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Key performance requirements for objective assessment & through-life management of structures

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Abstract

The overall process in the life cycle assessment is the condition control of new or existing structures respectively. This is necessary for safeguarding the condition of a structure during its lifetime, and includes condition survey, performance assessment as well as for the evaluation of maintenance strategies. Usually deterministic performance prediction models that describe the future condition through a functional correlation between structure condition characteristics, such as the age of the structure, and the characteristics of mechanical, chemical and physical processes are used to capture the deterioration processes in the life cycle analyses. With increasing experience with the use of surveying technologies for acquiring information related to the current condition of bridges there is an ongoing shift towards data-informed approaches to condition control. The identification and implementation of key performance indicators may improve existing assessment methods within management system of transport infrastructure. The IM-SAFE project aims to characterize and systematize performance indicators for bridges. Based on these project outcomes, in this contribution, the systematized performance indicators for bridge systems are presented and a case study is used to show how performance indicators can be coupled with risk-based performance requirements, data-informed assessment methods, inspection and monitoring concepts.

Keywords

Key performance indicators, Life cycle management, Condition control, Data-informed assessment, Risk-based approach, Bridge, Concrete structures

1 Introduction

Road and railway infrastructure networks form the backbone of European transportation systems, carrying more than 80% of passenger and 50% of goods transport in Europe. In particular, large infrastructure assets are crucial for the availability and safety of the Trans-European Transport Network. The assessment of a (existing) structure is in general based on doubts about the structural performance and this can have several reasons as change of use or loads, detected or suspected damage or deterioration process, etc. Structural performance might refer to the absence of different adverse states that compromise the intended purpose of the structure [1].

Structural failure of a component or the entire structure is obvious examples of such adverse states, excessive deflection, deformation or vibration are others. In the context of aging structures, the so-called condition limit states may be considered to describe adverse states that have the potential to lead to critical states for the struc-

tural integrity. The most important input parameters for an reliable and successful assessment can be defined as key performance requirements (KPR). In this paper, the systematized KPR for bridge structures are presented and a case studies is used to show in which way KPR can be coupled with risk-based performance requirements, data-informed assessment methods and inspection and monitoring concepts [2].

2 Performance concept

In general, the efficiency of a system can be described as that within a defined period of time the system requirements are met. That means the efficiency with regard to structural behaviour can denoted as structural performance. In the field of civil engineering, the assessment of the structural performance can be applied to e.g. bridge structures at various schema levels, according to the type of assessment and the scope of the analysis. For a infrastructure framework, the relevant levels can be described as (a) the network which is an certain amount of coupled

objects that all together fulfil a certain function and (b) the framework which is a delimited group of independent, connected or interacting objects that is assessed for a potential risk. Thereby a various number of frameworks can be treated as sub-framework as part of a larger entity. The definition of the boundaries of a framework is depending on the context. Accordingly, a structural framework is an arrangement of interacting structural members offering a potential solution to examine the bearing capacity to a specified combination of actions. Finally, (c) the component which is an individually identifiable part of an object. It can consist of one or more elements, designed to provide a specific function for the object. Specifically, a structural component is a portion of the structural system to be used as load-bearing part and designed to achieve mechanical resistance and stability as well as fire resistance, including aspects of serviceability and durability.

For all levels under consideration, the goals set for the asset management must be attained. When setting the goals for the asset management of transport infrastructure one must recognise the multiple levels of objectives and multiple tiers posing requirements and creating constraints.

The primary objectives of asset management are set at the highest strategic level by the policy objectives, prevailing legislation, and administrative agreements. Examples of objectives considered for infrastructure include:

- mobility
- sustainability
- resilience.

These strategic objectives are governing when the primary requirements are set for the function of the infrastructure during its full life cycle life and when the primary requirements are set for the properties that do not affect the basic functionality of the infrastructure but have impact on user expectations. These requirements are listed as the functional requirements and the non-functional requirements.

