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Rasmus Rempling, Carlos Gil Berrocal, Ignasi Fernandez

Chalmers University of Technology, Gothenburg, Sweden

Mats Karlsson

Chalmers University of Technology, Gothenburg, Sweden

Swedish Transport Administration, Solna, Sweden

Contact: rasmus.rempling@chalmers.se

Abstract

In recent years, significant worldwide research has been conducted regarding the performance assessment of bridges and the concept of performance indicator has been introduced However, there are still significant discrepancies in how these indicators are obtained and used.

Simultaneously, it is desirable to achieve processes and methods that are direct, i.e. that measured values are directly compared with projected values over time.

This project concerns methods for verification of technical performance requirements.

The feasibility study brought together interdisciplinary researchers, consultants, and entrepreneurs to gather knowledge, anchor the research agenda, and implement performance requirements.

The project concludes that there is a need for a “Holistic multi-parameter verification/validation system” that relies on the knowledge gained in structural health monitoring research.

Keywords: Structural Health Monitoring, Performance requirement, Bridges, Structural design, Structural Performance.

1 Introduction

Degradation and deterioration of transport infrastructure is a significant challenge for society. According to information reported by the OECD (OECD 2017), Sweden invested almost EUR 2094 million in 2015 (Figure 1) to maintain the current transport network. In addition, the current trend shows that the cost of preserving transport infrastructure has increased steadily over the last two decades. In 2017, the Swedish Government increased the investments to maintain the current infrastructure to EUR 4000 million. The increased investment is a change of trend that will persist, [1].

In recent years, significant worldwide research has been conducted regarding the condition assessment of bridges [2], [3]. The research has focused on non-destructive testing, monitoring systems and visual inspection methods. The measured values provide indirect information about the assessed state of the bridge condition; by counting backwards with advanced models and finite element analyses, indirect results are compared with projected values. Recently, the concept of performance indicator has been introduced, which simplifies communication between consultants, managers and owners. However, there are still significant deviations in how these indicators are obtained, and therefore the sector should take specific measures to standardize this procedure. At the same time, it is desirable to achieve a direct methodology, i.e. that measured values are directly compared with projected values over time. However, this requires a new approach to measurement methods, parameters, and bridge engineering.

1.1 Performance requirements

In this study, we have chosen the following definition of a performance requirement based system " A system that fulfils certain functions under specific and defined conditions". As such a system, in this case, a transport system, can fulfil functions on different levels it was essential to narrow the scope and focus on one of the possible levels:

- Level 1 – Requirements based on capacity and accessibility.
- Level 2 – Requirements based on structural properties of the transport infrastructure and/or structural part.
- Level 3 – Requirements based on structural properties of the structural component and/or section.

In this study, as point-of-departure, we have used "Level 2 - Requirements based on structural properties of the transport infrastructure and/or structural part" as we believe that introducing performance requirements on this level will have a long-term effect on sustainability and cost-efficiency of the transport infrastructure [2].

In Sweden, requirements in the form of performance requirements already exists in design assignments and contracts. However, there is a gap to fill in order to expand the scope and type of performance requirements for procurement of the project delivery.

