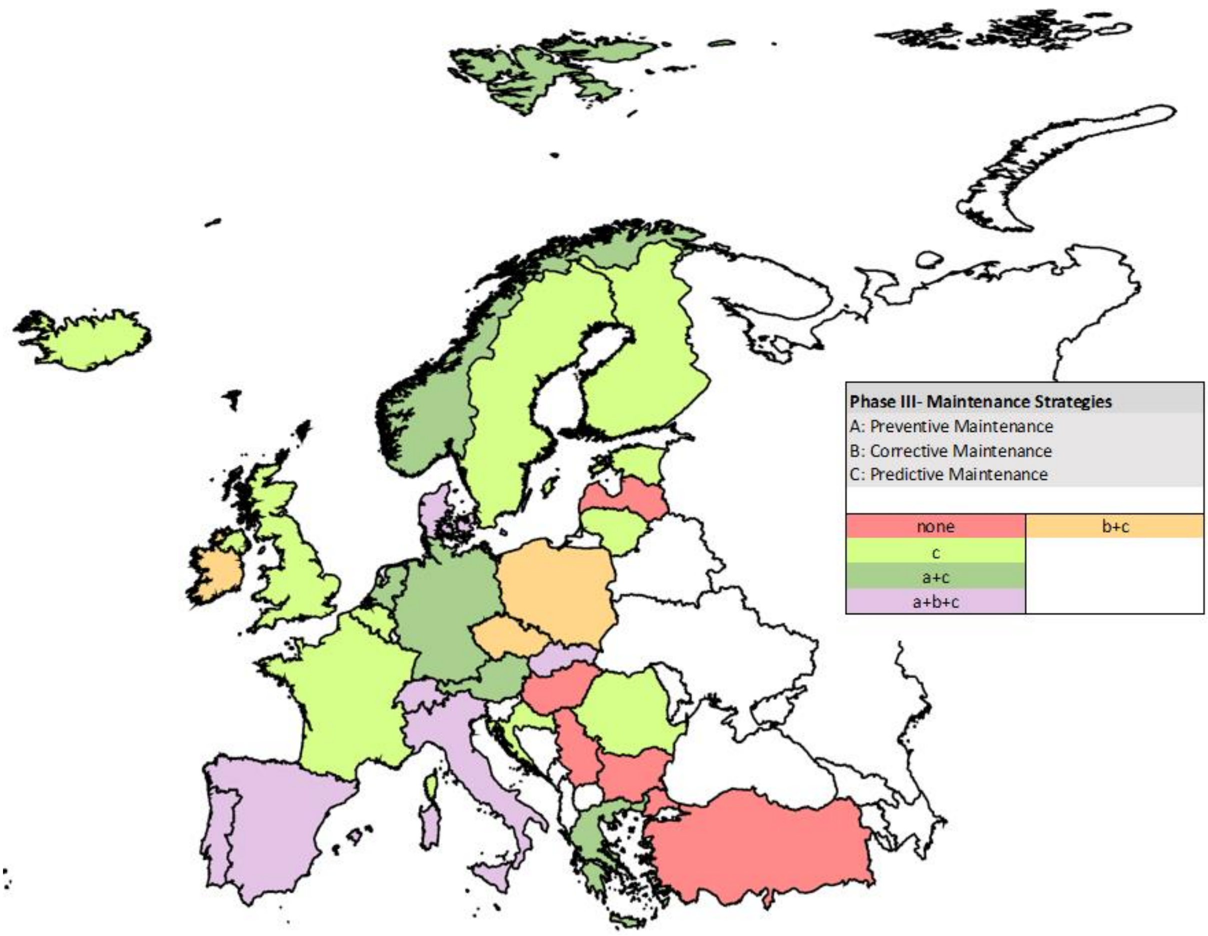
Table 4.3 – Maintenance Strategies used in Phase III based on the surveys in (COST TU1406) and IM-SAFE project report D1.3 (Hoff, et al., 2021).

	Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M		Prev.-M	Corr.-M	Pred.-M
Austria	+	0	+	France	0	0	+	Portugal	+	+	+
Belgium	0	0	+	Germany	+	0	+	Romania	0	0	+
Bulgaria	0	0	0	Hungary	0	0	0	Serbia	0	0	0
China	+	0	+	Icland	0	0	+	Slovakia	+	+	+
Creek	+	0	+	Irland	0	+	+	Spain	+	+	+
Croatia	0	0	+	Italy	+	+	+	Sweden	0	0	+
Czeck Republic	0	+	+	Latvia	0	0	0	Switzerland	+	+	+
Denmark	+	+	+	Lithuania	0	0	+	Turkey	0	0	0
Estonia	0	0	+	Netherlands	+	0	+	United Kingd	0	0	+
Finland	0	0	+	Norway	+	0	+	United State:	+	0	+
				Poland	0	+	+				



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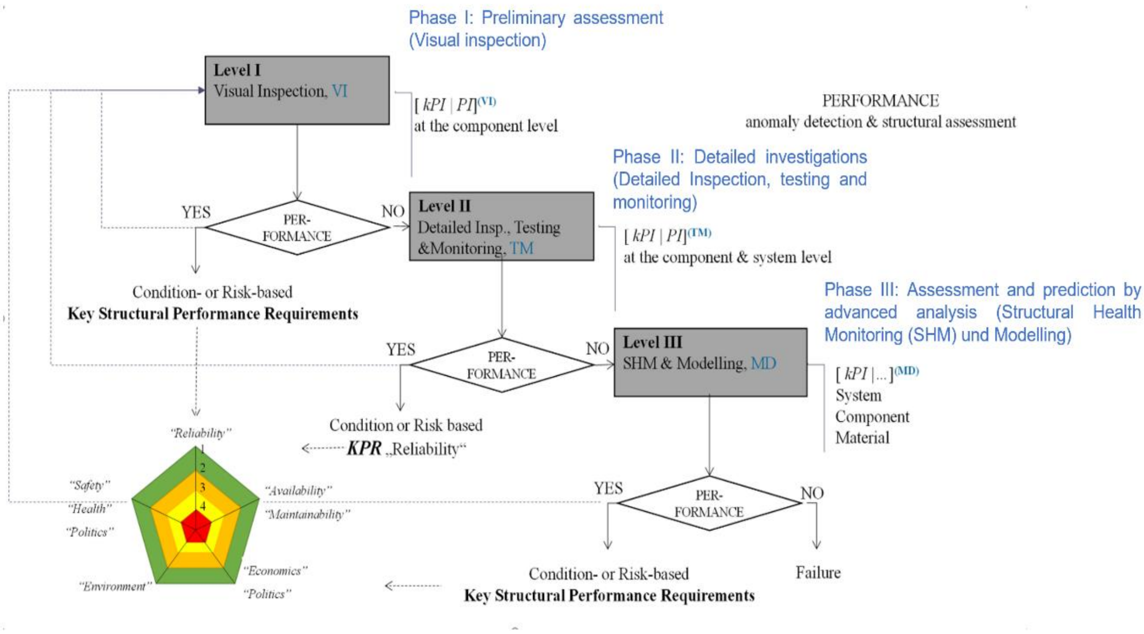

Figure 4.8 – Performance assessment according to the different inspection levels (Phase I Visual Inspections; Phase II Detailed Inspections, Testing and Monitoring; Phase III SHM and Modelling) for the comparison with the Key Performance Requirements, extracted from (Bigaj-van Vliet, et al., 2022)

4.5 Graphs representing maintenance strategies

The following graphs are suitable for displaying, optimizing, and evaluating the maintenance strategies. The performance graph shown in Figure 4.9 is a suitable 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 4.4. 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 graphs (strategies)

The grey graph shown in Figure 4.9 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.

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This graph is called the Preventive Maintenance Graph because the graph is a documentation of the past state and the actual state.

The blue graph shown in Figure 4.9 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.

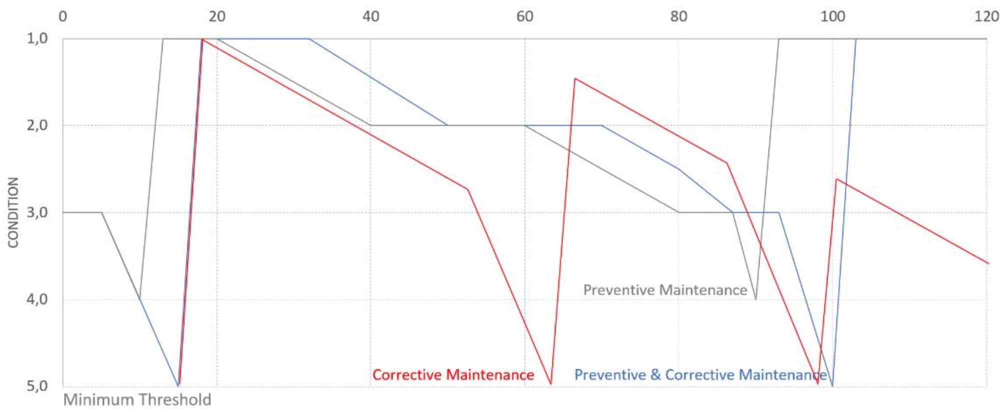

Figure 4.9 – Condition based maintenance graphs; preventive; reactive and predictive strategies (Adjusted from (COST TU1406))

Preventive & corrective maintenance graphs (strategies)
The blue graph shown in Figure 4.9 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 graphs of the pure corrective maintenance strategies reduce to three essential elements:

a) stable horizontal or slightly degrading graphs,
b) descending degrading graphs running to the minimum threshold,
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 Figure 4.9), 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.

4.6 Cost optimized maintenance strategies

Considering the graphs and strategies outlined in 4.5, the following elements can be identified which can be adapted to optimize the strategies:

- Preventive measures to slow down or prevent degradation processes - reduction descending graphs.
- Condition level to which the intervention is applied

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- Kind of intervention

For the optimized adaptation of strategies, it is useful to use tools such as inspection, testing, monitoring and modelling information, as also shown in Figure 4.9.

4.7 Optimization objectives for maintenance strategies

Cost optimized maintenance strategies
In 4.5 and Figure 4.9 the condition-based maintenance graphs were presented. Each of the presented elements (progressions of the graphs) and also the associated activities cause costs. Therefore, in addition to the condition-based maintenance graphs, it is recommended to develop the condition-based cost graphs as shown in Figure 4.10. 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-Condition based maintenance strategies
- Preventive-Predictive maintenance strategies

In the end, the objective function formulation "Minimization of maintenance costs over the lifetime" can be used to optimize the adaptable elements of the strategies, as presented in section 4.6.

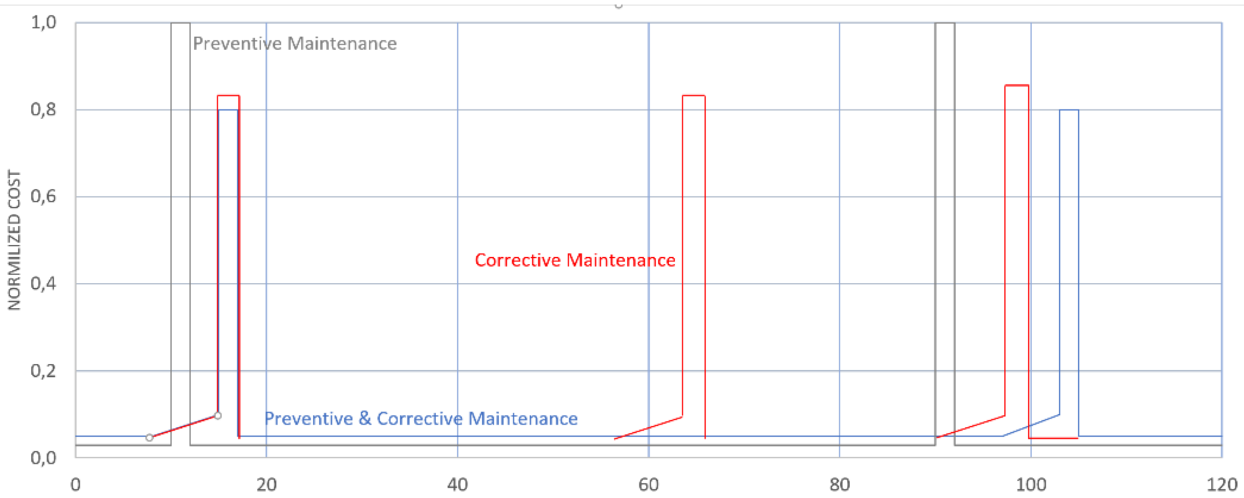

Figure 4.10 – Condition based cost graphs associated with the condition-based maintenance graphs as presented in Figure 4.9

Availability optimized maintenance strategies
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 CBM graphs, see e.g. Figure 4.11. 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 the end, the objective function formulation "Maximization of availability over the lifetime" can be used to optimize the adaptable elements of the strategies, as presented in section 4.6.

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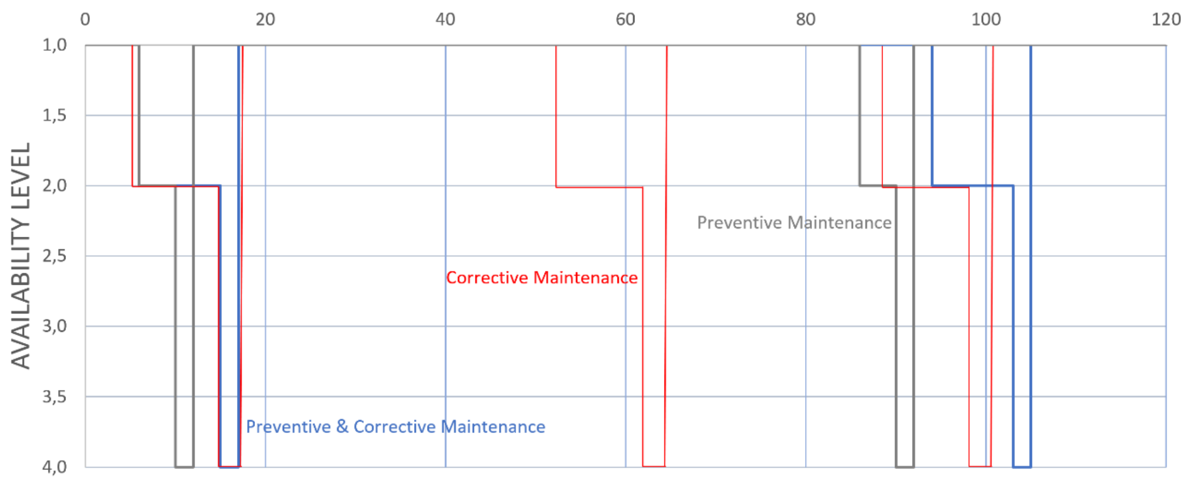

Figure 4.11 – Condition based availability graphs associated with the condition-based maintenance graphs as presented in Figure 4.9

4.8 Maintenance related advanced performance indicators

The aim further optimization elements for maintenance strategies is to record the maintenance share of the value added in the entire maintenance process. With big data and comprehensive data analysis, it is possible to carry out maintenance and servicing even more precisely and quickly - on the basis of various key performance indicators (KPI). The following key performance indicators can also be used for this purpose in the individual areas of practice.

Mean Time Between Failures (MTBF): *MTBF* refers to the mean time between failures of repairable units – it also refers to as *MTTF* (mean time to failure). The measured value is mostly highly dependent on the operating conditions prevailing at the site (ambient temperature, maintenance intervals, etc.). Note that the MTBF should be based without maintenance being done. The MTBF thus represents an indicator of the reliability of a system - the higher the MTBF value, the more reliable the system.

Mean Time To Repair (MTTR): The average repair time after a system failure. This indicates how long it takes on average to detect and localize a fault and replace the defective component. The MTTR figure thus provides important information about general system availability. The MTTR value is as small as possible – in general with a high MTTR, the consequence of failure is a relative high down time.

Mean Down Time (MDT): The mean fault duration describes the average time required to eliminate the failure after a system failure. In contrast to MTTR, MDT includes all times for repair and maintenance as well as all delays due to start-up and delivery times, spare parts logistics or failed attempts at unplanned maintenance. During MDT, the system is not operational. The MDT value should therefore also be as small as possible.

Overall System Effectiveness (OSE): Overall System Effectiveness OSE: The indicator of overall system effectiveness allows conclusions to be drawn about the productivity and value added of a e.g. infrastructure network, but also about unplanned losses in the operating time without planned shutdowns. Overall system effectiveness is determined as the product of the factors availability, performance and quality. However, since traffic and processes differ greatly from infrastructure network to infrastructure network, the OSE figure is only meaningful for the individual infrastructure network and cannot be generalized. Measures to improve the OSE value are not necessarily accompanied by an increase in efficiency and yield - it is important to ensure that the effort and benefit are in a sensible relationship to each other.

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Key performance indicators (KPR) are increasingly being used not only for business management, but also for the technical area and maintenance of facilities - because here, too, they open up a wide range of opportunities for identifying and exploiting potential for improvement. Facility operators can find initial indications of which key performance indicators are important for maintenance in the European standard (CEN-EN 15341) and in (DIN 31051) With the right key figures, it is not only possible to identify potential for improvement, but also to implement comprehensive maintenance controlling.

4.9 Maintenance Strategies Eurostruct - IMSAFE database

4.9.1 Introduction

In a survey with the representatives of the infrastructure managers in Europe, the aim was to survey the maintenance strategies, the associated assessment processes and the maintenance limits. From these surveys, a maintenance database was created which is accessible on the EUROSTRUCT WEBPage (EuroStruct - European association on quality control of bridges and Structures) in cooperation with EUROSTRUCT and IMSAFE. The example shown here for Netherland shows exemplarily the content and the structure of the database, whereby statistical analyses as well as deeper analyses concerning the development and origin of the process variables will follow.

4.9.2 Maintenance Example Netherlands

4.9.3 Maintenance Example Netherlands

In this section a brief introduction to risk-based inspections and life-cycle management is given. Note that terms and definitions in this sections are translated from Dutch to English and may not comply to terminology in the overall document. For understanding of the condition state classification in the Netherland it is important to realize the maintenance practice for structures is risk based instead of condition based and integrated with life-cycle management (LCC). Conditions states are allocated structural member level and structure bridge) level as well. These condition states have the role of indicators instead of steering parameters.

Risk based inspections:
Rijkswaterstaat has implemented risk-based inspections for structures since 2006. Risk Based Inspection is a process of gathering and analyzing information aimed at timely detection of risks due to undesired events. An undesired event is an event with a negative effect on the required performance of objects. Risk Based Inspection (RBI) is essentially different from traditional inspection, because risk analysis is the core of the inspection, rather than the detection of damages. Risks are defined as the product of the chance of an undesired event and the expected consequences of this event.

Life-cycle management:
For each bridge (general for each structure) a maintenance plan over the lifetime is drawn up. For a new bridge this plan consists of theoretical intervals and standardized maintenance measures at structural member level. This plan is updated during inspections and necessary measures are planned using time frames of optimal and technical ultimate time for execution. Standardized measures can be customized according to the actual situation of the bridge; also nonstandard measures can be added. Note that all measures (maintenance, monitoring and assessments) are motivated from the risk assessments

The condition rating at member level is derived from the measures determined for a member. For example: the condition within the time frame between optimal and ultimate is degree 3 and when time ultimate is reached degree 4. See Table 4.5 for details of condition states at structural member level.

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Table 4.4 – Condition states at structural member level

Survey types and classification types in Netherlands		
Degree	**Condition**	**Description of element, part or object faults** **Condition rating at structural member level**
0	Excellent state	New state, no maintenance scheduled
1	Very good state	Nearly new state, no maintenance scheduled
2	Good state	First signs of damage, maintenance may be scheduled at intermediate range
3	Reasonable state	Intervention level for preventive maintenance upcoming, schedule maintenance
4	Fair state	Intervention level reached, maintenance is required
5	Bad state	Beyond intervention level, backlog of maintenance, restrictions in use expected
6	Alarming state	Immediate action needed, dangerous for users, restrictions in use necessary

The core of risk-based maintenance management is that a risk score is allocated to bridge members. Measures are defined to mitigate this risk. Depending on the type of measure a resulting risk remains when the measure is executed. The risks are classified by type and severity. Type of risk and severity are used for prioritization of the measures of a bridge and also to prioritize between bridges and more general between all structures in a network. The classification by type use an extended RAMS classification. This is given in summarized definitions in the table below:

Table 4.5 – Standardized list of RAMSSHE€P-aspects.

Aspect		Aspect demands
Reliability	1.1-R	Functional Reliability Fulfil the reliability requirements for installations and moving parts
	1.2-R	Structural Reliability Fulfil the structural requirements in relation to the effect of damages and structural decay
	1.3-R	Structural Reliability Fulfil the structural requirements in relation to changed requirements
	1.4-R	Structural Reliability Fulfil the structural requirements in relation to change in use
	1.5-R	Structural Reliability Fulfil the structural requirements in relation to the effects of human failure in design, construction and maintenance
Availability	2.1-A	Fulfil the availability requirements in relation to the functions of the objects
	2.2-A	Avoid calamities related to availability
Maintainability	3.1-M	Fulfil the requirements in relation to the desired availability for maintenance and inspection
Safety	4.1-Sa	Fulfil the requirements in relation to safe fulfilment of all object functions
	4.2-Sa	Avoid calamities in relation to user safety
Security	5.1-Se	Fulfil the requirements in relation to avoiding vandalism
	5.2-Se	Fulfil the requirements in relation to securing of objects, including cyber security
Health	6.1-H	Fulfil the requirements for occupational safety, health and environment
Environment	7.1-E	Fulfil the requirements in relation to aesthetics
	7.2-E	Fulfil the requirements in relation to a sustainable environment
	7.3-E	Fulfil the requirements in relation to comfortable use
Economics (€)	8.1-Ec	Avoid disinvestments due to untimely maintenance
	8.2-Ec	Avoid large scale or unrepairable damage
Politics	9.1-P	Avoid situations that will damage the image of the ministry towards society

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In addition to a type of risk a risk level is determined by the chance of occurrence and the severity of the effect. Predefined tables describing the chances and effects are uses for this. These tables are not included in this summary. The result is a level ranging from 1 to 5:
Risk levels:

1. neglectable
2. limited
3. enlarged
4. high
5. unacceptable

The risk classification, type and level, are determined by the inspector. The bridge management system computes a bridge condition rating from the condition ratings and the risks levels at member level. The rating uses a matrix shown below.

Table 4.6 – Transformation condition rating from member level tot bridge level

Bridge condition state		Risk level (members)				
Condition state member level		1	2	3	4	5
	0	0	0	0	0	0
	1	1	1	1	1	1
	2	2	2	2	2	2
	3	3	3	3	3	3
	4	3	3	4	4	4
	5	3	3	5	5	5
	6	3	3	6	6	6

Bridge condition is classified into scale 0 to 6, comparable to the member level scale. See table below.

Table 4.7 – Condition states at bridge level, Netherlands

Survey types and classification types in Netherlands		
Degree	**Condition**	**Description of element, part or object faults** **Condition rating at structure level (bridge)**
0	Excellent state	New state, no maintenance scheduled
1	Very good state	Nearly new state, no maintenance scheduled
2	Good state	First signs of damage, maintenance may be scheduled at intermediate range
3	Reasonable state	Intervention level for preventive maintenance upcoming, schedule maintenance for one or more members
4	Fair state	Intervention level reached, maintenance is required.one or more members contribute to high risk of safe functioning (RAMSSHEEP) of the structure
5	Bad state	Beyond intervention level, backlog of maintenance, restrictions in use expected. One or more members contribute to unacceptable risk of safe functioning (RAMSSHEEP) of the structure
6	Alarming state	Immediate action needed, dangerous for users, restrictions in use necessary. One or more members contribute to unacceptable risk of safe functioning (RAMSSHEEP) of the structure

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Table 4.8 – Survey intervals and maintenance limits applied in Netherlands

Survey types and classification types in Netherlands
The inspection framework distinct between the three types of inspection types by their goal: 1. Routine inspection, "daily" bases: A regular surveillance aimed at detection of unexpected events. This inspection is effective in covering legal liability risks. 2. General (condition) inspection, annual basis (interval can be tuned to type of structure and risks) : An inspection of the current condition focused on at least the key issues of previous detected risks. Performance tests to detect for example hidden failure can be part of this inspection. 3. Major (programming) inspection, interval 6 years (interval varies depending state of structure, new, deteriorated, and planning of works): A risk based inspection resulting in a prognosis of future maintenance needs for a certain reference period. A desk study, interviews with maintenance manager, and risk analysis, before and after the inspection on site, are part of the major inspection. 4. Specials inspections, mostly triggered by major inspections: in depth inspection of members to assess causes of damage and/or to define measures. These first three inspection types are interlocking. Together they are the instruments for risk based inspection. The aim of the inspection framework is either to prevent undesired events, either to mitigate the effects and to gather information needed to implement control measures in time.

Table 4.9 – References associated with survey intervals and maintenance limits applied in Netherlands

References associated with survey types and classification types in Netherlands
The references for inspection and classification types are mainly specified by internal Rijkswaterstaat standards and guidelines. These are also used as contract specifications for external companies that perform inspections for Rijkswaterstaat. Where available international or national standards, and guidelines are used. Examples are: For decomposition of structures and the definition structural members is used: (NEN 2767-1+C1:2019, 2019) provides an unambiguous methodology to assess the condition of all assets identified in the built environment. (NEN 2767-2 , 2006) provides a summary of the assets that are to be assessed using the condition assessment methodology. For damage assessment and inspection and maintenance strategies the CROW knowledge base is used. CROW describes herself as: is the technology platform for transport, infrastructure and public space. It is a not-for-profit organization in which the government and businesses work together in pursuit of their common interests through the design, construction and management of roads and other traffic and transport facilities. https://www.crow.nl/english-summary Where available international standards can be used for example for damage classification of coatings on steel structures: (NEN-EN-ISO 4628-3:2016, 2016) specifies a method for assessing the degree of rusting of coatings by comparison with pictorial standards. The methodology of risk base inspections is described in (Bakker & Klatter, 2012). A bit more context on the integration in asset management is given by (van der Velde, Klatter, & Bakker, 2013).

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5 Quality Management (QM)

5.1 QM - Terms and Concepts

5.1.1 Quality

According to the standard (EN ISO 9000, 2015) (the valid standard for quality management), quality is defined as the "degree to which a set of inherent characteristics of an object fulfils requirements". Quality thus indicates the degree to which a product (good or service) meets existing requirements. The designation of quality can be used together with adjectives such as poor, good or excellent. Inherent, in contrast to "assigned", means inherent to a unit, especially as a permanent characteristic. This means objectively measurable characteristics such as length, width, weight, material specifications.

One of the major challenges that face us all is the mitigation and adaption of measures to climate change. Internationally, work has progressed from the formation of United Nations Convention on Climate Change. In order to achieve the commitment not to increase the global temperature by 1,5°C to 2 °C, the greenhouse gas (GHG) emissions have to be reduced also by active measures in the building industry.

(ISO 14001 , 2015b) deals with the need to manage environmental consequences including the climate change, loss of ecosystem services and biodiversity. Additionally, (ISO 14007, 2019) and (ISO 14008 , 2019) help organizations provide a 'value' and 'determine the costs' for the GHG they emit and to 'determine the cost benefit' in their organisation for any action they take to adapt to climate change.

In addition to the (EN ISO 9000, 2015) series referenced above, the (ISO 55000) series (asset management) should also be mentioned. The basis of the (ISO 55000) series is closely related to the (EN ISO 9000, 2015) series as it refers to the asset management system (while the 9000 series refers to management systems in general).

5.1.2 General principles of quality management

Quality management can include establishing quality policies and quality objectives , and processes to achieve these quality objectives through quality planning , quality assurance , quality control , and quality improvement .

Quality planning is part of quality management focused on setting quality objectives and specifying necessary operational processes , and related resources to achieve the quality objectives. Establishing quality plans can be part of quality planning.

Quality assurance is part of quality management focused on providing confidence that quality requirements will be fulfilled.

Quality control is part of quality management focused on fulfilling quality requirements

Quality improvement is part of quality management focused on increasing the ability to fulfil quality requirements. The quality requirements can be related to any aspect such as effectiveness, efficiency or traceability.

Management is the coordinated activities to direct and control an organization. Management can include establishing policies and objectives, and processes to achieve these objectives. The word "management" sometimes refers to people, i.e. a person or group of people with authority and responsibility for the conduct and control of an organization. When "management" is used in this sense, it should always be used with some form of qualifier to avoid confusion with the concept of "management" as a set of activities defined above.

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*Management system i*s a set of policies, processes and procedures used by an organization to ensure that it can fulfil the tasks required to achieve its objectives. These objectives cover many aspects of the organization's operations (including financial success, safe operation, product quality, client relationships, legislative and regulatory conformance and worker management). For instance, an environmental management system enables organizations to improve their environmental performance, and an occupational safety and health management system enables an organization to control its occupational health and safety risks. (EN ISO 9000, 2015) defines the term in section 3.5.3 as a "set of interrelated or interacting elements of an organization to establish policies and objectives, and processes to achieve those objectives".

5.1.3 QM topics in this chapter

Quality management applies to all activities of an organization, and it is perhaps important to emphasize that this means that it applies to all levels, processes and activities of the organization. For instance, the quality level can be associated for instance with the number of allowable defects in a structure, the condition rating and the reliability level. The acceptance quality level is agreed upon between the owner and the operator based on the importance of the structure. It should also be emphasized the Deming cycle (*plan, do, check, act*) that should apply to all these activities. In this way, a good starting point can be established for highlighting specific areas that are important for quality management.

The chapter has been divided into the following areas of consideration:

"QM-General" presents *the planning and strategic process steps* in the establishment of a quality assessment or quality control system for authorities or infrastructure operators. These QM associated process steps are part of a higher strategic level and require a planning and strategic orientation of authorities on the *management level*.

"QM-Engineering Practice" represents the *operational steps* of quality management, quality assessment and quality control to be handled by engineers in the design, construction, maintenance and demolition phases. QM is usually performed under the responsibility of the operator of the structure or infrastructure system. At this level, structural engineers, structural designers and structural inspectors are the main actors on the *operational level*.

“QM-ISO 9001” chapter presents the contents of which are dealt with following the two strategic and operational sections, it contains fundamental elements that are applied at the strategic and operational levels. The aim of this section is to show the ISO 9001 philosophy and its contents as well as their interrelation between the *operational* and *strategic levels*.

“QM-ISO 9001-Monitoring and Measurement” chapter shows in this section in particular for the QM-Engineering Practice the basic QA and QC elements and their basic philosophy regarding monitoring and measurement. This section is assigned to the *operational QM*.

“QM-ISO 9001 - Analysis and evaluation procedures” chapter shows in this section in particular for the QM-Engineering Practice the basic QA and QC elements and their basic philosophy regarding analysis and evaluation procedures. This section is also to be assigned to the *operational QM*.

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"QM-ISO 19650" ISO 19650-1 is the first part of the ISO 19650 series on building information modelling (BIM). This part outlines the concepts and principles and provides recommendations on how to manage building information.

"QM-Framework Data Informed Structural Assessment" These chapters will finally show the relationship of the QA and QC concepts outlined above to the assessment procedures developed in this project.

"QM-Framework Performance and Key Performance" Finally, these chapters show the relationship of the QA and QC concepts drafted earlier to the performance and key performance concepts prepared in this project.

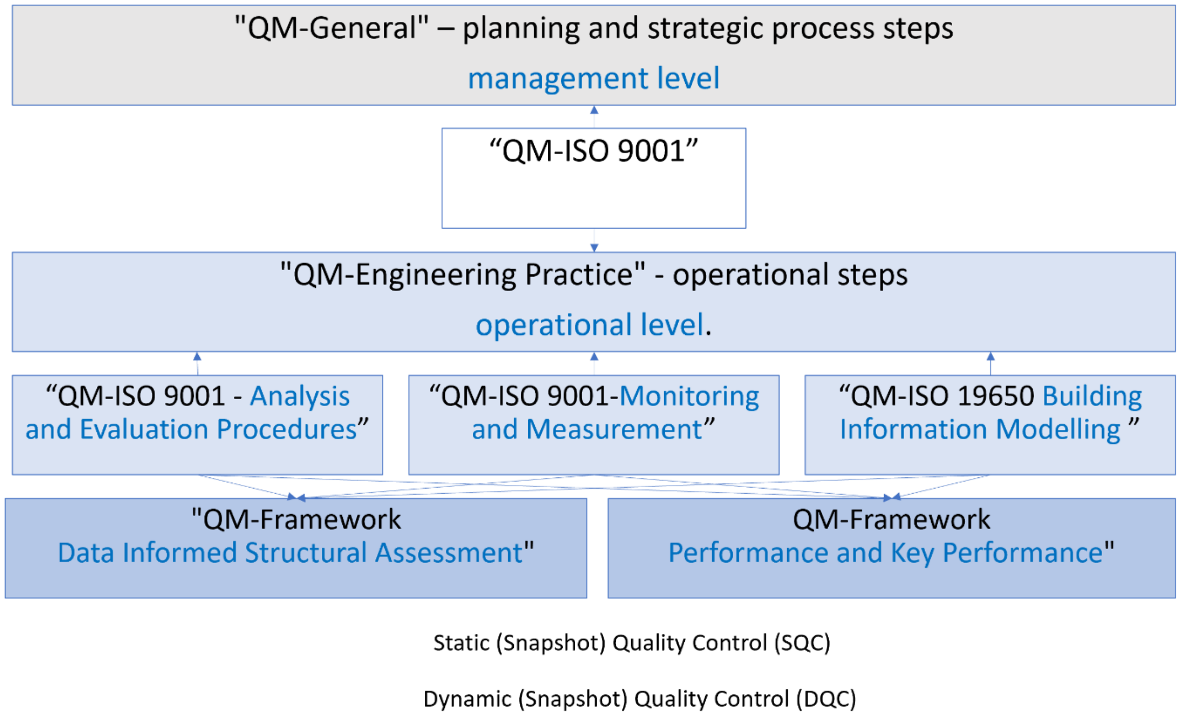

Figure 5.1 – QM topics organized in Chapter 5 of this report

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5.2 QM – planning and strategic process steps

In the following sections, some important aspects in the development of a QA system or QC system are presented from the perspective of QM system planners. The elements described in Figure 5.2 and in the following should be considered and complied with.

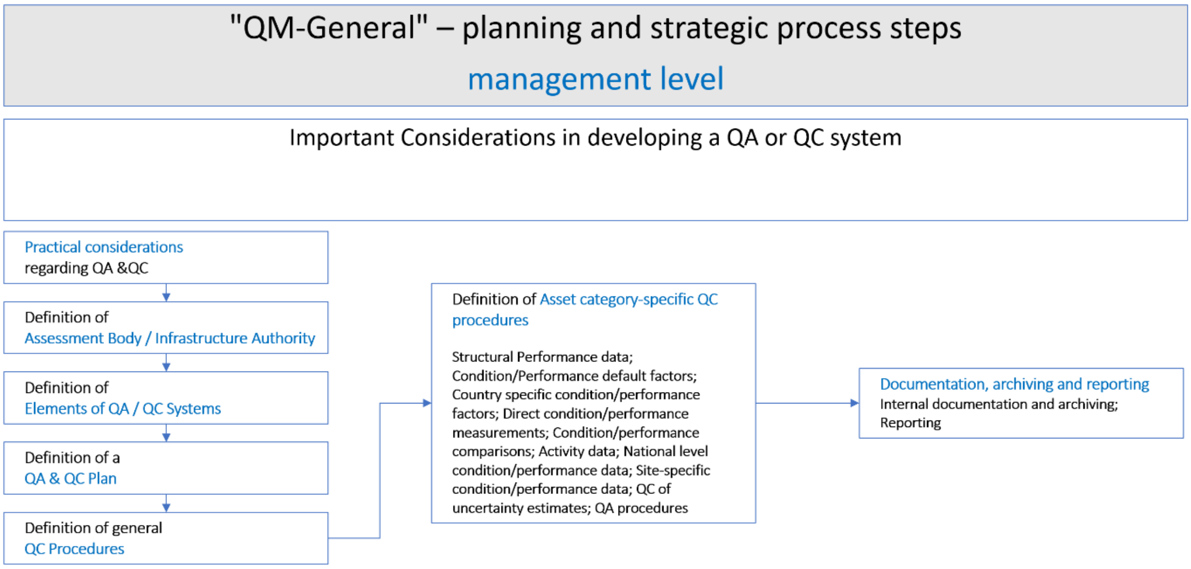

Figure 5.2 – QM - Planning and strategic process steps

5.2.1 QA&QC - Practical considerations

QA/QC procedures requires resources, expertise and time. In developing any QA/QC system, it is expected that judgements will need to be made on the following:

- Resources allocated to QC for different categories and the compilation process;
- Time allocated to conduct the checks and reviews;
- Availability and access to information on activity data and factors, including data quality;
- Procedures to ensure confidentiality of inventory and source information, when required;
- Requirements for archiving information;
- Frequency of QA/QC checks on different parts of the inventory;
- The level of QC appropriate for each source category;
- Whether increased effort on QC will result in improved estimates and reduced uncertainties;
- Whether sufficient expertise is available to conduct the checks and reviews.

In practice, the QA/QC system is only part of a process and valuation agencies do not have unlimited resources. Quality control requirements, improved accuracy and reduced uncertainty need to be balanced against requirements for timeliness and cost effectiveness. Within the QA/QC system, good practice provides for greater effort for key systems and for those systems where data and methodological changes have recently occurred, than for other. The optimal frequency of checks depends on national and regional circumstances. While focusing QA/QC activities on key systems will lead to the most significant improvements in the overall systems estimates. It is recognised that resource requirements will be higher in the initial stages of implementing any QA/QC system than in later years.

As capacity to conduct QA/QC procedures develops in the valuation agency and in other associated organisations, improvements in efficiency should be expected. The QA/QC

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process is intended to ensure transparency and quality. There may be some items that involve confidential information. The valuation agency should have procedures in place during a review process to ensure that reviewers respect that confidentiality.

5.2.2 Elements of Quality Assessment (QA) / Quality Control (QC) System

The following are the major elements to be considered in the development of a QA/QC system:

- A valuation agency responsible for coordinating QA/QC activities;
- A QA/QC plan;
- General QC procedures (Tier 1);
- Source category-specific QC procedures (Tier 2);
- QA review procedures;
- Reporting, documentation, and archiving procedures.

For purposes of the QA/QC system, the Tier 2 QC approach includes all procedures in Tier 1 plus additional specific activities.

5.2.3 Assessment Body / Infrastructure Authority

The assessment body is responsible for coordinating the QA/QC activities for the national asset. The assessment body may delegate responsibility for conducting and documenting these QA/QC procedures to other agencies or organizations. The assessment body should ensure that other organizations involved in the development of the system comply with applicable QA/QC procedures. The assessment body is also responsible for ensuring that the QA/QC plan is developed and implemented. It has proven effective for the assessment body to designate a QA/QC coordinator who is responsible for ensuring that the goals of the QA/QC program are implemented.

5.2.4 QA & QC Plan

A QA/QC plan is a fundamental element of a QA/QC system, and it is good practice to develop such a plan. The plan should generally outline the QA/QC activities to be performed and include a planned time frame to guide the system development from initial development through final reporting. It should include an overview of the procedures and schedule for review of all system items. The QA/QC plan is an internal document for organizing, planning, and conducting QA/QC activities. Once created, it can be referenced and used in subsequent system development or modified as needed (e.g., when procedures change or on the advice of independent reviewers). This plan should be available for external review. In developing and implementing the QA/QC plan, it may be useful to refer to standards and guidelines published by the International Organization for Standardization (ISO), including the (EN ISO 9000, 2015) series.

5.2.5 ISO as a data Quality Management System

The International Organization for Standardization (ISO) program provides standards for data documentation and audits as part of a quality management system. Although the ISO series is not specifically designed for construction performance evaluation, many of the principles can be applied to ensure the creation of a quality asset.

Assessment bodies may find these documents useful source material for developing QA/QC plans. The following standards and guidelines published as part of the ISO series can supplement source-specific QA/QC procedures for asset development and provide practical guidance for ensuring data quality and a transparent reporting system: ISO 10005: Guide to the preparation of quality plans for the management of specific projects (ISO 10005, 2018), ISO 10012: Guide to calibration systems and statistical controls to ensure that measurements are made with the intended accuracy (ISO 10012, 2003), ISO 10013: Guidelines for the development of quality manuals for specific requirements (ISO 10013, 2021).

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5.2.6 General QC Procedures

General QC procedures focus on the processing, handling, documenting, archiving, and reporting procedures common to all categories of assets. Table 5.1, General QC Procedures at Tier 1 of the assets, lists the general QC controls that the assessment body should routinely perform during the preparation of the annual asset. Most of the controls listed in Table 5.1 can be accomplished through cross-checks, recalculations, or visual inspections. The results of these QC activities and procedures should be documented (see Internal Documentation and Archiving below). If controls are performed electronically, these systems should be periodically reviewed to ensure the integrity of the control function. It will not be possible to review all aspects of the asset input data, parameters, and calculations every year. Checks can be performed on selected data sets and processes so that certain important assets are considered each year. Checks on other asset categories may be conducted less frequently. However, a sample of data and calculations from every sector should be included in the QC process each year to ensure that all sectors are addressed on an ongoing basis. In establishing criteria and processes for selecting the sample data sets and processes, it is good practice for the assessment body to plan to undertake QC checks on all parts of the asset over an appropriate period of time.

Table 5.1 – Tier 1 General asset level QC procedures

QC Activity	Procedures
Check that parameters and monitored units are correctly recorded and that appropriate conversation factors are used	• Check that units are properly labelled in (calculation) sheets. • Check that units are correctly carried through from beginning to end of calculations. • Check that conversation factors are correct. • Check that temporal and spatial adjustment factors are used correctly.
Check the integrity of database files.	• Confirm that the appropriate data processing steps are correctly represented in the database. • Confirm that data relationships are correctly represented in the database • Ensure that data fields are properly labelled and have the correct design specifications. • Ensure that adequate documentation of database and model structure and operation are archived
Check for consistency in data between asset categories	• Identify parameters that are common to multiple assets and confirm that there is consistency in the values and associated parameters.
Check that the movement of asset data among processing steps is correct	• Check that assessment data are correctly aggregated from lower reporting levels to higher reporting levels when preparing summaries • Check that assessment data are correctly transcribed between different intermediate products
Check methodological and data changes resulting in recalculations.	• Check for temporal consistency in time series input data for each asset category. • Check for consistency in the algorithm/method used for calculations through the time series.

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Undertake completeness checks.	• Confirm that estimates are reported for all asset categories and for al years from the appropriate base year to the period of the current asset. • Check that known data gaps that result in incomplete asset estimates are documented.
Compare estimates to previous estimates.	• For each asset category, current asset estimates should be compared to previous estimated. If there are significant changes or departues from expected trends, re-check estimates and explain any difference.

