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Performance indicators for an objective assessment and through-life management of bridges and tunnels

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ABSTRACT: The life cycle management process for new and existing concrete structures involves condition control which is the overall process 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. Management systems that capture deterioration processes are used in connection with analyses, however they are usually based on 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 or agents. With increasing experience with the use of surveying technologies for acquiring information related to the current condition of bridges and tunnels, 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 H2020 CSA IM-SAFE project aims to characterize and systematize performance indicators for bridge structures and tunnel systems. In the context of the use of monitoring systems for condition survey, the IM-SAFE project aims to provide background for the use of performance indicators for bridges and tunnels and to clarify how performance indicators are / should be linked to observations and implemented in performance and risk assessment, making use of performance and risk modeling, analysis and prediction methods. In this contribution, the systematized performance indicators for bridge and tunnel systems are be presented and case studies are used to show in which way performance indicators can be coupled with risk-based performance requirements, data-informed performance assessment methods and inspection and monitoring concepts.

INTRODUCTION

In general, performance can be defined as the efficiency of a system under consideration (the efficiency with regard to structural behavior is referred to as structural performance). In the Civil Engineering field, the concept of efficiency can be applied to structures at various schema levels, according to the assessment type and the scope of the analysis. For the infrastructure framework, the relevant levels can be described as:

- ***Network***: an aggregate of interconnected objects that collectively fulfil a *function*;
- ***Framework:*** a delimited group of interrelated, interdependent or interacting objects that is assessed for a potential risk. Each framework is part of a larger entity, making it actually a subframework. Where the boundaries of the framework are drawn will therefore be context-dependent.

Accordingly, a structural framework is an arrangement of interacting structural members offering a potential solution to provide bearing resistance to a specified combination of actions;

- ***Component***: individually identifiable part of an object consisting 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 of works designed to provide mechanical resistance and stability to the works and/or fire resistance, including aspects of durability and serviceability.

For all levels under consideration, the goals set for the asset management must be attained. When setting these goals, the multiple levels of objectives and multiple layers in posing requirements and creating constrains must be distinguished and adequately considered. As schematically shown in Figure 1, 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 at this level include e.g. mobility, climate adaptability, energy neutrality. These strategic objectives are governing when the primary requirements are set for the function of the infrastructure during its life cycle 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 referred to as the functional requirements and the non-functional requirements. Both categories of targets should be clearly specified in terms of aspect requirements.

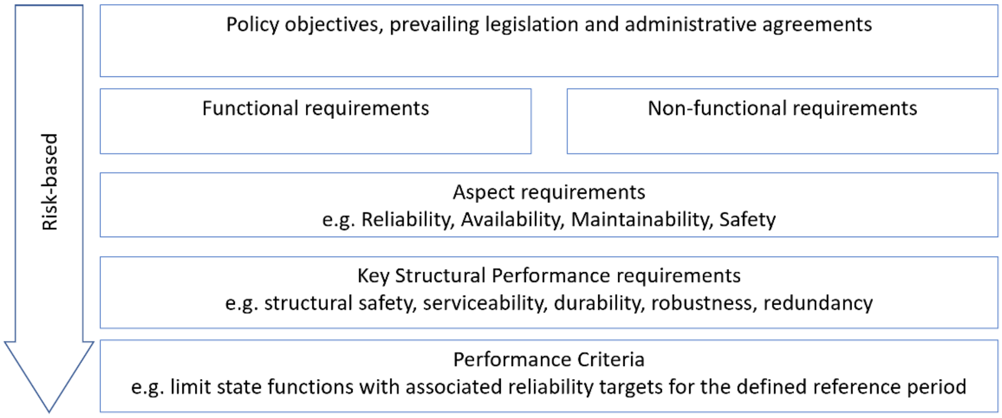

Figure 1: Multiple levels of objectives and multiple layers considered in identifying requirements for the infrastructure assets [4] IMSAFE D3.1

Aspect requirements considered for infrastructure usually include: reliability, availability, maintainability and safety (**RAMS**), sometimes extended by including security, health, environment, economics and politics (**RAMSSHE€P**) (for more information refer to e.g. [1-3]). The aspect requirements are established by means of the (Key) Performance Requirements, whereas the Key Performance Requirements (KPR) are the (main) requirements set for the primary functions or properties for all aspects considered, specified in terms of performance. Examples of KPRs 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. **Feil! Fant ikke referansekilden.** defines KPRs of RAMSSHE€P for both tunnels and bridges.

Table 1 Key performance requirements (KPRs) considered in management systems for both tunnels and bridges-. Adapted from: Dette and Sigrist (2011)[5]; Hajdin et al. (2018)[6], Strauss et. al.[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 Waste generation	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.