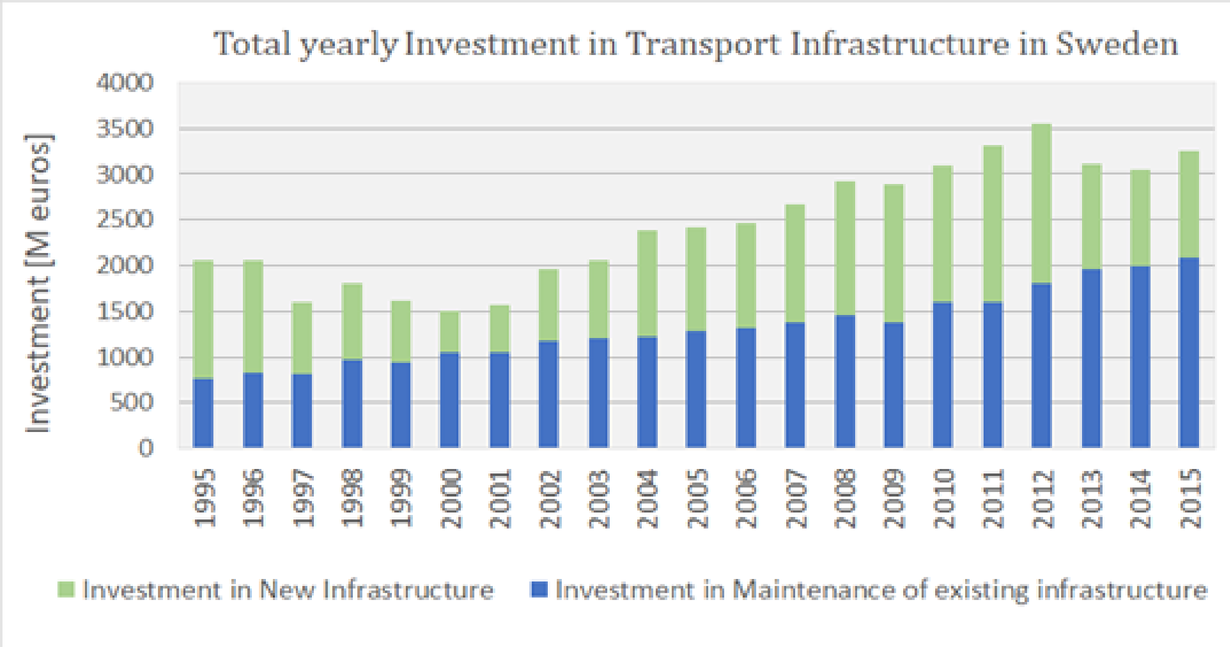

Figure 1. Investment in new infrastructure and maintenance of existing infrastructure in Sweden between 1995 and 2015 [4].

2 Purpose and aim

The overall purpose was to investigate the research base and the scope of the subject area and shed light on the area's complexity as well as short- and long-term effects. The specific goal includes defining, planning, organizing, and anchoring a research agenda with academia, industry, and authority. The target of the research agenda is that a future method should facilitate and transparently steer the definition of performance requirements and make it possible to estimate and monitor the condition state of transport infrastructures which in turn can reach better cost efficiency and sustainability.

3 Method

The research applied an abductive approach. Data was collected with two methods to gain insight in performance requirements, its implications and potentials:

- Literature and document study; and
- Focus group workshops.

For the literature study, knowledge was gathered concerning performance requirements, as well as enabling technologies relevant for an implementation and further development of requirements for the bridge construction industry.

Two workshops were organised. The workshops addressed the potential areas of research and implications of implementation, short- and long-term complexities that can be foreseen, as well as prioritised aspects to research. The workshops were inspired by the future workshop process of [5], in which the workshop groups follow the process of:

- identify challenges and barriers;
- discuss visions and opportunities; and
- visualising an action plan for implementation.

For the workshops, participants were selected based on their industrial expertise with bridge design, construction and maintenance; with the focus on creating a common picture of performance requirements in the Swedish bridge engineering industry.

4 Results

4.1 Proposed process for verification of performance requirements

In the analysis of the workshop results, a concept crystallized of how "Level 2 - Performance requirements" (see Section 1.1) can be described, followed up, and managed.

The concept includes three iterative steps that satisfy and fulfil the function by maintaining performance without sacrificing accessibility. The three steps are:

- Performance estimation – system design and planning;
- performance assessment - testing; and
- performance corrective actions.

In design, a forecast is made of a performance parameter where changes over the life of the building are projected. Next, the projected parameter is followed up with a system test with a snapshot or continuous parameters measurement. Finally, an assessment is made as to whether there is a reason for action outside the planned measures. In the case of an implemented measure, step three, an update is made of the forecast for selected performance requirements, and a new performance cycle is initiated, see Figure 2.

4.2 Performance estimation – system design and planning

Bridge management includes several activities that mean that the facility's value is maintained, which implies optimization regarding costs, risks, opportunities, and performance targets. Performance requirements can be seen as a system being maintained by forecasting the structure’s condition over time by breaking up the system into sub-components and following the development of each component's ability during its lifetime, which implies that different types of projected performance and availability indicators must be achieved at system and component level, as part of its maintenance strategy, see [2].

The performance indicator can be defined as a general indicator of a bridge's characteristic ability to fulfil the desired function. The indicator can be expressed in the form of a dimensional parameter or as a dimensionless index. The former is a measurable/testable parameter that quantitatively describes a specific performance aspect (e.g. crack width). The second is a qualitative representation of the performance aspect (e.g. the importance of a bridge component in the entire bridge structure).

Although the interaction between different performance indicators is inevitable, their categorization into technical, sustainable, and socio-economic indicators by component and system is essential for the design. Forecasting using artificial intelligence, where the forecast is calculated directly from measured values, is of extra great interest.