The checks in Table 5.1, should be applied irrespective of the type of data used to develop the asset estimates and are equally applicable to asset categories where default is used as the basis for the estimates. The valuation agency should ensure that the QC checks listed in Table 5.1, Tier 1 General asset Level QC Procedure, are communicated to the consultants/agencies. This will assist in making sure that QC procedures are performed and recorded by the consultant or outside agency. The assessment body should review these QA/QC activities. In cases where official national statistics are relied upon – primarily for activity data – QC procedures may already have been implemented on these national data. However, it is good practice for the assessment body to confirm that national (statistical) check bodies have implemented adequate QC procedures equivalent to those in Table 5.1. Due to the quantity of data that needs to be checked for some asset categories, automated checks are encouraged where possible. For example, one of the most common QC activities involves checking that data keyed into a computer database are correct. A QC procedure could be set up to use an automated range check (based on the range of expected values of the input data from the original reference) for the input values as recorded in the database. A combination of manual and automated checks may constitute the most effective procedures in checking large quantities of input data.

5.2.7 Asset category-specific QC procedures (Tier 2)

It is good practice that assessment bodies applying higher tier methods in compiling national assets utilise Tier 2 QC procedures. Asset category-specific QC activities include QC of uncertainty estimates. The actual QC procedures that need to be implemented by the assessment body will depend on the method used to estimate the performance for a given asset category. If estimates are developed by outside agencies, the assessment bodies may, upon review, reference the QC activities of the outside agency as part of the QA/QC plan. There is no need to duplicate QC activities if the assessment body is satisfied that the QC activities performed by the outside agency meet the minimum requirements of the QA/QC plan.

5.2.7.1 Structural Performance data QC

The following sections describe QC checks on performance default factors, country-specific performance factors, and direct performance measurements. Performance comparison procedures are described in the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022). Assessment bodies should consider the practical considerations discussed in "Practical Considerations in Developing QA/QC Systems" when determining what level of QC activities to undertake.

5.2.7.2 Condition/Performance default factors

Where Condition or Performance factors are used, it is good practice for the assessment body to assess the applicability of these factors to national circumstances. For key categories, assessment bodies should consider options for obtaining performance factors that are known to be representative of national circumstances. The results of this assessment should be

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documented. If possible, performance default factor checks could be supplemented by comparisons with national site or structure-level factors to determine their representativeness relative to actual sources in the country. This supplementary check is good practice even if data are only available for a small percentage of sites or plants.

5.2.7.3 Country specific condition/performance factors (PIs, KPIs, DIs)

Country-specific condition/performance factors may be developed at a national or other aggregated level within the country based on prevailing technology, science, local characteristics and other criteria. These condition/performance factors are not necessarily site-specific, but are used to represent a PRI category or sub-PRI category. Two steps are necessary to ensure good practice condition/performance factor QC for country-specific factors. The first is to perform QC checks on the data used to develop the condition/performance factors. Frequently, country-specific condition/performance factors will be based on secondary data sources, such as published studies or other literature. In these cases, the assessment body could attempt to determine whether the QC activities conducted during the original preparation of the data are consistent with the applicable QC procedures outlined in Table 5.1 and whether any limitations of the secondary data have been identified and documented. The assessment body could also attempt to establish whether the secondary data have undergone peer review and record the scope of such a review.

If it is determined that the QA/QC associated with the secondary data is adequate, then the assessment body can simply reference the data source for QC documentation and document the applicability of the data for use in condition/performance estimates. If it is determined that the QA/QC associated with the secondary data is inadequate, then the assessment body should attempt to have QA/QC checks on the secondary data established. It should also reassess the uncertainty of any condition/performance estimates derived from the secondary data. The assessment body may also reconsider how the data are used and whether any alternative data, (including Condition/Performance default values) may provide a better estimate of performance from this KPR category. Large differences between country-specific condition/performance factors and default factors should be explained and documented. A supplementary step is to compare the country-specific factors with site-specific or structure-level factors if these are available. For example, if there are performance factors available for a few structures (but not enough to support a bottom-up approach) these structure-specific factors could be compared with the aggregated factor used in the asset. This type of comparison provides an indication of both the reasonableness of the country-specific factor and its representativeness (see the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022) for details regarding PIs, KPIs, DIs).

5.2.7.4 Direct condition/performance measurements (survey technologies)

Condition/performance of a structure may be estimated using direct measurements in the following ways:

- Sample performance measurements from a structure may be used to develop a representative performance factor for that individual site, or for the entire category (i.e. for development of a structural level performance factor);
- Continuous condition/performance monitoring data or SHM may be used to compile a periodic estimate of condition/performance for a particular process. In theory, Continuous condition/performance monitoring can provide a complete set of quantified performance data across the asset period for an individual facility process, and does not have to be correlated back to a process parameter or input variable like a performance factor.

Regardless of how direct measurement data from survey technologies are being used, the assessment bodies should review the processes and check the measurements as part of the QC activities, see also (Sánchez Rodríguez, et al., 2022). Use of standard measurement methods improves the consistency of resulting data and knowledge of the statistical properties

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of the data. If standard reference methods for measuring specific condition-, performance- or damage indicators (and removals) are available, assessment bodies should encourage inspectors to use these. If specific standard methods are not available, the assessment body should confirm whether nationally or internationally recognised standard methods such as ISO 10012 are used for measurements and whether the measurement equipment is calibrated and maintained properly. For example, ISO has published standards that specify procedures to quantify some of the performance characteristics of measurement methods such as bias, calibration, instability, lower detection limits, sensitivity, and upper limits of measurement (ISO, 1994).

5.2.7.5 Condition/performance comparisons (PIs, KPIs, Dis – vulnerable elements)

It is standard QC practice to compare condition/performance from structures (structure category) with previously provided from the same structure (structure category) (see also (Longo, et al., 2022)) or against historical trends and reference calculations as described below. The objective of these comparisons (often referred to as 'reality checks') is to ensure that the condition/performance values are not wildly improbable or that they fall within a range that is considered reasonable. If the estimates seem unreasonable, condition/performance checks can lead to a re-evaluation of condition/performance factors and activity data before the asset process has advanced to its final stages. The first step of a condition/performance comparison is a consistency and completeness check using available historical inventory data for multiple years.

The condition/performance levels of most categories do not abruptly change from year to year, as changes in both activity data and condition/performance factors are generally gradual. In most circumstances, the change in condition/performance will be less than 15% per year.
Thus, significant changes in condition/performance from previous years may indicate possible input or calculation errors. After calculating differences, the larger percentage differences (in any direction) should be flagged, by visual inspection of the list, by visual inspection of the graphical presentation of differences (e.g. in a spreadsheet) or by using a dedicated software programme that puts flags and rankings in the list of differences.

It is good practice to also check the annual increase or decrease of changes in performance levels in significant sub source categories of some categories. Sub-source categories (e.g. expansion joints) may show greater percentage changes than the aggregated categories (system level). Source categories and sub-source categories should be ranked according to the percentage difference in condition/performance from the previous year. Supplementary condition/performance comparisons can also be performed, if appropriate, including order-of-magnitude checks and reference calculations.

Order-of-magnitude checks
Order of magnitude checks look for major assessment/calculation errors and exclusion of major categories or subcategories. Method-based comparisons may be made depending on whether the performance for a category were determined using a top-down or bottom-up approach. If significant differences are found in the comparison, further investigation using QC techniques, QC Procedures (Tier 2), would be necessary to answer the following questions:

- Are there inaccuracies associated with any of the individual site estimates (e.g. an extreme outlier may be accounting for an unreasonable quantity of performance)?
- Are the site-specific performance factors significantly different from each other?
- Are the site-specific rates consistent with published national level date?
- Is there any other explanation for a significant difference, such as the effect of controls, the way performance is reported or possibly undocumented assumptions?

This is an example of how the result of a relatively simple condition/performance check can lead to a more intensive investigation of the representativeness of the condition/performance data. Knowledge of the category is required to isolate the parameter that is causing the

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difference in condition/performance estimates and to understand the reasons for the difference.

Reference calculations
Another condition/performance comparison may be used for system categories that rely on empirical formulas for the calculation of conditions/performances. Where such formulas are used, final calculated performance levels should follow stochiometric ratios. Discrepancies between inventory data and reference calculations do not necessarily imply that the inventory data are in error. It is important to consider that there may be large uncertainties associated with the reference calculations themselves when analysing discrepancies.

5.2.7.6 Activity data QC

The estimation methods for many categories rely on the use of activity data and associated input variables that are not directly produced by the assessment agency, such as bridge structure bearing movement with ambient temperature input variables. Activity data are typically compiled nationally from secondary data sources (temperature readings) or from site-specific data collected by site or facility personnel based on their own measurements. In determining the scope of QC activities to be performed, assessment bodies should consider the practical considerations mentioned above.

5.2.7.7 National level condition/performance data

Where national activity data from secondary data sources are used, it is good practice for the assessment body or its designees to evaluate and document the associated QA/QC activities. This is particularly important with regard to activity data. Though not always readily available, many organisations, for example, have their own procedures for assessing the quality of the data independently of what the end use of the data may be. It is good practice for the assessment body to determine if the level of QC associated with secondary activity data includes those QC procedures listed in Table 5.1. In addition, the assessment body may establish whether the secondary data have been peer reviewed and record the scope of this review.

If it is determined that the QA/QC associated with the secondary data is adequate, then the assessment body can simply reference the data source and document the applicability of the data for use in its condition/performance estimates. If it is determined that the QC associated with the secondary data is inadequate, then the assessment body should attempt to have QA/QC checks on the secondary data established.

It should also reassess the uncertainty of condition/performance estimates in light of the findings from its assessment of the QA/QC associated with secondary data. The assessment body should also reconsider how the data are used and whether any alternative data, including condition/performance default values and international data sets, may provide for a better estimate of condition/performance. If no alternative data sources are available, the assessment body should document the inadequacies associated with the secondary data QC as part of its summary report on QA/QC. It is the responsibility of the assessment body to determine what QA/QC activities were implemented by the body that prepared the original data.

Questions that may be asked in this context are:

- Does the assessment body have a QA/QC plan that covers the preparation of the data?
- What sampling protocol was used to estimate condition/performance?
- How recently was the sampling protocol reviewed?
- Has any potential bias in the data been identified by the assessment body?

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National level condition/performance data should be compared with previous year's data for the category being evaluated. Performance data for most source categories tend to exhibit relatively consistent changes from year to year without sharp increases or decreases.
If the national condition/performance data for any year diverge greatly from the historical trend, the condition/performance data should be checked for errors. If the general mathematical checks do not reveal errors, the characteristics of the category could be investigated and any change identified and documented.

Where possible, a comparison check of condition/performance data from multiple reference sources should be undertaken. This is important for categories that have a high level of uncertainty associated with their estimates. As part of the QC check, the assessment body should ascertain whether independent data have been used to derive alternative condition/performance data sets. In some cases, the same data are treated differently by different bodies to meet varying needs. Comparisons may need to be made at a regional level or with a subset of the national data since many alternative references for such condition/performance data have limited scope and do not cover the entire nation.

5.2.7.8 Site-specific condition/performance data (vulnerable elements)

Some methods rely on the use of site-specific condition/performance data, in particular for the comparison of structures in a network e.g. infrastructure network. QC checks should focus on inconsistencies between sites to establish whether these reflect errors, different measurement techniques, or real differences in performance, operating conditions or technology.

A variety of QC checks can be used to identify errors in site-level condition/performance data. The assessment bodies should establish whether recognised national or international standards were used in measuring condition/performance data at the individual sites. If measurements were made according to recognised national or international standards and a QA/QC process is in place, the assessment body should satisfy itself that the QA/QC process at the site is acceptable under the inventory QA/QC plan and at least includes Tier 1 activities. Acceptable QC procedures in use at the site may be directly referenced. If the measurements were not made using standard methods and QA/QC is not of an acceptable standard, then the use of these condition/performance data should be carefully evaluated, uncertainty estimates reconsidered, and qualifications documented.

5.2.7.9 QC of uncertainty estimates

QC should also be undertaken on calculations or estimates of uncertainty associated with condition/performance estimates. Quantifying Uncertainties in Practice and relies on calculations of uncertainty at the category level that are then combined to summary levels for the entire asset. Some of the methods rely on the use of measured data associated with the performance factors or condition data to develop probability density functions from which uncertainty estimates can be made. In the absence of measured data, many uncertainty estimates will rely on expert judgement. It is good practice for QC procedures to be applied to the uncertainty estimations to confirm that calculations are correct and that there is sufficient documentation to duplicate them. The assumptions on which uncertainty estimations have been based should be documented for each category. Calculations of category specific and aggregated uncertainty estimates should be checked and any errors addressed. For uncertainty estimates involving expert judgement, the qualifications of experts should also be checked and documented, as should the process of eliciting expert judgement, including information on the data considered, literature references, assumptions made and scenarios considered.

5.2.7.10 QA procedures (vulnerable elements)

Good practice for QA procedures requires an objective review to assess the quality of the asset, and also to identify areas where improvements could be made. The asset may be

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reviewed as a whole or in parts. QA procedures are utilised in addition to the Tier 1 and Tier 2 QC. The objective in QA implementation is to involve reviewers that can conduct an unbiased review of the asset. It is good practice to use QA reviewers that have not been involved in preparing the asset. Preferably these reviewers would be independent experts from other bodies or a national or international expert or group not closely connected with national asset compilation. Where third party reviewers outside the valuation assessment bodies are not available, staff from another part of the valuation bodies not involved in the portion of the asset being reviewed can also fulfil QA roles. It is good practice for valuation body to conduct a basic expert peer review (Tier 1 QA) prior to asset submission in order to identify potential problems and make corrections where possible. It is also good practice to apply this review to all categories. However, this will not always be practical due to timing and resource constraints. Key categories should be given priority as well as categories where significant changes in methods or data have been made. Assessment bodies may also choose to perform more extensive peer reviews or audits or both as additional (Tier 2) QA procedures within the available resources.

Expert peer review

Expert peer review consists of a review of calculations or assumptions by experts in relevant technical fields. This procedure is generally accomplished by reviewing the documentation associated with the methods and results, but usually does not include rigorous certification of data or references such as might be undertaken in an audit. The objective of the expert peer review is to ensure that the asset results, assumptions, and methods are reasonable as judged by those knowledgeable in the specific field. Expert review processes may involve technical experts and, where a country has formal stakeholder and public review mechanisms in place, these reviews can supplement but not replace expert peer review. There are no standard tools or mechanisms for expert peer review, and its use should be considered on a case-by case basis. If there is a high level of uncertainty associated with a condition/ performance estimate for a category, expert peer review may provide information to improve the estimate, or at least to better quantify the uncertainty.

Expert reviews may be conducted on all parts of a category. The results of expert peer review, and the response of the valuation agency to those findings, may be important to widespread acceptance of the final asset. All expert peer reviews should be well documented, preferably in a report or checklist format that shows the findings and recommendations for improvement. AUDITS For the purpose of good practice in asset preparation, audits may be used to evaluate how effectively the assessment body complies with the minimum QC specifications outlined in the QC plan. It is important that the auditor be independent of the assessment body as much as possible so as to be able to provide an objective assessment of the processes and data evaluated. Audits may be conducted during the preparation of an asset, following asset preparation, or on a previous asset. Audits are especially useful when there are substantial changes to existing methods. It is desirable for the assessment body to develop a schedule of audits at strategic points in the asset development. For example, audits related to initial data collection, measurement work, transcription, calculation and documentation may be conducted. Audits can be used to verify that the QC steps identified in Table 5.1 have been implemented and that category-specific QC procedures have been implemented according to the QC plan.

5.2.7.11 Internal documentation and archiving

As part of general QC procedures, it is good practice to document and archive all information required to produce the national condition/performance asset estimates. This includes:

- Assumptions and criteria for selection of asset data and performance factors;
- Performance factors used, including references to the performance document for default factors or to published references or other documentation for condition/performance factors used in higher tier methods;

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- Asset data or sufficient information to enable asset data to be traced;
- Information on the uncertainty associated with asset data and performance factors;
- Rationale for choice of methods;
- Methods used, including those used to estimate uncertainty;
- Changes in data inputs or methods from previous years;
- Identification of individuals providing expert judgement for uncertainty estimates and their qualifications to do

Details of electronic databases or software used in production of the inventory, including versions, operating manuals, hardware requirements and any other information required to enable their later use;

- Worksheets and interim calculations for category estimates and aggregated estimates and any recalculations of previous estimates;
- Final inventory report and any analysis of trends from previous years;
- QA/QC plans and outcomes of QA/QC procedures.

It is good practice for valuation agencies to maintain this documentation for every annual inventory produced and to provide it for review. It is good practice to maintain and archive this documentation in such a way that every inventory estimate can be fully documented and reproduced if necessary. Valuation agencies should ensure that records are unambiguous. A full reference to the particular document is necessary in order to identify the source of the performance factor because there may have been several updates of default factors as new information has become available. Records of QA/QC procedures are important information to enable continuous improvement to inventory estimates. It is good practice for records of QA/QC activities to include the checks/audits/reviews that were performed, when they were performed, who performed them, and corrections and modifications to the inventory resulting from the QA/QC activity.

5.2.7.12 Reporting

It is good practice to report a summary of implemented QA/QC activities and key findings as a supplement to each country's national inventory. However, it is not practical or necessary to report all the internal documentation that is retained by the valuation agency. The summary should describe which activities were performed internally and what external reviews were conducted for each category and on the entire inventory in accordance with the QA/QC plan. The key findings should describe major issues regarding quality of input data, methods, processing, or archiving and show how they were addressed or plan to be addressed in the future.

5.3 QM - Engineering Practice

5.3.1 Quality and Information management during Execution

5.3.1.1 Objective

The objective of Quality Management (QM) during the execution of construction works is to ensure that the resulting built structure satisfies the assumptions adopted in the design (geometrical aspects, materials characteristics and materials performance, etc.), expressed in the drawings and specifications, in compliance with the applicable execution specifications and standards. For the real performance of the structure to resemble that predicted by the models applied during the design phase, strict controls during its execution are required, following a detailed quality and inspection plan that should be prepared at the end of the design phase and included in the tender (mandatory for QL2 and QL3). In particular, the location and orientation of the structural elements as well as their geometric dimensions shall be within the stipulated tolerances. This also applies to the positioning of the steel reinforcement and prestressing. The quality of the steel, concrete and other products shall be conform to the specifications and, especially regarding concrete, its processing on site must

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ensure that the intrinsic potential of the material is achieved during the construction phase. For mechanical performance, the cross-section dimensions, quality (especially strength and stiffness) and uniformity of the concrete, as well as quantity, quality and positioning of the reinforcement and prestressing steel are key factors. Regarding durability, besides avoiding deleterious internal reactions, the focus of the QM activities shall be on achieving a sufficiently thick and tight cover concrete.

5.3.1.2 QM Activities

The QM activities in the Execution phase of Construction works cover three stages:

- Preplacement inspection
- Placement inspection
- Postplacement inspection

The result of these activities shall be compiled in an Inspection Report, which is mandatory for QL2 and QL3. Correct positioning and firm fixation of the reinforcing and prestressing steel, as well as other reinforcing materials, shall precede concreting. Adequate and sufficiently closely located spacers are essential to achieve cover thicknesses conforming to the specification and tolerances, as well as to ensure sufficient room to allow the free flow of concrete between the bars and in the cover zone. A performing mix design, providing adequate workability of the concrete to achieve adequate compaction, especially between the reinforcing bars and the formwork surface, is key to achieve a tight cover concrete, to be complemented by proper curing conditions of the just placed concrete. Control and monitoring of these aspects shall be carried out in accordance with the Execution Specifications and in full conformity with the approved procedures of the Project Quality Plan.

5.3.1.3 Documentation at Handover/Commissioning

The objective is to provide the owner/operator with an as-detailed-as-possible documentation to facilitate monitoring and maintenance of the structure during its whole operational service life. The supplied documentation shall contain:

- Design o Basis for design o Execution specification o Concrete specifications
- Execution
  - Inspection report
  - As-built geometry
- Birth certificate o Maintenance and Condition assessment plan o Dismantlement and reuse plan

5.3.1.4 Birth Certificate

The Birth Certificate is a document, report or technical file (depending on the size and complexity of the structure concerned) containing engineering information formally defining the form and the condition of the structure on completion of construction. The birth certificate document (BCD) should provide and quantify specific details on parameters important to the durability and service life of the structure concerned (e.g. cover to reinforcement, concrete permeability, environmental exposure conditions, quality of workmanship achieved, etc.), and the basis upon which future knowledge of through-life performance should be recorded. These parameters should be categorized as either assumed, estimated, observed/measured, or inferred/deduced. The framework laid down in the birth certificate should provide a means of comparing actual in-service behaviour / performance with that anticipated at the time of design and/or the time of construction of the structure. The BCD might serve as the basis for monitoring the condition of the structure and for planning conservation activities during its service life.

5.3.2 Quality and Information management during Interventions Execution

5.3.2.1 Objective

Under certain circumstances, preventive or remedial interventions are required with the intention of keeping or restoring the performance of a new or existing structure to an acceptable level. The objective of QM with respect to the execution of interventions is to

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ensure that the principles and methods applied result in a performing structure during the specified or expected design or residual life

5.3.2.2 QM Activities

The QM activities in the execution of an intervention cover three instances: • Preparation • Execution • Inspection

5.3.2.3 Re-Birth Certificate

The Re-Birth Certificate is a document, report or technical file (depending on the size and complexity of the structure concerned) containing engineering information defining the condition of the structure after completion of a major preventative or remedial intervention. It should contain a post-intervention conservation plan, made according to the estimated long-term performance of the applied intervention method.

5.3.3 Quality and Information management during Operation and Conservation

5.3.3.1 Objectives

The objective of QM in conservation is to control and manage the activities and measures taken, which seek to ensure that the structure condition remains within satisfactory limits in order to meet the performance requirements for a defined period of time; this applies to structural and functional performance requirements, which may include considerations of aspects such as reliability, availability, user's safety, economy and environmental impact. The suggestions provided in the present chapter are applicable to the majority of structures. Complementarily, the reader may refer to other detailed documents for specific information concerning the analysed structure type. This is achieved through activities that may involve condition survey, monitoring the structure performance through its service life, condition assessment, condition evaluation, decision-making and the execution of any necessary intervention; the corresponding conservation activities and measures undertaken shall be properly documented.

5.3.4 Service life file

The service life file shall document all conservation activities carried out during the operational life of a structure. This file shall also include results from inspections performed on the structure or its components, during its service life. The service life file shall include:

- Structure classification and conservation strategy;
- Reference to relevant drawings, and details of immediate and surrounding environment;
- Details concerning inspection and evaluation procedures, including inspection and monitoring results, data on observed deterioration, estimated deterioration rate and condition rating of the structure;
- Details of the plan and actual design and execution of preventative and corrective interventions carried out.

An extract of the service life file, called the re-birth certificate document (RCD), includes results of in-service inspection of an existing structure after preventative or corrective interventions have been undertaken. The content of the RCD usually corresponds to the information included in the birth-certificate document (BCD).

The in-service inspection level of detail must be stipulated in accordance with the quality levels, defined in (Sánchez Rodríguez, et al., 2022), and with national standards. The information collected over the structure life-cycle should, however, be as relevant as possible to enable standardization to be achieved. The standardization of information facilitates the estimation of functional performance requirements for the definition of life-cycle management (LCM) activities, quality control plans (QCP), and physical intervention strategies for the implementation of efficient performance-based management approaches. The medium or long-term actions can be defined based on the development of different scenarios, allowing

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the choice between different intervention strategies. The pre-determination of needs, costs and the best timing of these interventions allows for an efficient planning of activities, as well as a long-term cost reduction.

The service life file must be preserved as long as a structure remains in service. It may also be desirable to keep such records for a definite ~~indefinite~~ period (e.g. 5 years) for reference purposes, namely for the design, construction and conservation of other similar structures. Such records must be kept in a format which can easily be understood.

5.3.5 Quality and Information management during Dismantlement and Reuse

5.3.5.1 Objectives

The objective of QM in dismantlement is to control and manage the activities and measures taken to allow the safe removal of an existing structure and the clearance of the site as appropriate through:

- preparing dismantlement;
- dismantling the structure into its components;
- demolishing the structure by physically breaking it up;
- or a combination of such measures, facilitating the reuse and/or recycling of the original components parts and materials for new uses in a manner that minimizes the associated environmental and social impacts;
- waste management, re-use and recycling. This topic will become much more important in the future. Specific testing and approval methods for the use of recycling material have to be worked out.

5.3.5.2 Dismantlement document

The dismantlement document sets down the activities, measures and procedures which will allow the safe removal of an existing structure and the clearance of the site in a manner that minimizes the associated environmental and social impact.

5.3.5.3 Waste management document

The waste management document sets down the activities, measures and procedures which will allow to re-use some wastes generated during the dismantling phase in a manner that minimizes the environmental and economic impact and increases the circular economy of the concrete sector.

5.4 QM - ISO 9001

ISO 9001 is a standard for quality management systems and defines the requirements for such systems. An organization must meet these requirements in order to be able to provide products and services that fulfils customer expectations as well as legal and regulatory requirements relevant to the product or service. At the same time, the management system should be subject to a continuous improvement process. The requirements contained in the standard are applicable to all organizations, regardless of type, size and product. If the requirements of the standard are met, the organization can have this confirmed with a certificate.

The structure of the current revision is based on the basic structure for management system standards defined in the ISO directives (High Level Structure) and therefore has the following 10 chapters:

1 Scope
2 Normative references
3 Terms
4 Context of the organization
4.1 Understanding the organization and its context

7.4 Communication
7.5 Documented information
8 Operation
8.1 Operational planning and control
8.2 Requirements for products and services

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4.2 Understanding the requirements and expectations of interested parties

4.3 Define the scope of the quality management system

4.4 Quality management system and its processes

5 Leadership

5.1 Leadership and commitment

5.2 Quality policy

5.3 Roles, responsibilities and authority in the organization

6 Planning for the quality management system

6.1 Measures for dealing with risks and opportunities

6.2 Quality objectives and planning to achieve them

6.3 Planning for changes

7 Support

7.1 Resources

7.2 Competence

7.3 Awareness

8.4 Control of externally provided processes, products and services

8.5 Production and service provision

8.6 Release of products and services

8.7 Control of nonconforming process results, products, and services

9 Performance evaluation

9.1 Monitoring, measurement, analysis and evaluation

9.2 Internal audit

9.3 Management evaluation

10 Improvement

10.1 General

10.2 Non-conformity and corrective actions

10.3 Continuous improvement

The documentation of a QA or QC according to ISO 9001 must include the following:

- Quality policy
- Quality objectives
- Scope of the quality management system
- Procedures
- Process maps (flowchart)
- Forms & Checklists
- Work Instructions

5.5 QM - ISO 9001 - Monitoring and Measurement

Following similar basic considerations to ISO 9001:2008, the operator or owner of bridge structures or tunnels is required to inspect and monitor structural properties to ensure that all requirements have been met at all stages of the manufacturing and use process and that the intended functionality has been achieved.

5.5.1 Control and monitoring of structural properties

Processes should be established for inspection, testing, and monitoring activities to verify that structures, structural components, and materials meet specified requirements throughout their service life by using appropriate

- References, e.g., specifications or legal and regulatory requirements
- Methodology, e.g., sampling, non-destructive testing, or in-process monitoring
- documents, e.g. inspection and test plans
- Acceptance criteria, e.g. defined by ISO standards, legal or regulatory requirements
- Responsibilities, e.g. authorities for acceptance

Materials, components, subassemblies, and components should be excluded from use, until required inspections are completed. Modified structures or structural components should be fully inspected again and retested against the acceptance criteria.

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5.5.2 Documentation of monitoring and measurements at structures

Documentation of monitoring and measurement on structures is not mandatory. Operating procedures that directly affect the quality of structures should be adequately defined and controlled. The performance of inspection and testing procedures is appropriate for most structures where the characteristics of the structure need to be verified before release to the user.

5.5.3 Documentation of processes from monitoring and supervision

Develop and implement a procedure that defines the responsibilities for

- Inspection and testing during construction
- Inspection and testing during operation
- Final inspection and testing
- Maintain inspection and testing records
- Handle non-conforming inspection and testing results

Inspection and test procedures can be supported by ISO templates.

5.5.4 Measuring the effectiveness of processes

The effectiveness of monitoring and measuring the structural performance is often determined by looking for documentary evidence that performance requirements have been met and that planned arrangements have been followed. Trends in structural defect rates must be monitored, as well as the effectiveness of corrective actions taken in the event of non-conformity.

5.6 QM - ISO 9001 - Analysis & Evaluation

The analysis and evaluation procedure should establish and define the roles and responsibilities for the collection and analysis of data. In the course of the analysis and evaluation procedure, the purpose should be worked out by means of the following considerations/questions:

- What should an ISO 9001 data analysis include?
- Why should data be analysed?
- Methods of data collection
- How should the data be analysed?
- What should be documented in the analysis and assessment process?
- What is the best way to document the process?
- How should analysis and evaluation be made available

The quality management system must be shown to be effective by means of meaningful and relevant data. This makes it possible to determine where targeted improvements should be made. The data useful for this purpose comes from within your own organization but can also come from external sources.

5.6.1 Content of an ISO 9001 data analysis

- Levels of user satisfaction
- Performance level of manufacturers
- Results of product and performance monitoring
- Rate of nonconformities
- Trends and opportunities for corrective action

If the analysis shows unacceptable performance, these items should become quality objectives and be the subject of preventive or corrective actions, as appropriate. As a basis for the analyses and assessments, expert templates are recommended which should be adapted to individual needs

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5.6.2 Purpose of ISO 9001 data analysis

The purpose of analysing data is to:

- Assess organizational performance against established plans and stated quality objectives,
- Identify areas for improvement,
- Help determine the cause of problems,
- Provide guidance for determining the most appropriate corrective or preventive action to take.

5.6.3 Methods of data collection

Data collected for analysis includes:

- Results of user surveys
- Results of operator surveys
- Feedback from users, suppliers and operators
- Results from internal audits
- Results from performance monitoring and measurements
- Results from product monitoring and measurements
- Reports on non-conformities
- Warranty claims and renewed components or structures

5.6.4 Data analysis

An essential component of any quality management system is effective data analysis.

- Use statistical techniques where appropriate (e.g. Statistical Process Control)
- Data should be analysed by designated, competent personnel
- Use data feedback for continuous structural and process improvement.

5.6.5 Documentation of analysis & evaluation process

It is not a mandatory requirement to document your analysis & evaluation process. However, you should always look to adequately define and control any processes that generate information on the performance of your quality management system. Therefore, the implementation of an analysis of data procedure will be appropriate.

5.6.6 Efficient documentation of the process

Developing and implementing a process that defines roles and responsibilities for analysing quality management system data to drive continuous improvement and facilitate a fact-based approach to decision making is important and includes:

- Data collection
- Data analysis
- Information output
- Reporting

5.6.7 Data Process Effectiveness

The effectiveness of the data analytics process is often determined by demonstrating that the owner or operator has made sufficient use of the data from the results of its activities and has used that data to drive continuous improvement and user satisfaction.

5.7 QM - ISO 19650

ISO 19650-1:2018: Concepts and principles (ISO 19650-1, 2018) is the first part of the (ISO-19650) series on building information modelling (BIM). This part outlines the concepts and principles and provides recommendations on how to manage building information.

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It is complemented by (ISO 19650-2, 2018), ISO 19650-3:2020: Operational phase of the plants (ISO 19650-3, 2020) and ISO 19650-5:2020 (ISO 19650-5, 2020). (ISO 19650-5, 2020) provides a common information management process that enables an appointing party (such as an asset owner, asset operator or outsourced asset management provider) to establish their information requirements during the operational phase of an asset, and to provide the appropriate collaborative environment. Within this environment, multiple appointed parties can produce information in an effective and efficient manner. It will encourage more effective collaboration on global projects and allow designers and contractors working on all kinds of building works to have clearer and more efficient information management.

5.8 QM Framework - Data Informed

5.8.1 Quality control - workflow

Quality management, as shown in the illustration, is assigned to the operational parts of Quality Assessment and Quality Control. The quality control framework is envisaged in two phases - a static and a dynamic one. The first involves generally the preparatory work, inspection tasks and snapshot of KPIs. The second mode includes the evaluation of the remaining lifetime, the evolution of the KPIs over time and finding an optimal maintenance scenario, i.e. decision making.

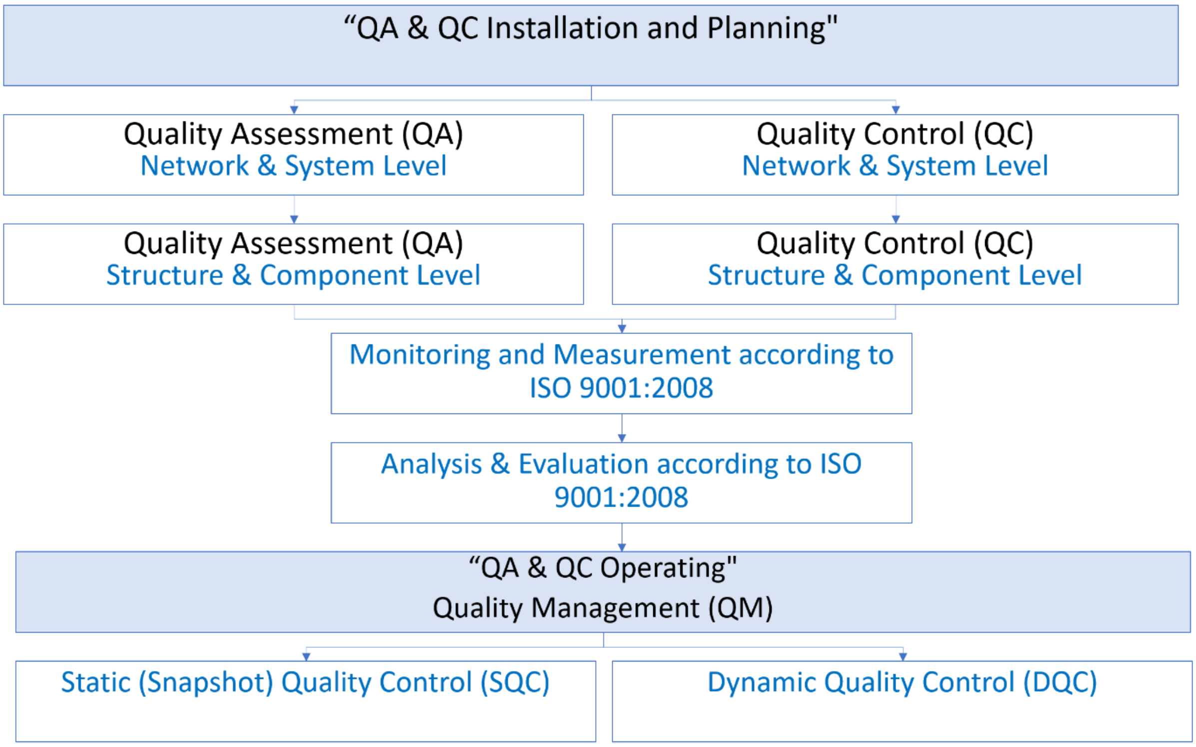

Figure 5.3 – Elements and Levels of Quality Management frameworks

5.8.2 Static quality control

In general, static quality control, as can be derived from the COP surveys, includes (a) preparatory work, (b) on-site inspection, (c) lab test, (d) assessment of condition or reliability, and (e) assessment of safety. The activities included in these individual quality control steps for performing the quality assessment are generally structured as follows:

Preparatory work
The preparatory work is usually divided into the subsequent process steps

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- Study an inventory information
- Identify conceptual weaknesses of the original design
- Identify the material weaknesses
- Compare the current traffic loads to traffic load model used in the original design
- Define the vulnerable zones
- Evaluate à priori reliability

For the individual activities enumerated here, more details can be found in IM-SAFE project reports D2.1 (Sánchez Rodríguez, et al., 2022) and D3.1 (Bigaj-van Vliet, et al., 2022)

Inspection on site
The inspection on site process steps can generally be broken down into the following:
- Identify damages (e.g. cracks, spalling, deformations, etc.)
- Measure on site material properties
- Collect samples

Lab test
Results of the on-site inspection may also cause in-depth laboratory analysis in justified cases, such as:
- lab testing of carbonatization depth
- lab testing of chloride ingress
- lab testing of concrete strength
- …

Assessment of the Condition or Reliability (KPI)
Subsequently, the observations and findings of the *inspection on site, monitoring* and the *lab test* are the basis for the following assessment steps, whereby the assessments should respectively be based on significant *key performance indicators* (KPI's) see (Bigaj-van Vliet, et al., 2022)
- Qualitative assessment of resistance (Condition assessment) reduction based on observed damages
- Qualitative assessment of reliability (Reliability assessment of structural safety and serviceability)

Assessment of the Safety (KPI)
Subsequently, the results of the Qualitative assessment of resistance (Condition assessment) or Qualitative assessment of reliability (Reliability assessment) are used to assess the safety (e.g. by means of safety factors, partial, global or KPIs), whereby reference is also made to the existing action situations, see also (Bigaj-van Vliet, et al., 2022).

5.8.3 Dynamic quality control

In general, dynamic quality control, as also confirmed from the COP surveys and seen in the expert references, includes (a) assessment of remaining service life (b) consideration of maintenance scenarios, and (c) elements of decision making. The activities taking place in these process steps of dynamic quality control can roughly be structured as follows:

Assessment of remaining service life
This process step usually comprises the following
- Evaluating the speed of active damage processes
- Prediction of damages
- Reliability and safety development over time

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Maintenance strategies

In this process step "Maintenance strategies", the following activities are usually performed for the planned remaining service life:

- Definition of a reference scenario "end-of-life intervention",
- Analysis and selection of clearly defined maintenance strategies or its combinations, see D3.2 chapters 3 & 4.
- Estimation of the long-term costs for the considered maintenance strategies,
- Estimation of availability for the considered maintenance strategies,
- Estimation of the impact of the considered maintenance strategies on reliability and safety.

Decision making

Decision making is the final step of a dynamic quality control process. In general, decision making is divided into the following steps:

- Performing multi-attribute or multi-objective optimization of e.g. maintenance strategies
- Monetization of non-monetary KPIs
- Determination of the optimal scenario

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5.8.4 Surveys on the application of "Static Quality Control”

The data given in IM-SAFE project reports D1.3 (Cuerva Navas, et al., 2021) and D1.3 (Hoff, et al., 2021), as well as a further, partly necessary detailed COP survey of the IMSAFE project including information from COST TU1406, were used to obtain an overview of the elements of static quality control applied in practice. The following is the result of these surveys, with the abbreviations having the following meanings: P = preparatory work; I = on-site inspection; L = laboratory test; ACR = assessment of condition or reliability AS = assessment of safety.

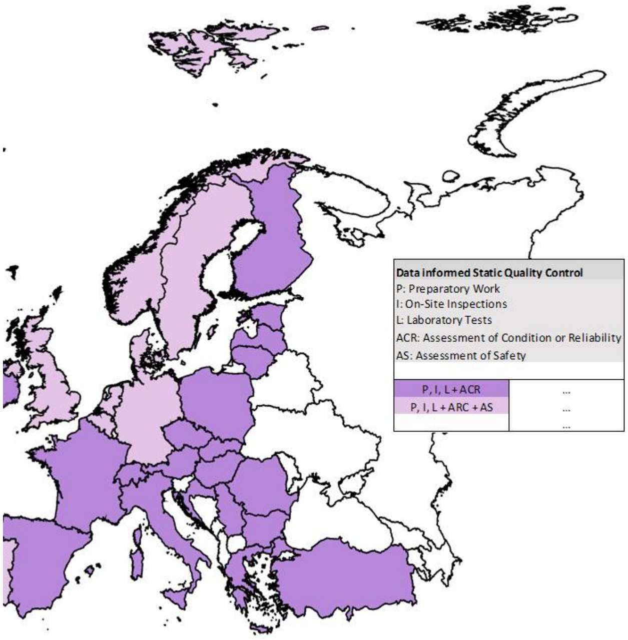

Figure 5.4 – Static Quality Control applied in European countries

	P	I	L	ACR	AS
Austria	+	+	+	+	o
Belgium	+	+	+	+	+
Bulgaria	+	+	+	+	o
China	+	+	+	+	o
Creek	+	+	+	+	o
Croatia	+	+	+	+	o
Czeck Republic	+	+	+	+	o
Denmark	+	+	+	+	+
Estonia	+	+	+	+	o
Finland	+	+	+	+	o
France	+	+	+	+	o
Germany	+	+	+	+	+
Hungary	+	+	+	+	o
Icland	+	+	+	+	+
Irland	+	+	+	+	o
Italy	+	+	+	+	o
Latvia	+	+	+	+	o
Lithuania	+	+	+	+	o
Netherlands	+	+	+	+	+
Norway	+	+	+	+	+
Poland	+	+	+	+	o
Portugal	+	+	+	+	+
Romania	+	+	+	+	o
Serbia	+	+	+	+	o
Slovakia	+	+	+	+	o
Spain	+	+	+	+	o
Sweden	+	+	+	+	+
Switzerland	+	+	+	+	o
Turkey	+	+	+	+	o
United Kingd	+	+	+	+	+
United State:	+	+	+	+	+

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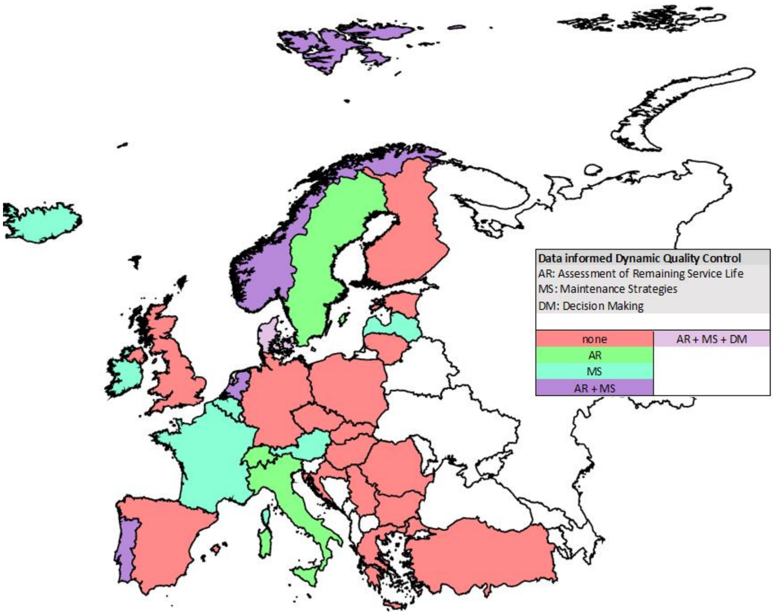
5.8.5 Surveys on the application of "Dynamic Quality Control"

As with the static quality control surveys, the data reported in D1.1 through D1.3, plus another detailed IMSAFE COP and COST TU1406 survey where appropriate, were used to evaluate the application of dynamic quality control in practice. The following is the result of these surveys associated with the of "Dynamic Quality Control", with the abbreviations having the following meanings: AR = assessment of remaining service life; MS = Maintenance Strategies; DM = Decision Making.