The Key Performance Requirements 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 behavior. 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 this contribution, the systematized performance indicators for bridge and tunnel systems are presented and case studies are used to show in which way performance indicators can be coupled with risk-based performance requirements, data-informed assessment methods and inspection and monitoring concepts.

STRUCTURAL PERFORMANCE REQUIREMENTS FOR BRIDGES AND TUNNELS

As described in (ISO_2394, 2015) [8], the performance of a structure relates to the structure as a whole or parts of it. In general, structures and structural members must be designed, constructed and maintained so that they perform adequately during their entire life cycle. According to (MC2010, 2013):[9] (a) they must remain fit for the use for which they have been designed; (b) they 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; (c) they must be able to contribute positively to the needs of humankind with regards to nature, society, economy and well-being. Keeping these objectives in mind, it is emphasized that sustainability perspective shall be the primary perspective when setting performance requirements for structures. Sustainability encompasses three requirements dimensions, which are defined as follows [10], [11] (a) Social requirements: referring to the accessibility and adaptability of infrastructures to society; (b) Environmental requirements: referring to resource use, waste generation and pollution, among many others; (c) Economic requirements: refers to life cycle cost and external costs. (d) The beforementioned classification of requirements into functional and non-functional. It is consistent with the concepts proposed for implementation in fib MC2020 [12], social requirements refer to both structural performance and other (non-structural) aspects of accessibility and adaptability of infrastructures (i.e. other aspects of structural performance).

The structural performance of an object or a component refer to the fulfilment of the essential demands of the stakeholders with regard the behaviour, or the condition as a consequence of actions during the intended lifetime of structures or structural elements, and in a sustainable way. The structural performance requirements are established by means of performance criteria with the associated performance indicators and constraints related to service life and reliability (e.g. reliability index, ratio between resistance capacity and action effect). The structural performance requirements describe the conditions for design, or for an actual, potential or intended options for intervention, aiming at meeting a specified performance criterion during the service life with appropriate reliability. Accordingly, the four categories of the structural performance that can be characterised by quantitative parameters are the following: (I) **serviceability**, that is the ability of a structure or structural members to perform, with appropriate levels of reliability, adequately for normal use under all (combinations of) actions expected during service life; (II) **structural safety**, that is the ability of a structure and its structural members to guarantee the overall stability, adequate deformability and ultimate bearing resistance, corresponding to the assumed actions (both extreme and/or frequently repeated actions and accidental and/or exceptional events) with appropriate levels of reliability for the specified reference periods. The structural safety must be analysed for all possible damage states and exposure events relevant to the design situation under consideration; (III) **durability**, that is the capability of a structure or any structural member to satisfy with planned maintenance the design performance requirements over a specified period of time under the influence of the environmental actions.; and (IV) **robustness**, that is the ability of a structure to withstand adverse and unforeseen events (like fire, explosion, impact) or consequences of human errors without being damaged to an extent disproportionate to the original cause. The structural performance is assessed by a set of activities to verify the reliability of an existing structure, allowing a prognosis to be made of current and future response, taking account of relevant deterioration mechanisms and, if appropriate, predictions of potential future damage (for more information see e.g.[13]. 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, keeping in mind that 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).

The following sections, therefore, show the concepts elaborated in IM-SAFE [4] project.

DAMAGE CLASSIFICATION PROCEDURES AND DAMAGE INDICATORS

When referring to damage in context of performance requirements and performance assessment it is necessary to make a clear distinction between the properties of damages, damage indicators and performance indicators. The development of a damage classification may be a crucial instrument for the assessment of new and existing bridges and tunnels, as well as for the evaluation of maintenance strategies.

Clustering and homogenization of the input data provided by inspection, testing and monitoring is indeed a great deal of effort for operators and infrastructure managers, which have to manage a huge amount of information in order to keep assets at a desired performance level. Hence, procedures for damage classification are needed, accounting for type, size and location of defects or other relevant issues depending on the type of structure, the actions on structure, and the risks that may potentially affect the structure in the future, such as the one following from changes in traffic loads or service life demand, and from resilience issues related to climate change and increased use. In case of bridges and tunnels, specific performance indicators (PIs) and damage indicators (DIs) can be included in 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. Accordingly, a damage classification procedure consists of the following steps:

1. **Damage detection**: damages affecting the structure under investigation are detected through inspection, testing and monitoring.
2. **Damage characterization**: Once damage has been detected, the following information is needed and must be inserted into the database. (a) **Level**: network / system / component level at which the damage is detected; (b) **Location**: identification of the elements of the structure on which damage is located; (c) **Type**: identification of the type of damage occurring on structures; (d) **Causes**: damage may be due to the overloading of the structure, to the aging of materials and to several damage processes. Damage causes are outlined in D2.1 [2.3.1] [13]; (e) **Quantification**: identification of the qualitative/quantitative parameters related to the detected damage; (f) **Extent**: characterization of the extent of damage, which is the basis for intervention and maintenance prioritization and planning.
3. **Information updating**: database information must be updated over time with additional information collected through inspection plan, maintenance interventions and monitoring systems.