Both categories of requirements should be specified in terms of aspect requirements. Aspect requirements considered for infrastructure include: (i) reliability, (ii) availability, (iii) maintainability and (iv) safety, sometimes extended by including (v) security, (vi) health, (viii) environment, (ix) economics and (x) politics.

Figure 1 shows schematically the hierarchy of terms in performance concept. The aspect requirements are established by means of the KPR, whereas the KPR are the most important requirements set for the primary functions or properties for all aspects considered, specified in terms of performance. Examples of KPR considered for infrastructure include requirements with regard to structural performance, which comprise, for instance, the requirements associated to structural safety, serviceability, durability, robustness or redundancy.

The KPR shall be established by means of the performance criteria, which are the quantitative limits, associated to a performance requirement, defining the border between desired and adverse behaviour.

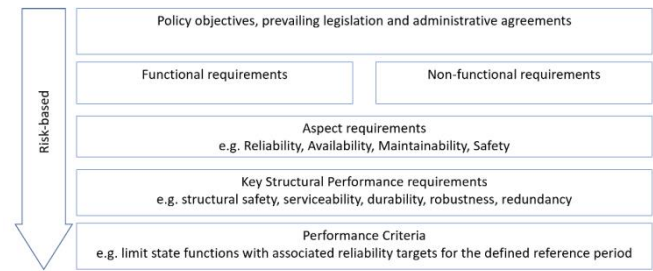


Figure 1 Multiple levels of objectives and multiple layers considered in identifying requirements for the infrastructure asset, see [3] and [4]

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.

2.1 Categorisation of performance requirements

Performance requirements can be classified into two main groups: technical performance requirements and non-technical performance requirements [5].

Technical performance requirements are those related to structural safety and serviceability, traffic safety and durability, while non-technical performance indicators are those related to sustainability, allowing an evaluation of the environmental, social and economic performance of a civil engineering work. Sustainability encompasses (i) Environmental requirements: referring to resource use, waste generation and pollution, among many others; (ii) Social requirements: referring to the accessibility and adaptability of infrastructures to society; and (iii) Economic requirements: refers to life cycle cost and external costs. Table 1 defines these KPR for bridges (but can be also used for tunnels).

Table 1 Key performance requirements KPR considered in management systems for bridges. Adapted from: [6], [7]

	definition
Safety	The probability of causing damage to the health and safety of the public. Safety is related to minimizing or eliminating the harm to people during the service life of a structure (the loss of life and limb due to structural failure is not included).
Reliability	The probability that a structure will be fit for purpose (i.e. able to carry out the work that is designed to perform, within specified limits of performance for a specified interval of time under stated conditions during its service life. The reliability with regard to structural safety is included.

Security	The aspect of security stands for the safety of a system with regard to conscious unsafe human action, such as vandalism, terrorism and cybercrime.
Availability	Time proportion in which a system is in a functioning condition incl. disruption originates from planned maintenance interventions.
Maintainability	The probability that a given active maintenance action for an item, under given conditions of use, can be carried out within a stated interval when the maintenance is performed under stated conditions and using stated procedures and resources. Maintainability refers to features with which a structure can be maintained to repair the damage or its cause, repair or replace defective components without having to replace still-working parts, and avoid unforeseen maintenance measures.
Owner's costs	Adequate life cycle costs for the owner incl., construction maintenance and operation costs, costs of claims and fines, etc.
Social costs	Acceptable and rare detours/accidents related to minimizing long-term costs and maintenance activities over the service life of a structure. Herein the user costs incurred due to detours and delays are not included.
Greenhouse gas emissions Resource consumption	Associated with minimizing negative impact on the environment during the life cycle of a structure and balancing impact with the utility of the structure.
Health	The physical, mental and/or social well-being, without failure or acute illness incl. absence of causes of diseases other than failure (for example, the use of asbestos), which in most cases is regulated. It relates to users of the infrastructure, persons working on or near the infrastructure and - where applicable - the infrastructure itself.
Politics	Reflects political-administrative and social consequences, e.g. the elimination of the causes of public protest, effects on the image protection of the management organisation or consequences for the reputation of the politically/administratively responsible parties responsible persons Includes etc.