	AR	MS	DM
Austria	o	+	o
Belgium	o	+	o
Bulgaria	o	o	o
China	o	+	o
Creek	o	o	o
Croatia	o	o	o
Czeck Republic	o	o	o
Denmark	+	+	+
Estonia	o	o	o
Finland	o	o	o

	AR	MS	DM
France	o	+	o
Germany	o	o	o
Hungary	o	o	o
Icland	o	+	o
Irland	o	+	o
Italy	+	o	o
Latvia	o	+	o
Lithuania	o	o	o
Netherlands	+	+	o
Norway	+	+	o
Poland	o	o	o

	AR	MS	DM
Portugal	+	+	o
Romania	o	o	o
Serbia	o	o	o
Slovakia	o	o	o
Spain	o	o	o
Sweden	+	o	o
Switzerland	+	o	o
Turkey	o	o	o
United Kingd	o	o	o
United State:	o	o	o

Figure 5.5 – Dynamic Quality Control applied in European countries

5.9 QM Framework - Data Informed Structural Assessment

5.9.1 Static quality control

Structural assessment is a multi-stage process, as already shown in 5.8.4 (Static Quality Control) and 5.8.5 (Dynamic Quality Control). This structure of the quality control frameworks can also be clearly represented according to COST TU1406 in the flow chart shown in Figure 5.3. Accordingly, a distinction is made between the following static quality control frameworks

- *Inventory* (*IN*) recording/detection process (see Figure 5.7 as part of the quality control process in which the following elements to be evaluated are documented:
  - the structural properties,
  - the component properties,
  - the structure type
- *Vulnerable Zones* (*VZ*) recording/detection process (see Figure 5.7) as part of the quality control where the following situations are recorded:

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- VZ observations from the past
- VZ observations on the existing structure
- VZ based on the design properties of the structure
- VZ based on the execution properties
- VZ due to the damage processes already taking place

Remark: The characterized Vulnerable Zones provide the essential information about the Failure Modes relevant for the structure.

- *Failure Mode* (*FM*) recording/detection process as part of the quality control process where the following is documented:
  - FM based on the vulnerability zones detected
  - FM observations from the past
  - FM observations on the existing structure
  - FM based on the design properties of the structure
  - FM due to the design characteristics
  - FM due to the damage processes already taking place
  - FM due to fragility/robustness verification

Remark: The *Failure* Modes (FM) characterized at the Inventory (IN) allow the determination of the relevant Damages, Damage Indicators, Performance Indicators, see IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022), and subsequently the Key Performance Requirements, as shown in Figure 5.7. The documentation of these elements shown in Figure 5.7 corresponds to the procedure described in sections 5.2 to 5.5 of this document.

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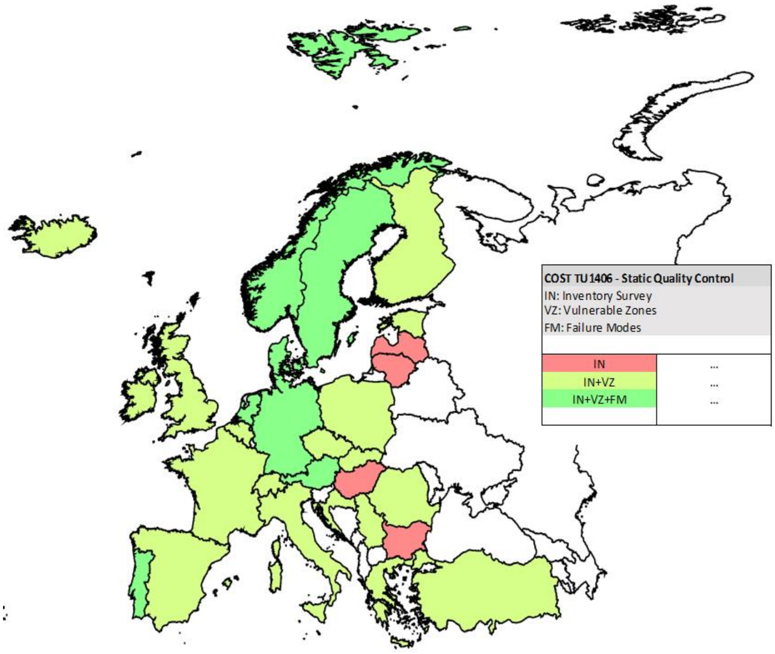
5.9.2 Practical application of "Static Quality Control"

As in the previous sections, the data from D1.1 through (Bigaj-van Vliet, et al., 2022), as well as an additional COP and COST TU 1406 survey, served as the basis for determining the extent to which the Inventory Survey (IN), Volunerable Zone (VZ), and Failure Mode (FM) surveys are implemented in practice according to the QA and QC methods described in the previous sections. From these surveys, the following country-specific pattern of results emerges:



	IN+VZ+FM	IN+FM	IN+VZ	IN
Austria	o	+	+	+
Belgium	o	o	+	+
Bulgaria	o	o	o	+
China	o	o	o	+
Creek	o	o	+	+
Croatia	o	o	+	+
Czeck Republic	o	o	+	+
Denmark	+	+	+	+
Estonia	o	o	+	+
Finland	o	o	+	+

	IN+VZ+FM	IN+FM	IN+VZ	IN
France	o	o	+	+
Germany	o	+	+	+
Hungary	o	o	o	+
Icland	o	o	+	+
Irland	o	o	+	+
Italy	o	o	+	+
Latvia	o	o	o	+
Lithuania	o	o	o	+
Netherlands	+	+	+	+
Norway	+	+	+	+
Poland	o	o	+	+

	IN+VZ+FM	IN+FM	IN+VZ	IN
Portugal	o	+	+	+
Romania	o	o	+	+
Serbia	o	o	+	+
Slovakia	o	o	+	+
Spain	o	o	+	+
Sweden	+	+	+	+
Switzerland	o	o	+	+
Turkey	o	o	+	+
United Kingd	o	o	+	+
United State:	o	o	+	+

Figure 5.6 – Static Quality Control – practical application

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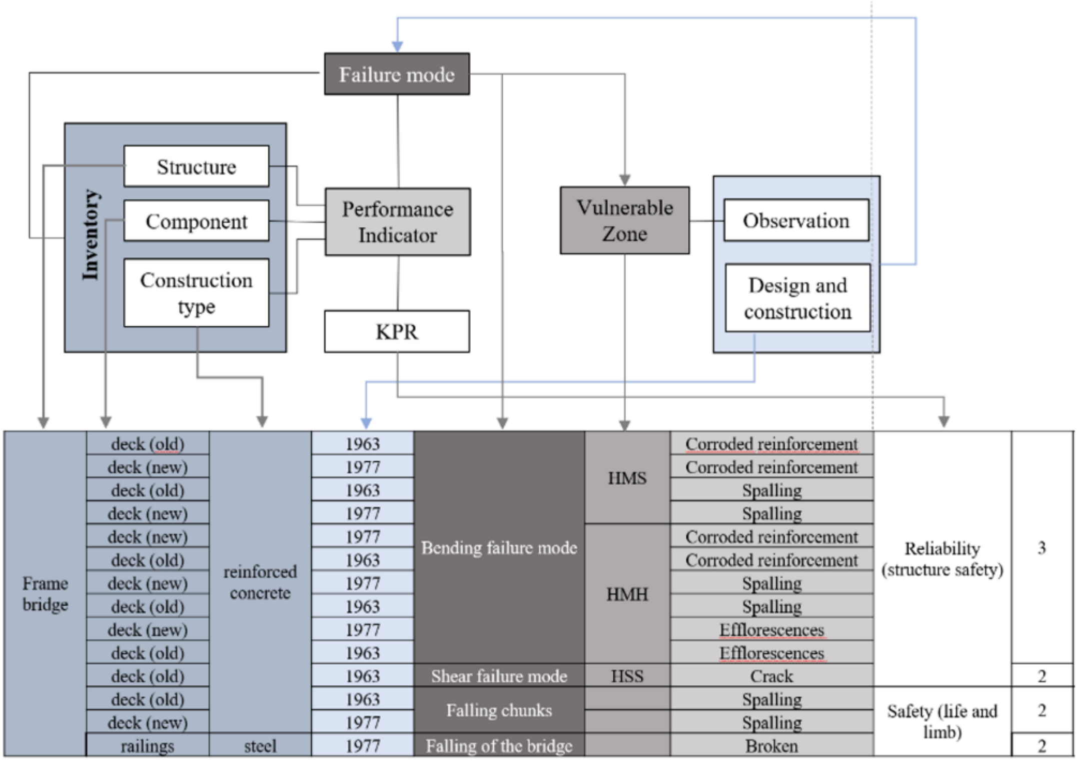

Figure 5.7 – Static quality control framework in structural assessment

5.9.3 Dynamic quality control – *Assessment of the remaining service life*

Figure 5.8 is an extension of Figure 5.7 by the elements of the "*Assessment of remaining service life".* As can be seen from the last three columns of the figure, a joint reliability evaluation is performed for the relevant FCs and FMs at the component level according to the minimum criterion (the worst evaluation parameter is decisive). Based on this evaluation and the criteria of the "Assessment of remaining service life" according to section 5.8.5, the remaining service life is estimated in the last column.

The *remaining service life assessment* can be performed on the level of:

- the classical condition assessment (condition classes) (CI),
- the reliability (reliability index) (RI),
- the risk (risk index) (RS),
-

The *remaining service life assessment* on the level of *reliability* requires either

- the direct conversion of the condition index into a reliability index using the performance index or key performance index approach, see (Bigaj-van Vliet, et al., 2022); Level I (CI→RI),
- Transferring the condition index with the help of the performance index or key performance index consideration and monitoring information into the reliability level, see (Bigaj-van Vliet, et al., 2022); Level II (CI→mon→RI),
- the conversion of the condition index into the reliability level using the performance index or key performance index approach and modeling, see (Bigaj-van Vliet, et al., 2022); Level III (CI→mod→RI),
- Transfer of the condition index to the reliability level with the help of the performance index or key figure consideration and the modeling and monitoring information, see (Bigaj-van Vliet, et al., 2022); Level III (CI→mod&mon→RI).

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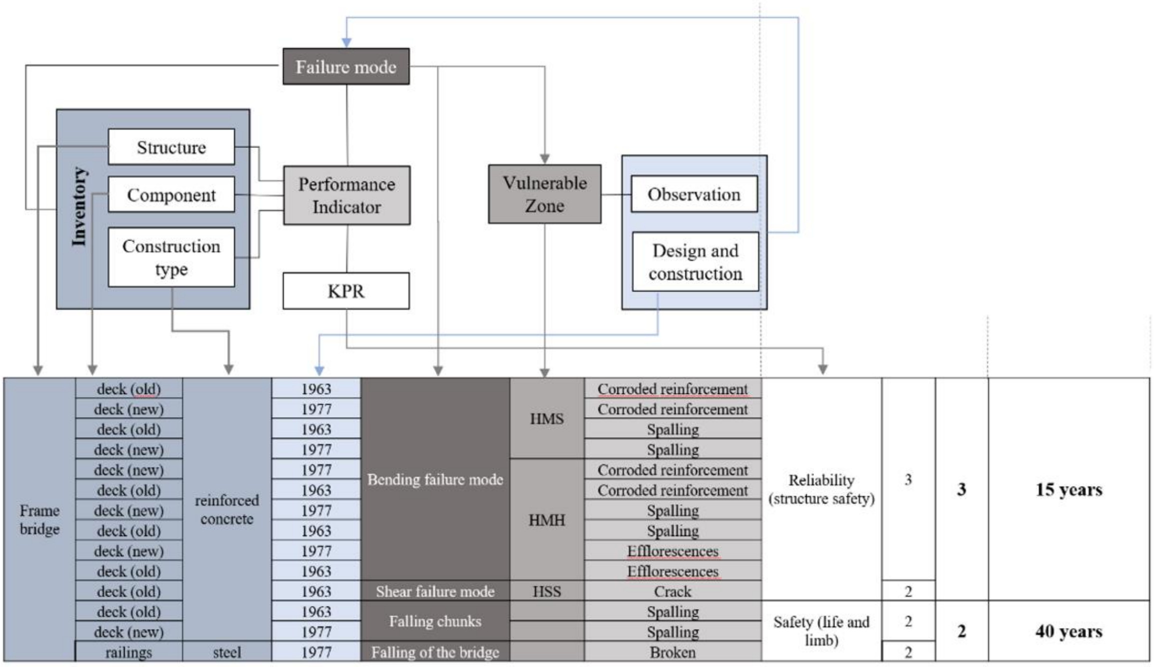

Figure 5.8 – Static and Dynamic quality control framework in structural assessment

Level I (CI→RI):

According to Figure 5.8, the reliability index ß is explicitly derived from the visual inspection for the decisive failure modes of the governing *Vulnerable* zone. This approach is to be considered as a first rough approximation, since the structural properties are only partly included in the considerations. The decisive indicator, shown in Figure 5.9 on the horizontal axis, is the reduction in bearing capacity. At this level, the decisive performance indicator from the visual inspection is selected for the relevant failure mode of the governing *Vulnerable* zone. As can be seen in Figure 5.9, the condition index on the left vertical axis is determined by evaluating the decisive indicator on the horizontal axis and the compliance function in the diagram shown in blue and grey. The compliance function in the diagram can be derived from experiments and modelling of the analysed vulnerable zone and associated failure mode, respectively.

The reliability indices of the considered vulnerable zone can be subsequently identified for the condition classes detected on the left vertical axis. For example, a condition class 1 corresponds to a reliability index ß = 4.7/year or a condition class 5 with a load reduction of 50% corresponds to a reliability index ß = 1.8/year (ß=1,8 the minimum acceptable reliability index). Subsequently, the reliability indices determined on the left vertical axis can be transferred to the failure probability information on the right vertical axis. A quality assessment (QA) and quality control (QC) according to the previous chapters requires the clear documentation of the procedure presented here and also the clear documentation of the changing conditions and states over time. It is the basis for a solid reliability based assessment of the remaining service life.

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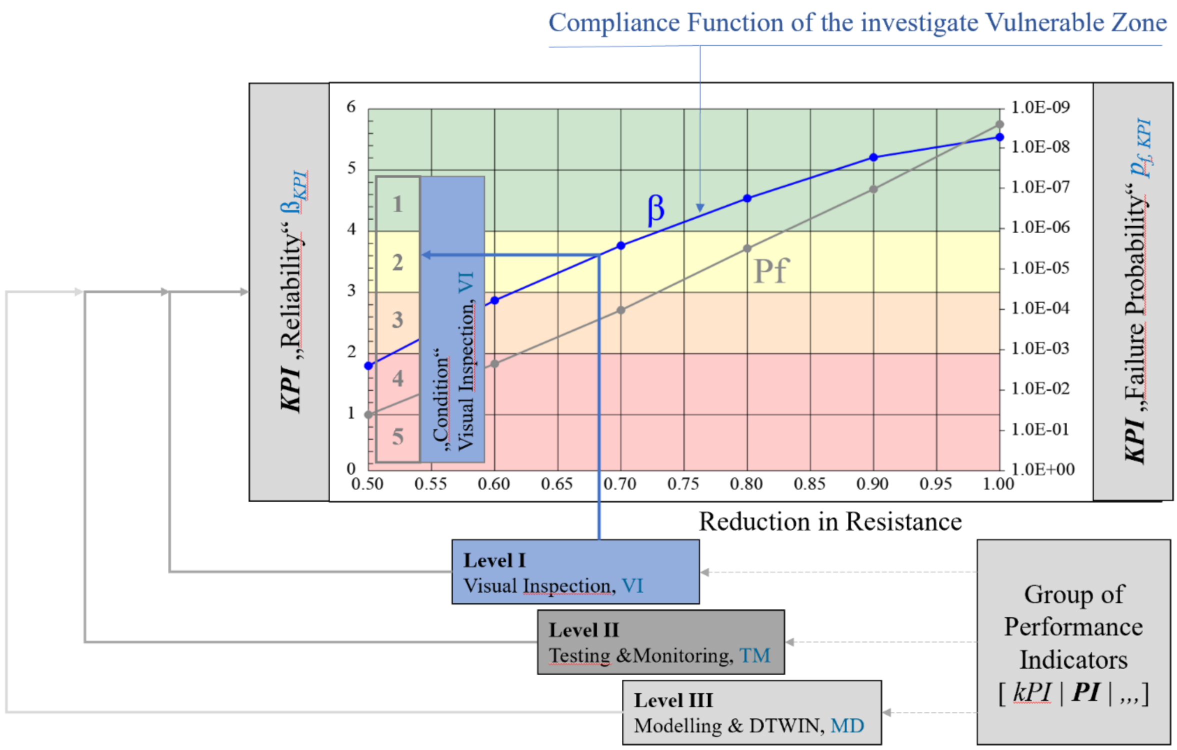

Figure 5.9 – Static and Dynamic quality control framework: Condition and Reliability index vs. the bearing capacity associated performance indicator of the dominate failure mode

Level II (CI→mon→RI):

In Level II, tests and monitoring activities are carried out which already facilitate a direct evaluation of the condition index and the reliability level. Thus, as can be seen in 5.5, it is no longer necessary to determine the condition index or the reliability index by means of performance indicators associated with compliance functions. In the sense of a data-informed structural performance assessment, the information from the system behaviour can already be taken into account in this Level II by testing and monitoring and the associated performance indicators or key performance indicators.
In terms of high quality assessment (QA) and quality control (QC), clear documentation of the procedures, monitoring systems, test procedures, and test or monitoring conditions is necessary according to the previous chapters.

Level III (CI→mod→RI):

Level III involves modelling activities for an explicit assessment of current and future performance condition and reliability performance. This approach allows modelling support for the determination of remaining service life.
With respect to high quality assessment (QA) and quality control (QC), the same provisions apply as in the previous sections

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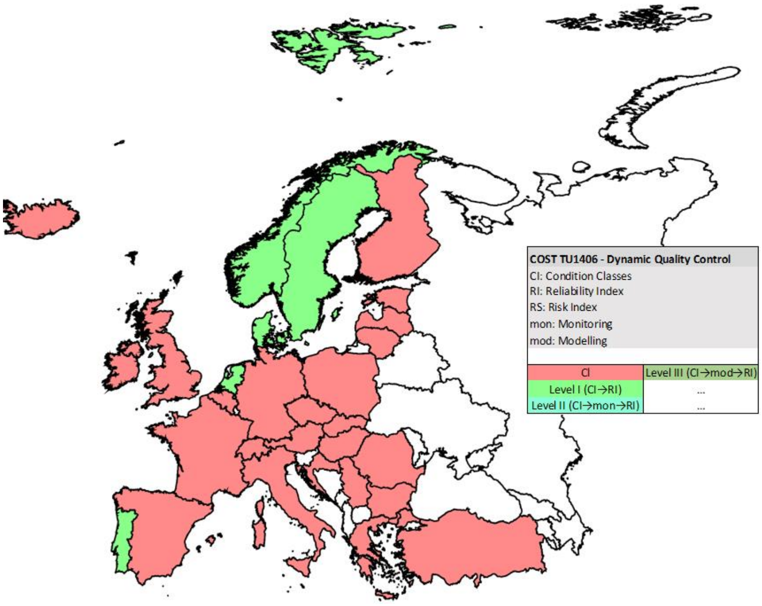
5.9.4 Practical application of "Dynamic quality control –*remaining service life*"

The surveys conducted in this project regarding the *Assessment of the remaining service life* show the following implementations in practice.



	CI	Level I (CI→RI):	Level II (CI→mon→RI),	Level III (CI→mod→RI)
Austria	+	o	o	o
Belgium	+	o	o	o
Bulgaria	+	o	o	o
China	+	o	o	o
Creek	+	o	o	o
Croatia	+	o	o	o
Czeck Republic	+	o	o	o
Denmark	+	+	o	o
Estonia	+	o	o	o
Finland	+	o	o	o

	CI	Level I (CI→RI):	Level II (CI→mon→RI),	Level III (CI→mod→RI)
France	+	o	o	o
Germany	+	o	o	o
Hungary	+	o	o	o
Icland	+	o	o	o
Irland	+	o	o	o
Italy	+	o	o	o
Latvia	+	o	o	o
Lithuania	+	o	o	o
Netherlands	+	+	o	o
Norway	+	+	o	o
Poland	+	o	o	o

Figure 5.10 – Dynamic Quality Control – practical application

5.9.4.1 Dynamic quality control – *Maintenance strategies*

The elements outlined in the previous sections 5.9.3 and 5.9.4 for the assessment of the remaining service life of the dynmaic quality control only partly include maintenance strategy concepts.

Maintenance strategies (MS): In general, the choice of maintenance strategy (corrective maintenance, preventive maintenance etc., see also section 3) influences the remaining service life. In particular, preventive maintenance strategies also try to optimize the future maintenance effort and the remaining service life.

Optimization of maintenance strategies (OMS): Preventive maintenance strategies as well as the optimization of these maintenance strategies can be done on the condition class level, see Figure 5.11 (a), the reliability class level, or also on the risk based level. The prediction models required for these strategies can be based on experimental, monitoring and modeling approaches.
In the sense of a QA and QC strategy, the recommendations of section 3 are to be taken to account and special attention is to be paid to the comparability of the results with similar systems.

Multi-objective optimization of maintenance strategies (MOMS): The optimization of the remaimg service life in terms of performance (based on condition, reliability or risk) mentioned above can also be extended to a multi-objective approach, in which, for example, in addition to performance (see Figure 5.11 (a)), availability (Figure 5.11 (b)), economic efficiency (Figure 5.11 (c)) or safety (Figure 5.11 (d)) are included in the optimization considerations. The requirements for the correct implementation of QA and QC according to section 5.2 & 5.3 of this chapter increase with the number of multilayers and require the special procedures to ensure the correct implementation of the methods.

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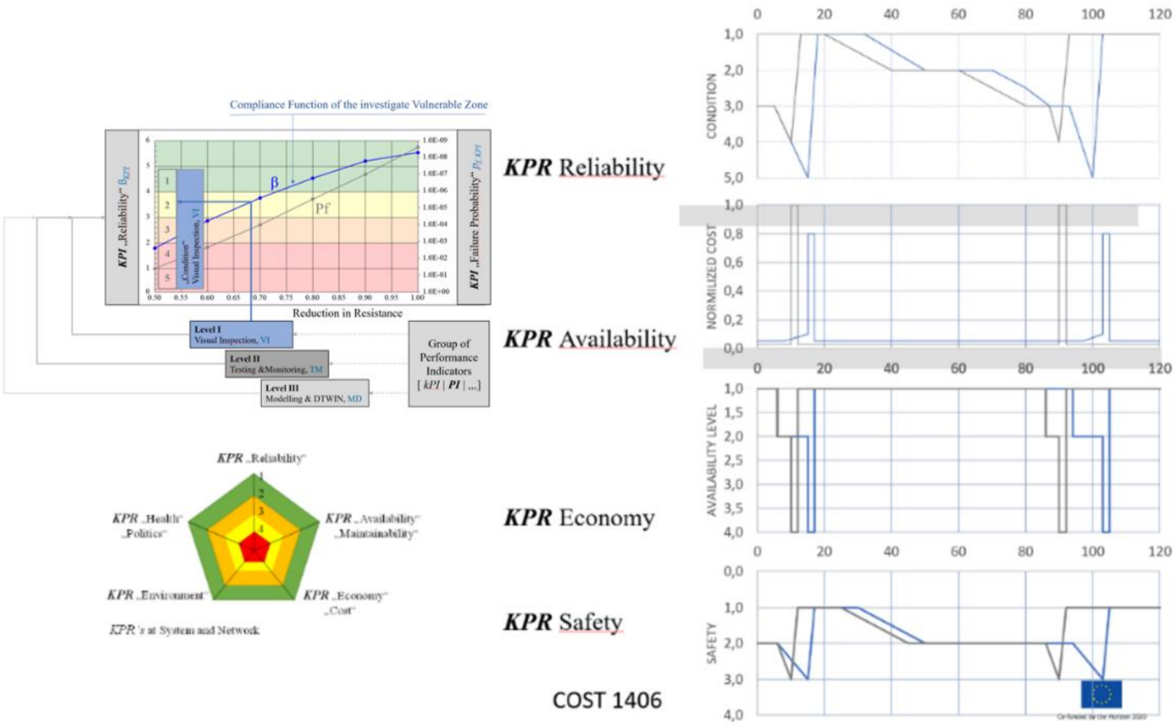

Figure 5.11 – Dynamic quality control – Single and multi-objective optimization of maintenance strategies for the remaining service life (adapted from (COST TU1406).

5.9.5 Practical application of "Dynamic quality control – *Maintenance strategies*"

The surveys conducted in this project regarding the *maintenance strategies and its optimization* show the following implementations in practice.

- MS for remaining service life: by Austria, Germany,…
- OMS for remaining service life: by Nobody
- MOMS for remaining service life: by Nobody

5.9.6 QA & QC Data informed assessment

Quality assessment QA and quality control QC must include, as already outlined in Section 5.2 and also shown in Figure 5.12, the policy guidelines, applicable legislation and administrative arrangements. From these the functional requirements and the non-functional requirements for structures and systems and the inventory are derived, for which in turn the static and dynamic quality controls outlined in the previous sections 5.2 to 5.3 must be applied.

QA& QC associated with Risk-based considerations

For good practice, the QC and QA methods and procedures outlined in sections 5.2 must also be applied to the risk-based assessments. These include, as shown in Figure 5.5, the assessment of the:

- Policy requirements, applicable laws and administrative agreements.
- Aspect requirements, e.g., reliability, availability, maintainability, safety.
- Key structural performance requirements, e.g., structural safety, serviceability, durability, robustness, redundancy.
- Performance criteria, e.g., limit state functions with associated reliability rates for the specified reference period

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QA & QC associated with Data informed through-life maintenance

The risk-based assessments of structures applied via through life cycle management require associated time-varying QA and QC. These procedures should consider the following quantities as basic inputs (see also (Bigaj-van Vliet, et al., 2022)):

- Damage indicators
- Performance indicators
- Key performance indicators

QA & QC associated with Structural performance assessment

Data informed through-life maintenance based on data such as damage indicators, performance indicators, key performance indicators (see Figure 5.12 & (Bigaj-van Vliet, et al., 2022)) can be carried out at different levels and in different phases (see also Chapter 5.8), whereby it should be mentioned that during through-life maintenance the phases can not only be increased, but a transition to a smaller phase is also possible. Consequently, when implementing the QA and QC methods, these phases and the associated inspection, monitoring and modelling tools must be taken into account and coordinated with each other. In summary, structural performance assessment distinguished into the following phases

- Evaluation on performance level I: Visual Inspection, Testing and Monitoring
- Evaluation on performance level II: Structural Health Monitoring
- Evaluation on performance level III : Modeling and Digital Twin Approaches

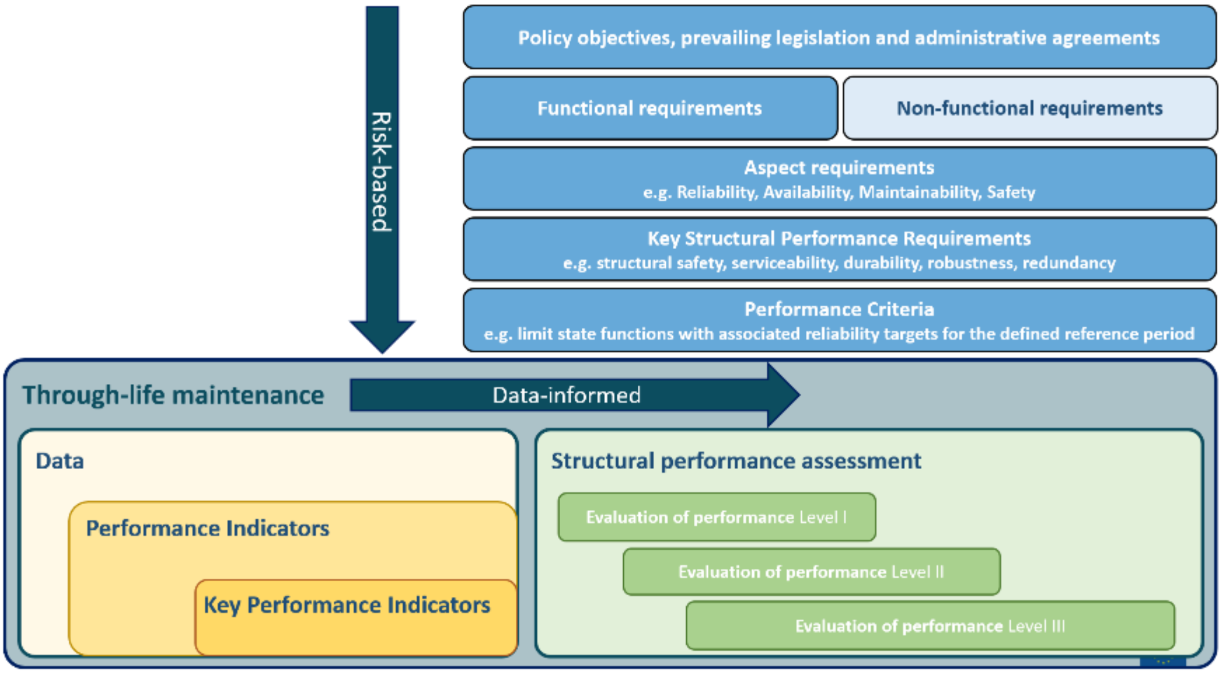

Figure 5.12 – Quality Assessment & Quality Control for Data informed assessment procedures

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5.9.7 QM Framework - Performance and Key Performance Indicators

As already stated in Chapter 9 of IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022) , breaking down the performance assessment of a structure or any other facility into a minimum of three levels is reasonable. Figure 5.13 presents these levels, in a flow chart. For more details see (Bigaj-van Vliet, et al., 2022). These process steps must also be assigned a Quality Assessment or a Quality Control QC. The QA and QC methods and their implementation must therefore be differentiated into:

- QA & QC in Level I: *Preliminary assessment (Visual inspection)*: The purpose of Level I is to remove existing doubts about the performance using fairly simple methods, which must, however, be adequate. The performance evaluation shown in Figure 5.13 is based on anomaly detection and leads to the KPR level or, in case of an insufficient condition, to level II.
- QA & QC in Level II: *Detailed investigations (Detailed Inspection, testing and monitoring)*: Structural investigations and updating of information are typical of Level II – it comprises detailed inspection, testing and monitoring among others. The additional information gained e.g. from the performance indicators of this investigations can be introduced into confirmatory calculations with the aim of finally dispelling or confirming any doubts as to whether the structure is safe. As in Level I (see Figure 5.13), in this II level the performance evaluation is based on the detection of anomalies and leads to the KPR stage or, in the case of an inadequate condition, to Level III.
- QA & QC in Level III: *Assessment and prediction by advanced analysis (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 level I and II. In assessing an existing structure, such an analysis (see Figure 5.13) 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 this level III, the distinction between key performance and performance indicators can be applied analogously to levels I and II.

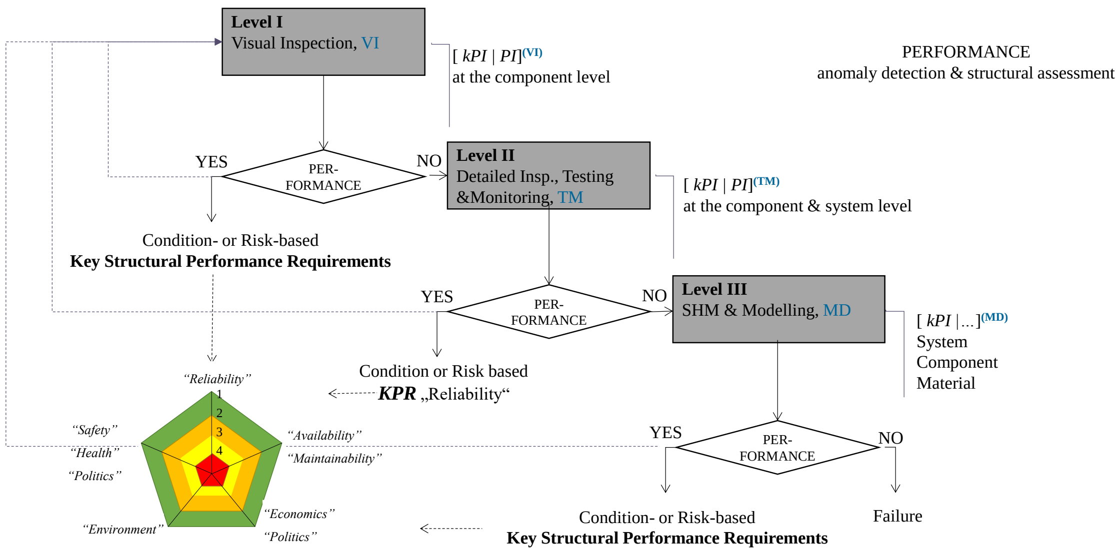

Figure 5.13 – Quality Assessment & Quality Control for Performance assessment according to the different inspection levels, see IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)

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6 Principles of Information Management

Information management plays a key role during the entire life cycle of an infrastructure. From design to demolition, vast amounts of information are constantly being generated, which is usually recorded in a heterogeneous manner. The construction sector still works using highly-document centric systems, statically storing data in heterogeneous formats which may result in information loss or huge costs and delays (Deshpande, Azhar, & Amireddy, 2014) (Isikdag, Aouad, Underwood, & Wu, 2007) (Borrmann, König, Koch, & Beetz, 2018).

A cost analysis report of inadequate interoperability done by Gallaher et al. estimated a 15.8-billion-dollar loss per year in U.S capital facilities industry (Gallaher, O'Conor, Dettbarn, & Gilday, 2004). Therefore, having a proper information management system in place serves to avoid unnecessary costs and delays, as well as the possible information loss. Furthermore, the digitalisation of information in the infrastructure domain has gained popularity over the last years. For instance, in 2018, a proposal to increase the transport budget of the Connecting Europe Facility (CEF) was issued. This budget increase, of at least €10 billion from 2021 to 2027, would be used to aid in the rail digitalization, and to assign specific budgets for telematics applications and automation (EPRS, 2019).

This chapter will be centred around the information collected in the maintenance and monitoring phase of an infrastructure, leaving the data generated in previous phases as existing information. Nevertheless, said pre-existing information will still be mentioned. The chapter will be split in the following manner: section 6.1 will deal with the type of data and its classification, while section 6.2 presents an introduction to the role of Building Information Modelling (BIM) in Information Management

6.1 Classification of relevant information for infrastructures

As mentioned previously, this section will focus on the type of data and its classification. It is also important to differentiate between possible data sources, the stage of the life cycle in which it is generated, and the requirements that it fulfils.

Classification: Inside the context of this chapter, and the IM-Safe project, the data can be classified in the following categories:

- **Geometry**
  Geometry is defined as the geometric properties of the structural system and of such non-structural elements that may affect the structural response (e.g., General cross-section drawings).

- **Construction details**
  Construction details are used to demonstrate compliance with regulations and other building code requirements. Furthermore, these details are of special interest for structural calculations (e.g., anchorage of longitudinal reinforcement).

- **Condition information**
  Describe the current state of the asset (e.g vibrations, deformations, soil movements…).

- **Materials**
  Materials includes all properties of the constituent materials (e.g., concrete mean compressive strength).

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- **Structural Setting**
  Structural setting refers to all factors which are not directly related to the structure that might affect its calculation (e.g., wind load coefficients).

- **Administrative Information**
  Administrative information comprehends all information used in managing or organizing the asset (e.g., birth certificate).

Sources: Indicates where data should be collected:
- Available documentation for the structure
- Code, standards, and documented practice at the time of construction
- Field investigations and measurements
- Material testing

Stage: Indicates the period of the life cycle of the asset in which the information was generated:
- Design
- Construction
- Service life
- Dismantlement and recycling

Requirements: Indicates the use of the information item:
- Geometric information
- Identification of defects
- Geographic information
- Design information
- Construction information
- Asset management and organization information

All these attributes were grouped in Table 6.1. The symbology used in the table is presented in Figure 6.1.

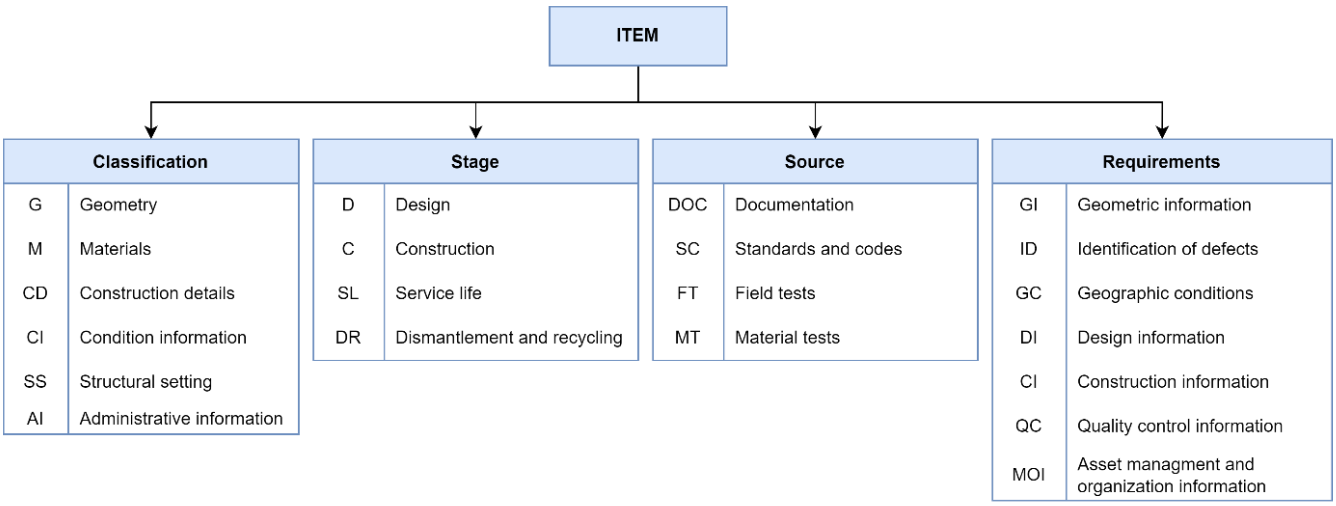

Figure 6.1 – Symbology - Classification of relevant information for infrastructures.