Once the damage characterization has been completed, it is important to define the damage indicators and their relationship to the performance indicators. A Damage Indicator (DI) is defined as an observation, or a parameter derived from observations, that serves for quantitative or qualitative damage detection, localization and/or characterization. On the other hand, a Performance Indicator (PI) is defined as an observation, or a parameter derived from observations, that quantitatively describes property of the structure and/or of the aspect of its performance and serves to qualify fitness of the structure for its purpose during service life. While similar, the domains of DI and PI are vastly different: a DI simply addresses the severity of a single damage, while a PI tackles the asset. At the same time, the DIs and PIs are inter-related: while the appearance of a certain damage in a structure might be considered non-relevant in structural calculations in the case of minor damages, it may still affect the PIs. The relationship between DIs and PIs is further tackled in a generalized manner, and in a top-down approach, whereby the first step is to define a hierarchical structure that represents the relation between the different PIs and the DIs. For more detail reference is made to [D2.1 & D3.1] [4], [13].

Once the structure that defines which DIs influences which PIs is set, the final step is to quantify said influence. For instance, an analytic hierarchy process can be used to quantify the importance of a certain set of DIs in a given PI (EUROSTRUCT, 2017) [14]. Both the relations between DIs and PIs and the quantification of the influence are to be evaluated in detail for a specific case, as the context and resources of each project are different from one another. The basic principles presented in these sections and elaborated in the IM-SAFE project served to define the PIs for bridges and tunnels presented in the following section.

PERFORMANCE INDICATORS

As discussed before, for the quality control of bridges and tunnel structures, knowledge of the interaction between the damage-related measurable observations and the PIs is of highest relevance. The definition of these relationships requires a deep understanding of the underlying damage processes.

Table 2 Common Drivers/Damage Processes and selected Performance Indicators of Bridges

	Observations / Performance Indicator **Damage Process**	Cracks	Crushing	Rupture	Delamination	Scaling	Spalling	Holes	Debonding	Obstruction/impending	Displacement	Deformation	Wire break	Prestressing cable	Reinforcement bar failure/bending	Stirrup rupture	Tensioning force deficiency	Loss of section	Deteriorated mortar joints	Frequency	Vibrations/oscillations
1	Abrasion			O				O				O	O					O	O	O	O
2	Aggradation (alluviation)									O	O	O									
3	Erosion	O		O		O		O			O	O	O		O	O		O	O	O	O
4	Changing geotechnical properties	O	O	O				O			O	O	O	O	O	O	O			O	O
5	Aging of material	O							O		O	O					O	O	O	O	O
6	Alkali aggregate reaction (alkali-silica reaction)	O			O						O	O			O	O	O			O	O
7	Sulphate reaction	O			O	O	O	O			O	O			O	O	O			O	O
8	Chemical attack				O	O						O	O	O	O	O		O	O		
9	Fatigue	O		O				O				O	O	O	O	O			O	O	O
10	Pitt ing corrosion	O				O							O	O	O	O		O		O	
11	Corrosion related to prestressing steel	O	O	O										O				O		O	O
12	Corrosion related to structural steel	O		O		O												O		O	O
13	Corrosion related toreinforcement steel	O		O	O	O	O	O	O						O	O		O		O	O
14	Corrosion related to equipment made of steel	O		O		O												O		O	O
15	Corrosion related to fixings, connectors	O		O		O			O									O		O	O
16	Overloading of an element	O	O	O							O	O	O	O	O	O	O		O		
17	Biological growth	O	O	O				O	O	O	O	O							O	O	
18	Freeze-thaw	O			O	O	O	O	O			O						O	O		
19	High temperature				O						O	O					O		O	O	O

Visual Inspection, O; Visual inspection & testing and monitoring, D

Table 3 Drivers/Damage Processes and selected Performance Indicators of Tunnels (Part I)