2.2 Structural performance concept

The structural performance of a system or a component refers to the behaviour, or a condition as a consequence of actions, usually classified by means of a quantitative parameters e.g. reliability index, ratio between resistance capacity and action effect. As described in ISO-2394 [8], the performance of a structure relates to the structure as a whole or parts of it. Structures and structural members must be designed, constructed and maintained so that they perform adequately and in an economically reasonable way during construction, service life and dismantlement. In general, according to fib MC2010 [9]:

- structures and structural members must remain fit for the use for which they have been designed;
- structures and structural members must withstand extreme and/or frequently repeated actions and environmental influences occurring during their construction and anticipated use, and must not be damaged by accidental and/or exceptional events to an extent that is disproportional to the triggering event;
- structures and structural members must be able to contribute positively to the needs of humankind with regards to nature, society, economy and well-being;

Accordingly, the four categories of the structural performance that can be characterised by quantitative parameters are the following:

- serviceability
- structural safety
- sustainability
- robustness

In order to assess the performance, one shall select a set of quantitative performance indicators which express physical states that can be used in relation to the performance requirements. Performance indicators can be defined on various levels of abstraction for the following:

- structural characteristics (e.g. stiffness/flexibility, load bearing capacity);
- response parameters (e.g. internal forces, stresses, deflections, accelerations, crack sizes);
- utilization factors;
- functionalities (e.g. safety for people, energy consumption, robustness, usability, availability, failure probabilities).

Models shall be set up to establish the relation between the various levels of abstraction.

3 Damage classification and damage indicators

Numerous processes can have a detrimental effect on a structure. Those which may act individually or in combination to generate safety and serviceability problems are here referred to as damage processes. The information on damage processes is crucial for a performance prediction, planning of preventive maintenance as well as for planning of eventual rehabilitation. Some damage processes are gradual and observable (e.g. corrosion related to structural steel). These can be detected with a proper inspection strategy. Other damage processes are gradual and non-observable (e.g. corrosion of post-tensioning

steel). These should be handled by a proper maintenance strategy. By means of reliable information on the processes, inspection and maintenance strategies can be optimized. In order to assess damage processes, damage should be graded with respect to their nature, intensity, extent and location. The gradation should be in accordance with the damage type, the cause of damage, and the material of an affected structural element.

In case of bridges, damage indicators (DI) can be included in a database, in order to describe the health status of the assets and accounting for damage in performance assessment and maintenance strategies. These indicators can be qualitative or quantitative based, and they can be obtained during principal inspections, through a visual examination, a non-destructive test or a temporary or permanent monitoring system.

4 Performance indicators

Describing desired performance levels and determining how data is interpreted is as important as selecting the measure. It defines good and bad performance, and determines how the data is used. Performance is based on targets, the desired level of performance for a specific reporting period, and thresholds. Thresholds are upper and lower limits of desired performance around a target value. Thresholds create the exact points where an indicator displays within a condition assessment thresholds can be expressed in numerical format, in safety or reliability requirements but also in risk formats and should be assigned to performance indicators (PI).

For the quality control of bridges and structures, knowledge of the interaction between the observations and the PI is of highest relevance. The definition of this relationship therefore requires a deep understanding of the underlying damage processes, see Figure 2. The correlation of observable symptoms with potential damage processes may reveal what damages can be expected or what observation one might make in the future. Figure 3 summarizes most common drivers/damage processes and associated selected PI vs DI of bridges and distinguishes between Phase I: visual inspection, Phase II: detailed inspection, testing & monitoring, Phase III: structural health monitoring and modelling. This figure indicate which performance indicator is related to which damage processes and can be detected with the highest probability by means of visual inspection or by means of extended test and monitoring procedures.