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Table 6.1 – Classification of relevant information for infrastructures

No.	Item	Classification	Stage	Source	Requirement
1	General layout drawings	G	D	DOC	GI/DI/QC
2	General elevation drawings	G	D	DOC	GI/DI/CI/QC
3	General cross-section drawings	G	D	DOC	GI/DI/CI/QC
4	Foundation details drawings	G	D	DOC	GC/DI/CI/QC
5	Foundation geometry drawings	G	D	DOC	GI/DI/CI/QC
6	Foundation cross-section drawings	G	D	DOC	GI/DI/CI/QC
7	Super-structure details drawings	G	D	DOC	GI/DI/CI/QC
8	Super-structure geometry drawings	G	D	DOC	GI/DI/CI/QC
9	Super-structure cross-section drawings	G	D	DOC	GI/DI/CI/QC
10	Distribution systems drawings	G	D	DOC	GI/DI/CI/QC
11	Construction procedure drawings	CD	D	DOC	CI/DI/QC
12	Concrete cover depth	CD	D/C	DOC	DI/ID/CI
13	Reinforcement lap-splices characteristics	CD	D	S&C	DI/CI
14	Spacing of bars	CD	D	S&C	DI/CI
15	Permissible mandrel diameters for bent bars	CD	D	S&C	GI/DI/CI
16	Ultimate bond stress	CD	D	S&C	ID
17	Anchorage of longitudinal reinforcement	CD	D	S&C	ID
18	Anchorage of links and shear reinforcement	CD	D	S&C	ID
19	Anchorage by welded bars	CD	D	S&C	ID
20	Anchorage of bundles of bars	CD	D	S&C	ID
21	Laps length	CD	D	S&C	DI/CI
22	Lapping bundles of bars	CD	D	S&C	DI/CI
23	Mechanical couplers	CD	D	S&C	DI/CI
24	Bundled bars	CD	D	S&C	DI/CI
25	Anchorage of prestressing tendons	CD	D	S&C	DI/ID/CI
26	Anchorages and couplers for prestressing tendons	CD	D	S&C	DI/ID/CI
27	Rupture	CI	SL	FT/MT	ID
28	Holes	CI	SL	FT/MT	ID
29	Deformation	CI	SL	FT/MT	ID
30	Wire break	CI	SL	FT/MT	ID
31	Loss of section	CI	SL	FT/MT	ID
32	Deteriorated mortar joints	CI	SL	FT/MT	ID
33	Frequency	CI	SL	FT/MT	ID
34	Obstruction/impending	CI	SL	FT/MT	ID
35	Displacement	CI	SL	FT/MT	ID
36	Cracks	CI	SL	FT/MT	ID

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37	Scaling	CI	SL	FT/MT	ID
38	Reinforcement bar failure/bending	CI	SL	FT/MT	ID
39	Stirrup rupture	CI	SL	FT/MT	ID
40	Crushing	CI	SL	FT/MT	ID
41	Debonding	CI	SL	FT/MT	ID
42	Tensioning force deficiency	CI	SL	FT/MT	ID
43	Vibrations/oscillations	CI	SL	FT/MT	ID
44	Delamination	CI	SL	FT/MT	ID
45	Prestressing cable failure	CI	SL	FT/MT	ID
46	Spalling	CI	SL	FT/MT	ID
47	Loss of section	CI	SL	FT/MT	ID
48	Deformation	CI	SL	FT/MT	ID
49	Reinforcement bar	CI	SL	FT/MT	ID
50	failure/bending	CI	SL	FT/MT	ID
51	Concrete mean compressive strength	M	D/C	MT	DI/ID/QC
52	Concrete water-cement ratio	M	D/C	DOC	DI/ID/QC
53	Concrete mean uniaxial tensile strength	M	D/C	MT	DI/ID/QC
54	Concrete flexural tensile strength	M	D/C	MT	DI/ID/QC
55	Stress-strain concrete relation	M	D/C	MT	DI/ID/QC
56	Concrete density	M	D/C	DOC	DI/ID/QC
57	Concrete shrinkage coefficient	M	D/C	DOC	DI/ID/QC
58	Concrete creep coefficient	M	D/C	DOC	ID/QC
59	Concrete elastic deformation	M	D/C	DOC	DI/ID/QC
60	Concrete Young's modulus	M	D/C	DOC	DI/ID/QC
61	Concrete poisson ratio	M	D/C	DOC	DI/ID/QC
62	Concrete thermal expansion coefficient	M	D/C	DOC	ID/QC
63	Concrete workability	M	D/C	FT/MT	ID/QC
64	Concrete segregation	M	D/C	FT/MT	ID/QC
65	Concrete bleeding	M	D/C	FT/MT	ID/QC
66	Concrete plastic shrinkage	M	D/C	FT/MT	ID/QC
67	Concrete setting	M	D/C	FT/MT	DI/ID
68	Temperature of fresh concrete	M	D/C	FT/MT	ID/QC
69	Fresh concrete water-cement ratio	M	D/C	FT/MT	DI/ID/QC
70	Reinforcement elastic limit	M	D	DOC	DI/ID/QC
71	Reinforcement maximum real elastic limit	M	C	MT	ID/QC
72	Reinforcement tensile strength	M	D	S&C	DI/ID/QC
73	Reinforcement bending capability	M	D	S&C	DI/ID/QC
74	Reinforcement adherence	M	D	S&C	ID/QC
75	Reinforcement steel yield strength	M	D	S&C	DI/ID/QC
76	Reinforcement steel maximum actual yield strength	M	D	S&C	ID/QC

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77	Reinforcement steel tensile strength	M	D	S&C	DI/ID/QC
78	Reinforcement steel ductility	M	D	S&C	ID/QC
79	Reinforcement steel bendability	M	D	S&C	ID/QC
80	Reinforcement steel bond characteristics	M	D	S&C	ID
81	Reinforcement steel section sizes and tolerances	M	D	S&C	GI/DI/ID
82	Reinforcement steel fatigue strength	M	D	S&C	DI/ID
83	Reinforcement steel weldability	M	D	S&C	ID
84	Reinforcement steel shear and weld strength	M	D	S&C	DI/ID
85	Prestressing steel type	M	D	DOC	DI
86	Prestressing steel cross section	M	D	DOC	GI/DI
87	Prestressing steel tensile strength	M	D	DOC	DI/ID
88	Prestressing steel elongation at failure	M	D	DOC	DI/ID
89	Prestressing steel fatigue strength	M	D	DOC	DI/ID
90	Exposure conditions characteristics	SS	D	S&C	GC/DI
91	Snow load coefficients	SS	D	S&C	GC/DI
92	Wind load coefficients due to location	SS	D	S&C	GC/DI
93	Temperature load coefficients due to isotherm lines	SS	D	S&C	GC/DI
94	Seismic load coefficients	SS	D	S&C	GC/DI
95	Load coefficients due to planned use	SS	D	S&C	GC/DI
96	Topography drawings	SS	D	DOC	GC/DI
97	Geology and geotechnics drawings	SS	D	DOC	GC/DI
98	Birth certificate	AI	C	DOC	MOI
99	Re-Birth certificate	AI	SL	DOC	MOI
100	Project specifications	AI	All	DOC	MOI
101	Ownership	AI	All	DOC	MOI
102	Purpose of the infrastructure	AI	All	DOC	MOI
103	Preconditions	AI	All	DOC	MOI
104	People and resources available	AI	All	DOC	MOI
105	Function of the infrastructure	AI	All	DOC	MOI
106	Perception	AI	All	DOC	MOI
107	Permits	AI	All	DOC	MOI
108	Certifications	AI	All	DOC	MOI
109	Warranties	AI	All	DOC	MOI
110	Safety measures	AI	All	DOC	MOI
111	Escape route	AI	All	DOC	MOI
112	Safety organization	AI	All	DOC	MOI
113	Maintenance organization	AI	All	DOC	MOI
114	Service ramps and routes	AI	All	DOC	MOI
115	Consultation structure	AI	All	DOC	MOI

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116	Financial management	AI	All	DOC	MOI
117	Information Management approach	AI	All	DOC	MOI
118	Information systems in place	AI	All	DOC	MOI
119	Vision, strategy and planning	AI	All	DOC	MOI
120	Planned maintenance approach	AI	All	DOC	MOI
121	Corrective maintenance approach	AI	All	DOC	MOI
122	Failure definitions	AI	All	DOC	MOI
123	Inspection procedure	AI	All	DOC	MOI
124	Evaluation reports structure	AI	All	DOC	MOI
125	Functional testing procedure	AI	All	DOC	MOI
126	Distribution systems management	AI	All	DOC	MOI
127	Current situation report	AI	All	DOC	MOI
128	Operations during maintenance	AI	All	DOC	MOI
129	Relevant decisions log	AI	All	DOC	MOI
130	Construction methods	AI	All	DOC	MOI
131	Construction history	AI	All	DOC	MOI
132	Related buildings for construction	AI	All	DOC	MOI
133	Timeline report	AI	All	DOC	MOI
134	Infrastructure asset inventory	AI	All	DOC	MOI
135	Demolition waste estimation	AI	DR	DOC	MOI/QC
136	Identification of hazardous materials	AI	DR	DOC	MOI/QC
137	Classification of demolition waste	AI	DR	DOC	MOI/QC
138	Demolition plan	AI	DR	DOC	MOI/QC
139	Safety measures for the demolition	AI	DR	DOC	MOI/QC
140	Revalorization or recycling plans for the demolition waste	AI	DR	DOC	MOI/QC
141	Demolition waste logistics	AI	DR	DOC	MOI/QC

6.1.1 Level of knowledge approach

All structural assessment analyses are approximations of reality. These approximations are performed using the available information of the structure. Depending on the targeted analysis, the level of detail of this information may differ, which results in having different levels of accuracy in each analysis. However, these levels can be progressively refined through a better estimation of the condition of the structure. Therefore, the level of analysis, approximation, and modelling of a structural assessment is dependent on the detail of information used in the analysis itself, which is known as *level of knowledge* (Taerwe & Matthys, 2013). Figure 6.2 provides a simplified representation of different Levels of Analysis, although it is also applicable to Level of Modelling and Level of Approximation, as is seen in the X-axis.

The first levels are to provide simple and safe hypothesis for the evaluation of the structural condition of the asset. This leads to safe, yet realistic, values of the structural behaviour. These levels are simple, not time-consuming, and usually sufficient to establish a preliminary knowledge of the structural condition.

The medium levels (level 2 to 3) include more detailed information in their analysis. The condition of the asset is evaluated considering inspection results and structural health

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monitoring, while physical parameters of the structure are typically evaluated through simplified analytical procedures. These levels are usually sufficient to cover most of the structural assessments, and while they take longer than lower levels, they are still seen as no-time-consuming.

Finally, the highest levels (level 3 to 4) include the modelling of the structural performance with detailed information about loads and resistance parameters as well as information. They employ numerical procedures that typically result in the best estimates of the structural condition. However, the use of these numerical procedures can be very time-consuming and is only advised for the assessment of critical existing structures. This is also justified when a more accurate estimate can lead to significant savings by avoiding or limiting the strengthening of the structures (Taerwe & Matthys, 2013).

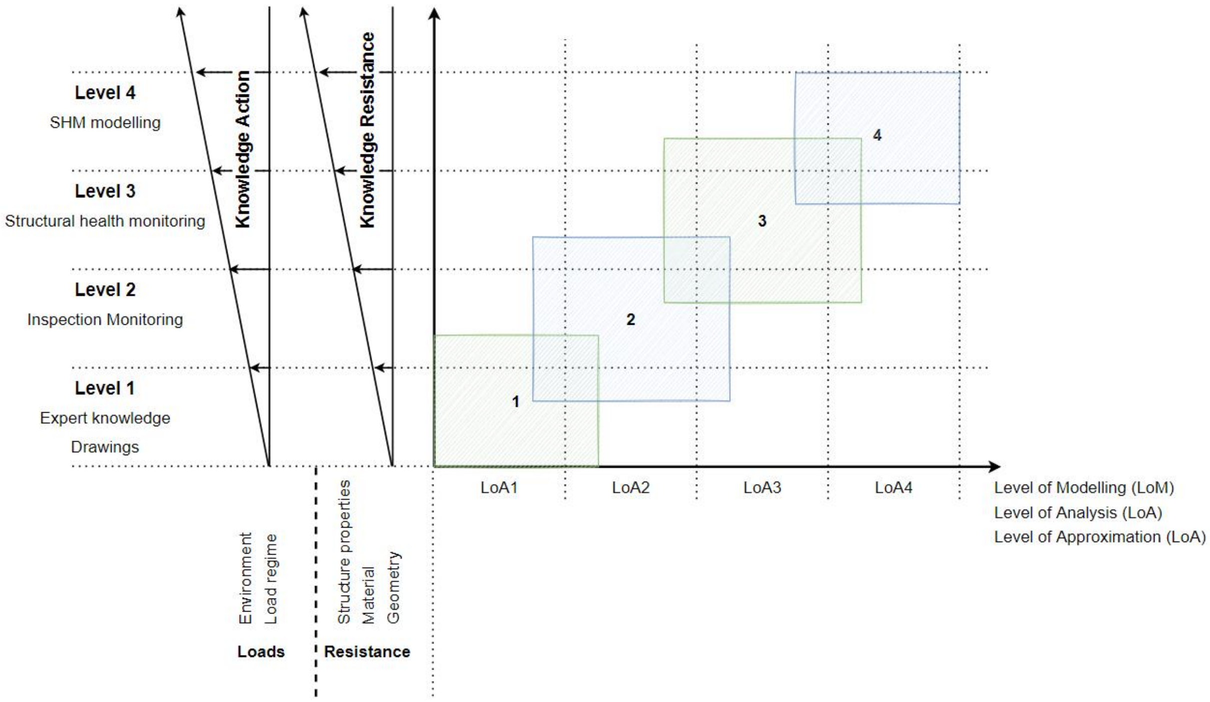

Figure 6.2 – Level of knowledge approach

6.2 Information Management using BIM

Building Information Modelling (BIM) provides powerful means to manage any information related to an asset. It describes a virtual model constructed around a single file following a standardized data model, where it is possible to represent all the information generated throughout the lifecycle of a structure. Additionally, it is directly related to the visualization of data, whether it represents geometrical or semantical information. This, along with the collaborative drive that is the core of BIM, eases the understanding of information and improves the efficiency and sharing capabilities of the system with the related parties.

Section 6.2.1 will describe the ways of classifying BIM from an information perspective, two classifications are differentiated, BIM levels and BIM dimensions. Section 6.2.2 is a brief introduction to which are the benefits to include BIM in SHM and maintenance procedures. Finally, Section 6.2.3 introduce the role of *Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling – Part 3 Operational phase of the assets* (ISO 19350-3, 2020) for the operational phase of a BIM-managed asset.

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6.2.1 BIM classification

A BIM model can be classified depending on both its maturity, and the dimension of information that it encompasses. In the first case, the maturity is directly related to the collaboration between involved parties. The reason behind this is that the core of BIM is the collaborative workflow that it represents. It is driven by the parallel work of different specialized teams over the same federated model, stored in a Common Data Environment (CDE). A CDE is a central repository that acts as the single source of information for the project. However, not all BIM implementations include the same level of collaboration. As such, there are levels that describe the maturity of BIM (BIM, 2022):

- **Level 0:** No collaboration plans. Uses paper-based two-dimensional (2D) Computer Aid Design (CAD).
- **Level 1:** Zero to low collaboration, everyone manages their own data. Three-dimensional (3D) CAD for conceptual works and 2D CAD for the generation of statutory approval documentation and Production Information. The data is shared electronically using a CDE managed by the contractor.
- **Level 2:** Parties work on their local 3D CAD and the information is exchanged through a common file format, such as the Industry Foundation Classes (IFC). The system in place allows the combination of the local models into a federated BIM model.
- **Level 3:** Deeper collaboration through a shared model stored in a central repository. It allows for simultaneous work in the same model, which eliminates the possibility of conflicting information. It proposes the use of an integrated solution built around standards like IFC.

A BIM model can also be characterized by the dimensions of information that it contains, which is also related to its direct applications. The higher the BIM dimension, the further away you move from a simple 3D CAD representation to a complete digital twin of the asset (BIM, 2022).

- **3D Geometry**
- **4D Time:** Duration, timeline and scheduling
- **5D Money:** Cost estimation and budget analysis
- **6D Sustainability:** Energy analysis
- **7D Facility Management:** Status, maintenance/operation manuals, warranty information...

6.2.2 Application of BIM in the SHM and maintenance process:

As information grows in size, the need of a fitting information management procedure increases as well. In the case of a structure, which is constantly generating vast amounts of data throughout its life-cycle, this requirement is further highlighted. In IM-SAFE project report D4.2 (Weise, Sebastian, Mitsch, & Sánchez Rodriguez, 2022), a framework to integrate BIM of transport infrastructures is presented, while in this section the role of BIM supporting SHM and maintenance process is brief described.

BIM plays an important role in SHM and maintenance procedures, since it presents the information in an accessible, practical and understandable manner and can be applied to the entire life-cycle of structures (Ismail, 2021).

BIM is a conventional basis for the description of monitoring-related information. It presents a methodology for interdisciplinary modelling of information and is centred around the collaboration of these disciplines. It comprehends different tools, processes and technologies for the documentation and exchange of data in 3D digital models (Theiler & Smarsly, 2018), In that sense, SHM datasets can be incorporated into a dynamic BIM environment to visualize real-time data and the associated structural behaviour. Specifically, this can be used to help

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identify anomalies in the data (e.g. faulty sensors, anomalous behaviour, etc.), as well as to visualize the structural condition (strain, forces and stresses) and its distribution in the structure (Ye, y otros, 2019). The creation of such a model, with real-time data, would result in a digital twin of the real asset.

Digital models (DM), or twins, have an intelligent data processing capability because they combine mathematical models describing the physics of the structure, with data collected and processed from real operations, which make them ideal to decision-making approaches (Twi, 2022). In the case of BIM-based digital models, their workflows facilitate the real-time evaluation of model changes.

Additionally, effective data management is possible by linking elements of SHM systems with DM in several aspects. These aspects include monitoring states, repair actions, and maintenance decisions (Twi, 2022). In order to do so, however, a fitting data format is needed, such as the Industry Foundation Classes (IFC). IFC is an open international standard for the description of the built environment. In its origin, its scope was limited to buildings, but it has been evolving towards civil infrastructure over the last years. More specifically, the IFC 4.1 version introduced key concepts such as the alignment, or the possibility of using linear placement (Building Smart , 2022). This feature greatly benefits infrastructures like roads, which often use kilometric points to mark certain spots. The IFC standard can be used to describe the asset information thought its entire life-cycle, from identification of objects, to geometrical information or abstract concepts like performance (Panah & Kioumarsi, 2021). This is possible due to its object-oriented approach, in which the different objects or entities that form the structure have several attributes that further characterize it. Furthermore, IFC provides a set of types, functions and rules to obtain information properly to the area of interest (Panah & Kioumarsi, 2021). Overall, three fundamental aspects can be highlighted to describe the role of BIM in SHM and maintenance procedures in structures: the good management and control of SHM data, the better interpretation by connecting real-time data in BIM models, and the preparation of a confident database for various projects (Panah & Kioumarsi, 2021).

6.2.3 Operational phase

Throughout the life cycle of an asset, a wide range of information is constantly generated. Some of this information has been classified in the table presented in section 6.1, as well as tagged depending on the stage of the asset in which it was generated. This vast amount of information needs to be managed, and BIM serves as a way to do so. However, as the usual scale of the projects involving BIM deal with several teams specialized in different fields, the role of standardization is a key factor determining its success. For information management specifically, the (ISO-19650) series deals with this factor, and should be used as a reference. Specifically, the standard deals with the operational phase, which comprehends information generated by surveying technologies for monitoring purposes. If this new information is to be included in the model, some steps are required. These steps are summarized below (ISO-19650):

1. **Check availability of reference information and shared resources**.
2. **Generate information.** The information should comply with the asset information standard and the asset information production methods and procedures. The information should not exceed the required level of information, go beyond the allocated information container, or duplicate other information.
3. **Undertake quality assurance check.**
4. **Review the information and approve for sharing.**
5. **Review the information model.**
6. **Authorize information model for delivery to the appointing party**.

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7 Impact of costs of information on decision-making

Information that supports decisions in structures is usually limited and difficult to assess. Nowadays, with the progressive implementation of advanced structural health monitoring, good amount of information can be collected. This information can be analysed thinking in sustainability purposes, as to minimize the lifecycle cost of structures, and can also be used to help the decision-making procedures.

This chapter is centred around the impact of cost of information on decision-making and is split in the following manner. Section 7.1 deals with life cycle cost analysis formulation including the analysis of cost of inspection, monitoring, and testing which are also included in the general formulation; section 7.2 focuses on the cost-benefit of information based on decision-making.

7.1 Life-cycle cost analysis

Structures which are not adequately planned, designed, and constructed usually require more costly and extensive maintenance and repairs throughout structure service life. Life cycle cost analysis (LCCA) is a data-driven tool that provides a detailed account of the total costs of the project over its expected life. In order to obtain an optimal trade-off between maintenance and repair plans LCCA methodology can be used. Since all costs involved in LCCA of structures depend on its typology, construction methods, monitoring system, among others. This section does not consider any quantitive example of LCCA.

LCCA methodology is often used to supplement the design process for structures deemed of great economic and societal importance because it allows to account for various costs, including those related to construction, inspection, maintenance, users, between others. This methodology helps to quantify the long-term benefit of the structure considering all costs during its useful life (Torti, Venanzi, Laflamme, & Ubertini, 2021). LCCA have been also used to quantify costs and benefits of bridges equipped with structural health monitoring systems, since the versatility of the LCCA is optimal to find maintenance strategies based on monitoring information. In this section, a general formulation to calculate the life cycle cost is presented.

7.1.1 General formulation of whole life cycle cost

There are several costs involved during the service period of structures, a general formulation for all costs associated around their life-cycle project may include:

- $C_{capital}$ include, but not limited to, the plan and design cost, which means all costs involved to have the structure “ready to use”.
- $C_{operational}$ include all maintenance (preventive and corrective) and structural health information (inspection, monitoring and testing) costs.
- C_{user} may include all indirect costs associated with traffic delays or reduced travel time.

The general equation that describes the cost associated with the structure during its whole life is presented in Eq. 7.1.Figure 7.1 shows the relationship between costs in the general formulation.

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$$C_{lifecycle} = C_{capital} + C_{operational} + C_{user} \qquad [7.1]$$

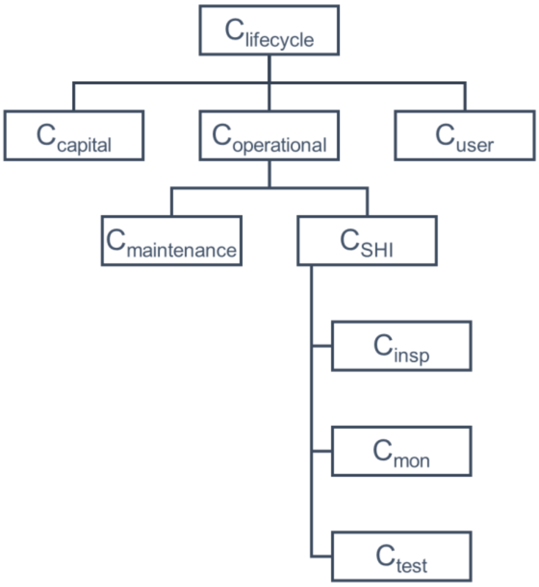

Figure 7.1 – General formulation of life cycle cost analysis

$C_{lifecycle}$	Cost of life cycle
$C_{capital}$	Capital cost
$C_{operational}$	Operational cost
C_{user}	User cost
$C_{maintenance}$	Maintenance cost
C_{SHI}	Cost of Structural Health Information
C_{insp}	Cost of inspection
$C_{monitoring}$	Cost of monitoring
C_{test}	Cost of testing

Table 7.1 – Notation list of the formulation of life cycle cost

7.1.1.1 Capital Cost (CAPEX)

Capital costs are related with the processes of planning, designing and building the project (management and engineering costs). These costs vary depending on the nature of the project but commonly include materials cost, transportation and placement, cost of labour, equipments, design and procurement, right-of-way purchase and construction costs. Some of these costs are calculated directly (e.g., labour and material) but some are computed as a percentage of the total costs (e.g., insurance policy). The percentage and the value with respect to which that percentage is taken should be based on the market or on statistical data of the owner. All these costs are executed at the beginning of the life cycle.

7.1.1.2 Operational Costs

Operational Expeditures (OPEX) or operational costs includes all day-to-day costs of operating the project after structure is in service. Operational costs should at least include all maintenance, inspection, monitoring and testing costs. Specific operational costs are described in follow sections:

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Maintenance costs

As was discussed in section 3.6, there are two types of maintenance works in structures preventive and corrective maintenance. Costs get reduced if a significant amount of preventive maintenance works are performed, and it also increases the service life of the structure. Figure 7.1 shows an example of the effect of preventive maintenance on the occurrence of the corrective maintenance for the different bridge types (Dubey, 2007). Values shown in Table 7.2 are not fixed for typologies shown, by contrast, these values are just to show how cost of corrective maintenance is significantly decreased when preventive maintenance is carried out.

Table 7.2 – Estimated unit cost for superstructure of composite concrete bridges and reinforced concrete bridges. Adapted from (Dubey, 2007).

	With preventive maintenance (€/m²)		**Without preventive maintenance (€/m²)**	
Bridge type	Reinforced Bridge	Steel/Concrete Composite bridge	Reinforced Bridge	Steel/Concrete Composite bridge
Preventive maintenance cost	61	116	0	0
Corrective maintenance cost	315	333	745	851
User cost for a preventive maintenance	138	156	0	0
User cost for corrective maintenance	581	507	5637	2693

As is shown in Table 7.2 corrective maintenance should be early needed when the structure does not have a previous preventive maintenance. On the other hand, preventive maintenances are usually a cyclic maintenance, and they are performed in intervals, but essential maintenances are generally performed once in lifetime. To calculate the expected life cycle maintenance cost these correlations must be considered.

Maintenance costs formulation

Total maintenance costs will depend on the number of maintenance preventive cycles, which will further depend on the year of corrective maintenance. The number of cycles can be calculated with Eq. 7.2 and 7.3.

$$N_c = \frac{t_e}{t_p} \qquad if\ t_p\ is\ not\ divisor\ of\ t_e \qquad [7.2]$$

$$N_c = \frac{t_e}{t_p} - 1 \qquad if\ t_p\ is\ divisor\ of\ t_e \qquad [7.3]$$

where,

- N_c is number of preventive maintenance cycles before corrective maintenance is performed.
- t_p is the preventive maintenance cycle period.
- t_e is the year of essential maintenance is performed.

If the time of consideration (lifetime period) is larger than the time of corrective maintenance, the total preventive maintenance cost is given by .

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$$TMC = \sum_{r=1}^{N_c} PMC_j + TCMC + \sum_{r=N_c+1}^{N_{pt}} PMC_k \qquad [7.4]$$

where,

- TMC is the total maintenance costs (preventive and corrective).
- PMC_j is the total preventive maintenance cost for each individual path preformed before corrective maintenance.
- PMC_k is the total preventive maintenance cost for each individual path preformed after corrective maintenance.
- N_c is number of preventive maintenance cycles performed before the corrective maintenance.
- N_{pt} is number of preventive maintenance cycles performed after the corrective maintenance.
- r is the cycle number.

The number of cycles of preventive maintenance performed after the corrective maintenance can be calculated following Eq. 7.5.

$$N_{pt} = \frac{t - t_e}{t_j} \qquad [7.5]$$

where:

- t is the lifetime period of analysis.
- t_e is the expected year of corrective maintenance.
- t_j is the period of preventive maintenance activities.

Cost of Structural Health Information (C_{SHI})

This section refers to the cost of the Structural Health Information (SHI), which includes inspection, monitoring and testing, so SHM is also included in the term (Diamantidis, Sykora, & Sousa, 2019). Thus, the cost of SHI (see Eq. 7.6) includes the cost of inspection, monitoring and testing.

$$C_{SHI} = C_{insp} + C_{mon} + C_{test} \qquad [7.6]$$

The following paragraphs will break down the costs of inspection, monitoring and testing, addressing the optimum Structural Health Information approach. This optimum approach explains in which cases it would not be necessary to take into account Structural Health Information, and therefore not to incur this cost, and the ways to choose the best Structural Health Information option when you have several inspection, monitoring and testing alternatives.

Cost of inspection

The expected inspection costs at time t can be computed following Eq. 7.7 (Torti, M.; Venanzi, I.; Laflamme, S.; Ubertini, F., 2021).:

$$E\left[C_{insp}(t)\right] = C_I^{schd}(t) + E\left[C_I^{SHM}(t)\right] \qquad [7.7]$$

Where C_I^{schd} denotes costs associated with scheduled and periodic inspection, with [7.8:

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$$C_I^{schd}(t) = \sum_{l=1}^{L(t)} n_{I,l}(t) \cdot (C_{I,l}^{schd} + C_{I,l,ind}^{schd})\, Eq \qquad [7.8]$$

where:

- L is the total number of scheduled inspection operation types at time t.
- $n_{I,l}$ the number of l-type inspections planned at time t.
- $C_{I,l}^{schd}$ is the l-type scheduled inspection direct cost.
- $C_{I,l,ind}^{schd}$ is the indirect cost, here defined as the cost corresponding to the discomfort to users for interruptions or deviations of traffic caused by inspection operations.

$E\left[C_I^{SHM}(t)\right]$ represents the costs of additional inspections with respect to scheduled operations (see Eq 7.9), which are activated following alerts from the monitoring system.

$$E\left[C_I^{SHM}(t)\right] = \sum_{i=1}^{N} p_{I,i}^{schd}(t) \cdot (C_{I,i}^{schd} + C_{I,i,ind}^{schd})) \qquad [7.9]$$

where:

- N is the total number of types of limit states, or damages, that the monitoring system is capable to detect
- $p_{I,i}^{schd}$ the probability that the monitoring system detects the ith type of damage
- $C_{I,i}^{schd}$ and $C_{I,i,ind}^{schd}$ are the direct and indirect inspection costs associated to the ith type of damage

Cost of monitoring

The general formulation for monitoring cost C_{mon} associated with the duration t_{md} (years) is computed following (Kim, 2011) as follows in Eq. 7.10.

$$C_{mon} = C_{mon,ini} + \sum_{i=1}^{n_{mon}} t_{md} \cdot C_{mon,ann}\, Eq \qquad [7.10]$$

where,

- $C_{mon,ini}$ is the initial cost of the monitoring system
- $C_{mon,ann}$ is the annual cost related to operation, inspection, and repair of the monitoring system
- n_{mon} is number of monitoring

Cost of testing

The general formulation for testing cost can be calculated following Eq 7.11 (Sykora, Diamantidis, Müller, & Sousa, 2020) is:

$$C_{test} = C_{test,NDT} + C_{test,DT} + C_{test,report} \qquad [7.11]$$

where:

- $C_{test,NDT}$: Includes repair of surface after tests. Dependent on accessibility of the location. To be increased for surfaces with heritage value.
- $C_{test,DT}$: Includes repair after tests. To be increased for surfaces with heritage value.
- $C_{test,report}$: Analysis of results (fixed cost) and reporting (25% of cost of NDTs and DTs).

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Optimum Structural Health Information approach
When performing these calculations, it can be considered to use the structural health information (SHI) or not. The approach without SHI can be beneficial particularly in the cases of short working lives, relatively low failure consequences, relatively high SHI costs, or highly reliable structures. Considering SHI, several options for inspection, monitoring and testing are possible. To choose the best approach, total cost ($C_{SHI,i}$) for different options are compared and the optimum is selected.

The optimum strategy considering SHI mentioned above is due to find an optimum threshold for each option. A simplified cost-benefit analysis can be conducted to specify the target reliability level related to a limiting value of the monitored parameter. When the limiting value is exceeded, reliability becomes unacceptable, and a safety measure must be implemented. The cost-benefit analysis aims to balance the safety measure cost and the expected failure consequences (accepted risk) and defines the rule for the decision on risk and mitigation actions (Diamantidis, Sykora, & Sousa, 2019).

A safety measure is implemented whenever the risk – failure probability, $p_f(x)$, depending on the observed x multiplied by C_F – exceeds the safety measure costs, C_{safe} (Diamantidis, Sykora, & Sousa, 2019) as follows in Eq. 7.12.

$$C_{safe} \geq C_F \cdot p_f(x) \qquad [7.12]$$

Increasing the safety of structures is generally associated with costs. The optimal level of safety is achieved by minimizing the total costs, which are defined as the sum of the safety costs (invested or committed for the purpose of risk reduction) and the expected value of failure costs, see the figure (Fischer, Viljoen, Köhler, & Faber, 2019), as Figure 7.2 shows.

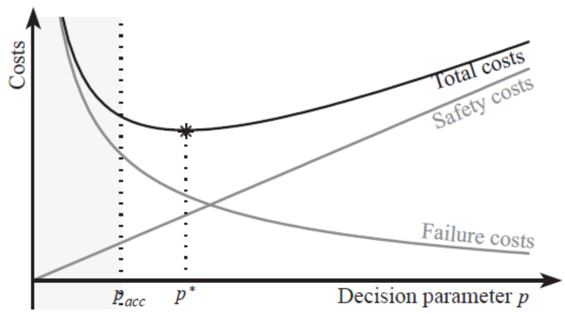

Figure 7.2 – Monetary optimization with societal acceptance criterion for investments into life safety. Extracted from (Fischer, Viljoen, Köhler, & Faber, 2019).

7.1.1.3 User cost calculation (C_{user})
The infrastructure disservice can be quantified in monetary terms where user costs are associated with delay and detouring from the most convenient route due to the impossibility of transit over the structure (Messore, Capacci, & Biondini, 2020). Thus, user costs should be properly considered into the life-cycle analysis when dealing with loss quantification and risk assessment for road transportation networks.

Furthermore, user costs can be classified into three different components, which are driver delay costs (DDC), vehicle operating cost (VOC) and accident cost (AC). In order to include user costs in bridge life-cycle cost analysis, each component can be related to the Total Travel Time (TTT) or to the Total Travel Distance (TTD) in the network. Times mentioned before could be calculated as follows in Eq. 7.13 and 7.14, respectively.

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$$TTT(d) = \sum_{0 \in Z} \sum_{0 \in Z} T_{0d}(d) \times f_{0d} \quad [7.13]$$

$$TTD(d) = \sum_{0 \in Z} \sum_{0 \in Z} L_{0d}(d) \times f_{0d} \quad [7.14]$$

where:

- T_{0d} is the travel time associated with the fastest route from origin o to destination d.
- L_{0d} is the travel distance associated with the fastest route from o to d.
- f_{0d} is the traffic flow from o to d in terms of vehicles per unit time.

DDC quantifies in monetary terms the value of time lost by the users due to detouring. With reference to the previously introduced notation, DDC is expressed as cost per unit time as follows in Eq. 7.15.

$$DDC(d) = (TTT(d) - TTT_0) \times q_{DDC} \quad [7.15]$$

where:

- TTT_0 is the total travel time associated with a full functionality.
- q_{DDC} is the estimated cost of time lost by each vehicle in the time unit.

By other hand, VOC represents the additional operational expenses associated with longer travel distances of vehicles. Consistently with DDC, it can be defined as follows in Eq. 7.16.

$$VOC(d) = (TTD(d) - TTD_0) \times q_{VOC} \quad [7.16]$$

where:

- TTD_0 is the total travel distance associated with a full functionality state.
- q_{VOC} is the unitary operating cost per vehicle in the road length unit.

The cost parameter qVOC includes all the costs related to the vehicle operations, mainly: fuel and engine oil consumption, tyres consumption, maintenance and deterioration (represented by the depreciation of the vehicle).

7.2 Cost-benefit based decision-making

Despite the availability of different methods for decision-making, the Cost-Benefit Analysis (CBA) will be addressed in this project in order to select the best SHI strategy and consequently the best systems to implement. CBA is a technique that allows to evaluate the possible alternative strategies in a monetary way, being able to demonstrate in terms of money that an application is worthwhile or not. However, in many occasions aspects that are not easily quantifiable monetarily must be evaluated, so multicriteria analysis is used in combination with CBA. Under the framework of selecting the best SHI strategies and their systems with which the CBA is to be applied in this work, it is of great importance that this method be combined with the VOI. With regard to this, in section 8.1 a general decision-making flowchart is proposed. In this section the Cost-Benefit Analysis will be addressed, explaining their characteristics and how can be solved their limitations with the combination multicriteria analysis methods and the value of Information.

In general terms, Cost-Benefit Analysis is a useful tool from an economic point of view for making investment decisions. It allows evaluate public spending to avoid inadequate distribution of resources. CBA must be used before the decision is made to compare and evaluate the different alternatives of action by reference to the net social benefit that they

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produce for the comunity as a whole, identifying the best one based on the costs and benefits of each project. (Kazimieras, Liias, & Turskis, 2008), (Damart & Roy, 2009), (CoA, 2006).

The main steps of the Cost-Benefit analysis are shown in the Figure 7.3.

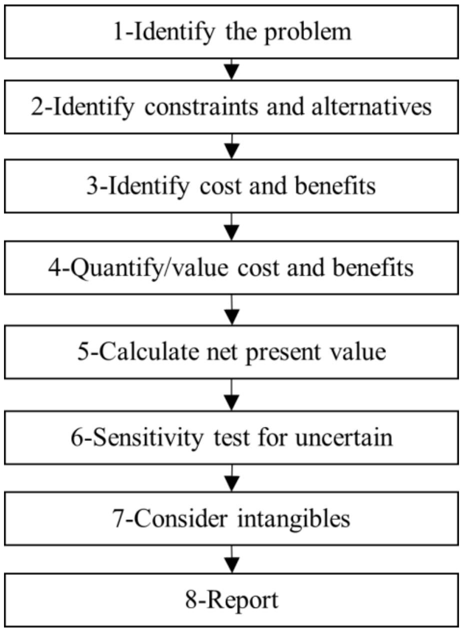

Figure 7.3 – Main steps of the Cost-Benefits Analysis. Adapted from (Commonwealth of Australia, 2006)

One application of the Cost-Benefit analysis can be to investigate monetary effects of a possible new technology or method, such as the introduction of SHI strategies and the systems to implement it. For instance, CBA can be performed to determine the feasibility and effectiveness of certain monitoring techniques to monitoring infrastructures. This example of application is explained in the section 7.2.1, which was extracted from (Ozden, Faghri, Li, & Tabrizi, 2016).

However, nowadays other aspects apart from economic aspect are evaluated, as is represented in step 7 of Figure 7.3 and in which the CBA has limitations. These elements, known as intangibles, are difficult to quantify in monetary terms and it may be proper to consider them in qualitative forms in a multicriteria analysis.

Multicriteria analysis methods are flexible manners in optimising decisions under complex environment. They can consider quantitative as well as qualitative factors in the decision-making process (Kazimieras, Liias, & Turskis, 2008), (Damart & Roy, 2009).

Multicriteria analysis methods can be divided into two groups. The first consists of using the multicriteria evaluation to generate a synthesizing criterion (net present social value or internal rate of return). The second one employs pairwise comparisons of the proposed projects according to the different criteria (there is no need to quantify the assessments of the criteria). The most common multi-criteria decision making methods are addressed in the Table 7.3 (Velasquez & Hester, 2013), showing their advantages and disadvantages. The table also shows the area of application for each method, that it is important since some methods suited better in a specific area than other methods:

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Table 7.3 – Advantages, disadvantages, and areas of application for the most common multi-criteria decision methods (extracted from (Velasquez & Hester, 2013))

Method	Advantages	Disadvantages	Areas of application
Multi-Attribute Utility Theory (MAUT)	Takes uncertainty into account; can incorporate preferences.	Needs a lot of input; preferences need to be precise.	Economics, finance, actuarial, water management, energy management, agriculture
Analytic Hierarchy Process (AHP)	Easy to use; scalable; hierarchy structure can easily adjust to fit many sized problems; not data intensive.	Problems due to interdependence between criteria and alternatives; can lead to inconsistencies between judgment and ranking criteria; rank reversal.	Performance-type problems, resource management, corporate policy and strategy, public policy, political strategy, and planning.
Case-Based Reasoning (CBR)	Not data intensive; requires little maintenance; can improve over time; can adapt to changes in environment.	Sensitive to inconsistent data; requires many cases.	Businesses, vehicle insurance, medicine, and engineering design.
Data Envelopment Analysis (DEA)	Capable of handling multiple inputs and outputs; efficiency can be analysed and quantified.	Does not deal with imprecise data; assumes that all input and output are exactly known.	Economics, medicine, utilities, road safety, agriculture, retail, and business problems.
Fuzzy Set Theory	Allows for imprecise input; takes into account insufficient information.	Difficult to develop; can require numerous simulations before use.	Engineering, economics, environmental, social, medical, and management.
Simple Multi-Attribute Rating Technique (SMART)	Simple; allows for any type of weight assignment technique; less effort by decision makers.	Procedure may not be convenient considering the framework.	Environmental, construction, transportation and logistics, military, manufacturing and assembly problems.
Goal Programming (GP)	Capable of handling large-scale problems; can produce infinite alternatives.	It's ability to weight coefficients; typically needs to be used in combination with other MCDM methods to weight coefficients.	Production planning, scheduling, health care, portfolio selection, distribution systems, energy planning, water reservoir management, scheduling, wildlife management.
ELECTRE (Elimination Et Choice Translating Reality)	Takes uncertainty and vagueness into account	Its process and outcome can be difficult to explain in layman's terms; outranking causes the strengths and weaknesses of the alternatives to not be directly identified.	Energy, economics, environmental, water management, and transportation problems.
PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations)	Easy to use; does not require assumption that criteria are proportionate.	Does not provide a clear method by which to assign weights.	Environmental, hydrology, water management, business and finance, chemistry, logistics and transportation, manufacturing and assembly, energy, agriculture.
Simple Additive Weighting (SAW)	Ability to compensate among criteria; intuitive to decision makers; calculation is simple does not require complex computer programs.	Estimates revealed do not always reflect the real situation; result obtained may not be logical.	Water management, business, and financial management.
Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS)	Has a simple process; easy to use and program; the number of steps remains the same regardless of the number of attributes.	Its use of Euclidean Distance does not consider the correlation of attributes; difficult to weight and keep consistency of judgment.	Supply chain management and logistics, engineering, manufacturing systems, business and marketing, environmental, human resources, and water resources management.

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CBA is focused on an economic evaluation considering the whole infrastructure. However, to analyse the feasibility of Structural Health Information systems other methods are more adequate, as the Value of Information (VoI).

The decision-making process on the implementation of a SHM system depends on the expected benefit from its use reflected in the VoI analysis from Bayesian statistical decision theory. VoI is a decision analytic method for quantifying the benefit of acquiring additional information to support analyses VoI can be understood as the maximum price an infrastructure operator should pay for the information from a Structural Health Monitoring (SHM) system: the SHM system should be installed only if the corresponding VoI is higher than the cost of the system itself (Larsson Ivanov, Björnsson, Honfi, & Leander, 2021), (Giordano, Prendergast, & Limongelli, 2020), (Diamantidis, Sykora, & Sousa, 2019), (Straub, 2013). The advantages of VoI are the following (Pozzi & Der Kiureghian, 2011):

- rank competitive SHM solutions under specific conditions,
- compare the value of information gained from an SHM system. So to conclude if it is better to adopt that system or do nothing,
- treat the adoption of a sensing system or of a test as an ordinary selectable option among a set of general actions, such as repair or rehabilitation.

According to the available information, three types of decision analyses are possible, namely prior analysis, posterior analysis and pre-posterior analysis (Kamariotisa, Chatzi, & Straub, 2021).

- Prior analysis is referred to as a situation when decision is to be made based on previously available (often generic) information
- Posterior analysis corresponds to a situation when new information about the structural state becomes available for example through tests but a decision whether to carry out this inspection is not included in the decision process
- Pre-posterior analysis provides the framework for the consistent quantification of the VoI through SHM before it has become available

With the value of information and the pre-posterior analysis the Value (V) of the Structural Health Monitoring may be quantified as the difference between the expected value of life cycle benefits with or without SHM systems (Thöns & Faber, 2013). The formulation is as follows in Eq. 7.17.

$$V = B_1 - B_0 \qquad [7.17]$$

Being B_1 the expected value of life cycle benefit undertaking SHM and B_0 not undertaking SHM.

The multicriteria tools discussed above could be used together with CBA tools for economic evaluation. In the case that intangibles components appear in the CBA, these are separately presented to the decision-maker for evaluating together with the quantified estimated of the net social benefit (CoA, 2006).

The multicriteria tools can be combined with the Value of Information as well.
However, how this complementary use will be conceived both depends on the identified objectives and evolves throughout the concertation process.

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7.2.1 Example of Cost-Benefit Analysis

In this section an example of Cost-Benefit Analysis extracted from (Ozden, Faghri, Li, & Tabrizi, 2016) is showed.

To understand the cost and benefits associated with SAR[1]-based monitoring, it is evaluated its applicability for bridges and federal highways in New Castle County (USA). In this example, cost alternatives are investigated based on three options and three resolution levels, and satellite imagery purchasing cost calculated as is showed in the Table 7.4.

Table 7.4 – Summary of Cost-Benefit Analysis

			Cost/Benefit (C/B) ratio		
			Option 1	Option 2	Option 3
	Size	Resolution	Purchasing data and in-house data processing	Purchasing data and outsourcing data processing	Outsourcing data collection and data processing
High resolution	7x7 km	1m	2,326	2,564	2,439
Medium resolution	10x10 km	1m	0,746	0,806	0,763
Low resolution	40x40 km	5m	0,054	0,043	0,039

Once Cost/Benefit (C/B) ratio is obtained, the decision can be taken and other methods such as multi-criteria decision method are helpful. This is caused because the lowest ratio is from low resolution (40x40 km, 5m resolution), but it is only useful for detection of sinkhole formations. Low-resolution images cannot be used to clearly identify the distress type in pavement surface. Therefore, despite low resolution has the lowest C/B ratio, it is not the best option. Considering the spatial resolution and low C/B ratio, option 1 of medium resolution would be a good option for SAR-based pavement and infrastructure monitoring.

[1] Synthetic Aperture Radar

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8 Data-informed evaluations and decision-making for maintenance activities

The IM-SAFE project proposes a framework for the data-informed safety assessment highly interrelated with the through-life management of the transport infrastructure. The need for the clarification of the relationship between the available data, the need of assessment and the maintenance strategies has led to the development of the data-informed performance assessment flow introduced in Chapter 8 of IM-SAFE project report (Bigaj-van Vliet, et al., 2022) and thoroughly developed in the following paragraphs. 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 this flow are:

- Implement in practice the data-informed safety assessment methods;
- Rationalize the decision-making process with regards to interventions;
- Provide an efficient asset management tool as further guidance on the use of data.