ID associated with Table 5-5	**Performance Indicator** / **Damage Process**	Cracks	Crushing	Rupture	Delamination	Scaling	Spalling	Holes	Debonding	Obstruction/impending	Displacement	Deformation	Wire break	Prestressing cable	Reinforcement bar failure/bending	Stirrup rupture	Tensioning force deficiency	Loss of section	Deteriorated mortar joints	Frequency	Vibrations/oscillations	ULS(U)	Functionality/operational safety(F)
1	Continuous vertical rock movement	o	o	o																		5	7
1	Bending stress	o	o	o																		5	7
2	Local rock movement (punching)	o	o	o							o	o										9	10
3	Higher horizontal actions (underestimation of lateral action)	o	o	o											D			D				9	5
3	Missing reinforcement	o	o	o											D			D				9	5
4	Deformation due to shrinkage, temperature within the shell-blocks	o									o	o										4	4
4	Missing reinforcement	o									o	o										4	4
5	Corrosion of reinforcement	o					o		o						o							6	2
5	debonding	o					o		o						o							6	2
5	Partial spalling of concrete cover	o					o		o						o							6	2
6	Different casting times	o									o	o										4	2
6	Different concrete qualities	o			o						o	o										4	2
6	Delaminations of concrete layers (e.g. spreaded concrete)	o			o						o	o										4	2
7	Overloading (rock movement) of prestressing	o	o	o						o	o											9	10
7	Anchor failure	o	o	o						o	o											9	10
7	Impact due to an accident			o						o	o											9	10
8	Deformation of the ground			o						o	o											6	4
8	Water impact			o						o	o											6	4

Visual Inspection, O; Visual inspection & testing and monitoring, D

The correlation of observable symptoms with potential damage processes may reveal which damages can be expected or which observation one might make in the future. Table 2 and Tables 3-4 summarize the most common drivers/damage processes and selected associated PIs for bridges and tunnels, respectively. These tables 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.

Table 4 Drivers/Damage Processes and selected Performance Indicators of Tunnels (Part II)

ID associated with Table 5-5	**Performance Indicator** / **Damage Process**	Cracks	Crushing	Rupture	Delamination	Scaling	Spalling	Holes	Debonding	Obstruction/impending	Displacement	Deformation	Wire break	Prestressing cable	Reinforcement bar failure/bending	Stirrup rupture	Tensioning force deficiency	Loss of section	Deteriorated mortar joints	Frequency	Vibrations/oscillations	ULS(U)	Functionality/operational safety(F)
8	Soil liquefaction			o						o	o											6	4
9	Thermal reaction	o			o			o	o	o												3	2
9	Lack of concrete curing	o			o			o	o	o												3	2
9	Plastic shrinkage	o			o			o	o	o												3	2
10	Different (partial) shrinkage between layers of concrete	o			o			o	o	o												3	2
11	Higher freeze-thaw cycles (exposure class)	o			o			o	o	o												3	5
11	Insufficient concrete quality	o			o			o	o	o												3	5
11	Freeze-thaw cycles in the first 100 m of a tunnel	o			o			o	o	o												3	5
12	Electrochemical reaction lowers the alkalinity, rebar corrosion														o							3	4
13	Chemical (salt) attack														o							3	5
13	Rebar corrosion (chloride penetration distributed)														o							3	5
14	Lack in the drainage system																					2	4
14	Lack in the waterproofing system																					2	4
15	Lime efflorescence																					1	2
16	Low quality curing		o	o								o										3	3
16	Settlement of the fresh concrete		o	o								o										3	3
17	vibration														o							7	6
17	accident														o							7	6
17	Construction error														o							7	6
17	Lack of anchorage protection														o							7	6

Visual Inspection, O; Visual inspection & testing and monitoring, D

In Tables 3 and 4, in the last two columns the influence of the damage on the load-bearing capacity and on the functionality / operability of the tunnel is additionally assessed, rating high level of influence at 10 and rating no influence at 0. The procedure of selecting the most important PIs is discussed in [D3.14]. When assigning performance indicators to damage processes, the above-mentioned relationships to the damage indicators must be considered, as well as the different levels to which the performance indicators must be assigned.

Performance indicators at the component level

Inspections of structures are generally carried out at the level of components. For bridges, three main subsystems can de distinguished: substructure, superstructure and 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.

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 PIs 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 updating data 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.

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 [15] 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 or tunnel structural performance assessment is based on four criteria: structural safety, serviceability, durability, and robustness related to the (general) condition of the structure, the bridge importance in the network is based on five criteria: road category, annual average daily traffic, detour distance, largest span, total length. Such criteria are usually reduced to comparable values with the help of preference functions and with the help of an adequate thresholds of indifference and preference for each criterion. Indicators for the key performance requirements are determined at this level.