4.1 Selection of Performance Indicators

In order to select the most important Performance Indicators the following steps should be followed: 1. Define crucial Performance Goals (for example: safety, serviceability, reliability, durability, availability, maintainability etc.) 2. Categorise Performance indicators in relation to Performance Goals (at different levels: component, system, network; taken into account different aspects: technical, sustainability, socio-economic), 3. Answer following questions: Is it measurable? Is it quantifiable? Is target value available? Is it valid for ranking purposes? Does it allow decision with economic implications?

4.2 Performance indicators at the component level

Inspections of structures are generally carried out at the level of components. For bridges, three main subsystems can be distinguished: (i) substructure, (ii) superstructure and (iii) road-/railway, with specific bridge components associated with these systems, including constitutive materials. For tunnel systems, a similar decomposition is possible, distinguishing e.g. ridge, callous, abutment and base area, or inner shell, outer shell and sealing level. At the component level, one of the important goals to be reached (or task to be performed) is the damage assessment. This implies the detection of damages but also the identification and evaluation of damage within the set thresholds. The categorisation of damage as a primary performance indicator at the component level, requires considering related detection methods, performance thresholds and evaluation methods.

4.3 Performance indicators at the system level

A qualitative assessment can show how the collapse of a particular element would affect the individual Structural Performance Requirements. Structural performance assessment at the system level will require an adequate knowledge level on particular PI and DI with related properties, such as e.g. stiffness changes traffic load characteristics, which may require investment in additional inspection, testing or monitoring method, advanced modelling techniques and model- and data-updating on resistance and loads. Besides technical indicators, at this level sustainability and socio-economic indicators will have an essential position within the set of the performance requirements. Additionally, indicators related to scientific achievements in, for example, testing and monitoring, dynamic behaviour and reliability of structures, should be elaborated at this level, as well.

4.4 Performance indicators at the network level

At the network level, based on bridge condition assessment gained through standard inspection and evaluation procedures with additional evaluation of bridge importance in the network, the primary goal to be reached is supporting the maintenance management and asset management decision process. Priority repair ranking, is an example [10] of the essential indicator for the final goal: optimal management plan of road-/railway bridges, which is to be evaluated through decision ranking by power and weakness of decisions. While the bridge structural performance assessment is based on four criteria: (i) structural safety, (ii) serviceability, (iii) durability, and (iv) robustness related to the (general) condition of the structure, the bridge importance in the network is based on five criteria: (i) road category, (ii) annual average daily traffic, (iii) detour distance, (iv) largest span, (v) total length. Such criteria are usually reduced to comparable values with the help of preference functions and with the help of adequate thresholds of indifference and preference for each criterion. Indicators for the key performance requirements are determined at this level.