Since the identification of the type and the properties of each asset is crucial to the definition of specific reliability requirements, the assets have been subdivided and differentiated in 3 relevant classes:

- New structures
- Existing structures
- Existing structures after intervention

The proposed flow is shown in Figure 8.1 and is divided into three main parts:

- **Structures prioritization**, which starts with a simplified assessment of the structures that are part of the same road network supported by a network data-informed risk-based analysis (section 8.1.2) and a vulnerability analysis (section 8.1.1). Assets are then classified and prioritized based on the results of the preliminary assessment (section 8.1.3).
- **Maintenance strategies and detailed assessment based on prioritization**: once assets have been classified, the intervention prioritization for low and medium-high priority structures is given in section 8.2.1 and section 8.2.2, respectively. Methods for detailed data-informed structural assessment are presented in section 8.2.3.1, whilst the differentiation of the mitigation actions to be taken based on the target reliability levels are described in section 8.2.3.2.
- **SHM monitoring system design and data processing**: in case SHM systems are used, based on the Level of Approximation of the analysis, damage scenarios should be defined (section 8.3.1) and SHM systems should be properly designed (section 8.3.2). Thus, the analysis strategies (section 8.3.3) and thresholds for diagnostics (section 8.3.4) should be defined as well. Lastly, data gathered from SHM system are to be used as an input for structural diagnostics procedures, which have to be supported by a thorough data processing phase (section 8.3.5).

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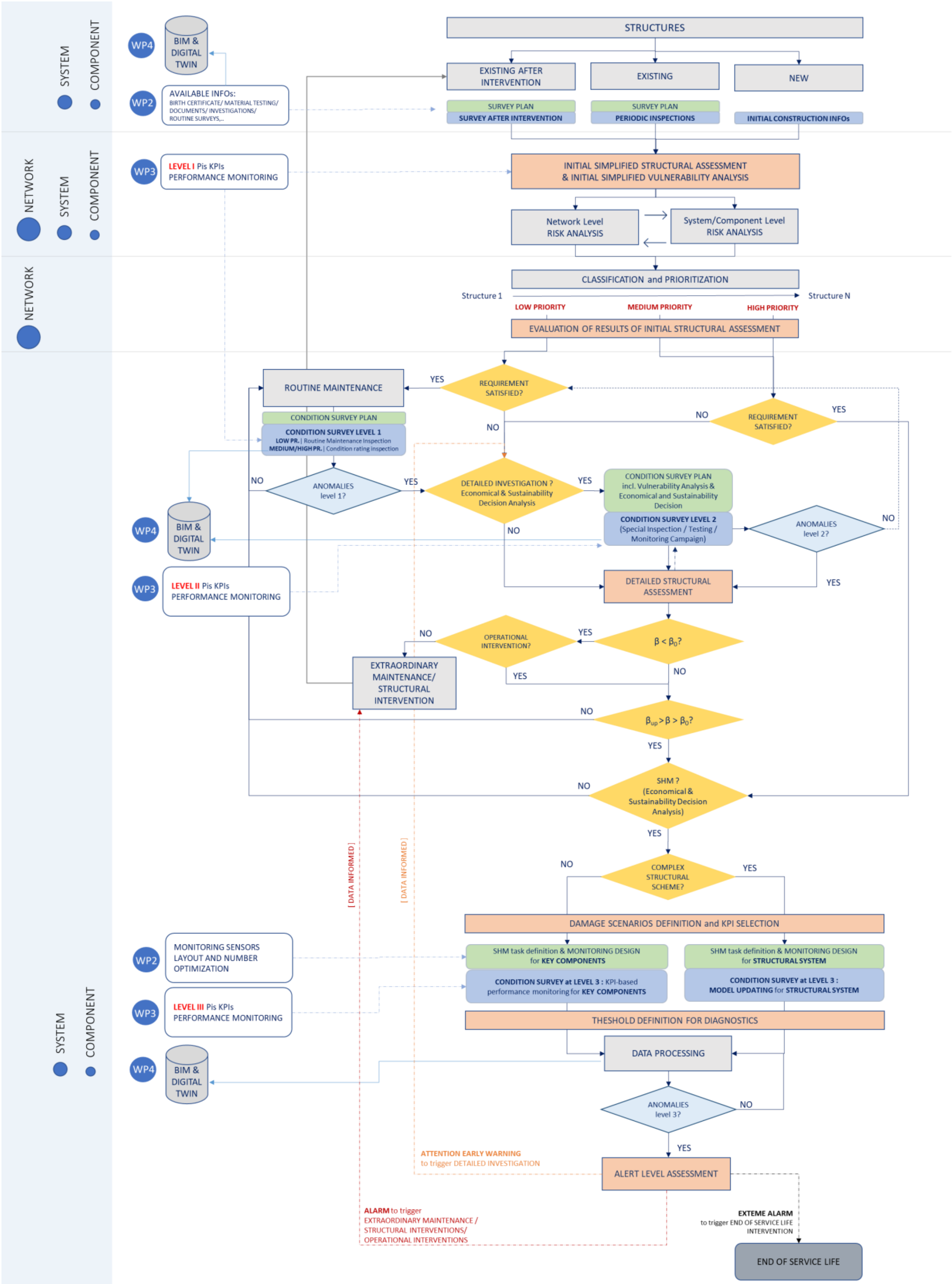

Figure 8.1 – Generic framework and process flow for risk management, from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

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8.1 Structures prioritization

The first step of the framework for the data-informed safety assessment consists of a simplified assessment of the structures that are part of the same road network: results of the assessment of transportation relevance and related socioeconomic impacts provide useful information for an evaluation of the impact of transport through an analysis of the resilience of the network, identifying the critical elements of a network of infrastructure assets and the assets which have criticalities within the network itself.

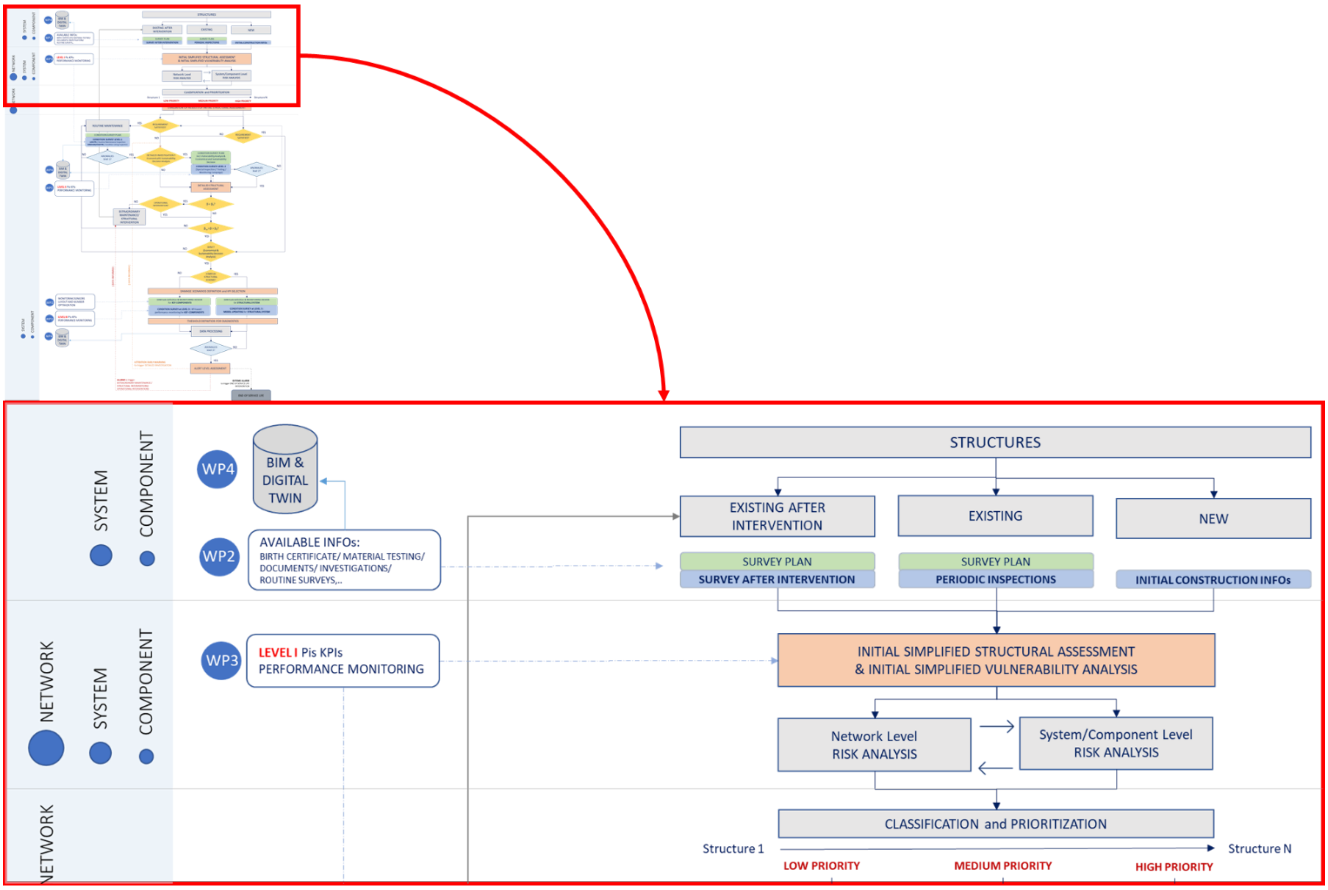

Figure 8.2 – Extract of the decision-making flow: structures prioritization, extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

This analysis is based on the review of the available relevant information:

- Design documents;
- Inspection documents;
- Birth Certificate;
- Re-birth Certificate and intervention reports;
- Structural investigations and material testing outcomes.
- Monitoring reports

and it is supported by a vulnerability analysis aiming to identify the critical elements of each asset. The methods for the characterization of the vulnerable zones are described in section 2.3.2 of IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

The different types of information and the principles of information management are provided in Chapter 4. To perform the network level analysis, a summarized table with different types of information is presented in Chapter 6. Relevant information is ranked in six groups. Different requirements, stages and sources are setting for each item of relevant information.

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Additionally, in section 6.1.1 a brief approximation of Level of Knowledge is performed using the available information.

The simplified assessment is performed based on the Level I PIs and KPIs: the purpose of level I (section 8.3.6) is to remove existing doubts about the performance using fairly simple methods, which should, however, be adequate. Key Performance Indicators allow a rough assessment, while Performance Indicators are used for detailed inspection and to define performance targets and performance thresholds.

The information gained in Level I must be summarised in a report for the owner and should result in Key Performance Requirement Indexes (KPRs) for the strategic asset management and budget allocation.

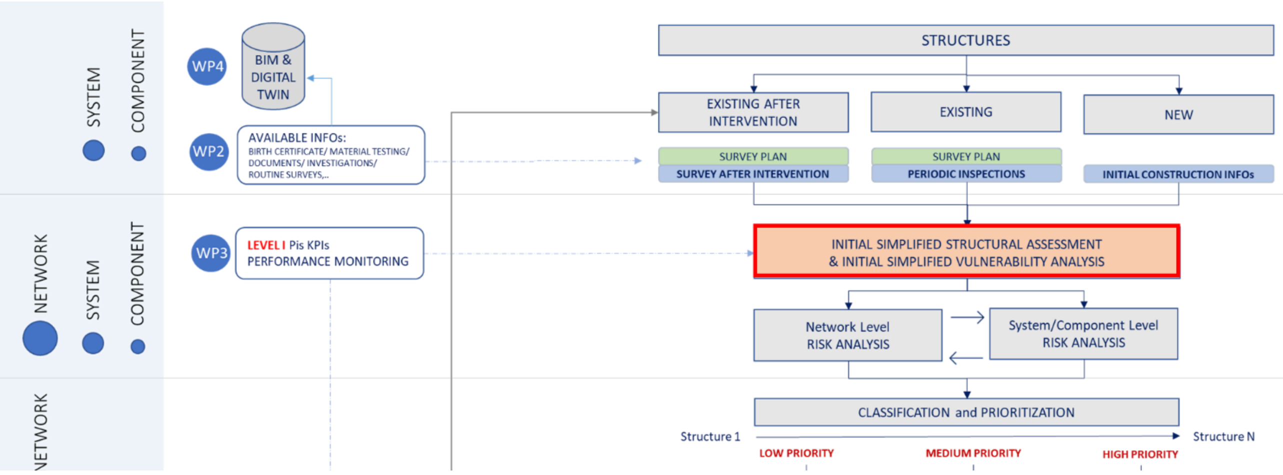

Figure 8.3 – Extract of the decision-making flow: initial simplified assessment.

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, which can be performed either at the network level or at the system/component level. Risk analyses at the network level and at the system and component level are suggested for the purpose of defining the priority list for optimized maintenance and interventions policies.

8.1.1 Summary of the vulnerable element analysis

Vulnerability analysis (see Figure 8.3) aims to identify the vulnerable zones, which are defined as the physically distinguishable parts of an entity (e.g. network, object, component or element, or the parts thereof), for which change of its condition or other direct consequences of a hazardous event have the largest impact on its performance. Each vulnerable zone may be related to several risks and failure modes.

Hence, vulnerability analysis allows to characterize which are the vulnerable zones of the object (network/structure) that are worthwhile for investigation.

Several methods for the characterization of the vulnerable elements of a structure are available:

- Robustness related detection method
- Sensitivity related detection method
- Force and loading based vulnerability analysis
- Deformation based vulnerability analysis
- Performance based vulnerability analysis

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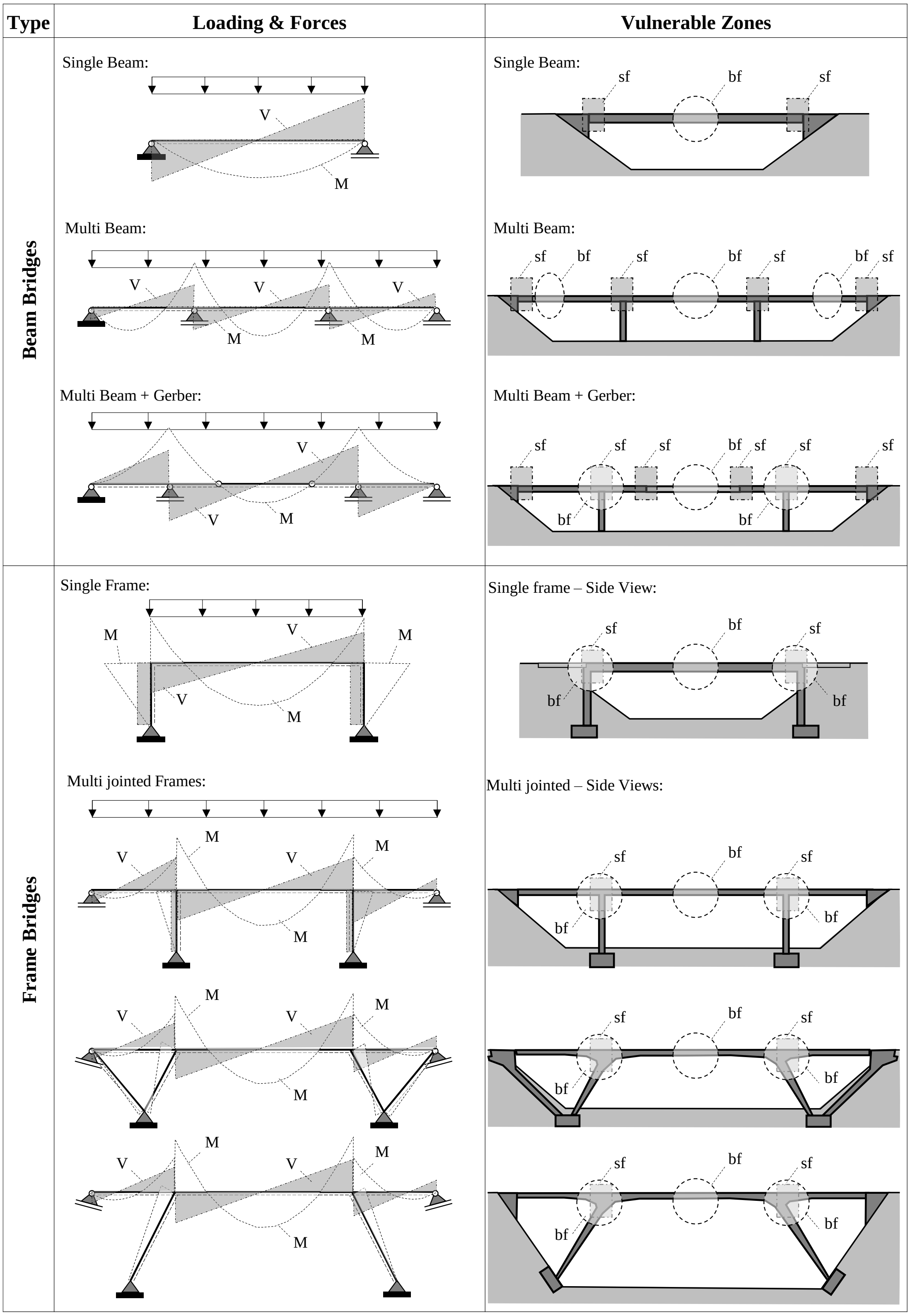

Figure 8.4 – Identification of vulnerable zones – Part 1: beam bridges and frame bridges (Extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)).

In the IM-SAFE project report D3.1, (Bigaj-van Vliet, et al., 2022), the assessment of vulnerable zones for bridges and tunnels is illustrated through two different approaches: the force and loading based approach and the performance-based approach. An example of the former is provided in Figure 8.4.

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When evaluating vulnerable areas, it is important to take into account that some vulnerable areas can develop only with the aging of the structure or also the occurrence of degradation processes. Some vulnerable areas also cannot be assessed by visual inspection or monitoring because they are not accessible. In such cases, modelling or advanced inspection techniques are recommended for the assessment.

8.1.2 Summary of the Network data-informed Risk-based analysis

Risk-based analysis aims to identify the sources of risk, which can be defined as a measure of hazard severity and includes the information with regards to the likelihood or probability of that source causing human or material loss, injury, or some other form of damage.

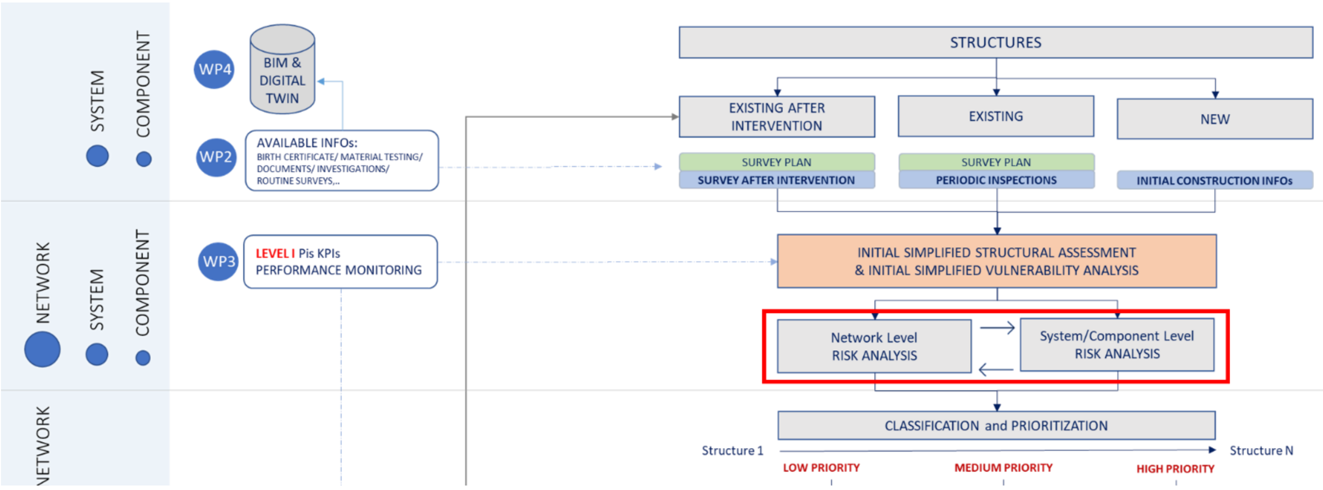

Figure 8.5 – Extract of the decision-making flow: Network data-informed Risk-based analysis, from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)

Risk can be evaluated from the probability of occurrence of a consequence, eventually taking into account hazard and vulnerability, and the consequences itself. It is often (e.g. tunnels) represented with risk curves, which show the probability of exceedance for a certain magnitude of consequences, for instance the F-N curve, which expresses the probability of exceedance of N fatalities.

A generic framework for risk management is represented in Figure 8.6 and consists of the following components:

- defining risk management goals,
- performing the risk assessment to evaluate risk levels,
- risk treatment based on the evaluated risk levels,
- monitoring and review.

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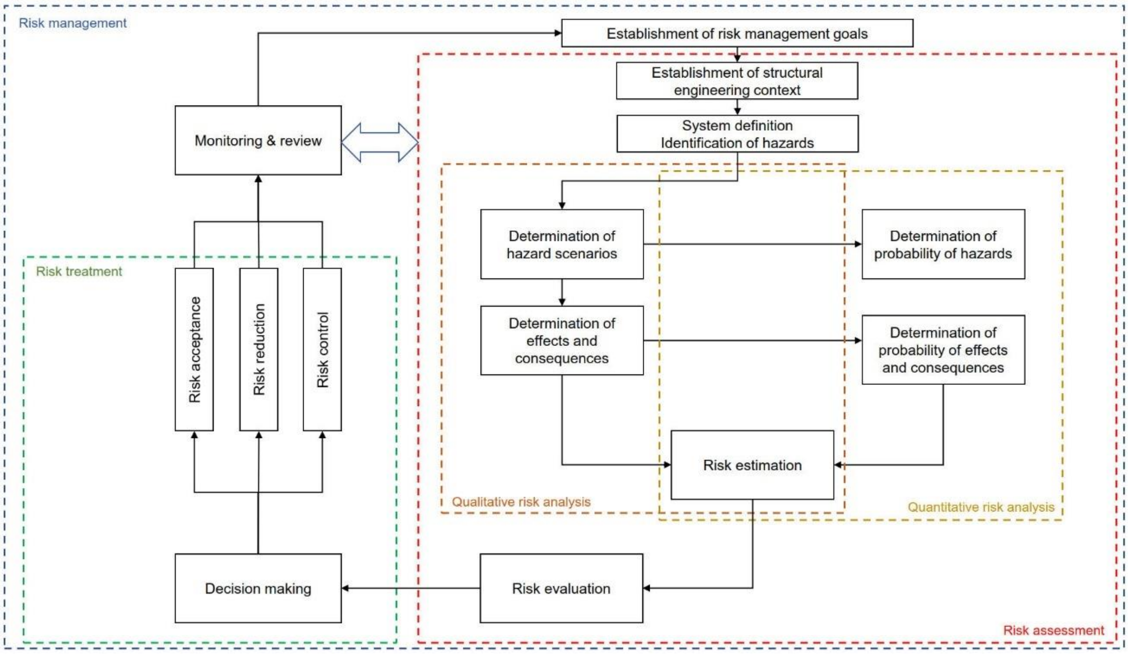

Figure 8.6 – Generic framework and process flow for risk management (Extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)).

Risk management aims to reach the optimal distribution of resources for the stakeholders, such as organizations, local communities, or society. Specifically, in terms of risk management of structures, it is expected that the risk-management goals are expressed in terms of protection measures or optimization of asset use, maintenance of the designed performance of the structure, environmental changes, and regulatory demands. The goals are determined either by the cost-benefit of optional solutions or by various risks, such as those that are known to the society.

The first step of the analysis is the establishment of the structural engineering context, which involves the definition of the external and internal parameters to be taken into account when managing risk and setting the scope, as well as risk criteria for the risk management policy.
The second step is the definition of the system on which the analysis has to be taken: a system is a delimited group of interrelated, interdependent or interacting objects, determined on the basis of established context for the support of decision-making. It is usually divided into subsystems and components, which together form a configuration that is representative of the total system by means of internal relations.

Once the system has been defined, hazards and their consequences can be identified, either with a qualitative or a quantitative risk analysis, which allows to estimate:

- Probability of hazards;
- Probability of occurrence of consequences.
-

This process is followed by a risk evaluation, in which the decision whether the estimated risk is acceptable or not is made, and if measures to reduce risk should be undertaken. This is therefore a decision-making step, supported by the results of the quantitative analysis and by risk criteria, consistent with the established risk management goals.
The last step of the risk management process is monitoring and review, in which the level of risk is monitored in order to keep it under a target level, regardless of whether the risk is treated. For further information about risk management and its framework, see the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)

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8.1.3 Network infrastructures census and risk-based classification

Risk analysis, performed either at the network level or at the system/component level, provides the basis for the classification and prioritization of the assets that are part of the same road network: for each asset it is possible to identify the consequence of failures and the risks for human life and, therefore, to determine which network assets are in need of maintenance of intervention, how urgently, and which type of actions should be taken in order to meet the performance requirements.

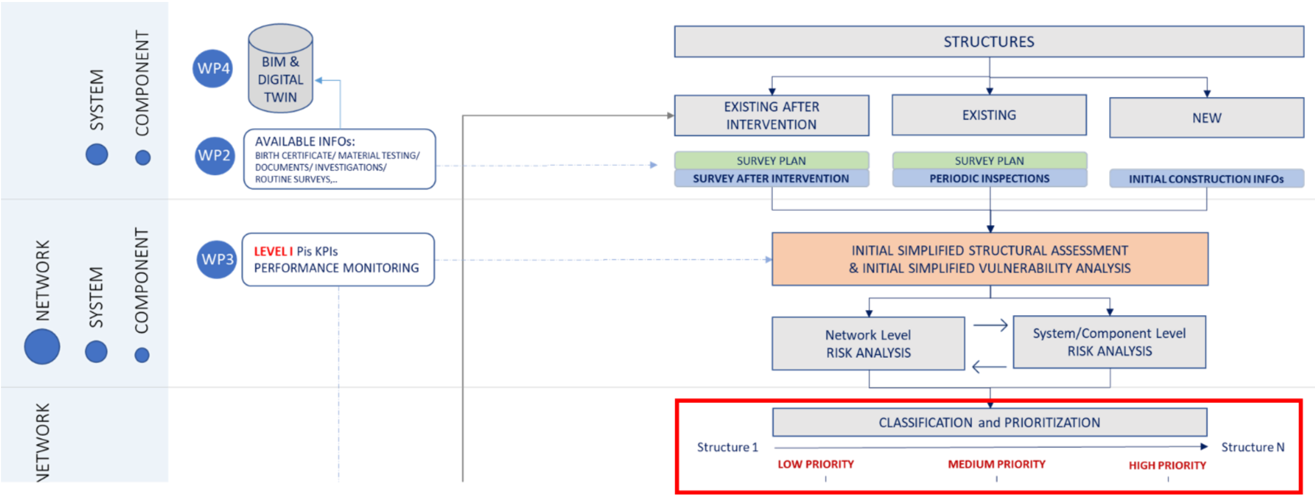

Figure 8.7 – Extract of the decision-making flow: assets classification and prioritization from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

Hence, based on the outcomes of risk analysis, structures can be assigned to one of the following classes:

- **Low priority**;
- **Medium priority**;
- **High priority**.

When a single structure is being analysed, instead, a prioritization of intervention is not required. In this case, the need for assessment might be originated by different causes:

- **External causes**
  - Scheduled assessment for asset management programme
  - Change of design loads
  - Change of hazards
  - Retrofitting
  - Need for extension of the working life
- **Structural issues**
  - Construction errors
  - Deterioration processes

The type of assessment, either preliminary or detailed, and its level of application (network, system or component) is defined on the basis of the need for which it is required and on the various available information. These principles are summarized in Figure 8.8.

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[CEN/TS 17440]

<table>
<tr><th colspan="2">NEED FOR ASSESSMENT IN TIME</th><th rowspan="2">N – S – C LEVEL*</th><th rowspan="2">ASSESSMENT TYPE</th><th rowspan="2">AVAILABLE / REQUIRED INFOs</th></tr>
<tr><th>EXTERNAL CAUSE</th><th>STRUCTURAL ISSUES</th></tr>
<tr><td></td><td>CONSTRUCTION ERRORS</td><td>S | C</td><td>DETAILED</td><td>• ORIGINAL DESIGN DOCUMENTS
• AS-BUILT & CONSTRUCTION DETAILS (BIM)</td></tr>
<tr><td>SCHEDULED ASSESSMENT for ASSET MANAGEMENT PROGRAMME</td><td></td><td>N | S | C</td><td>PRELIMINARY | DETAILED</td><td>• PERIODIC/DETAILED INSPECTION, SURVEYS OUTCOMES</td></tr>
<tr><td></td><td>DETERIORATION PROCESSES</td><td>N | S | C</td><td>PRELIMINARY | DETAILED</td><td>• DEFECTS, DETERIORATION CHARACTERIZATION</td></tr>
<tr><td>CHANGE OF DESIGN LOADS</td><td></td><td>N | S | C</td><td>PRELIMINARY | DETAILED</td><td rowspan="4">INSPECTION AND TESTING RESULTS ON:
• MATERIAL PROPERTIES
• HAZARDS
DISCRETE/CONTINUOUS (IN SPACE AND TIME) DATA FROM:
• NDT/DT
• MONITORING SYSTEMS</td></tr>
<tr><td>CHANGE OF HAZARDS (e.g. landslide, accidental actions)*</td><td></td><td>S | C</td><td>DETAILED</td></tr>
<tr><td>RETROFITTING</td><td></td><td>S | C</td><td>DETAILED</td></tr>
<tr><td>NEED FOR EXTENSION OF WORKING LIFE</td><td></td><td>S | C</td><td>DETAILED</td></tr>
</table>

Working life

Incremental level of knowledge

*[IM-SAFE integration to CEN/TS 17440]

[*N=Network S=System C=Component]

Figure 8.8 – Need for assessment in time (CEN/TC-250, 2020) revised by IM-SAFE (Extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)).

Each of the classes defined above is characterized by a specific prioritization plan of interventions, based on the results of the preliminary assessment. In the following paragraphs the intervention prioritization for each class is described. The description will also be supported by the graphic visualization of the path to be followed based on each specific case.

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8.2 Maintenance strategies and detailed assessment based on prioritization

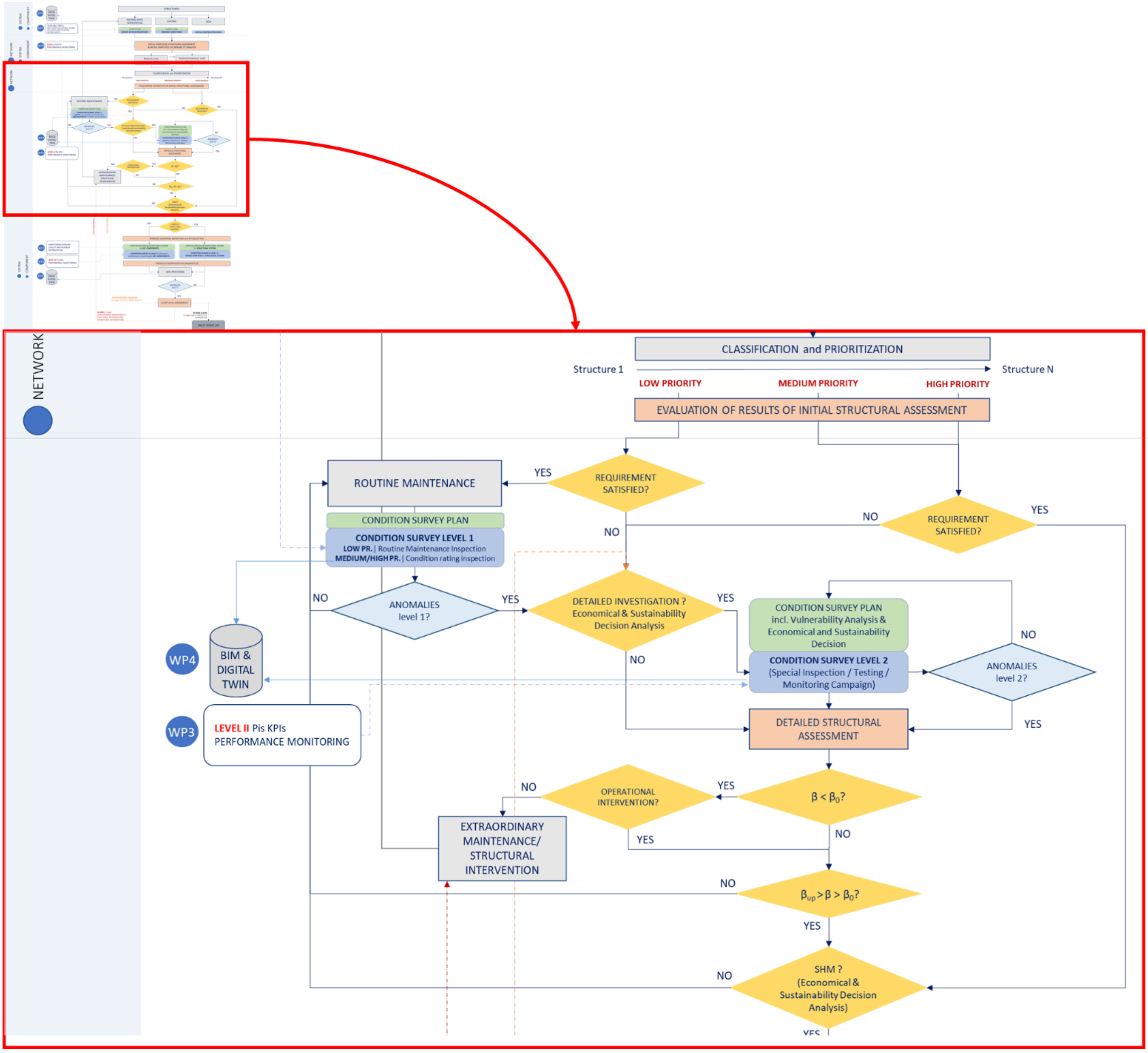

Figure 8.9 – Extract of the decision-making flow: Maintenance strategies and detailed assessment based on prioritization from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

8.2.1 Low priority structures

The initial simplified structural assessment allows to determine if the specific performance requirements for the structure being assessed are met. It is, thus, possible to distinguish between two cases:

- When performance requirements are satisfied, low priority structures can undergo routine maintenance inspection plans, though it should be noted that each structure may change class based on the outcomes of the ordinary maintenance or eventually light monitoring.

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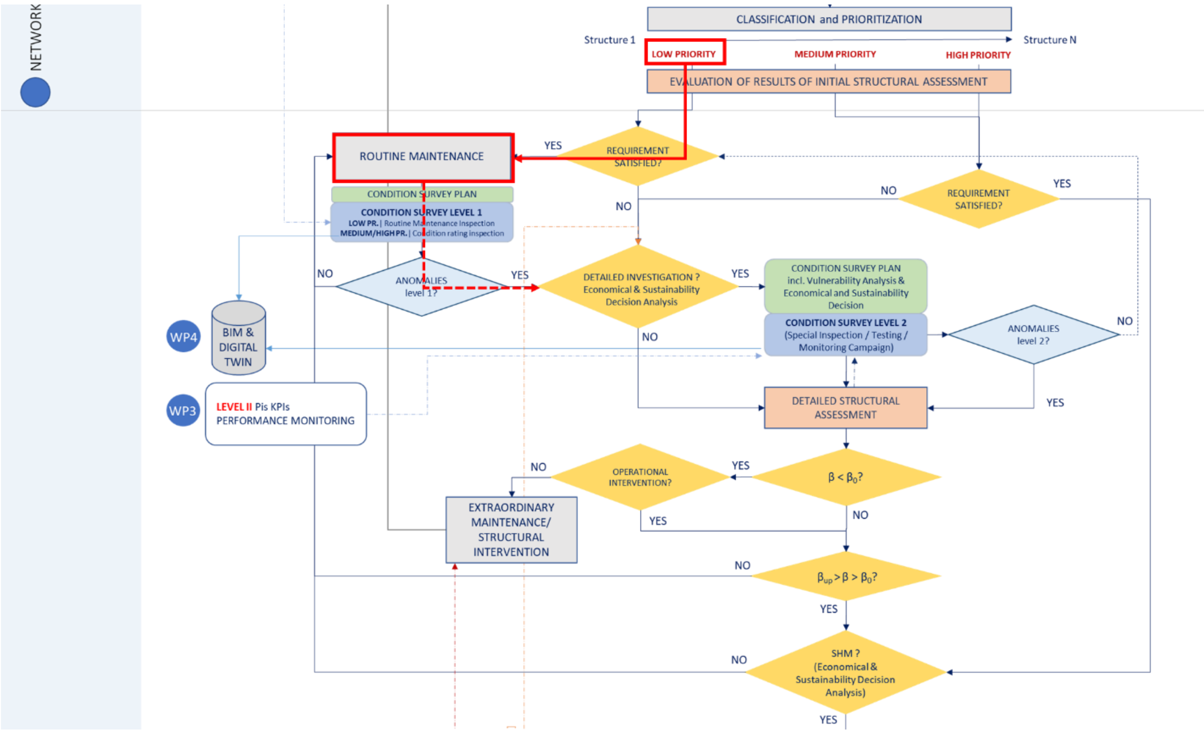

Figure 8.10 – Extract of the decision-making flow: Low priority structures and routine maintenance from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

- When requirements are not satisfied, a detailed structural assessment of the structure might be needed. The need for a detailed assessment may also be generated by an anomaly detection (Level I Pis) during the routine visual inspections and/or periodic control with light monitoring. Detailed assessment might be preceded by a detailed investigation plan, whose extent, in terms of inspections, testing and monitoring campaigns, is defined on the basis of an economical and sustainability decision analysis. Condition survey plan aims to improve the knowledge of the status of the structures and to identify possible anomalies. In case of detected or suspected anomalies, these have to be thoroughly analysed through the detailed structural assessment and/or further condition survey plans, which include special inspections, testing and monitoring campaigns that constitute a Level II PIs and KPIs information degree, otherwise structures may undergo routine maintenance inspection plans.

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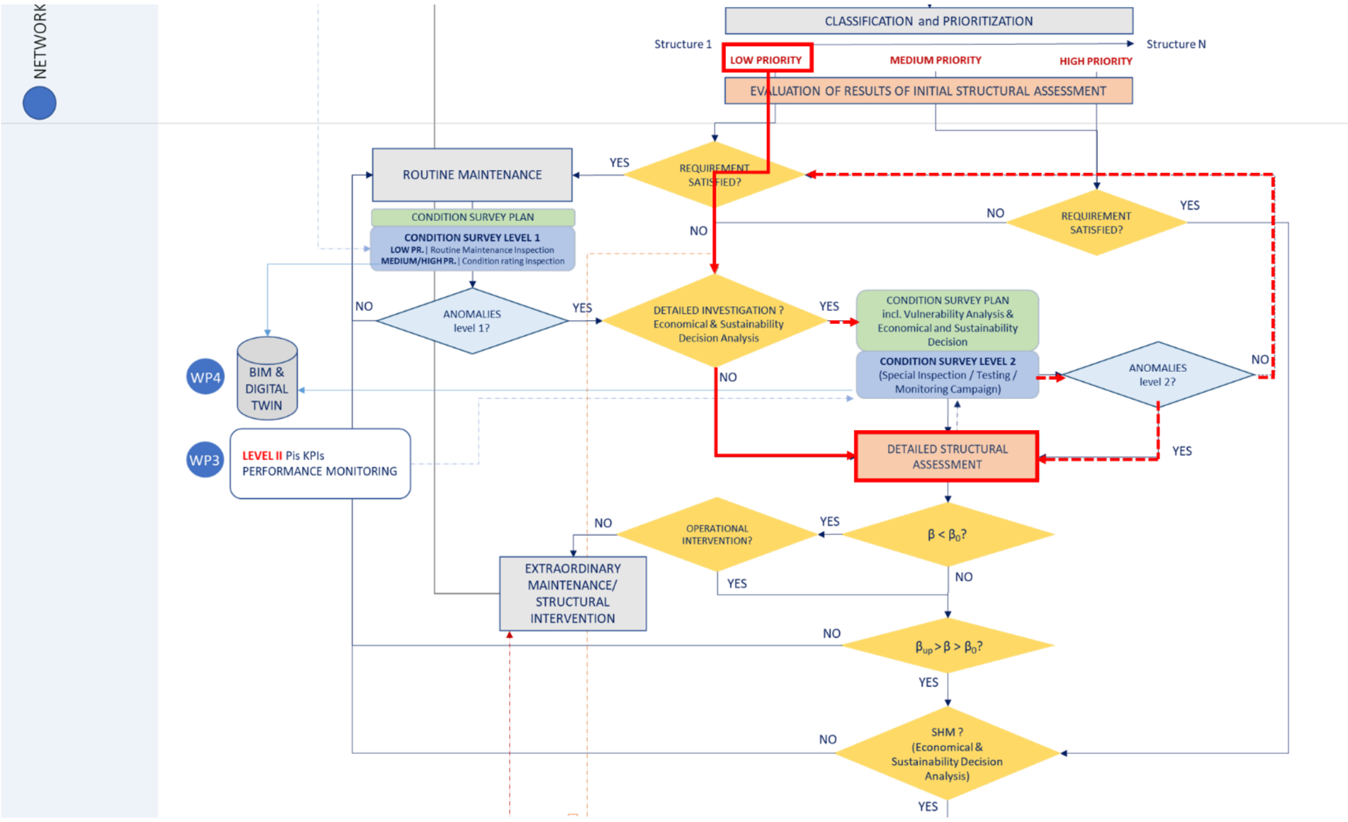

Figure 8.11 – Extract of the decision-making flow: Level II condition survey and detailed assessment from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

8.2.2 Medium-High priority structures

The initial simplified structural assessment allows to determine if the specific requirements for the structure being assessed are met. It is, then, possible to distinguish two cases:

- When requirements are met (Figure 8.12), a structural health monitoring might be used to further integrate the information gathered via the routine maintenance plan. 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. Economical and sustainability decision making processes guide the choice of the monitoring strategy to be implemented, as well as the types of sensors to be installed. These analyses can also guide the choice of monitoring sensor layouts or key parameters to be detected. An example is showed in section 7.2.1, where cost alternatives for SAR-based monitoring are investigated based on three options and three resolution levels. However, Cost-Benefit Analysis is adequate for the economical part, but not for sustainability. For this, one of the multi-criteria decision methods shown in Table 7.3 should be applied. Permanent monitoring system might be coupled with dedicated inspections and destructive/non-destructive testing ((Sánchez Rodríguez, et al., 2022)).