CASE STUDY SEITENHAFENBRIDGE

Using a performance-based approach, a structure or a structural component is designed to perform in a required manner during its entire life cycle. In the case of existing structures, by using a performance-based approach we can assess whether the actual performance of an existing structure or structural members and their performance during the residual life satisfies the demands of the stakeholders. The choice of performance requirements used in the design depends on the situation that is being modelled. Case study of Seitenhafenbridge illustrates in which way performance requirements may been verified, making use of the concept based on performance indicators implemented in data-informed performance assessment method. For more information about the decision making process and quantitative limits applied with regard to maintenance management, reference is made to [16, 17]. 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. In the following nine points the assessment and decision-making process is describing.

1) The Seitenhafenbridge 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.

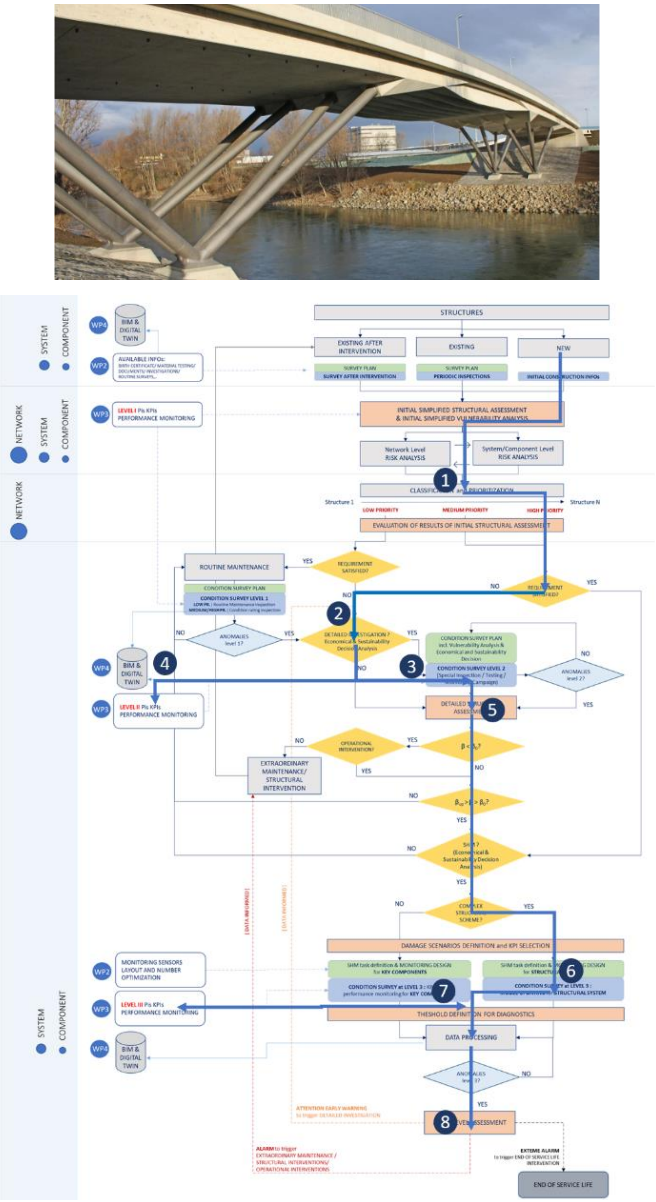

Figure 2: Performance indicators for an objective assessment and through-life management of the integral bridge structure "Seitenhafenbrücke" in Vienna, Austria

In the planning and production process of the "Seitenhafen Bridge" integral bridge structure, the following performance requirements were defined for the assessment of the functionality of the special solution of the flexible abutment: (a) no earth pressure may build up behind the abutments due to the bridge movements, (b) the deformation behaviour of the bridge must comply with the standardisation specifications, and (c) the model deviations of the real behaviour from the bridge model formations must be less than 10%. To check the performance requirements, the monitoring systems mentioned in Figure 2 were installed to record the performance indicators such as the earth pressures, the horizontal and vertical deformations and the inclinations of the bridge components, there was also a risk based assessment procedure set up for the through life management of the structural performance using the monitored performance indicators [17]. 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 of the bridge structure.

SUMMARY

Identification and implementation of performance indicators can improve existing assessment methods within the transport infrastructure management system. In this contribution it could be shown how to characterise and systematise performance indicators for bridge structures and tunnel systems. Systematised performance indicators for bridge and tunnel systems were presented and a case study was used to show how performance indicators can be coupled with risk-based performance requirements, data-informed performance assessment methods and inspection and monitoring concepts.

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