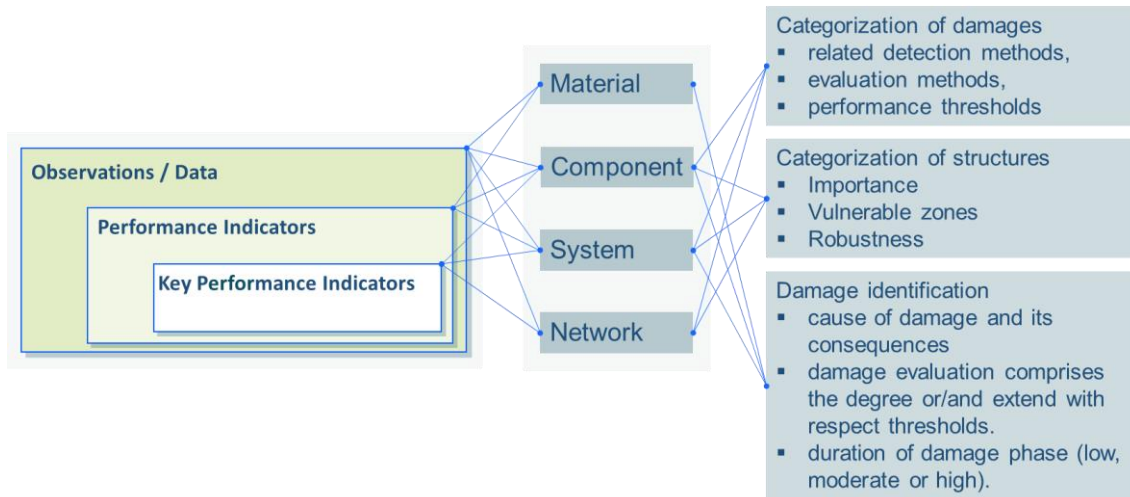


Figure 2 Performance indicators and levels of application

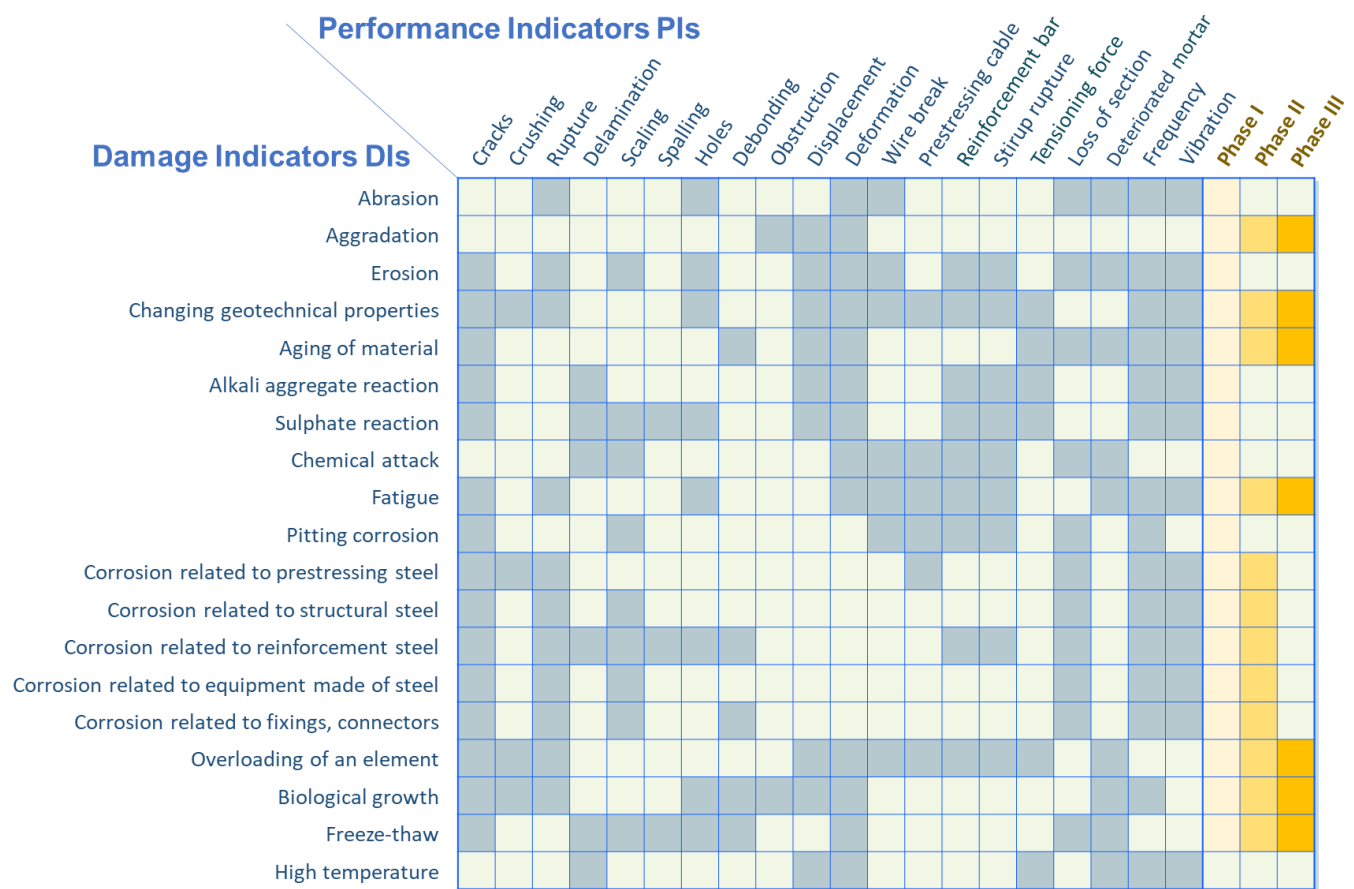


Figure 3 Common drivers/damage processes and selected performance vs damage indicators of bridges, distinguishing 3 Phases, Phase I: visual inspection, Phase II: detailed inspection, testing & monitoring, Phase III: structural health monitoring and modelling

5 Case study

Using a performance-based approach, a structure or a component of a structure is designed to perform in a required manner during its entire life cycle. Applying a performance-based approach on an existing structure or structural members it is possible to assess the actual performance or the performance during the residual life. Thereby it can be verified if the necessary demands of the involved stakeholders are met. The choice of performance requirements used in the design depends on the situation that is being modelled. The Case study presented here is examined for the so-called Seitenhafenbridge

B0245, located 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 approx. 130 m divided in 5 fields and the width 15 m. The locally limited support options and the requirement to comply with the low leveling resulted in a solution of statically resolved V-shaped pillars, which are based on the embankments between the Donaukanal. As a result, the individual spans could be minimized, which led to slim cross-section dimensions and a structurally light structure. The optimal support structure, meeting all

requirements, was developed as a pre-stressed reinforced concrete structure, elevated on inclined steel struts. Figure 4 shows a view of the Seitenhafenbridge.



Figure 4 View of the Seitenhafenbridge, Vienna Austria