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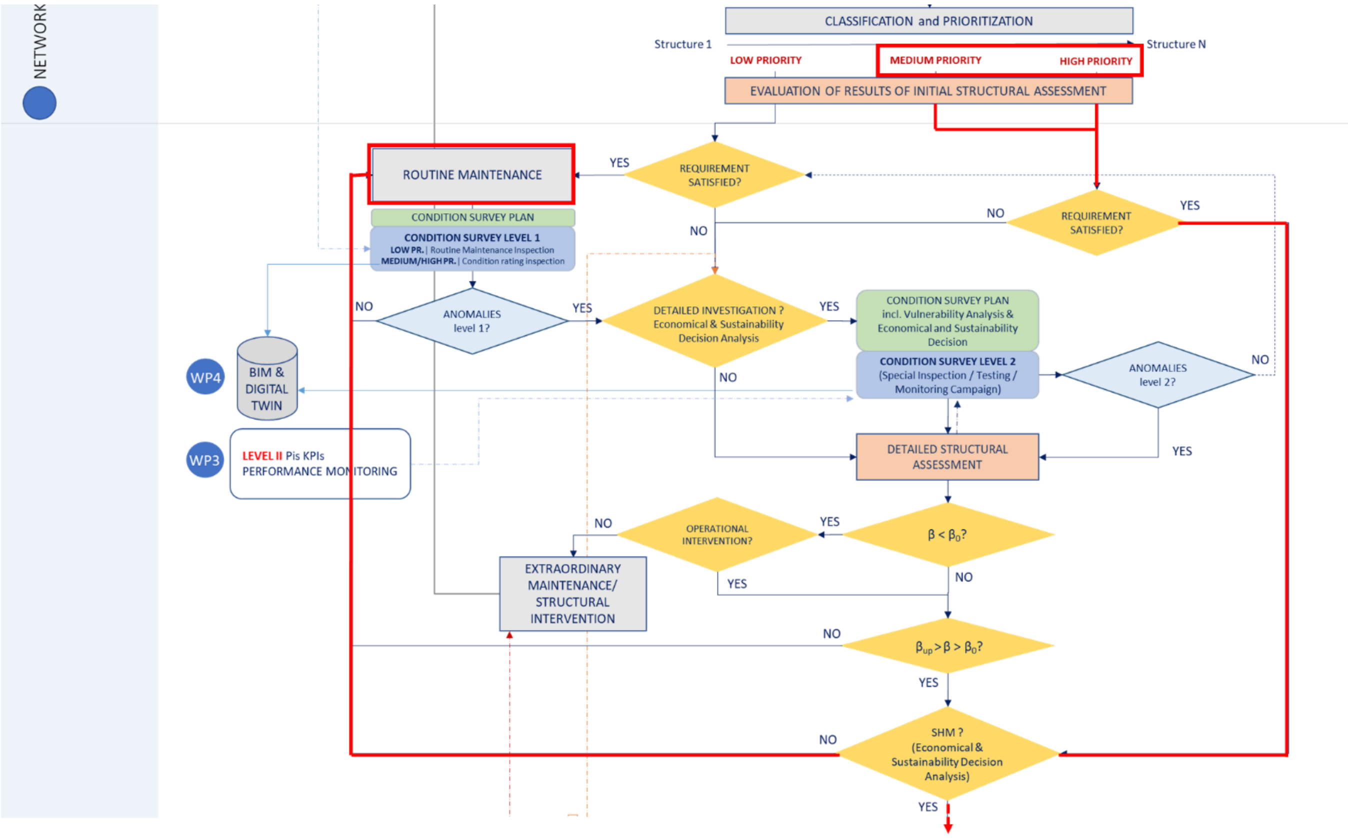

Figure 8.12 – Extract of the decision-making flow: Medium to high priority structures from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

- When requirements are not met (see fig 8.13), a detailed assessment might be triggered and might be preceded by a detailed investigation plan, whose extent, in terms of inspections, testing and monitoring campaigns, is defined on the basis of an economical and sustainability decision analysis. Condition survey plan aims to improve the knowledge of the status of the structures and to identify possible anomalies. In case of detected or suspected anomalies, these have to be thoroughly analyzed through further the detailed structural assessment and/or condition survey plans, which include special inspections, testing and monitoring campaigns that constitute a Level II PIs and KPIs information degree, otherwise structures may undergo routine maintenance inspection plans.

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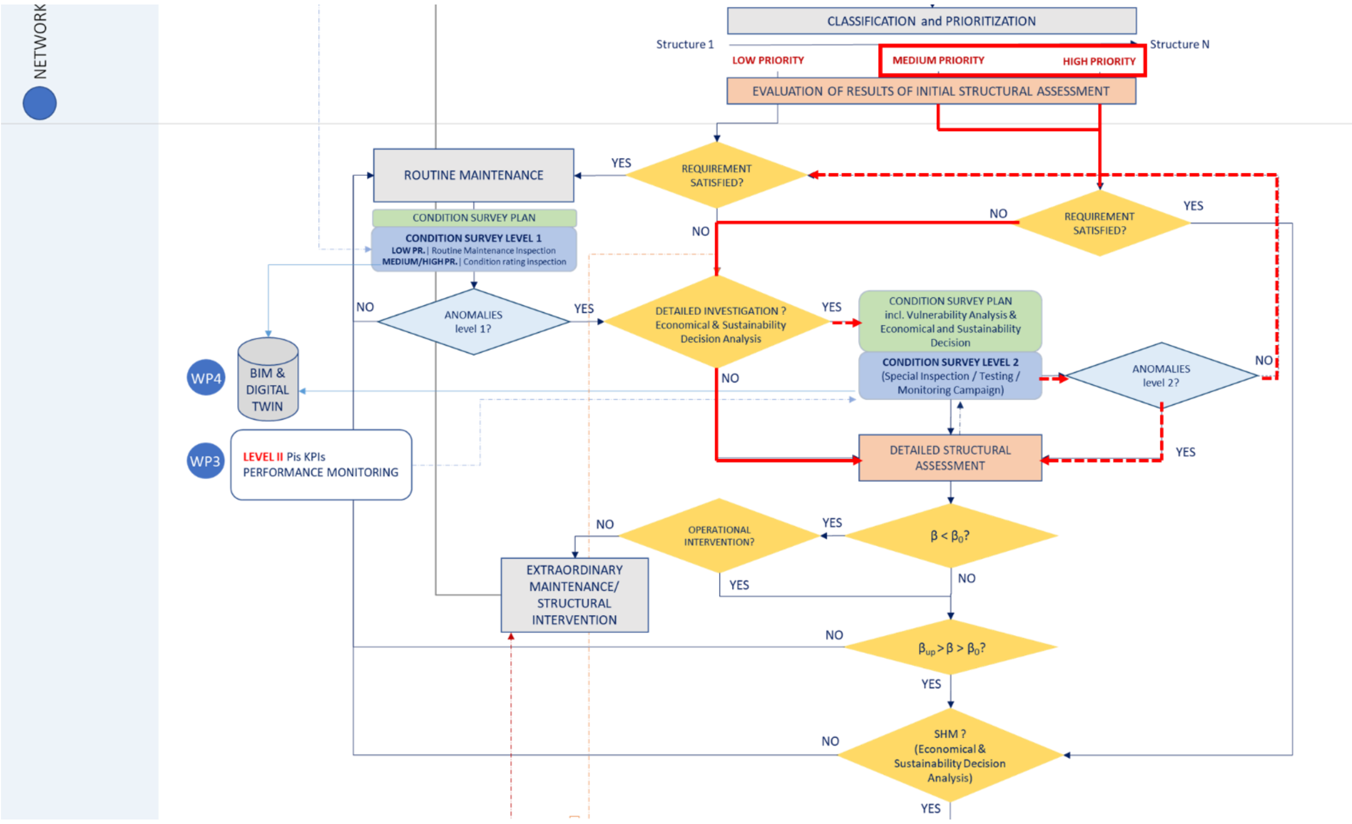

Figure 8.13 – Extract of the decision-making flow: Level II condition survey and detailed assessment from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

8.2.3 Detailed structural assessment

A system/component level analysis is based on the performance of detailed assessment of a structure, which can be carried out using one or more of the following verification methods, which have been thoroughly described in paragraph [6.2] of (IMSAFE-WP3, 2022):

- Risk-informed method;
- Reliability-based method;
- Semi-probabilistic method.

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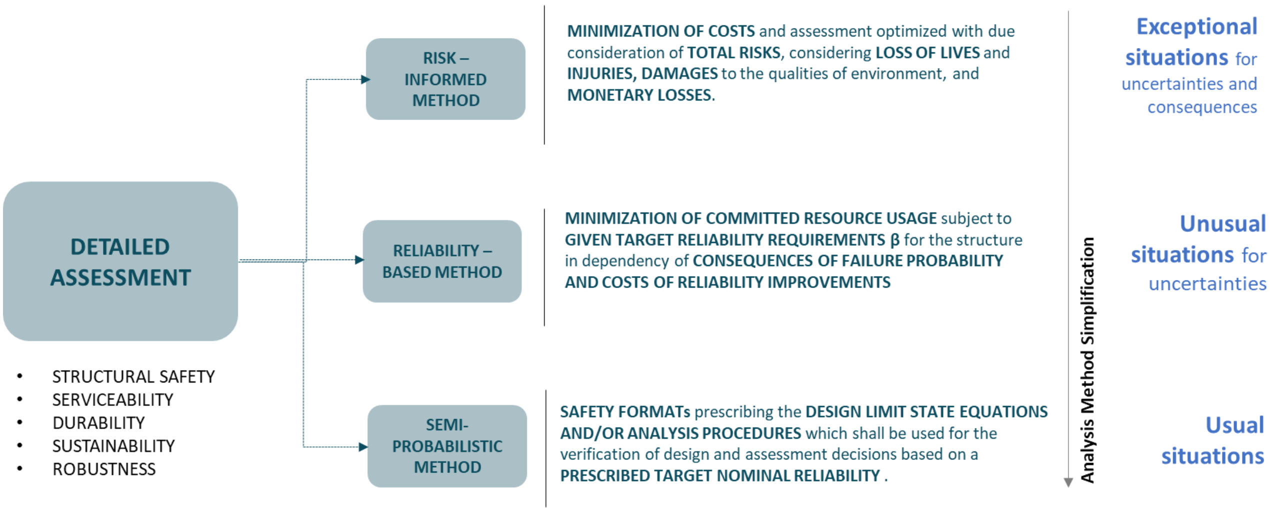

Figure 8.14 – Detailed structural assessment methods (extracted from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)).

Figure 8.14 summarizes the key aspects related to each method. The information about the objective and the most common application is summarized in Figure 8.15.

	Commonly applied when:	Objective:
Risk-informed decision making: - decisions are taken with due consideration of the decision makers preferences.	Exceptional design situations in regard to uncertainties and consequences.	Maximize the expected utility of the decision maker.
Reliability-based design and assessment: - estimation of the probability of adverse events.	Unusual design situations in regard to uncertainties.	Satisfy reliability requirements.
Semi-probabilistic: - safety format prescribing design criteria in terms of the design equations and the analysis procedures to be used.	Usual design situations in regard to consequences and uncertainties. Default method of most design codes.	Satisfy deterministic design criteria.

Figure 8.15 – Levels of Structural Engineering Decision Making according to (Kohler, 2021)

Given that risk and reliability-based approaches are applied for the calibration of semi-probabilistic approaches, as well as for supporting design and assessment decisions for special structures and projects which are not covered by semi-probabilistic codes, this flow is based on the use of reliability-based approaches, though risk-based approach should be recommended in case of strategic structures. Reliability-based approaches are suitable for the differentiation between new and existing structures introduced in (fib MC2020, 2022), since existing structures often have a remaining working life and reference period smaller than design life of 50 years and their condition must be assessed based on available information and of data gathered from testing, inspection and monitoring.

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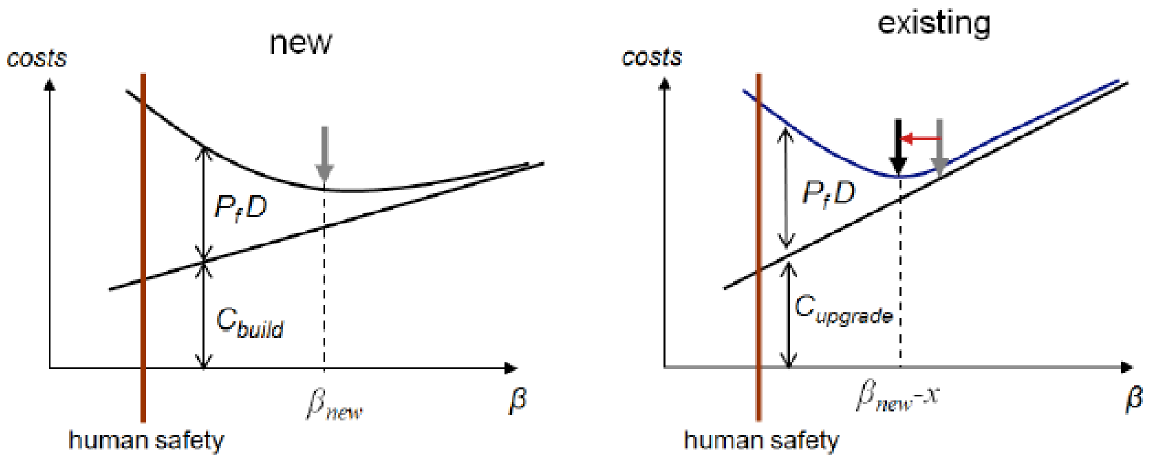

Figure 8.16 – Illustration of the difference in cost optimisation for the design of new structures versus upgrading of existing structures (fib Bulletin 80, 2016)

Figure 8.16 shows, for instance, how target reliability levels for existing structures decrease compared with new structures, due to difference in terms of the needed effort and investment to achieve functionality requirements for the remaining working life.

For further information on the differentiation between new and existing structures, see section 8.1 of the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

8.2.3.1 Summary of the Structural data-informed safety-assessment methods

Updating information of properties and performance modelling of a structure is an essential part of the assessment of existing structures. In assessment, an existing structure can be inspected/tested so that load, resistance, environmental parameters and global static and dynamic response can be measured on-site. Information acquired by inspection, testing and monitoring, indeed, can greatly improve the accuracy of performance prediction by more precisely assessing the variability of the input parameters, which are typically assumed to be random variables.

Performance verification using a data-informed approach based on the information collected from inspections, testing and monitoring is still an open research topic under development as more advanced knowledge is gained in the fields of data processing, monitoring and maintenance planning.

As already stated in section 8.1.2, the assessment can be performed following different methods of progressively decreasing complexity (risk-based, reliability based and semi-probabilistic methods)

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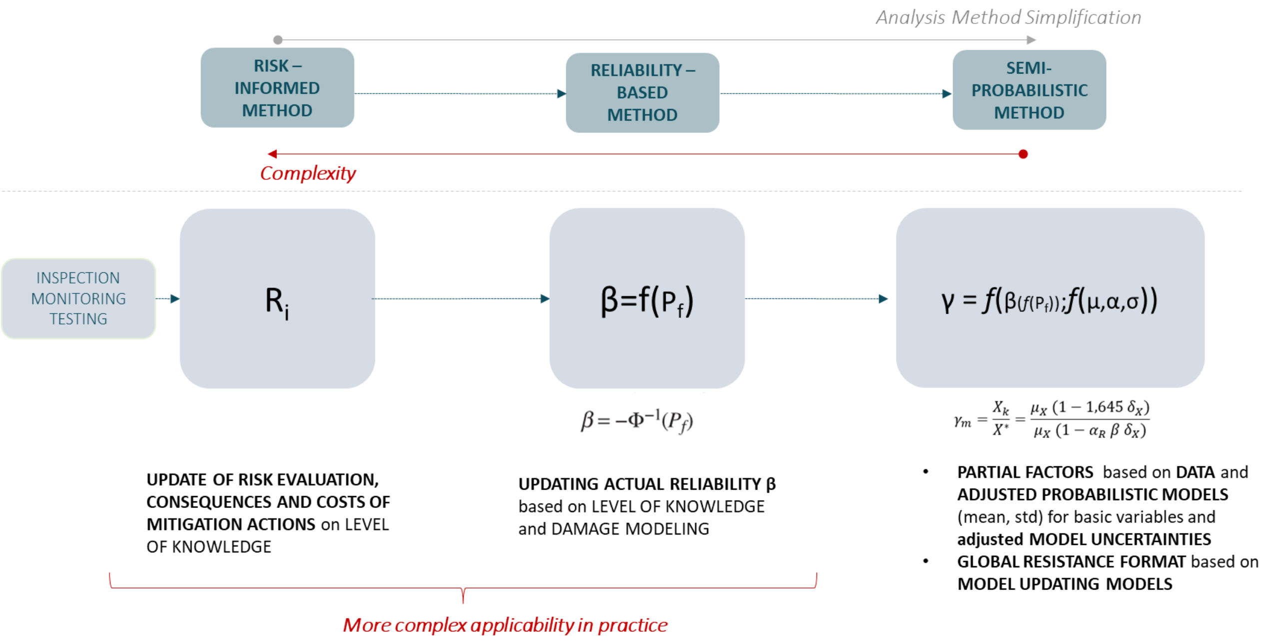

Figure 8.17 – Data-informed safety assessment methods, extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)

Data can be differently used in the structural assessment based on the verification method selected (risk-based, reliability-based and semi-probabilistic approach). A framework to move towards a data-informed verification process is outlined in Chapter 8 of the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022). In such analysis, particular attention has to be given to the definition and modelling of the deterioration processes over time with the aim to move towards a provisional assessment of the evolution of the structural performance during the residual service life.

Locations where inspection, testing and condition monitoring activities are to be undertaken must be carefully selected so that the desired information about the deterioration of materials and/or structural performance can be obtained, keeping in mind factors such as:

- the likely mechanism(s) and rate of deterioration;
- the environmental conditions;
- the conservation strategy and tactics;
- the inspection testing and monitoring regimes defined at the time of design or redesign.

Use of data in risk-based, reliability-based and semi-probabilistic approaches is described in section 8.2 of the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

8.2.3.2 Detailed Data-informed structural assessment

As outlined in 8.1.3, low, medium and high priority structures might need a detailed structural assessment, which can be based on the gathered information about the condition of the structure (data-informed) or not. However, decisions regarding the use of inspections, monitoring and testing should be evaluated and the differentiation between new and existing structures must be considered. In particular, with respect to the reliability levels differentiation proposed for the assessment of existing structures, actions may vary based on the following target levels:

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- $\boldsymbol{\beta_0}$ - level below which the existing structure is considered unreliable and should be upgraded;
- $\boldsymbol{\beta_{up}}$ - level indicating an optimum upgrade strategy while upgrading of existing structures;
- $\boldsymbol{\beta_{new}}$ - level indicating desired reliability for design of new structures.

Based on the reliability (β), it is then possible to distinguish the following three cases:

1) $\boldsymbol{\beta < \beta_0}$ (see Figure 8.18): If the reliability is lower than the minimum accepted β_0, the outcome of detailed assessment can result directly in immediate extraordinary maintenance or interventions. In case operational interventions (e.g. traffic limitation) are needed before any structural intervention is performed, it may be considered to apply monitoring strategies as a step to prevent undesired events before the structural upgrade.

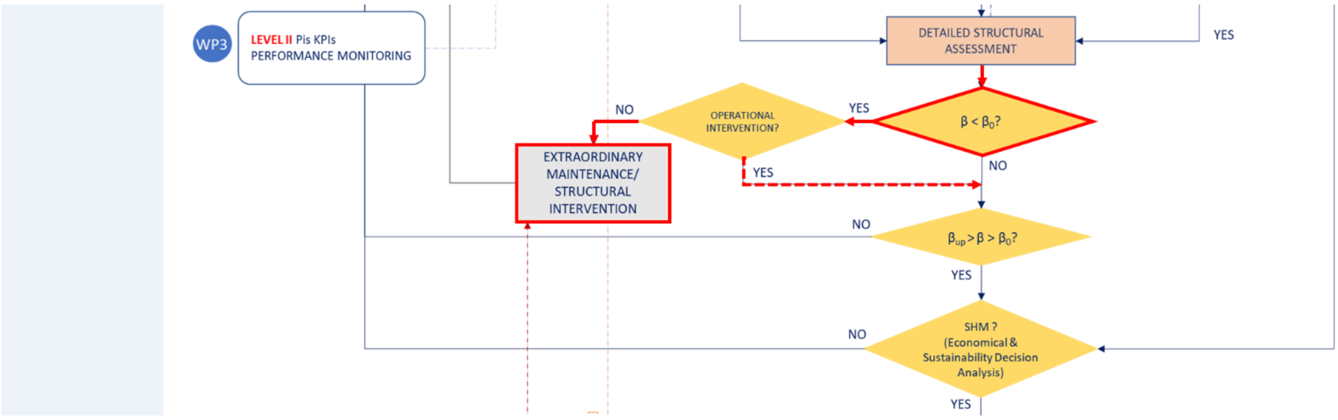

Figure 8.18 – Extraordinary maintenance and structural intervention (β <β_0), extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

2) $\boldsymbol{\beta_0 < \beta < \beta_{up}}$ (Figure 8.19): 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. Cost-benefits optimization analyses can guide the selection of monitoring sensor layouts or key parameters to be detected. Permanent monitoring system might be coupled with dedicated inspections and destructive/non-destructive testing, see the IM-SAFE project report D2.1 (Sánchez Rodríguez, et al., 2022). In cases of continuous SHM systems are not used, structures undergo routine maintenance plan.

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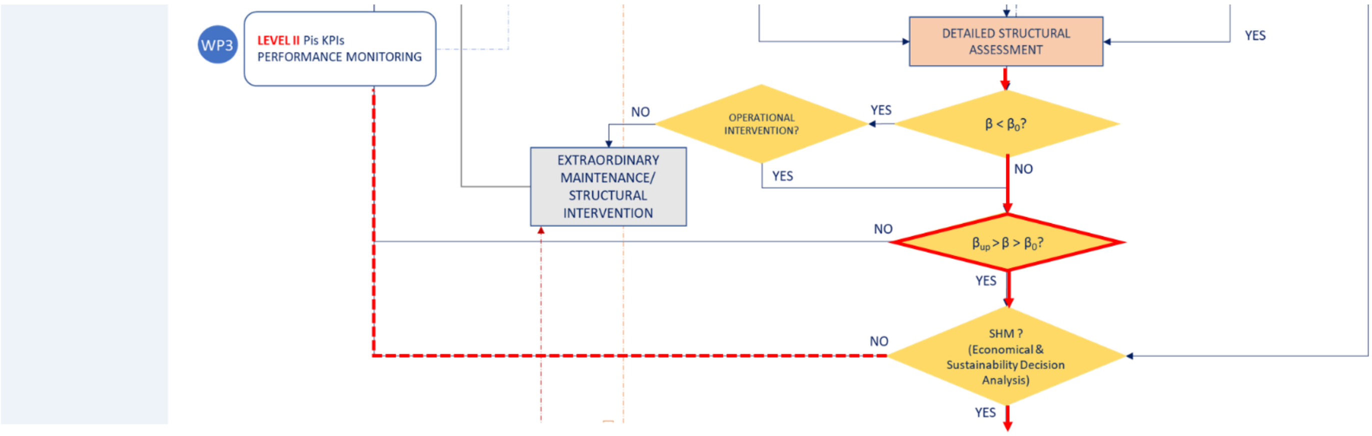

Figure 8.19 – Reliability evaluation ($\beta_0 < \beta < \beta_{up}$), extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

3) $\boldsymbol{\beta > \beta_{up}}$ (Figure 8.20): If the reliability is higher than β_{up}, structures can be subjected to routine maintenance plans, only potentially enhanced by SHM systems whenever required for further diagnostics and control of the structural response.

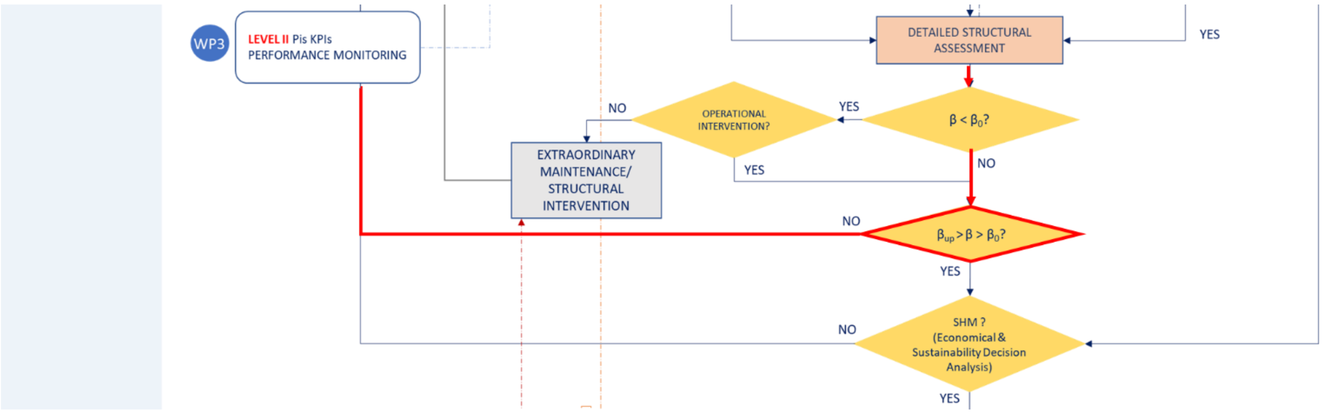

Figure 8.20 – SHM system design and data processing, extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)

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8.3 SHM monitoring system design and data processing

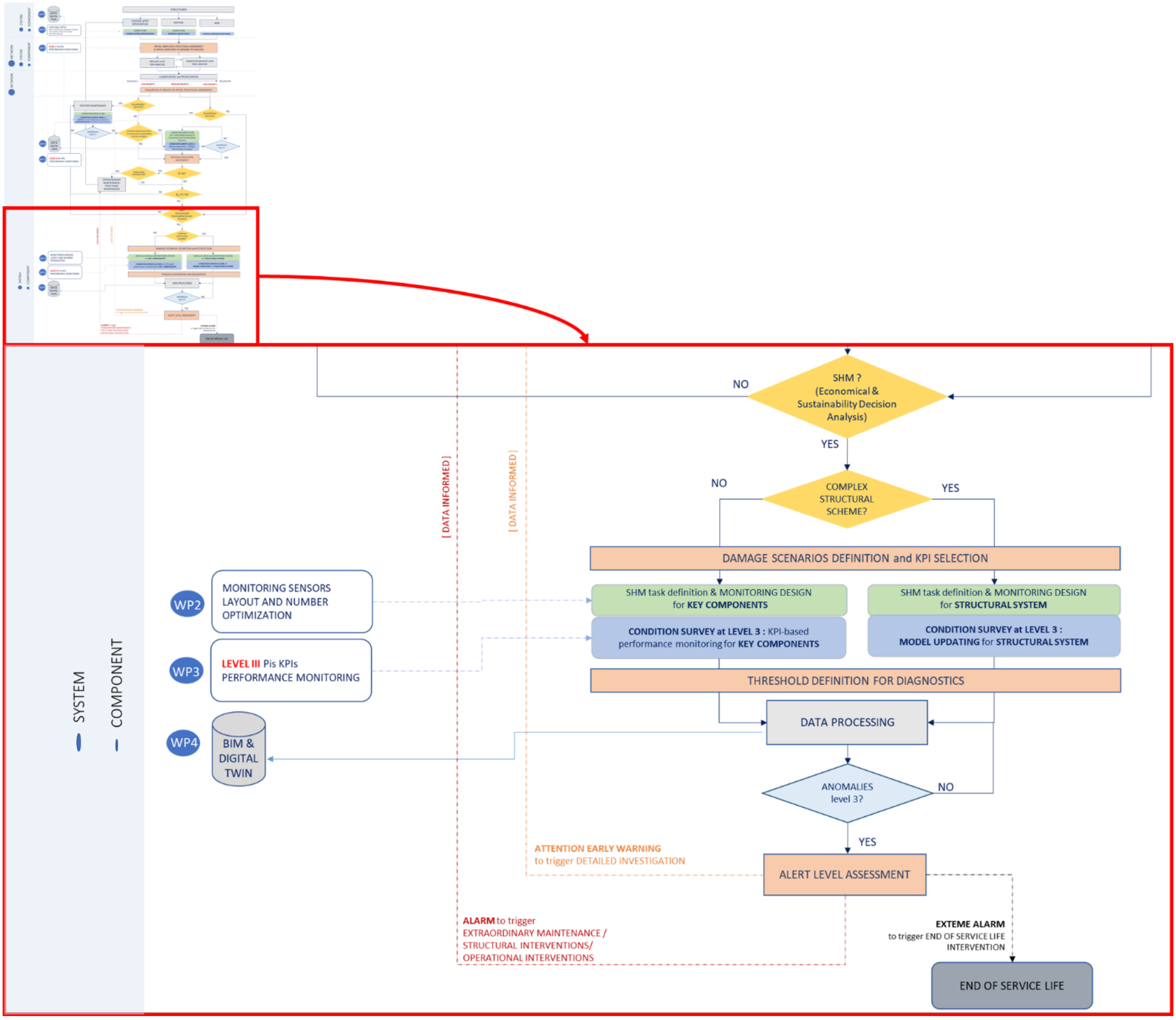

Figure 8.21 – Extract of the decision-making flow: SHM system design and data processing, extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

8.3.1 Damage scenarios definition

In case continuous SHM systems are used, the approach to monitoring differs depending on the complexity of the structural scheme, as is represented in Figure 8.20:

- Complex structural schemes require a higher level of approximation of the analysis and performance monitoring. The focus is on the overall structural system, favouring the analysis of the global response. The analysis implies numerical modelling, model updating processes and deeper analysis of the presence and localization of damages.
- Simple structural schemes, or cases where a detailed NLFEA analysis process is not applicable, may comprise monitoring of the structural performance through the response of a selection of key structural components.

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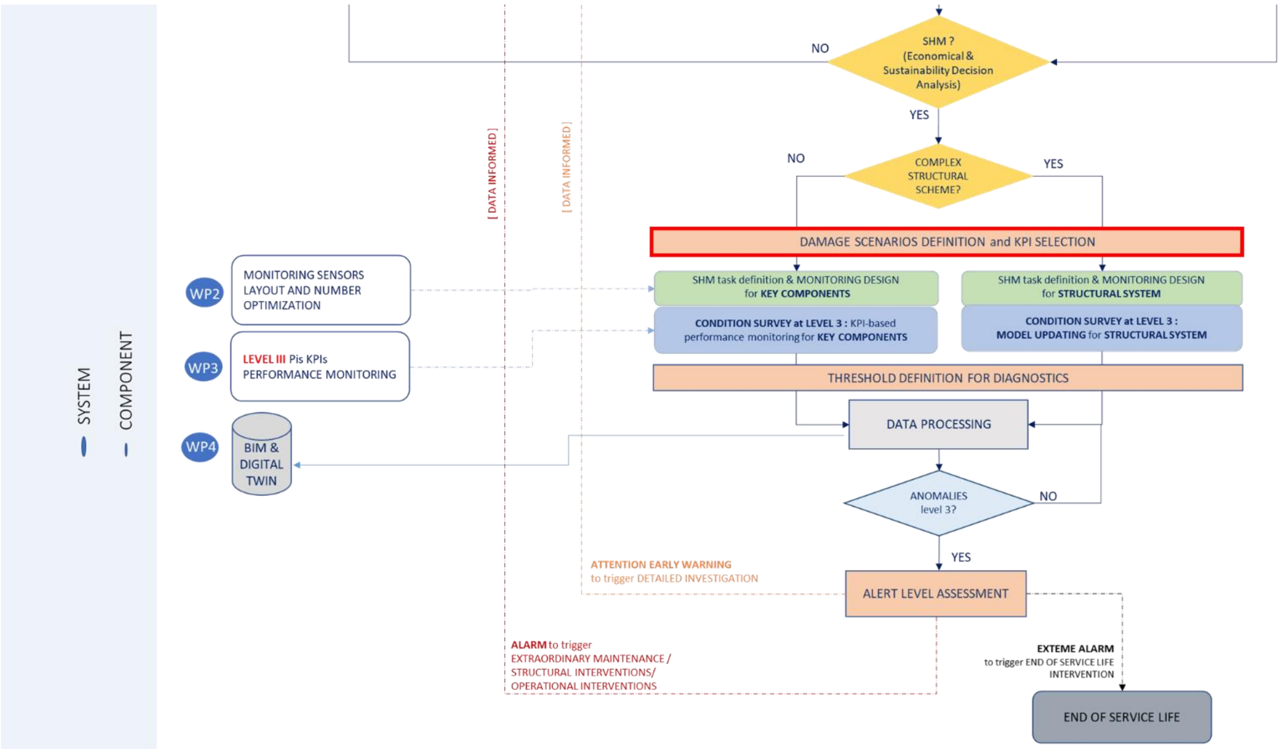

Figure 8.22 – Extract of the decision-making flow: damage scenarios definition and KPI selection, extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

In both cases the aim is to control the structural performance over time. In this respect, damage scenarios definition and the selection of Level III KPIs and PIs related to either structural system/ key components are suggested.

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.

In this context, it is particularly relevant to refer to the maintenance systems outlined in Chapter 4 in the area of condition, reliability and risk-based maintenance and the associated preventive and predictive maintenance concepts.

8.3.2 SHM system design

Structural monitoring systems aim to implement an in-service control process, which consists of identifying the value assumed by specific parameters that characterise the behaviour of the structure and determining the changes in the values of these parameters that occur due to deterioration processes.

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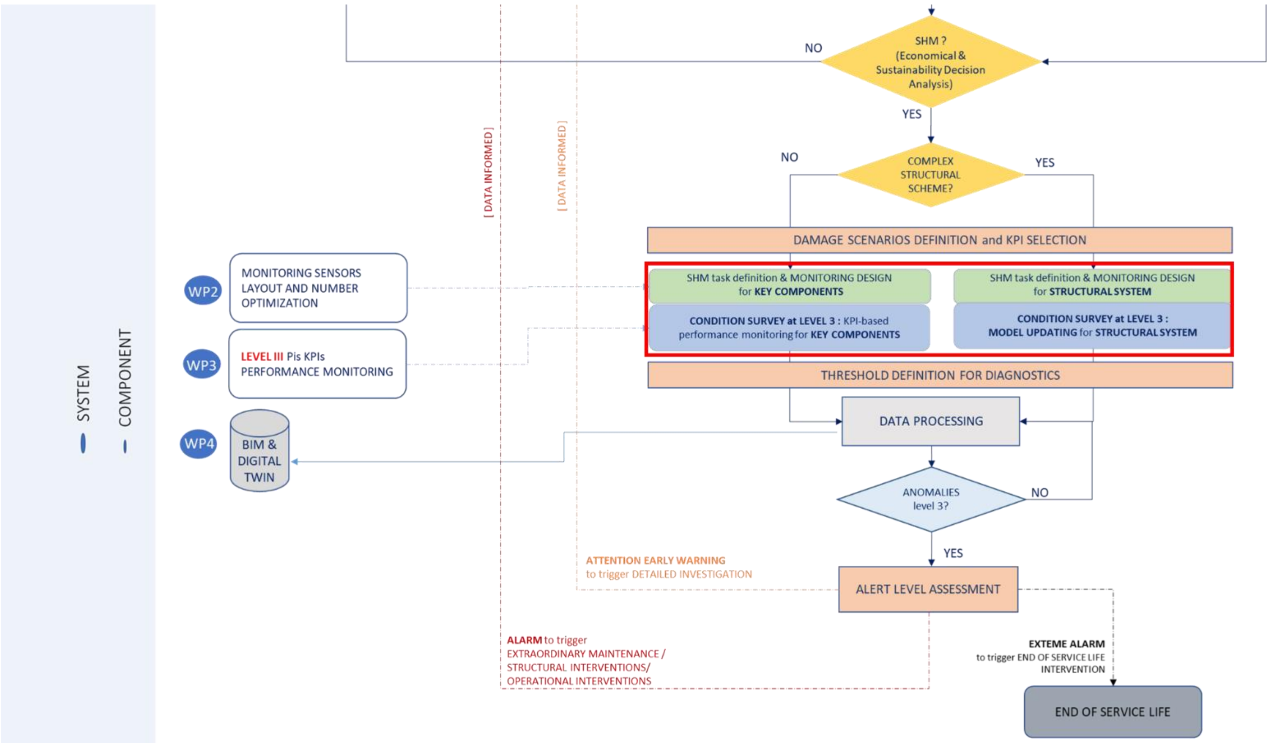

Figure 8.23 – Extract of the decision-making flow: SHM system design, extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

According to (UNI, 2016), the following fundamental functions of any monitoring scheme, simple or complex, are to be performed:

- **A data collection and management system**: information obtained by structural diagnostics (inspections, samples, load tests, etc.) and by a network of sensors directly installed on the structure is processed in the system.
- **A set of data processing procedures**: assessment of the condition of the structure and its developmental trend.
- **Decision-making procedures**: guidance on the choice of subsequent actions based on the indications provided by monitoring.
- **Numerical model of the structure**: this model is validated through an initial calibration, which is developed with a level of detail consistent with the complexity and relevance of the structure.

The decision on the use of the monitoring system and its characteristics is based on an in-depth cost-benefit analysis, on the basis of which it is possible to identify, in realistic terms, the role to be assigned to the monitoring system and to design the sensor network and, more generally, the whole system in order to be proportionate to the benefits to be obtained.
The flowchart in the following figure represents the sequence of activities that are carried out in the preliminary monitoring system design phase, which has the task of providing the detailed specifications for the development of the final design.

For the description of the diagram above and further information on SHM systems, see Chapter 4 of IM-SAFE project report D2.2 (Longo, et al., 2022).

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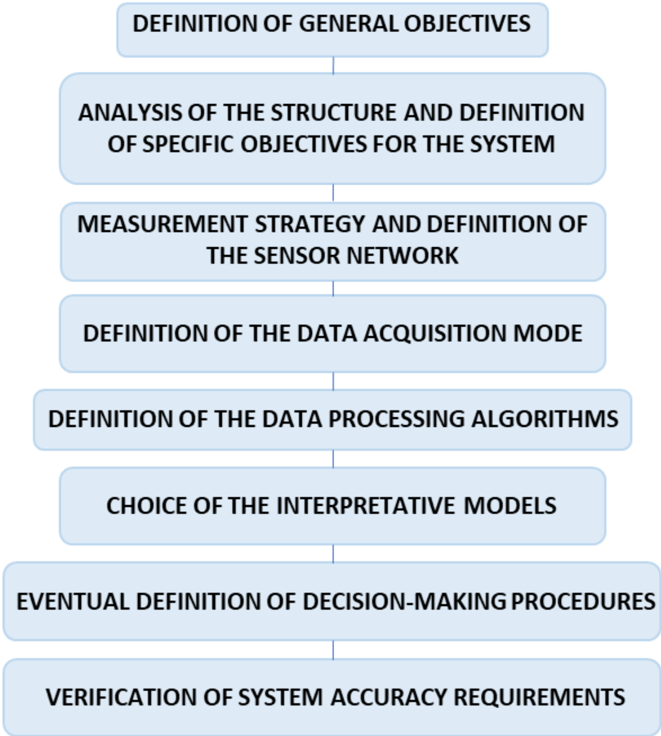

Figure 8.24 – Diagram of the monitoring system design process (extract from IM-SAFE project report D2.2 (Longo, et al., 2022))

8.3.3 FE modelling, proof load test and Model Updating procedures

Based on the complexity of the structural scheme, it is possible to have two different approaches, which are characterized by different Levels of Approximation (LoA): design and assessment of existing structures can be carried out with different levels of detail, on the basis of the level of accuracy required to fully describe the structural response.

In the Level of Approximation (LoA) approach, in fact, a series of parameters and a set of design equations are used in order to characterize the behaviour and the strength of structural members, remembering that, in any case, all analyses performed for the design of structural members are approximations of reality with different levels of accuracy.

Parameters involved can be physical, mechanical and geometrical variables. The more time spent on the analysis, the more accurate the parameters involved and the higher the LoA, as shown in the Figure 8.22 below.

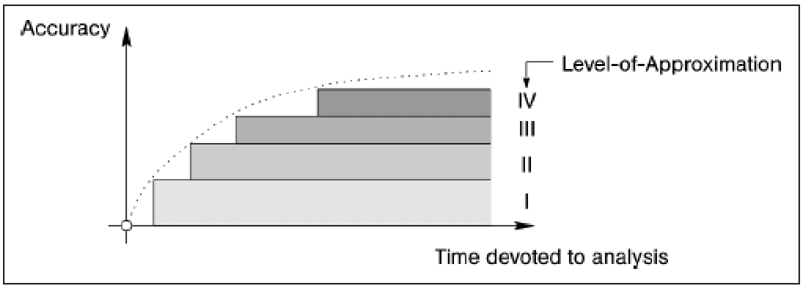

Figure 8.22 – Accuracy on the estimate of the actual behaviour as a function of time devoted to the analysis for various levels-of-approximation (extract from (fib MC2010, 2013))

In this respect, complex structural schemes require a higher LoA, based on analysis which implies analytical and numerical modelling, model updating processes and deeper analysis of

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the presence and localization of damages. These types of analysis and how to use data gathered from inspection, testing and monitoring are described in Chapter 8 of the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022). Simple structural systems require a lower LoA, which implies the analysis of KPI-based performance monitoring of key components of the structures.

8.3.4 Thresholds definition for diagnostics

As outlined in section 4.4.2, threshold values describe the structural condition to be fulfilled and need to be set in order to support decisions for maintaining a prescribed performance level. In this respect, the selected indicators of the structural performance identified from measurements have to be compared with target values. This is the basis for the decision-making process underlying asset management and maintenance scheduling: depending on the set target performance levels, threshold exceedance may trigger different corrective measures, ranging from low impact actions to extraordinary maintenance or the end of service life of the structure under investigation.

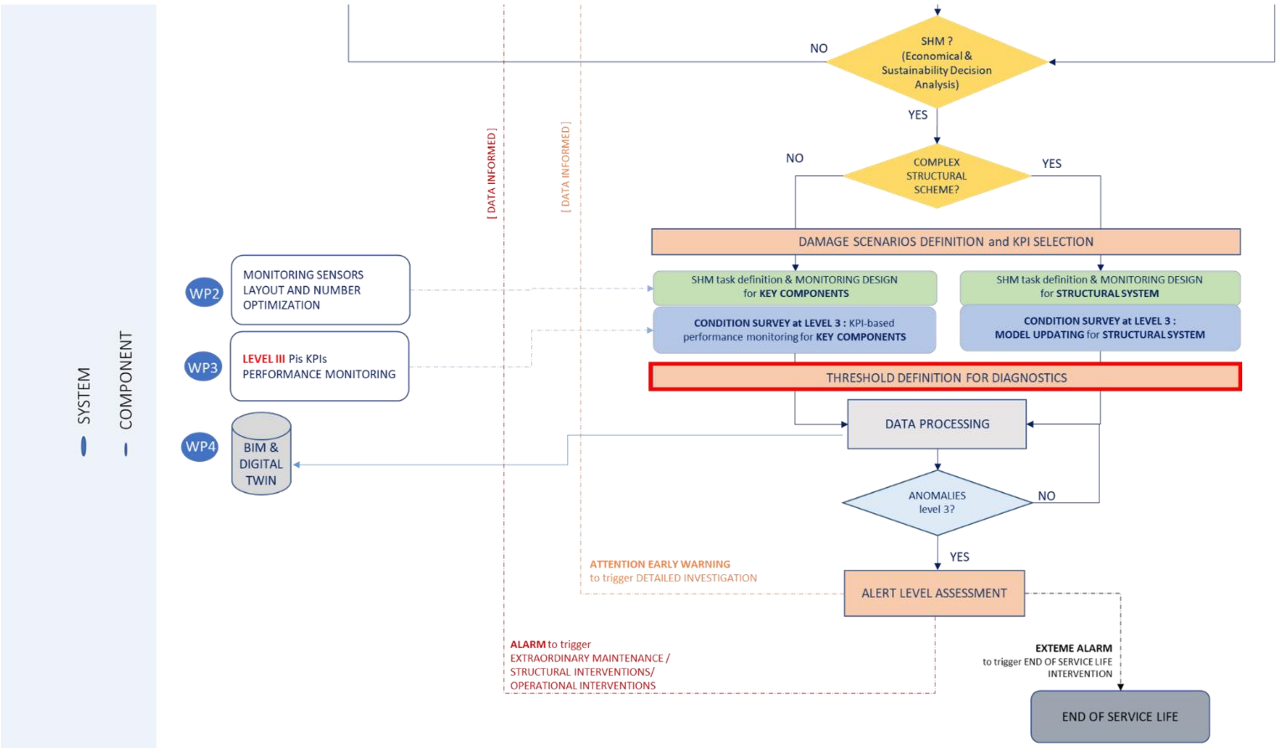

Figure 8.23 – Extract of the decision-making flow: thresholds definition for diagnostics, extract from the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

Protocols relevant to the actions to perform following the exceedance of a threshold (alert event) should be issued, for instance (fib Bulletin TG3.3, 2021):

- the prompt communication of the alert to the decision maker for subsequent decision making, based on the identified severity level.
- protocols for data management, e.g., raw data relevant to the exceedance of a threshold and the issuing of an alert event should be made available to the decision maker so that an in-depth analysis can be done, to confirm or neglect the urgency.
- Improvement of the alerting robustness.

In this respect, Artificial Intelligence and Machine Learning algorithms may be employed, enabling the automation of the issuing of alerts and, however, retaining the decisions at the hands of specialists further allows for engineering judgement to weigh in on the chosen policy.

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8.3.5 Data processing and diagnostics

Once damage scenarios and key-performance indicators are defined, data gathered from SHM system serve as an input for structural diagnostics procedures, which have to be supported by a thorough data processing phase.

Data processing 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.

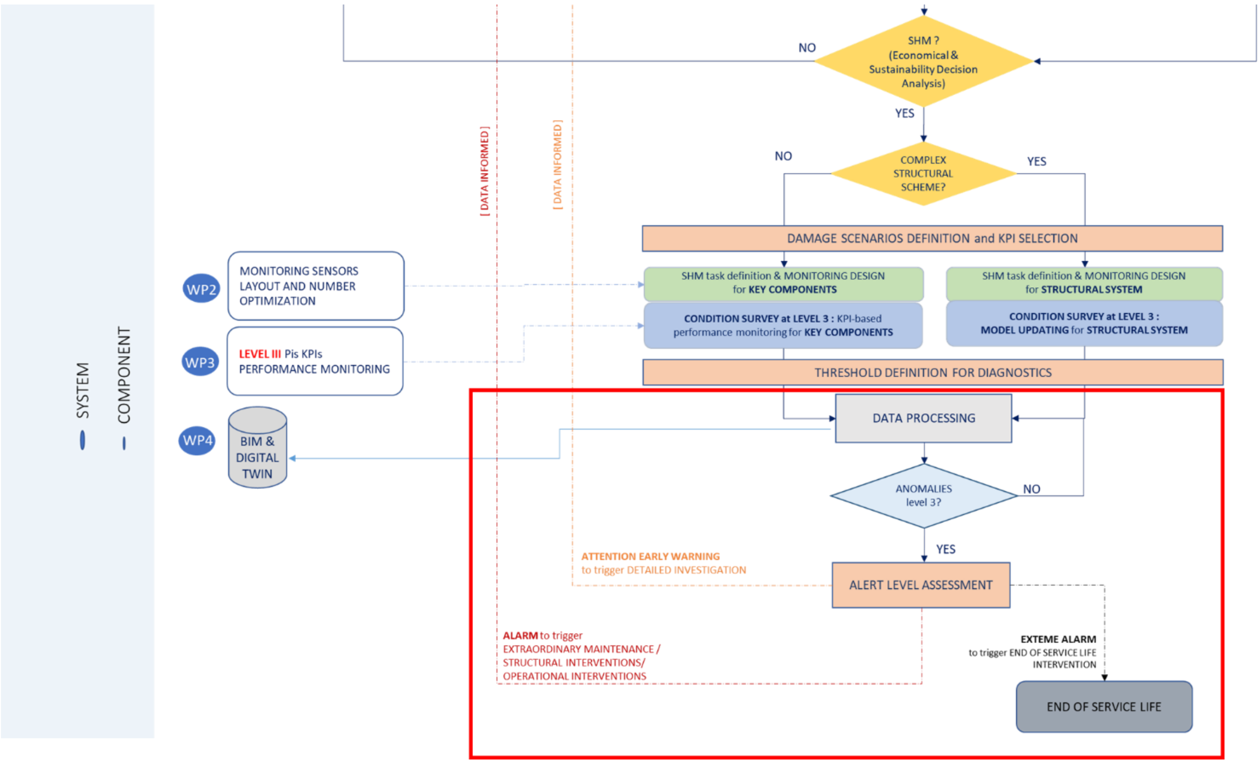

Figure 8.24 – Extract of the decision-making flow: Continuous data processing phase, extract from the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

Consequently, the detection of anomalies may be considered as a trigger for decisions regarding dedicated inspections, extraordinary maintenance and interventions or, in extreme cases, the end of service life of the structure. Based on exceedance of the threshold values, it is possible to distinguish the following alert levels:

- **Extreme alarm**, in case of very extreme events or exceedance of the alarm levels. This level might potentially trigger the end of service life of the structures or interventions plan for the structures under investigation. In case of end of service life, consideration to dismantling processes and re-use of materials are to be taken into account as part of a sustainable approach.
- **Alarm**, in case of severe thresholds levels exceedance. This level might potentially trigger either extraordinary maintenance extraordinary maintenance plans or structural/operational interventions plan for the structures under investigation.
- **Attention early warning**, which triggers further investigation levels or, eventually, another detailed structural assessment to evaluate if a structural intervention or an upgrade is needed.

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8.3.6 Related KPIs and Dis

In the IM-SAFE project the performance assessment of a structure, or any other asset, has been divided into a minimum of three levels, reflected in the decision-making flow.
Figure 8.25 introduces these levels in a flow chart:

- Level I- Visual Inspections
- Level II- Detailed Inspections, Testing and Monitoring
- Level III- SHM & Modelling

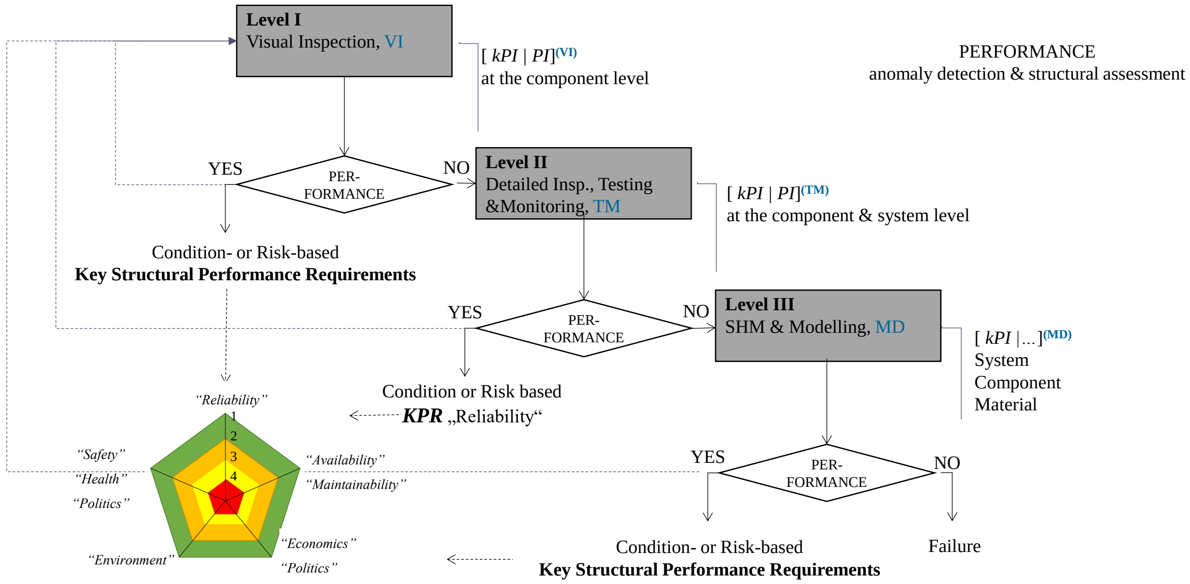

Figure 8.25 – Performance assessment according to the different inspection levels (Level I Visual Inspections; Level II Detailed Inspections, Testing and Monitoring; Level III SHM and Modelling) for the comparison with the Key Performance Requirements (extract from IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022))

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

The purpose of Level I is to remove existing doubts about the performance using fairly simple methods, which must, however, be adequate. The preliminary evaluation consists of a rough assessment based on inspection, an accompanying study of the available documents, and a rough check on the structural safety. In this first level, it makes sense to distinguish between key performance indicators, which allow a rough assessment, and performance indicators for detailed inspection and to define performance targets and performance thresholds.
The information gained in Level I must be summarised in a report for the owner and must result in Key Performance Requirement Indexes (KPRs) for the strategic asset management and budget allocation. The performance evaluation shown in Figure 8.25 is based on anomaly detection and leads to the KPR level or, in case of an insufficient condition, to level II.

Level II: Detailed investigations (Detailed Inspection, testing and monitoring)

Structural investigations and updating of information are typical of Level II – it comprises detailed inspection, testing and monitoring among others. 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.
A detailed inspection of the structure or structural part in question is extremely important, especially the recognition of typical hazard scenarios that could endanger the structure's

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residual service life. Further any defects and damage process due to excessive loading must be detected e.g. by using the visual inspection associated observations or performance indicators. Performance indicators or observations in these levels are mainly received from detailed inspection, testing and monitoring. As in the first level, it is recommended to distinguish between key performance indicators, which allow an assessment based on a minimum of detailed inspection, testing or monitoring related observations, and performance indicators associated with detailed testing and monitoring.
The results of Level II must be summarised in a report. In particular, the report must give information on the structural safety based on the performance indicator findings of levels I and II, and must contain the information about the Performance Requirement Indexes (RPIs) for e.g. network assessment purposes. As in Level I in this II level the performance evaluation is based on the detection of anomalies and leads to the CPR stage or, in the case of an inadequate condition, to Level III.

Level III: Assessment and prediction by advanced analysis (Structural Health Monitoring (SHM) und 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 level 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. In particular, the acceptance of increased risks should be left to the assessment team of experts.
In this level, extended surveys such as continuous monitoring or SHM are usually necessary for the in-depth analyses with regard to levels I and II for the determination of the analysis input variables. Some of the observations in these surveys of the input variables as well as some of the analysis responses are suitable for the performance assessment and can therefore be assigned to the class of performance indicators. In this level III, the distinction between key performance and performance indicators can be applied analogously to levels I and II. These principles have been implemented in the assessment and decision-making flow, as input at various level of the analysis process.

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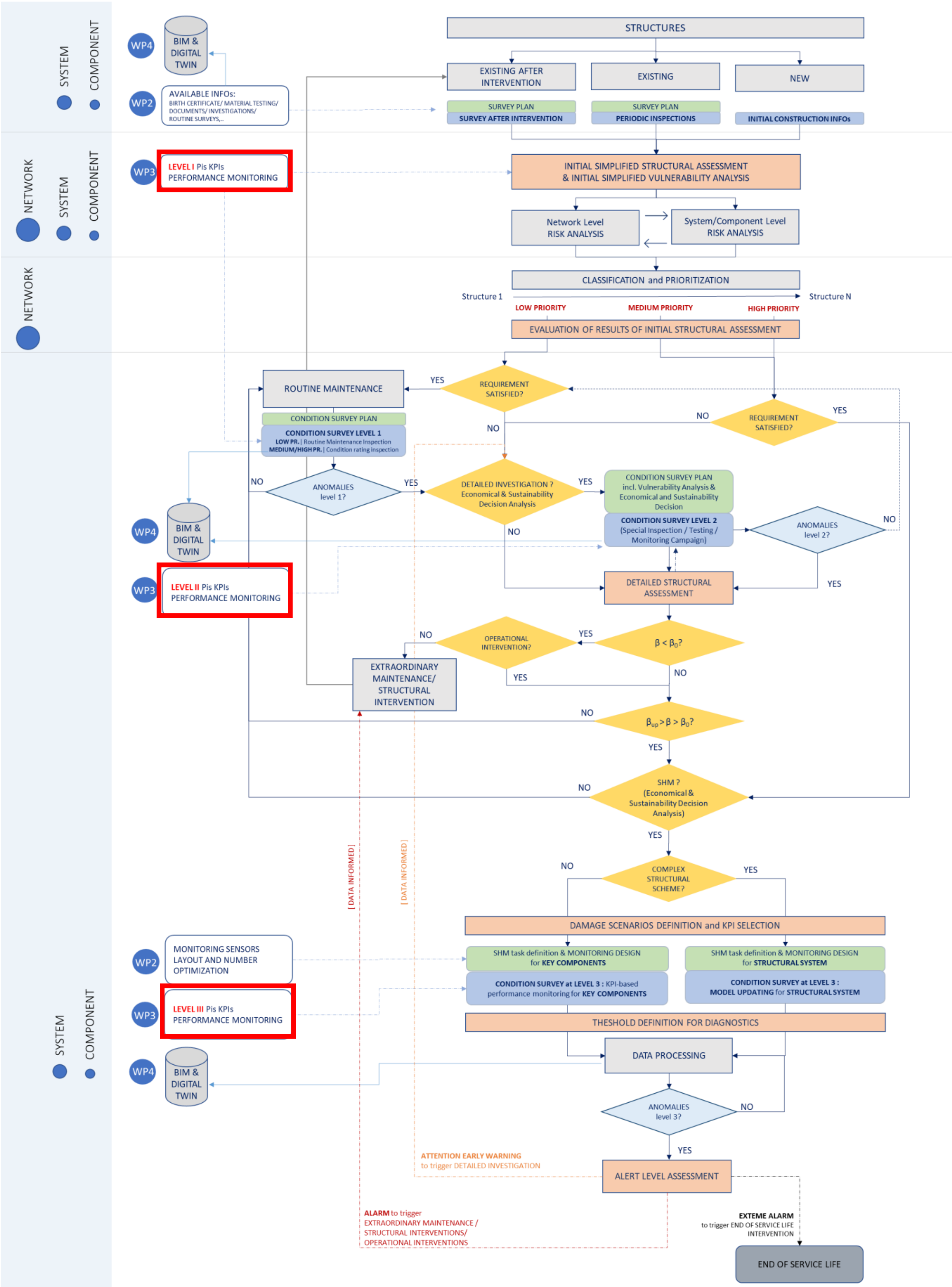

Figure 8.26 – Level I, II and II PIs and KPIs feeding the decision-making process at different steps, extract from the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022).

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9 Application on a real-case scenario of the TEN-T Corridor

9.1 Showcase of practical application of the decision-making process to real-case scenarios on TEN-T corridors and regional transport networks

9.1.1 General

This chapter aims to include a practical application of the decision-making process described in chapter 8 to real case scenarios located on TEN-T corridors and regional transport networks. The selected case studies are representative of how the proposed decision-making flow is already applied, at different levels, in current practice experiences. Case studies Profile Sheets are presented in the Appendix 2.

9.1.2 Case studies Profile sheets: Template description

The following template has been created in order to summarize the information on each case study and the application to the assessment flow in a single Case study Profile Sheet. The aim is to describe visually and clearly some of the possible paths covered in the decision-making process.

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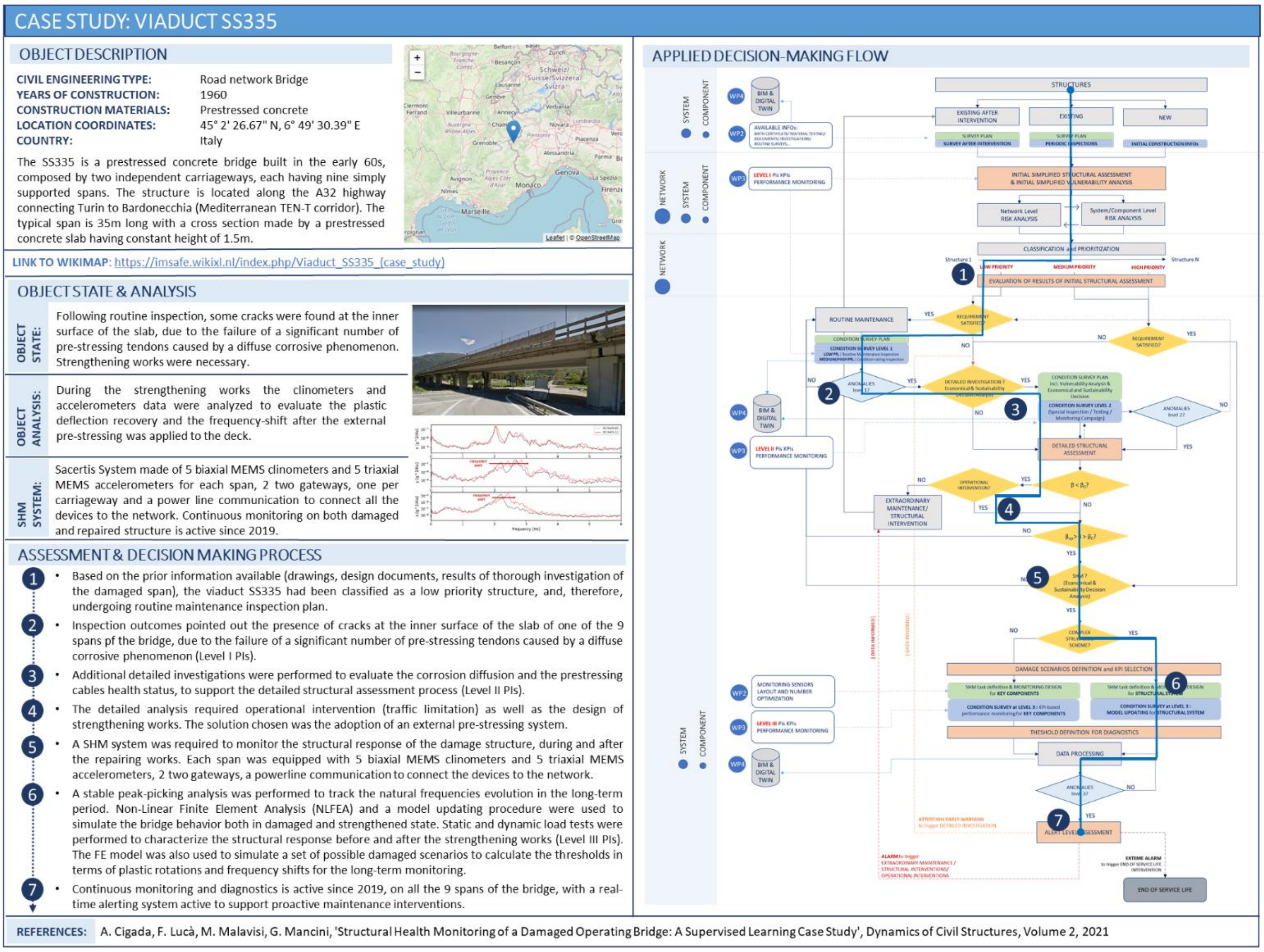
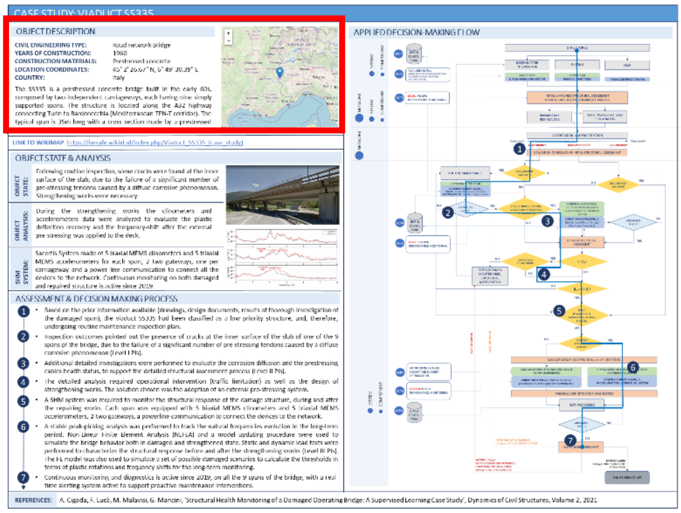


Figure 9.1 – Case study profile sheet template

9.1.2.1 Object description



This section includes a general description of the structure and information about:

- Civil engineering type
- Years of construction
- Construction materials
- Location coordinates
- Country

Figure 9.2 – Case study profile sheet template-Object description

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9.1.2.2 Link to Wikimap

This section includes the link to the Wikimap, where all the general case description is available online on an interactive map.

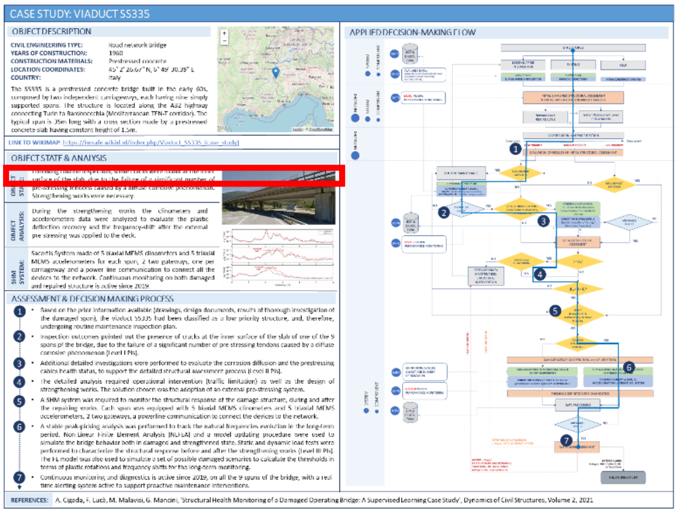

Figure 9.3 – Case study profile sheet template-Link to Wikimap

9.1.2.3 Object state and analysis

This section includes a general description of the object state and analysis, including information on the SHM system installed on the structure.

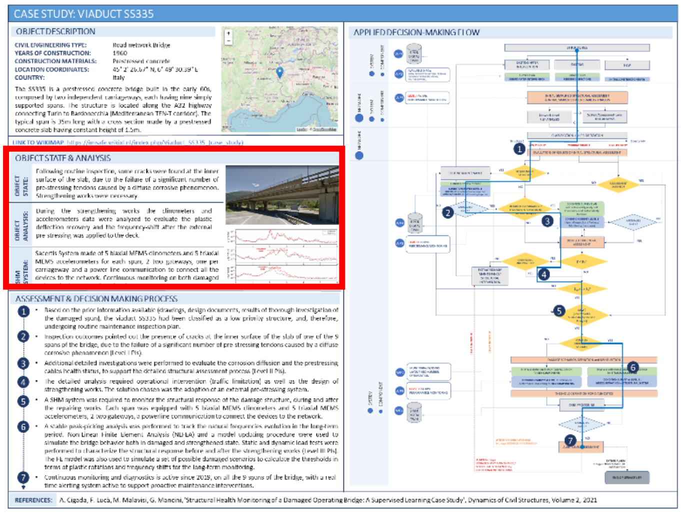

Figure 9.4 – Case study profile sheet template- Object state and analysis

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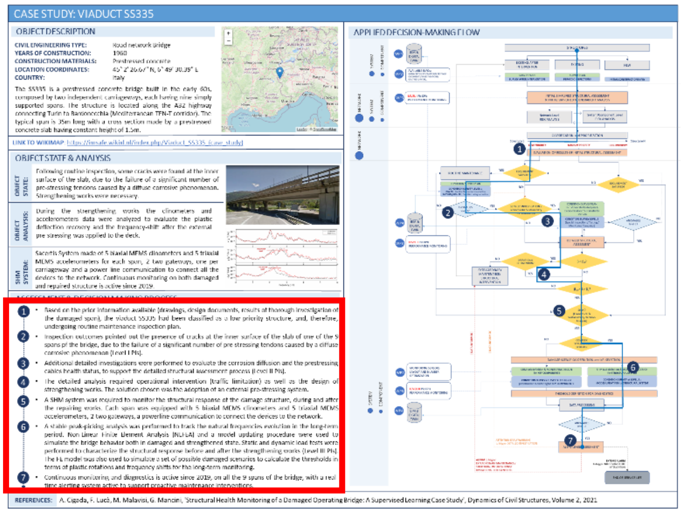
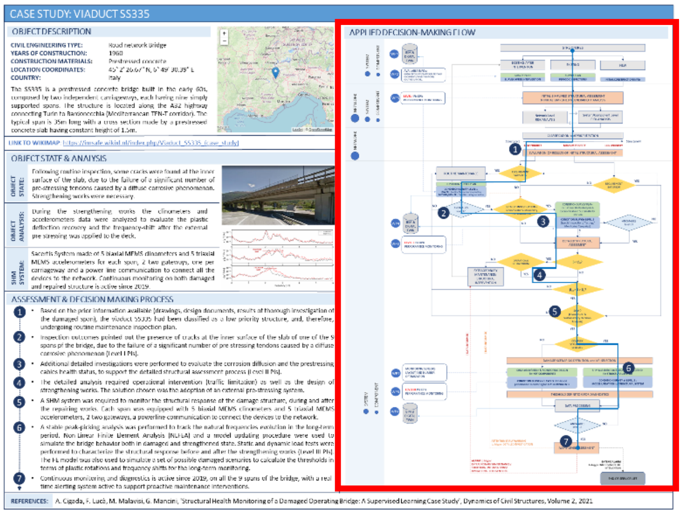
9.1.2.4 Assessment and decision-making process



This section includes the description of the assessment and decision-making progress, with respect to the path followed in the flow for the specific case under review.

Figure 9.5 – Case study profile sheet template- Assessment and decision-making process

9.1.2.5 Applied decision-making flow



This section includes the graphic representation of the decision-making process described in the previous section.

Figure 9.6 – Case study profile sheet template-Applied decision-making flow

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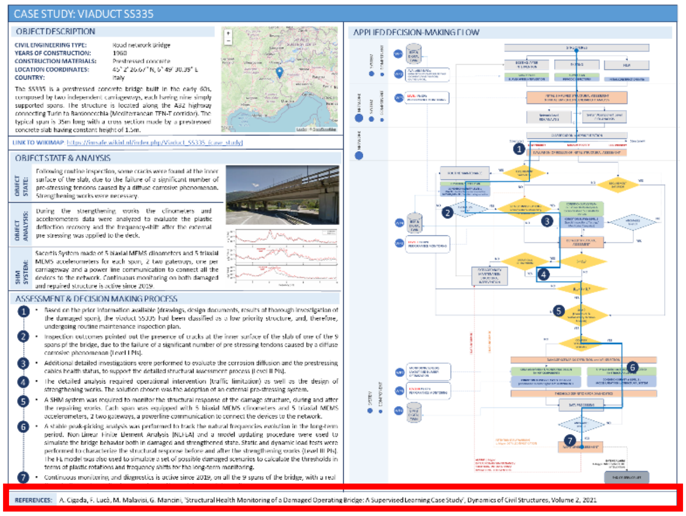
9.1.2.6 References



If available, reference documents are provided in this section.

Figure 9.7 – Case study profile sheet template- References

The detailed description of the selected case studies (9.1.3) is provided in the Case studies Profile Sheets, which aims to show how the proposed decision-making flow can be practically applied. Case studies Profile Sheets are presented in Appendix 2.

9.1.3 Case studies

In the following paragraphs a brief description of the case studies to which the assessment and decision-making flow has been applied is given.

9.1.3.1 Viaduct SS335 (along the Mediterranean TEN-T corridor)

The SS335 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. Following an inspection, some cracks were found at the inner surface of the slab, due to the failure of a significant number of pre-stressing tendons caused by a diffuse corrosive phenomenon. The structure was classified as high priority. Strengthening works were necessary, the solution chosen was the adoption of an external pre-stressing system. A SHM system was required to monitor the structural response of the damage structure, during and after the repairing works. Each span was equipped by the Engineering company Sacertis with 5 biaxial MEMS clinometers and 5 triaxial MEMS accelerometers, 2 two gateways, a powerline communication to connect the devices to the network. During the strengthening works the clinometers and accelerometers data were analysed to evaluate the plastic deflection recovery and the frequency-shift after the external pre-stressing was applied to the deck. Nonlinear model updating procedures and damage scenarios have been used to define thresholds based on reliability considerations. Continuous monitoring and diagnostics is active since 2019, on all the 9 spans of the bridge, with a real-time alerting system active to support proactive maintenance interventions.

The specific application of the decision-making flow to this case is provided in Appendix 2 (page 167).

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9.1.3.2 Gad bridge (along the Mediterranean TEN-T corridor)

The GAD bridge is located along the A32 Turin-Bardonecchia motorway, above the Turin-Modane railway and on the SS24 state road. The bridge, built in 1983, has a slab deck with alternated continuous and Gerber simply supported spans. In particular, the structure is a prestressed reinforced concrete plate bridge with variable length spans along the development of the asset; the two-way deck is 10.35 m wide.
Based on the prior information available (drawings, design documents, results of thorough investigations and preliminary network assessment), and to its strategic position overpassing the railway, the Gad bridge has been classified as a high priority structure. The Gerber saddles were subject to attention in the past due to the presence of strengthening works to restore the shear resistance, not sufficient for a lack of shear reinforcement. The saddles showed local cracks and presence of corrosion signs (Level I Pis). Nonlinear model updating procedures and damage scenarios have been used to define thresholds based on reliability considerations. The Gad bridge has been subject to continuous monitoring since March 2019 as part of a consulting project of Sacertis Ingegneria srl, to specifically control the structural behaviour over time of the Gerber saddles of the simply supported spans over the Turin-Modan railway, until the deck replacement (planned within the next 5 years' time).

The specific application of the decision-making flow to this case is provided in Appendix 2 (page 168).

9.1.3.3 Olympic footbridge (Italian regional network)

The Turin Olimpic Arc footbridge (Passerella Olimpica) is located in southern Turin and consists of a pedestrian walkway that connects the former Olympic village with the multi-purpose complex of Lingotto, overpassing the railway. It is one of the urban architectural symbols left in memory of the XX Winter Olympic Games which took place in 2006 in Turin. The pedestrian steel walkway is 368 meters long, has a maximum height of 11.8 meters, includes a single span of 156 meters supported by 32 stays over a large red metal arch with a parabolic shape, 69 meters high and 55 meters long. Lateral access spans 212 meters long are supported on V-shaped columns. Due to the complexity of the static scheme, model updating procedures and description of damage scenarios have been used to define thresholds based on reliability considerations
The Olimpic footbridge has been subject to continuous monitoring since august 2020 as part of a consulting project (Sacertis Ingegneria srl). The assessment has been undertaken due to reliability checks required by the municipality and a monitoring system has been installed to control the structural behaviour over time and optimize the maintenance procedures.

The specific application of the decision-making flow to this case is provided in Appendix 2 (page 168).

9.1.3.4 Seitenhafenbridge in Vienna (Austria)

The Seitenhafenbridge is part of a new road connection in Vienna crossing the Donaukanal (Danube Channel). The bridge was designed for road, pedestrian and bicycle traffic. The total length of the bridge is 128,69 meters divided in 5 fields and the width 15 meters. The abutments are not aligned at right angles with the road axis.
The Seitenhafenbridge in Vienna is currently the longest integral bridge in Austria. The client requested and installed a complex system for the monitoring of the movements of the construction. Monitoring information are also used to verify the Digital Twin and its loading assumptions.

The specific application of the decision-making flow to this case is provided in Appendix 2 (page 169).

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9.1.3.5 O Barqueiro Bridge (Spain)

O Barqueiro Bridge is a historical three-isostatic-span steel arch bridge built in 1901 as a road network bridge. Nevertheless, in 1980 the bridge was closed due to the damage presented in it. In 2006 a rehabilitation and a pedestrianization of the bridge was performed. It is placed in Galicia, northwest of Spain, crossing the Sor river and linking the municipalities of Vicedo and O Mañón. Each span has a length of 48.1 m and a width of 6.4 m. All the structural elements are made of structural steel, but the deck is made of wood beams.

After a random visual inspection some corroded spots were found in the bridge. This was particularly acute in the deck girders and at the lower nodes of the bridge. In fact, the corrosion has led to the total erosion of some structural elements presented in these nodes. Structural assessment was necessary.

Prior to the assessment several experimental campaigns were performed to characterize the geometry, material and dynamic behaviour of the structure. This information was useful for the uncertainty quantification, the modelling and the calibration of the model. Finally, a reliability assessment was carried out.

The specific application of the decision-making flow to this case is provided in Appendix 2 (page 169).

9.1.3.6 Galecopper bridge (the Netherlands)

The Galecopper bridge a strategic motorway for the Netherlands. In addition, the bridge spans the Amsterdam Rijnkanaal which is one of the most intensively used shipping canals in the Netherlands. The Galecopper bridge is a steel cable-stayed bridge in highway A12, crossing the Amsterdam-Rijn canal near the city of Utrecht. The bridge consists of two parts (north and south bridge), which have been opened in 1971 and 1976, respectively. The bridge has a total length of 320 meter, with a main span of 180 meters. Around 220.000 vehicles pass the bridge each day. Following inspection, corrosion related problems were found near the anchorages of the stay-cables. On the short term temporary strengthening of the cables was required, whilst on the longer term replacement of the cables was necessary.

To monitor the status of the stay cables, visual inspection and AE monitoring are used. The force in the strengthening system, partially bypassing the damaged part of the stay-cables, is also being monitored.

The specific application of the decision-making flow to this case is provided in Appendix 2 (page 170).

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10 Appraisal with regards to standardization

10.1 Review of current frameworks for Quality Control Plans

Quality management as part of operational quality assessment and quality control should be divided into a static and a dynamic phase. The static phase includes the preparation work, inspection tasks and snapshot of KPIs, the dynamic phase includes the evaluation of the remaining life, the evolution of the KPIs over time and the identification of an optimal maintenance scenario, i.e. by decision making. The implementation of quality management in these two phases requires the application of ISO 9001 and ISO 19650.

10.1.1 Static quality control

In general, static quality control, as can be derived from the COP surveys, includes:

- preparatory work,
- on-site inspection,
- lab test,
- assessment of condition or reliability,
- assessment of safety.

The activities included in these individual quality control steps for performing the quality assessment are generally structured as follows:

Preparatory work
The preparatory work is usually divided into the subsequent process steps

- Study an inventory information
- Identify conceptual weaknesses of the original design
- Identify the material weaknesses
- Compare the current traffic loads to traffic load model used in the original design
- Define the vulnerable zones
- Evaluate à priori reliability

For the individual activities enumerated here, more details can be found in the IM-SAFE project reports D2.1 (Sánchez Rodríguez, et al., 2022) and D3.1 (Bigaj-van Vliet, et al., 2022)

Inspection on site
The inspection on site process steps can generally be broken down into the following:

- Identify damages (e.g. cracks, spalling, deformations, etc.)
- Measure on site material properties
- Collect samples

Lab test
Results of the on-site inspection may also cause in-depth laboratory analysis in justified cases, such as:

- lab testing of carbonatization depth
- lab testing of chloride ingress
- lab testing of concrete strength
- lab testing of permeability….

Assessment of the Condition or Reliability (KPI)
Subsequently, the observations and findings of the inspection on site, monitoring and the lab test are the basis for the following assessment steps, whereby the assessments should respectively be based on significant key performance indicators (KPI's) see the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)

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- Qualitative assessment of resistance (Condition assessment) reduction based on observed damages
- Qualitative assessment of reliability (Reliability assessment of structural safety and serviceability)

Assessment of the Safety (KPI)
Subsequently, the results of the Qualitative assessment of resistance (Condition assessment) or Qualitative assessment of reliability (Reliability assessment) are used to assess the safety (e.g. by means of safety factors, partial, global or KPIs), whereby reference is also made to the existing action situations, see the IM-SAFE project report D3.1 (Bigaj-van Vliet, et al., 2022)

10.1.2 Dynamic quality control

In general, dynamic quality control, as also confirmed from the COP surveys and seen in the expert references, includes (a) assessment of remaining service life (b) consideration of maintenance scenarios, and (c) elements of decision making. The activities taking place in these process steps of dynamic quality control can roughly be structured as follows:

Assessment of remaining service life
This process step usually comprises the following
- Evaluating the speed of active damage processes
- Prediction of damages
- Reliability and safety development over time

Maintenance strategies
In this process step "Maintenance strategies", the following activities are usually performed for the planned remaining service life:
- Definition of a reference scenario "end-of-life intervention",
- Analysis and selection of clearly defined maintenance strategies or its combinations, see Chapters 3 & 4.
- Estimation of the long-term costs for the considered maintenance strategies,
- Estimation of availability for the considered maintenance strategies,
- Estimation of the impact of the considered maintenance strategies on reliability and safety.

Decision making
Decision making is the final step of a dynamic quality control process. In general, decision making is divided into the following steps
- Performing multi-attribute or multi-objective optimization of e.g. maintenance strategies
- Monetization of non-monetary KPIs
- Determination of the optimal scenario

10.1.3 IMSAFE Quality Control Plan relation to prEN1990

Where used, the DQL, DCL, and IL should be chosen according to the consequences of failure and associated data driven testing and monitoring concepts should be applied. The consequences of this management and monitoring task on the consequence factor k_f are to be implemented according to (EN-1990, 2002).

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Consequence class	Minimum design quality level (DQL)	Minimum design check level (DCL)	Minimum execution class (EXC)	Minimum inspection level (IL)
CC3	DQL3	DCL3	See relevant execution standards[a]	IL3
CC2	DQL2	DCL2		IL2
CC1	DQL1	DCL1		IL1
[a] Relevant execution standards might not be available for all materials, see B.6(2).				

Table 10.1 - Minimum design quality level (DQL), design check level (DCL), execution class (EXC) and inspection level (IL) for different consequence classes (CC), extracted from prEN1990

10.2 Proposal of framework for determining maintenance strategies and plans

Through-life management of infrastructure aims to ensure that the performance requirements are satisfied during the life cycle of the structure and assists in making informed choices between various design, construction, use, through-life intervention, and end of life options, on the basis of evaluation of relevant life cycle management scenarios at the planning stage, as a means of ensuring the performance requirements are attained. This requires the development, execution, review and updating of maintenance plans and programs.

In this regard, two aspects are considered of high importance:
- Prioritization of assets and maintenance activities.
- The consideration and selection of suitable maintenance strategies.

Prioritization can be achieved using a quantitative risk-based approach to enable the optimal use of maintenance resources from an economic perspective to minimize the risks associated to failure across the infrastructure network or asset portfolio. The risk-based approach shall apply a multidisciplinary engineering analysis to ensure that all performance requirements relevant for the assets are satisfied i.e. all targets related performance, and reliability, availability, maintainability and safety (eventually extended with requirements of security, health, environment, economics and politics) are met. These shall be achieved by 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) on the basis of 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 framework in place, the preliminary set-up of the risk-based maintenance management and the choice of the maintenance strategy must be defined during the re-design stage. Both the chosen risk-based maintenance management approach and the maintenance strategy must be confirmed/revised on the basis of the outcome of the current condition evaluation and current performance requirements.

The maintenance strategies are in general be classified as follows (see section 3.5):
- Corrective maintenance strategy
- Preventive maintenance strategies
  - Predetermined maintenance strategies
    - Time based

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        - Use base
    - Condition based maintenance strategies
        - Non-predictive
        - Predictive

The choice of maintenance strategy depends on various factors (and thus data and information regarding those factors) including:

- **Risk**, considering the probabilities and consequence of failure
- **How probabilities of risk occurring changes over time**. For example, if the probability of failure is considered constant over time (e.g. random failure), versus probabilities of failure that increase over time.
- **The degree in which the moment of failure can be predicted accurately a priori**. When such an estimate can be made, a predetermined maintenance strategy will likely be an effective maintenance strategy.
- **The degree in which failure can be detected and anticipated prior to occurring**. In cases where and condition-based maintenance strategy may prove useful, there should be possibilities to e.g. measure condition, detect failure, or otherwise collect information in order to determine when failure is likely and maintenance is required.
- **Costs**. Each strategy will entail different activities to be employed such as inspections, monitoring, maintenance, etc. All which incur costs. The cost structure of maintenance strategies varies. For example, a condition-based strategy entails investing in activities such as inspections and/or monitoring, to prevent costly failures and/or to postpone maintenance to the last moment possible. Also, many strategies will result in maintenance being anticipated better, thus making it easier to plan which typically is more cost-effective that unplanned maintenance.

The above criteria are also shown in section 3.5, which should be considered as a basic structure for determining an appropriate maintenance strategy. The best choice of strategies is case depended. It should be noted that in some cases, no satisfying maintenance strategy may be found, in which case criteria should be reconsidered, or it may be considered useful to explore other options such as asset modification (redesign).

Lastly, it should also be noted that devising a maintenance plan will include seeking out synergies. A maintenance strategy will initially be developed per risk identified. This leads to many specific tailored maintenance strategies for an asset. In practice, it is usually considered effective to combine activities into larger clusters of activities (e.g. large survey, major overhaul). A maintenance plan thus entails a degree of clustering and further optimization. This can be done on an element, asset, portfolio, and network level.