The case study illustrates in which way performance requirements maybe verified, making use of the concept based on KPR implemented performance assessment method by using data based on PI and DI. In [10] can be gathered more information about the decision making process and quantitative limits applied with regard to maintenance management. The following points describe the assessment and decision-making process.

- The Seitenhafenbridge in Vienna is currently the longest integral bridge in Austria. Due to the total length of approx. 130 m, the client requested an in-depth performance analysis and risk assessment
- The client required monitoring of the movements of the structure.
- The consulting firm and the client (City of Vienna – Department of Bridge Construction & Foundation Engineering) defined performance and key indicators and their thresholds. (Level II: first order reliability method)
- The monitoring system continuously measures temperatures and movements of the structure, such as deflection, inclination, length change, and soil pressure at the abutment.
- 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: full probabilistic method)
- The digital twin models were updated and the functionality of the critical details was verified.
- Thresholds were set for the monitored performance indicators using the digital twin models.
- An alarm system was set up in combination with the monitoring system and the client
- Continuous monitoring and diagnostics is active since 12/2011, on all the 5 spans of the bridge, with a real-time alerting system active to support proactive maintenance interventions.

The design of the supporting structure was based on a synthesis of function, form and economy. The Seitenhafenbridge was designed as an integral bridge structure. Figure 5 shows drawings of two representative cross-sections [11].

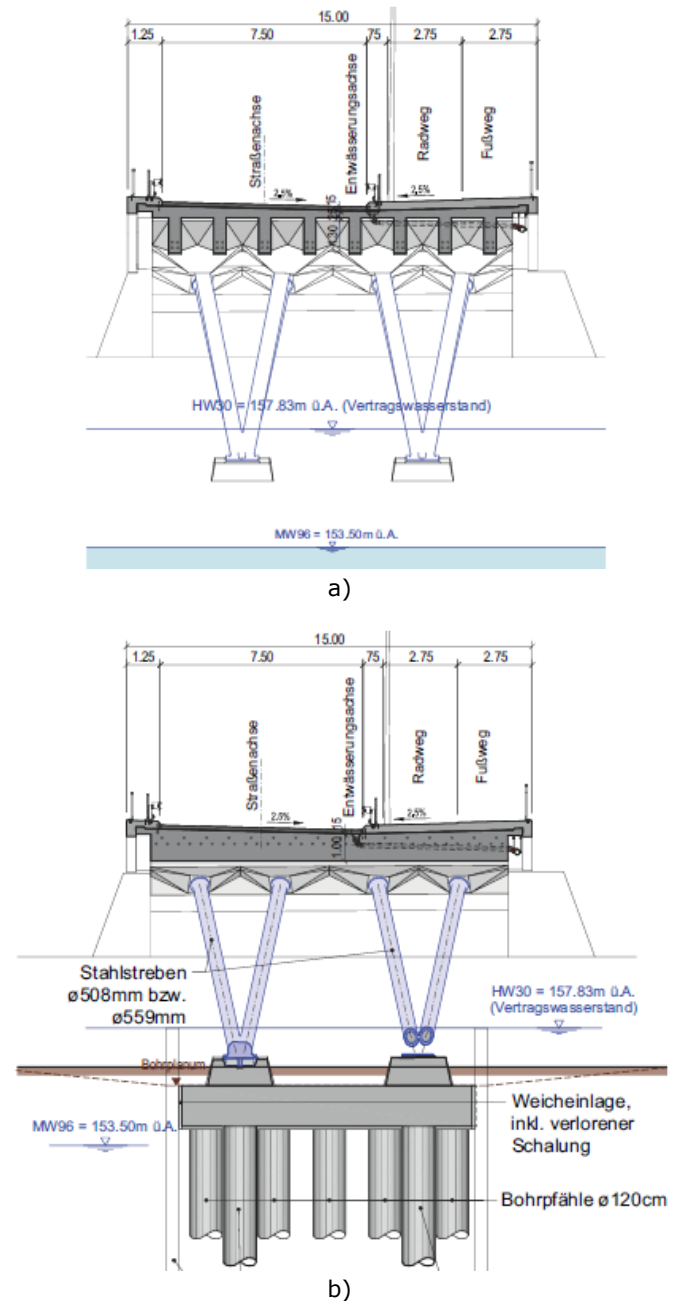


Figure 5 cross-section of the Seitenhafenbridge a) in the middle and b) close to the bank-area

To check the performance requirements, a monitoring systems were installed, see figure 6, to record the performance indicators such as the earth pressures, the horizontal and vertical deformations and the inclinations of the bridge components, for further details see [12].

The following performance requirements were defined for the assessment of the functionality of the special solution of the flexible abutment:

- no earth pressure may build up behind the abutments due to the bridge movements
- the deformation behaviour of the bridge must comply with the standardisation specifications
- the model deviations of the real behaviour from the bridge model formations must be less than 10%.