10.3 Proposal of framework for data-informed decision-making for safety and risk management of the European transport infrastructures, aiming at a sustainable and efficient management of both single bridges and a network of bridges

Review of the concepts and methods provided in the preceding chapters is the basis for the proposal of the framework for data-informed decision-making for safety and risk management of the European transport infrastructure. Aiming at a sustainable and efficient management of both single bridges and a network of bridges, the following framework is proposed for consideration for the future extension of the existing EU standards:

- Simplified assessment of the structures that are part of the same road network, identifying the critical elements of a network of infrastructure assets and the assets within the network

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itself and required as a prerequisite to perform a classification and prioritization of the assets that are part of the same road network. It is supported by:
    - A network data-informed Risk-based analysis (see section 8.1.2)
    - A vulnerability analysis (see section 8.1.1)

- Network infrastructure census and risk-based classification (see section 8.1.3), assigning structures to the following categories:
    - Low priority structures
    - Medium priority structures
    - High priority structures

- Intervention prioritization for each of the classes above based on the results of the preliminary assessment (see section 8.2), which may include:
    - Routine/extraordinary maintenance
    - A detailed investigation campaign
    - A detailed structural assessment
    - The implementation of a health monitoring system based on an economical and sustainability decision analysis

- Data-informed safety assessment procedures, based on the gathered information about the condition of the structure (data-informed), should be performed. Decisions regarding the use of inspections, monitoring and testing should be evaluated and the differentiation between new and existing structures must be considered. In particular, with respect to the reliability levels differentiation proposed for the assessment of existing structures, actions may vary based on adjusted target reliability levels.

- The decision on the use of monitoring system and its characteristics shall be based on an in-depth cost-benefit analysis, on the basis of which it is possible to identify, in realistic terms, the role to be assigned to the monitoring system and to design the sensor network and, more generally, the whole system in order to be proportionate to the benefits to be obtained.

- In case continuous SHM systems are used, it is possible to distinguish between two approaches, based on the complexity of the structural scheme. In both cases, the aim is that gathered data should feed appropriate key-performance indicators and should serve as input for structural diagnostics procedures. Based on the Level of Approximation, the following actions may be performed:
    - Definition of damage scenarios and selection of KPIs for components/structural systems
    - Definition of the objectives and SHM design
    - Condition survey campaign (KPI based performance monitoring for key components/ model updating for structural systems)
    - Threshold definition
    - Data processing and diagnostics
    - Alert level assessment

- The above should constitute the basis for the decision-making process underlying asset management and maintenance scheduling: depending on the set target performance levels, threshold exceedance may trigger different corrective measures, ranging from low impact actions to extraordinary maintenance or the end of service life of the structure under investigation. Protocols relevant to the actions to perform following the exceedance of a threshold (alert event) should be issued.

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11 Summary and conclusions

The main goal of this Coordination and Support Action (CSA) "Monitoring and safety of transport infrastructure", which has been opened by the European Commission opened in 2019 is to ensure the safety of the transport infrastructure during operation through the improvement of maintenance policies across Europe. (H2020 CSA IM-SAFE, 2020) supports this goal by providing input to preparation of a mandate for a CEN standard for the maintenance and control of the European transport infrastructure.

This report explains the context, the approach and the aim of the of the activities carried on in Task 3.2 of WP3 of the IM-SAFE project and aims to provide technical background information and practical guidance material, with specific focus on road and railway bridges and extension of some of the main considerations to tunnels, for the formulation of the proposal for the mandate to CEN for a further amendment to the existing EU standards on the existing gaps in the standards. For this purpose, principles of life cycle management and the main maintenance strategies have been provided in Chapter 2 and Chapter 3, taking into consideration various assessment levels (i.e., network-, asset-, component-level) and keeping in mind differences in service lives for the various parts of the systems considered. Moreover, conservation processes and investigations, evaluations and decision-making for maintenance activities have been classified and described. In a further step, maintenance strategies have been thoroughly described, identifying their positive aspects and limitations. The strategies used in today's practice have been presented, as well as the predictive methods that already exist in practice but have not yet been fully implemented. In Chapter 4 the Condition-based Maintenance approach specifically for bridges is described, providing an overview of the maintenance strategies commonly used for asset management adopted by the CoP in the different European countries. Chapter 5 focuses on the principles of Quality Management (QM), aiming to ensure that the resulting built structure fulfils the requirements, have been presented, emphasizing its application to all levels, processes and activities of an organization. Furthermore, principles of Information Management have been given in Chapter 6, focusing on information collected in the maintenance and monitoring phase of an infrastructure and providing a classification for the relevant information for infrastructures, as well as the impact of costs of information on decision-making and the analysis of the Value-of-information based decision-making for investigations activities (see Chapter 7).

Based on the information above, a practical decision-making process for asset owners and operators has been proposed, aiming to facilitate proactive maintenance, overcoming the current barriers and reflecting the most recent developments monitoring, damage detection, and digital technologies is outlined in Chapter 8. This proposal, that presents the concept of proactive maintenance plan, with the aim to reduce the risks of further structural deterioration, to minimize costs, and simultaneously to ensure the quality of the transport infrastructure performance, has been developed together with the CoP direct involvement (see results of IM-SAFE WP6). Then, the decision-making process has been applied to 6 relevant real-case scenarios on the TEN-T corridors or regional transport networks, and the outcomes are presented in Chapter 9 and Appendix 2.

An appraisal with regards to standardization is given in Chapter 10 and the following is proposed for consideration for the future extension of the existing EU standards:

- Simplified assessment of the structures that are part of the same road network, identifying the critical elements of a network of infrastructure assets and the assets within the network itself and required as a prerequisite to perform a classification and prioritization of the assets that are part of the same road network,
- Network infrastructure census and risk-based classification, assigning structures to the low, medium and high priority categories,

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- Intervention prioritization for each of the classes based on the results of the preliminary assessment,
- Data-informed safety assessment procedures, based on the gathered information about the condition of the structure (data-informed).
- Differentiation between new and existing structures, in particular, with respect to the reliability levels differentiation proposed for the assessment of existing structures,
- The implementation of a health monitoring system based on an economical and sustainability decision analysis, to identify, in realistic terms, the role to be assigned to the monitoring system and to design the sensor network and, more generally, the whole system in order to be proportionate to the benefits to be obtained.
- In case continuous SHM systems are used to gathered data the feed appropriate key-performance indicators and serve as input for structural diagnostics procedures, differentiation based on the complexity of the structural scheme is to be considered.
- The above should constitute the basis for the decision-making process underlying asset management and maintenance scheduling: depending on the set target performance levels, threshold exceedance may trigger different corrective measures, ranging from low impact actions to extraordinary maintenance or the end of service life of the structure under investigation.
- Protocols relevant to the actions to perform following the exceedance of a threshold (alert event) should be issued.

In order to continuously disseminate the outcomes reported here to the wide community of practice, an extension is delivered to the online IM-SAFE Wiki with respect to the maintenance methods in the EU (see https://imsafe.wikixl.nl/ maintenance_management_information). This online implementation includes also the description of Case Studies implemented in the online IM-SAFE Knowledge Base. Details of the knowledge model implemented are explained din Appendix 1.

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- CEN: EN 15341 Maintenance - Maintenance Key Performance Indicators
- CEN: EN 16991 Risk-based inspection framework
- CEN: prEN1990-2: Eurocode - Basis of assessment and retrofitting of existing structures: general rules and actions
- CEN: prEN1992: Eurocode 2: Design of concrete structures
- ISO: ISO 13822: Bases for design of structures — Assessment of existing structures
- ISO: ISO14963 Mechanical vibration and shock - Guidelines for dynamic tests and investigations on bridges and viaducts
- ISO: ISO4866 Mechanical vibration and shock - Guidelines for the measurement of vibrations and evaluation of their effects on structures
- Italy: Guidelines for risk classification and management, safety assessment and monitoring of existing bridges
- SAMCO: Guideline for Structural Health Monitoring
- Switzerland: SIA 269-0: Existing structures - Bases
- Switzerland: SIA 269-1: Existing structures - Actions
- Switzerland: SIA 269-2: Existing structures - Concrete structures
- The Netherlands: Guideline for the assessment of structures
- The Netherlands: NEN 8700: Assessment of existing structures in case of reconstruction and disapproval - Basic Rules
- The Netherlands: NEN 8701: Assessment of existing structures in case of reconstruction and disapproval – Actions
- UK: CM 430 Maintenance of road tunnels
- UK: CS 454 Assessment of highway bridges and structures
- UK: CS 455 The assessment of concrete highway bridges and structures
- UK: CS 456 The assessment of steel highway bridges and structures
- UK: CS 459 The assessment of bridge substructures, retaining structures and buried structures

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APPENDIX 1: Semantic Wiki : maintenance methods in EU

This appendix includes description of the extension of the interactive Semantic Wiki, created to disseminate the outcomes of WP3 of IM-SAFE project. This extension complements the previously delivered online best practice guide of the WP1 of the IM-SAFE project (Bektas, Köhler, & Liljefors, 2021), and can be accessed via the following Wiki link :

https://imsafe.wikixl.nl/index.php/Maintenence_management_introduction .

This IM-SAFE online Semantic Wiki extension provides a concise summary and overview of the knowledge related to the Maintenance Practices for transport infrastructure, reported in this report including online interactive wiki-like map of best practice in risk management and use of KPIs. In order to facilitate the understanding and interrelationship between the digital Semantic Wiki and the content used for the digital deliverable itself, this Appendix reports on the Knowledge Model and Visualization and User Interface implemented. For details of the general Wiki concept the reader is referred to the IM-SAFE project deliverable D1.2 (Bektas, Köhler, & Liljefors, 2021).

1. Knowledge Model extension

Taking into consideration the structure of the IM-SAFE knowledge model previous developed, the extension of the knowledge model has to be made and implemented in the Semantic Wiki platform so that all data on the Maintenance Practices, including case studies, can then be imported. These details extension of the knowledge model can be seen in Figure A1.1.

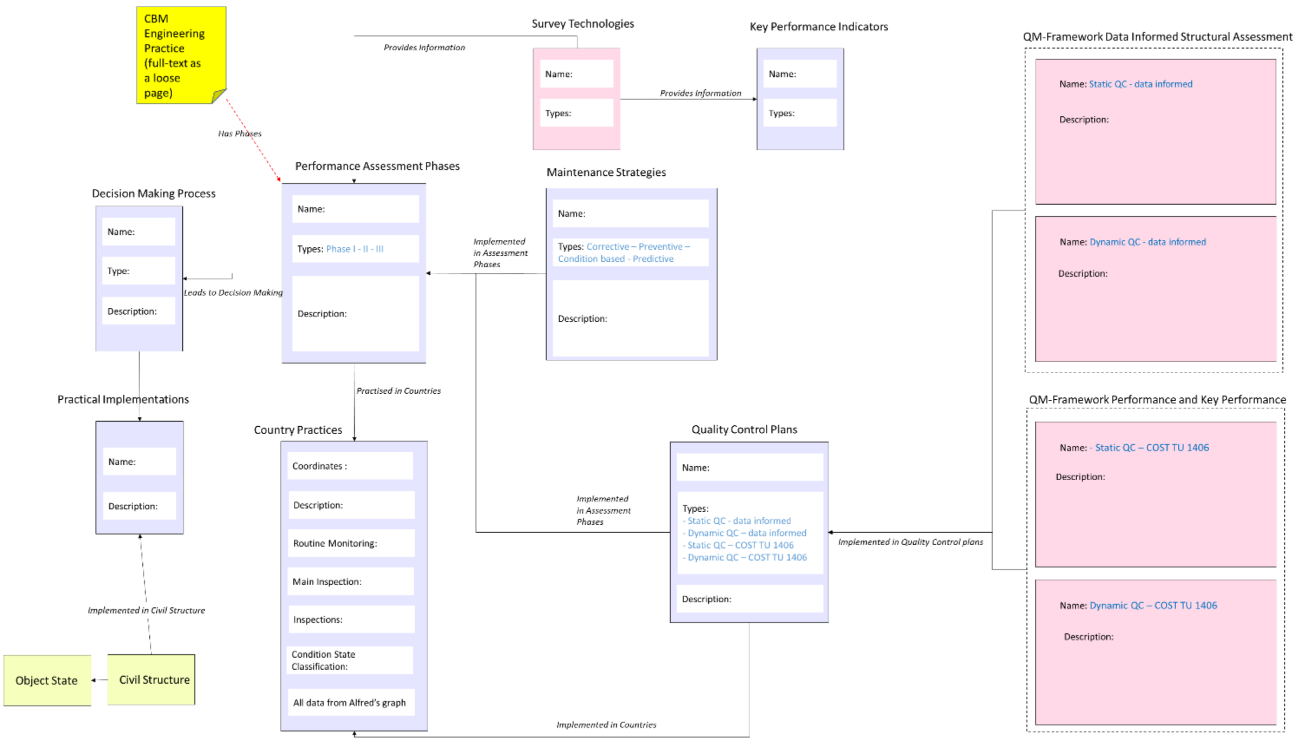

Figure A1.1 - Extension of the IM-SAFE knowledge model related to the Maintenance Practices for transport infrastructure

All the data and information on knowledge topics and cases have been collected and brought to the IM-SAFE Semantic Wiki to identify classes, subclasses, data /object

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properties and their relationships of the knowledge model. Thereafter, the search and retrieval patterns that have been defined help the end-users to navigate information embedded in the IM-SAFE Semantic Wiki. Finally, extension of the Knowledge Model related to the Maintenance Practices for transport infrastructure has been delivered online.

2. Visualization and User Interface extension

This extended knowledge model is implemented in the IM-SAFE Semantic Wiki as seen in Figure A1.2. The visualisation online shows under the Maintenance Management seven Key Pages:

- *Introduction*
- *Monitoring and inspection intervals*
- *Maintenance strategies*
- *Quality control elements*
- *Key performance indicators*
- *Decision making flow*
- *Map view of maintenance management*

Key Page *Decision Making Flow* presents the content for (6) case studies collected with regard to the Maintenance Practices all these cases. Each of the case studies listed in this document shows the information related to the best practice (e.g. geolocation, information of the infra assets, applied monitoring systems, etc.) gathered by IM-SAFE project with regard to the Maintenance Practices. The *Map view of Best Practice* under the Case studies displays all cases studied with regard to Maintenance Practices. In Appendix 2, the content details for all these cases are reported in full detail.

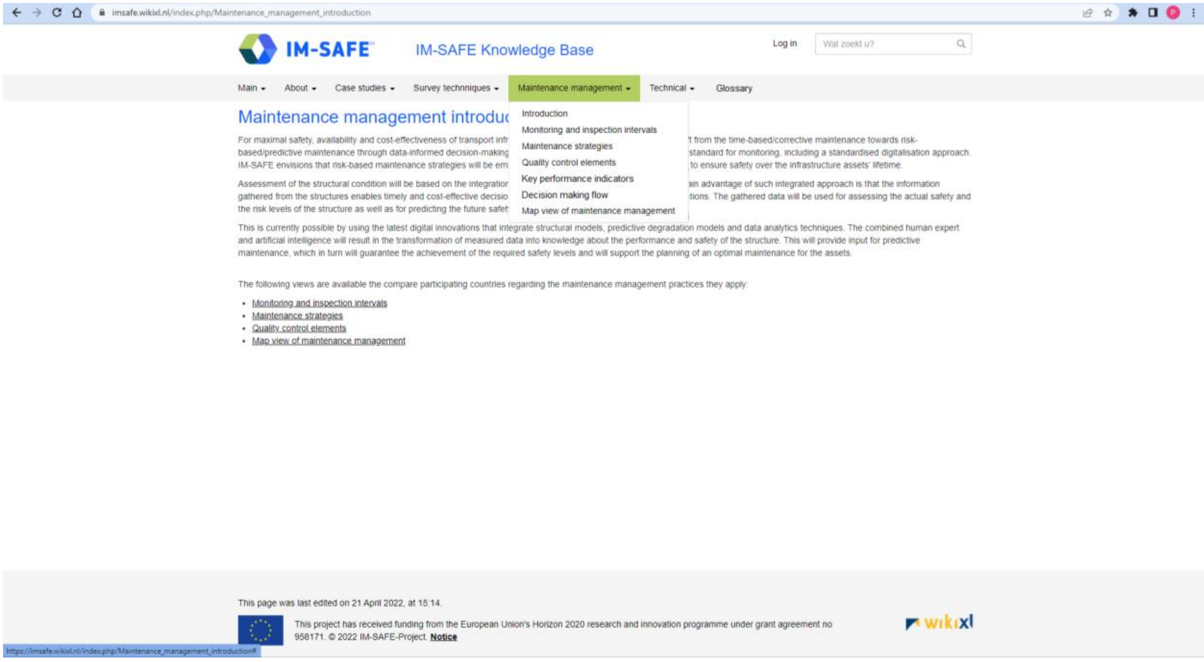

Figure A1.2 - Extension of the IM-SAFE Visualization and User Interface related to the Maintenance Practices for transport infrastructure

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APPENDIX 2: Maintenance Management Case Studies

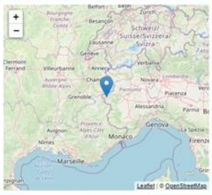
This appendix includes profile sheets of cases analysed and implemented in the IM-SAFE online Knowledge Base with regard to maintenance practises, https://imsafe.wikixl.nl/Maintenance_management_introduction .

CASE STUDY: VIADUCT SS335

OBJECT DESCRIPTION

CIVIL ENGINEERING TYPE:	Road network Bridge
YEARS OF CONSTRUCTION:	1960
CONSTRUCTION MATERIALS:	Prestressed concrete
LOCATION COORDINATES:	45° 2' 26.67" N, 6° 49' 30.39" E
COUNTRY:	Italy

The SS335 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.

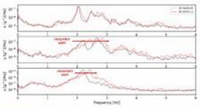


LINK TO WIKIMAP: https://imsafe.wikixl.nl/index.php/Viaduct_SS335_(case_study)

OBJECT STATE & ANALYSIS

OBJECT STATE: Following routine inspection, some cracks were found at the inner surface of the slab, due to the failure of a significant number of pre-stressing tendons caused by a diffuse corrosive phenomenon. Strengthening works were necessary.

OBJECT ANALYSIS: During the strengthening works the clinometers and accelerometers data were analyzed to evaluate the plastic deflection recovery and the frequency-shift after the external pre-stressing was applied to the deck.

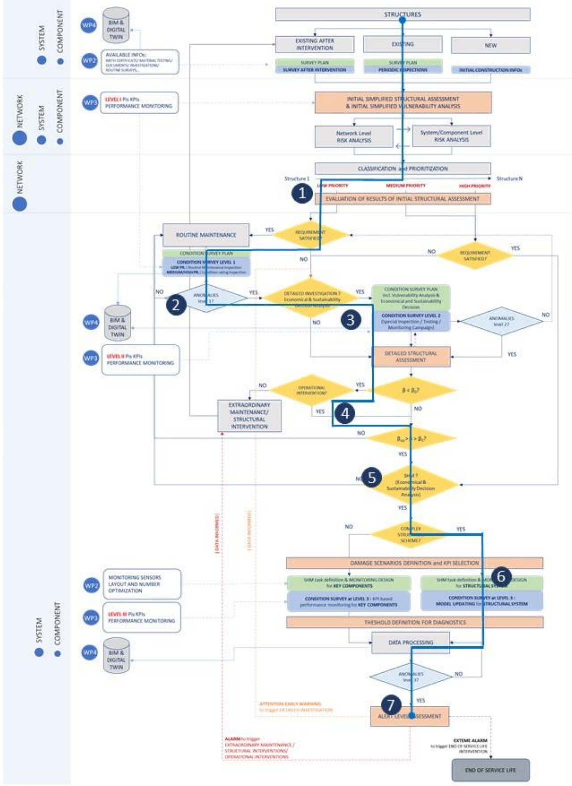


SHM SYSTEM: Sacertis System made of 5 biaxial MEMS clinometers and 5 triaxial MEMS accelerometers for each span, 2 two gateways, one per carriageway and a power line communication to connect all the devices to the network. Continuous monitoring on both damaged and repaired structure is active since 2019.

ASSESSMENT & DECISION MAKING PROCESS

1. Based on the prior information available (drawings, design documents, results of thorough investigation of the damaged span), the viaduct SS335 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 pf the bridge, due to the failure of a significant number of pre-stressing tendons caused by a diffuse corrosive phenomenon (Level I PIs).
3. Additional detailed investigations were performed to evaluate the corrosion diffusion and the prestressing cables health status, to support the detailed structural assessment process (Level II PIs).
4. The detailed analysis required operational intervention (traffic limitation) as well as the design of strengthening works. The solution chosen was 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 equipped 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 period. Non-Linear Finite Element Analysis (NLFEA) and a model updating procedure were used to simulate the bridge behavior both in damaged and strengthened state. Static and dynamic load tests were performed to characterize the structural response before and after the strengthening works (Level III PIs). The FE model was also used to simulate a set of possible damaged scenarios to calculate the thresholds in terms of plastic rotations and frequency shifts for the long-term monitoring.
7. Continuous monitoring and diagnostics is active since 2019, on all the 9 spans of the bridge, with a real-time alerting system active to support proactive maintenance interventions.

APPLIED DECISION-MAKING FLOW



REFERENCES: A. Cigada, F. Lucà, M. Malavisi, G. Mancini, 'Structural Health Monitoring of a Damaged Operating Bridge: A Supervised Learning Case Study', Dynamics of Civil Structures, Volume 2, 2021

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CASE STUDY: GAD BRIDGE

OBJECT DESCRIPTION

CIVIL ENGINEERING TYPE: Road network Bridge
YEARS OF CONSTRUCTION: 1983
CONSTRUCTION MATERIALS: Prestressed concrete
LOCATION COORDINATES: 45° 2' 41.09" N, 6° 50' 44.43" E
COUNTRY: Italy

The GAD bridge is located along the A32 Turin-Bardonecchia motorway, above the Turin-Modane railway and on the SS24 state road (Mediterranean TEN-T corridor). The bridge, built in 1983, has a slab deck with alternated continuous and Gerber simply supported spans. The structure is a prestressed reinforced concrete plate bridge with variable length spans along the development of the asset.

LINK TO WIKIMAP: https://imsafe.wikixl.nl/index.php/Gad_Bridge_(case_study)

OBJECT STATE & ANALYSIS

OBJECT STATE: The Gerber saddles were subject to attention in the past due to the presence of strengthening works to restore the shear resistance, not sufficient for a lack of shear reinforcement. Strengthening works were necessary, the solution chosen was the adoption of prestressing transversal dywidag bars.

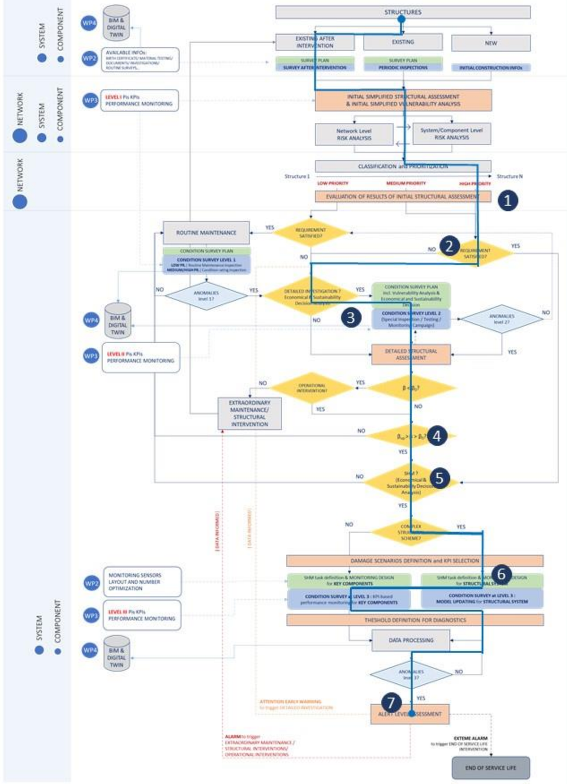
OBJECT ANALYSIS: The Gad bridge has been subject to continuous monitoring since March 2019 as part of a consulting project of Sacertis Ingegneria srl, to specifically control the structural behaviour over time of the Gerger saddles of the simply supported spans over the Turin-Modan railway, until the deck replacement (planned within the next 5 years time).

SHM SYSTEM: Each Gerber saddle is equipped N.5 biaxial MEMS clinometers and N.4 IoT crackmeters, n.2 two gateways, one per carriageway and a power line communication to connect all the devices to the network.

ASSESSMENT & DECISION MAKING PROCESS

1. Based on the prior information available (drawings, design documents, results of thorough investigations and preliminary network assessment), and to its strategic position overpassing the railway, the Gad bridge has been classified as a high priority structure.
2. The Gerber saddles were subject to attention in the past due to the presence of strengthening works to restore the shear resistance, not sufficient for a lack of shear reinforcement. The saddles showed local cracks and presence of corrosion signs (Level I Pis).
3. Additional detailed investigations were performed to evaluate the corrosion diffusion and the prestressing cables health status, to support the detailed structural assessment process (Level II PIs).
4. The detailed analysis proved the structure to have a reliability level between β_0 and β_{up}, as such requiring future structural interventions consisting of the deck replacement, planned within the next 5 years time.
5. To guarantee the expected structural performance up to the structural interventions, a SHM system was installed in 2019. Each span was equipped with 5 biaxial MEMS clinometers and 4 IoT crackmeters installed locally on the Gerber saddles (key components), 2 two gateways, a powerline communication to connect the devices to the Cloud.
6. Model updating procedures and damage scenarios have been used to define thresholds based on reliability considerations. A non-linear FE model has been calibrated using optimization algorithms based on the static diagnostics load test results and the analysis of the structural response through long-term data analytics. A local 3D shell FE model has been developed to further validate the results and perform sensitivity tests. The definition of the thresholds, for each sensor of the monitoring system, has been based on the simulation of significant damage scenarios causing a targeted reduction of the reliability levels.
7. Continuous monitoring and diagnostics is active since March 2019, on all the Gerber saddles of the bridge, with a real-time alerting system active to support proactive maintenance interventions.

APPLIED DECISION-MAKING FLOW



CASE STUDY: OLIMPIC FOOTBRIDGE ('Passerella Olimpica')

OBJECT DESCRIPTION

CIVIL ENGINEERING TYPE: Other network Bridge
YEARS OF CONSTRUCTION: 2006
CONSTRUCTION MATERIALS: Steel
LOCATION COORDINATES: 45° 1' 54.38" N, 7° 39' 39.29"E
COUNTRY: Italy

The Turin Olimpic Arc footbridge (Passerella Olimpica) is located in southern Turin and consists of a pedestrian walkway that connects the former Olympic village with the multi-purpose complex of Lingotto, overpassing the railway. It is one of the urban architectural symbols left in memory of the XX Winter Olympic Games which took place in 2006 in Turin. The pedestrian steel walkway is 368 meters long, has a maximum height of 11.8 meters, includes a single span of 156 meters supported by 32 stays over a large red metal arch with a parabolic shape, 69 meters high and 55 meters long. Lateral access spans 212 meters long are supported on V-shaped columns.

LINK TO WIKIMAP: https://imsafe.wikixl.nl/index.php/Passerella_Olimpica_(case_study)

OBJECT STATE & ANALYSIS

OBJECT STATE: The Olimpic footbridge, built in 2006, has no sign of deterioration or occurring damage processes. The aim of the monitoring system is to control the structural behaviour over time and optimize the maintenance procedures.

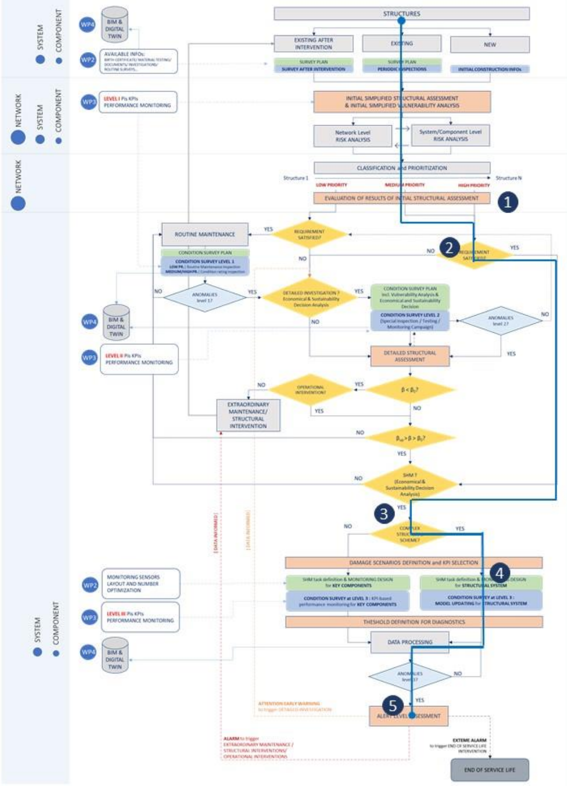
OBJECT ANALYSIS: The Olimpic footbridge has been subject to continuous monitoring since august 2020 as part of a consulting project of Sacertis Ingegneria srl. The assessment has been undertaken due to reliability checks required by the municipality and a monitoring system has been installed to control the structural behaviour over time and optimize the maintenance procedures.

SHM SYSTEM: The Sacertis monitoring system consists of 34 triaxial MEMS accelerometers installed on the deck and on a selection of stays.

ASSESSMENT & DECISION MAKING PROCESS

1. Based on the prior information available (drawings, design documents, results of the proof load test, and n.2 previous dynamic measuring campaigns), the Olimpic footbridge has been classified as a medium priority structure.
2. It has no sign of deterioration or occurring damage processes.
3. A SHM system was installed to control the structural behaviour over time and optimize the maintenance procedures. It consists of 34 triaxial MEMS accelerometers installed on the deck and on a selection of stays.
4. Due to the complexity of the static scheme, model updating procedures and description of damage scenarios have been used to define thresholds based on reliability considerations. A non-linear FE model has been calibrated based on the dynamic characterization (mode shapes and natural frequencies of the stays and the overal structure) and data analytics. The definition of the thresholds, for each sensor of the monitoring system, has been based on the simulation of significant damage scenarios that can cause a significant reduction of the safety and reliability target levels.
5. Continuous monitoring and diagnostics is active since 2020 with a real-time alerting system active to support proactive maintenance interventions.

APPLIED DECISION-MAKING FLOW



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CASE STUDY: SEITENHAFENBRIDGE

OBJECT DESCRIPTION

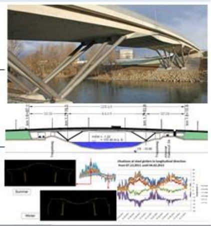
CIVIL ENGINEERING TYPE: Road network Bridge
YEARS OF CONSTRUCTION: 2011
CONSTRUCTION MATERIALS: Concrete/Steel Composite Bridge
LOCATION COORDINATES: 48° 17′ 94.34" N, 16° 46′ 14.52" E
COUNTRY: Austria

The Seitenhafenbridge is part of a new road connection in Vienna crossing the Donaukanal (Danube Channel). The bridge was designed for road, pedestrian and bicycle traffic. The total length of the bridge is 128,69 meters divided in 5 fields and the width 15 meters. The abutments are not aligned at right angles with the road axis

LINK TO WIKIMAP: https://imsafe.wikixl.nl/index.php/Seitenhafenbridge_(case_study)

OBJECT STATE & ANALYSIS

OBJECT STATE: To manage a flexible abutment, an EPS layer and a reinforced earth behind the abutment were arranged. For verification of the model assumption and the functionality of the solution, a multi-layer monitoring and modeling system was ordered by the owner.



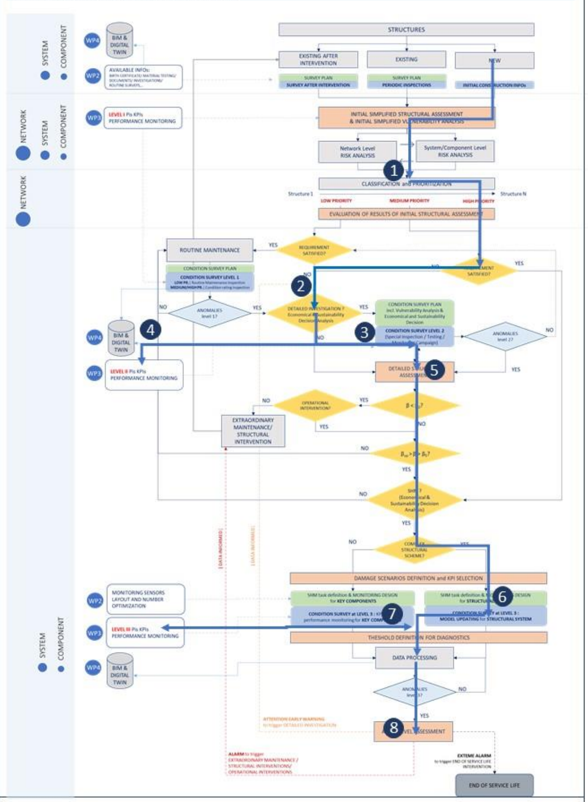
OBJECT ANALYSIS: The Seitenhafenbridge in Vienna is currently the longest integral bridge in Austria. The client requested and installed a complex system for the monitoring of the movements of the construction. Monitoring information are also used to verify the Digital Twin and its loading assumptions.

SHM SYSTEM: The monitoring system constantly measured the temperatures and the movements of the construction, like for example deflection, inclination, length variation and ground pressure at the abutment. The data are continuously assessed and summed up in intermediary reports showing actual behaviour of the structure.

ASSESSMENT & DECISION MAKING PROCESS

1. The Seitenhafenbrücke in Vienna is currently the longest integral bridge in Austria. Due to the total length of approx. 130 meters, the client requested an in-depth performance analysis and risk assessment
2. The client required monitoring of the movements of the structure.
3. The consulting firm and the client defined performance and key indicators and their thresholds. (Level II)
4. The monitoring system continuously measures temperatures and movements of the structure, such as deflection, inclination, length change, and soil pressure at the abutment.
5. The client engaged the consulting firm to perform a detailed digital twin analysis using the monitoring data to verify the performance of the critical details. (Level III)
6. The digital twin models were updated and the functionality of the critical details was verified.
7. Thresholds were set for the monitored performance indicators using the digital twin models.
8. An alarm system was set up in combination with the monitoring system and the client
9. Continuous monitoring and diagnostics is active since 2011, on all the 5 spans of the bridge, with a real-time alerting system active to support proactive maintenance interventions.

APPLIED DECISION-MAKING FLOW



REFERENCES: R. Geier, T. Mack, A. Strauss, 'Monitoring Experiences on Integral Bridges', IABSE Symposium Report · January 2009

CASE STUDY: O BARQUEIRO BRIDGE

OBJECT DESCRIPTION

CIVIL ENGINEERING TYPE: Pedestrian Bridge
YEARS OF CONSTRUCTION: 1901
CONSTRUCTION MATERIALS: Structural steel and wood
LOCATION COORDINATES: 43° 43′ 52.3" N, 7° 41′ 55.9" E
COUNTRY: Spain

O Barqueiro Bridge is a historical three-isostatic-span steel arch bridge built in 1901 as a road network bridge. Nevertheless, in 1980 the bridge was closed due to the damage presented in it. In 2006 a rehabilitation and a pedestrianization of the bridge was performed. It is placed in Galicia, northwest of Spain, crossing the Sor river and linking the municipalities of Vicedo and O Mañón. Each span has a length of 48.1 m and a width of 6.4 m. All the structural elements are made of structural steel, but the deck is made of wood beams.

LINK TO WIKIMAP: https://imsafe.wikixl.nl/index.php/OBarquieirobridge_(case_study)

OBJECT STATE & ANALYSIS

OBJECT STATE: After a random visual inspection some corroded spots were found in the bridge. This was particularly acute in the deck girders and at the lower nodes of the bridge. In fact, the corrosion has led to the total erosion of some structural elements presented in these nodes. Structural assessment was necessary.

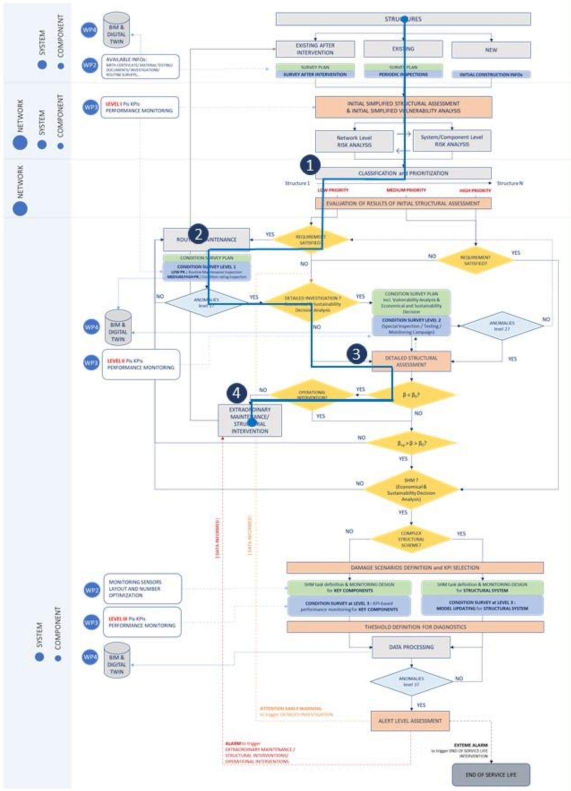
OBJECT ANALYSIS: Prior to the assessment several experimental campaigns were performed to characterize the geometry, material and dynamic behavior of the structure. This information was useful for the uncertainty quantification, the modelling and the calibration of the model. Finally, a reliability assessment was carried out.

SHM SYSTEM: No SHM systems were used for the safety evaluation of the structure. Nevertheless, some non-destructive devices such as a TLS, an ultrasonic gauge, a caliper and 6 uniaxial seismic accelerometers were used for capturing the required experimental data.

ASSESSMENT & DECISION MAKING PROCESS

1. Based on the available information (drawings, history, location, data extracted from the visual inspection), the bridge has been classified as a low priority structure according to the definitions of the EN 1990 standard. The main reasons for this decision were:
   - The bridge is a pedestrian bridge
   - It is located in an area with little pedestrian traffic
   - There are other bridges that can be used as an alternative crossing in case of collapse
2. In this project, the possibility of abolishing the vehicle restriction in the bridge was studied. Therefore, an evaluation of the structure using the load models established by the current standards had to be performed. In order to calibrate the structural model and define the probability density functions of its parameters, a thorough structural characterization of the bridge was carried out.
3. Once the distributions were defined, the bridge was assessed for a SLS referred to the existence of local damage that affects the appearance, efficacy or functionality of the structure; and for an ULS referred to the failure because of excessive deformation, transformation of the structure into a mechanism and collapse or loss of stability of the structure.
4. The assessment of the bridge for the SLS leads to a calculated reliability index above the threshold values. However, regarding the ULS, the assessment showed that the calculated reliability index was lower than the threshold values. Therefore, it was concluded that a structural intervention was required in order to abolish the vehicle restriction in the bridge under study.

APPLIED DECISION-MAKING FLOW



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

CASE STUDY: GALECOPPER BRIDGE

OBJECT DESCRIPTION

CIVIL ENGINEERING TYPE: Road network Bridge
YEARS OF CONSTRUCTION: 1971 and 1976
CONSTRUCTION MATERIALS: Steel
LOCATION COORDINATES: 52° 4′ N, 5° 6′ E
COUNTRY: Netherlands

The Galecopper bridge is a steel cable-stayed bridge in highway A12, crossing the Amsterdam-Rijn canal near the city of Utrecht. The bridge consists of two parts (north and south bridge), which have been opened in 1971 and 1976, respectively. The bridge has a total length of 320 meter, with a main span of 180 meters. Around 220.000 vehicles pass the bridge each day.

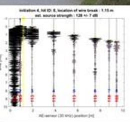
LINK TO WIKIMAP: https://imsafe.wikixl.nl/index.php/Galecopperbrug_(case_study)

OBJECT STATE & ANALYSIS

OBJECT STATE: Following inspection, corrosion related problems were found near the anchorages of the stay-cables. On the short term temporary strengthening of the cables is required. On the longer term replacement of the cables is necessary.

OBJECT ANALYSIS: Both visual inspection and AE monitoring are used to assess the status of the cables in the time before replacement of the stay cables. The AE monitoring system and strengthening system have been tested and calibrated in a laboratory environment.

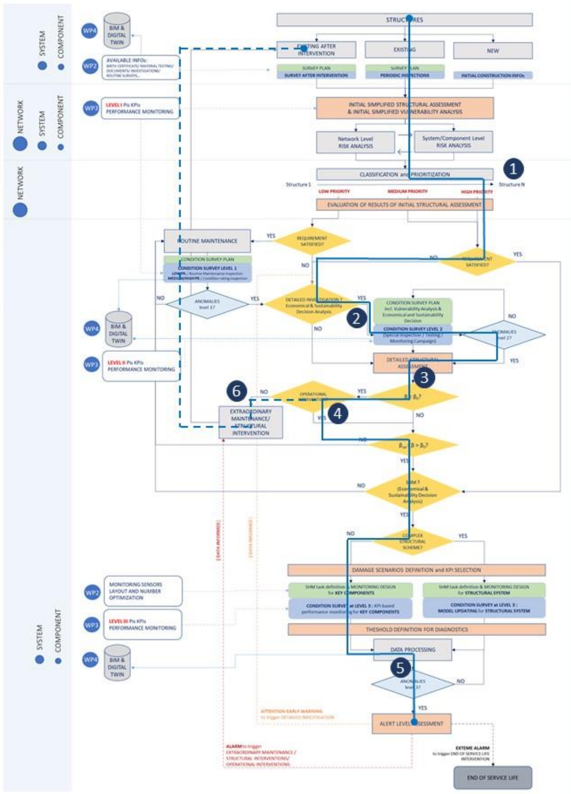
SHM SYSTEM: To monitor the status of the stay cables, visual inspection and AE monitoring are used. The force in the strengthening system, partially bypassing the damaged part of the stay-cables, is also being monitored.



ASSESSMENT & DECISION MAKING PROCESS

1. During the renovation of the bridge between 2013 and 2015, corrosion related issues near the anchorage were discovered. To slow down or stop the corrosion process, a climate chamber was installed. Given the present status of the cables and the fact the bridge is the second most busy bridge in the Netherlands, the bridge has been classified as high priority.
2. Despite the measures, during inspection in 2019 it turned out that the situation of the stay cables has deteriorated. Since then, the inspection rate has been intensified to once each month. Laboratory tests have been performed to quantify the level of structural safety, including data from the inspections.
3. A detailed corrosion fatigue analysis showed that one of the cables did not pass the assessment and three additional cables only just passed the assessment.
4. As a temporary solution, these cables are strengthened using a specially designed system. The strengthening takes over a portion of the load in the cables (350 kN through bypass of total load of around 2100 kN SLS on the cable)
5. Laboratory tests have been performed to develop a protocol for installation of the strengthening structure and to test its structural behavior. The force in the strengthening is monitored by force transducers and strain gauges. The AE and visual inspection of corrosion related issues continue in the meantime.
6. The strengthening is considered a temporary solution until the replacement of the stay cables in the summer of 2022.

APPLIED DECISION-MAKING FLOW



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