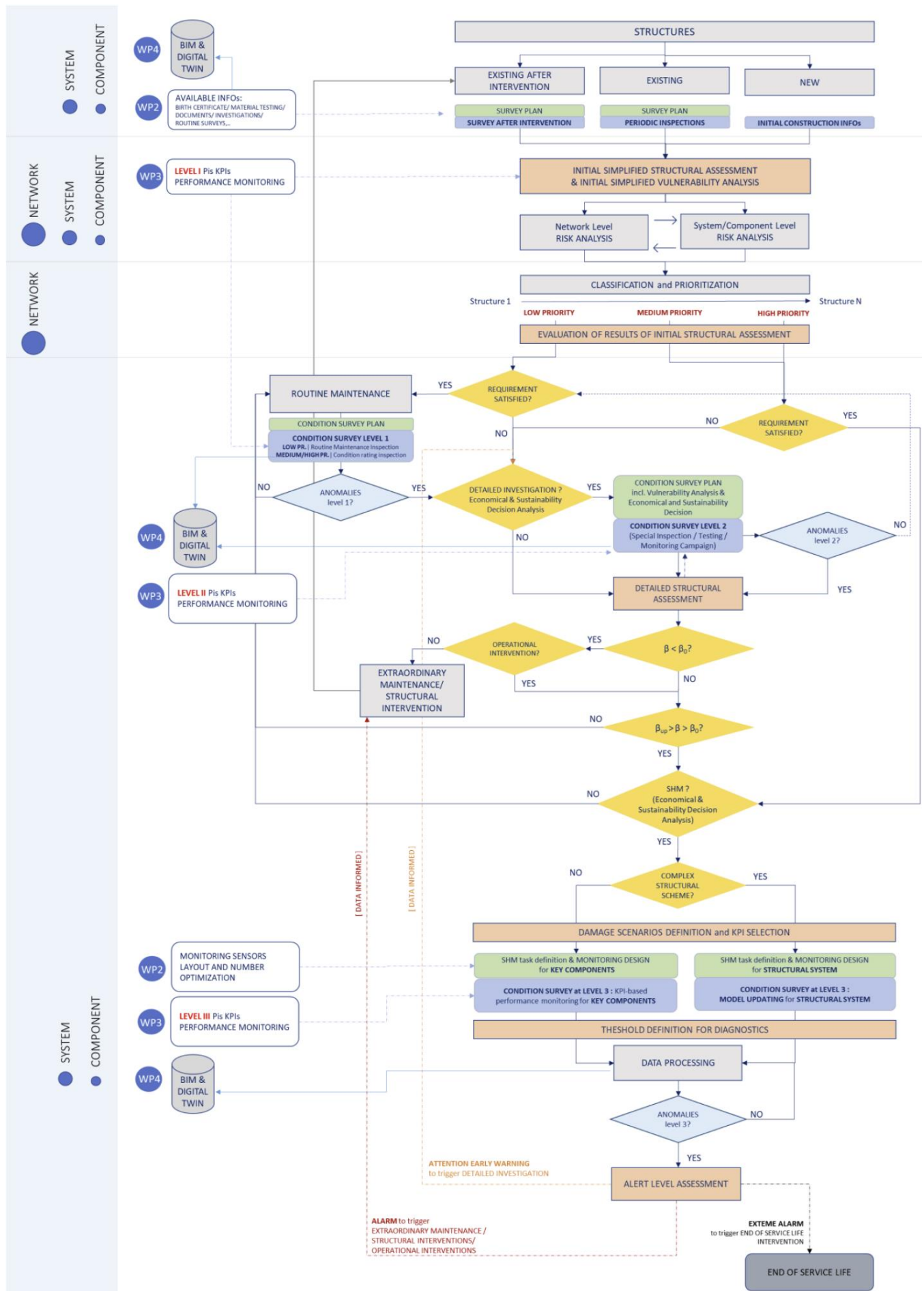


Figure 6 Performance indicators for an objective assessment and through-life management for the Seitenhafenbridge in Vienna, Austria

There was also a risk based assessment procedure set up for the through life management of the structural performance using the monitored performance indicators. Furthermore, a comparison of the "digital twin" model with the monitoring data measured over three years was carried out. This procedure also allows a data-driven performance assessment and life cycle evaluation for the investigated Seitenhafenbridge.

6 Summary

Identification and implementation of performance indicators can improve the state of the art assessment methods for engineering structures and in detail, as presented here, for bridge structures. Using infrastructure management systems which are able to incorporate deterioration processes, expressed as damage indicators, are able to determine future conditions through functional correlations between structure condition characteristics

Further it can be implemented in a transport infrastructure management system in order to capture deterioration processes. In this contribution it could be shown how to characterise and systematise performance indicators for bridge structures.

Systematised performance indicators for bridges were presented and in terms of a case study the updated assessment method was used to show how performance indicators in cooperation with damage indicators can be coupled with risk-based performance requirements, data-informed performance assessment methods and inspection and monitoring concepts.

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