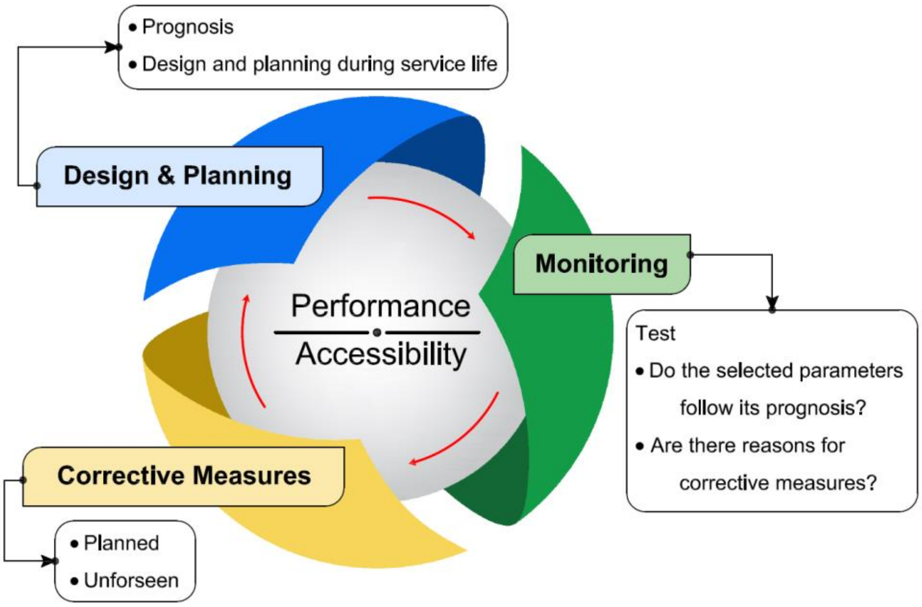

Figure 2. The proposed concept includes three iterative steps that satisfy and fulfil the function by maintaining performance without sacrificing accessibility. The three steps are: Performance estimation – system design and planning; performance assessment - testing; and performance corrective actions.

4.3 Performance assessment - testing

In the proposed process, the designed system´s performance is assessed. In the following bullets the main results from the workshops are summarized:

- The purpose of monitoring is to ensure both the reliability and availability of structural components and entire systems. The results of the tests are transferred to a general and objectified evaluation system where all constituent components are included. The most important parts of the evaluation system are the assessment of any deterioration in functionality and decisions on necessary measures, as well as "redesign" with conventional and artificial intelligence (AI) methods.

- Monitoring of structures shall be of a non-destructive type and based on measurement data. They should as far as possible be continuous but can also be applied manually or mathematically at defined intervals. The collected measurement data can describe the load side but should as far as possible represent the resistance side. Depending on the measurement task, different physical values can be collected at different intervals.

- Monitoring measures cannot replace detailed inspection. Instead, monitoring should complement ocular inspections when there is a need for taking measures but will be a heavy basis for decision-making.

4.4 Design of performance-corrective measures – Re-design

In the event of errors or deficiencies, special inspections and further tests or deeper analyzes/investigations must be performed. They are carried out to assess whether measured defects affect the usability of the structure or not and whether there is action.

The action can be part of a maintenance plan or unplanned interventions. However, the proposed process, and the use of measurement to base decision, should lead to a predictive maintenance.

5 Discussion

5.1 Challenges and barriers

Requirements in the form of performance requirements already occur today in design assignments and contracts. The participants raised the importance to address the conditions and possibilities for expanding the scope to include performance requirements for procurement and project delivery. This also led to a discussion of the responsibilities of the involved roles.

The responsibilities between the client and the consultant/contractor do not change, which implies that the current client-consultant and client-contractor standard agreements (in Sweden knowns as AB, ABT and ABK) are still relevant with minor exceptions. The same situation also applies to other standard agreements such as FIDIC and others. However, the delivery interfaces will vary depending on how the performance requirements are designed and how the verification occurs. Thereby, the status of the structure should be assessed at delivery and a birth certificate issued.

These above conclusions lead to the following proposed research areas:

- Project delivery;
- definition of the asset's initial status – birth certificate; and
- responsibility at instances of non-performing assets.

Inadequate performance compliance is regulated in the same way as today. Therefore, the current standard agreements are applicable in this case as well. On the other hand, forecasting (design) and verification of set performance requirements can be more extensive and, in some cases, more difficult to evaluate than the current design limit value and criteria.

5.2 Opportunities

To utilize performance requirements, the delivery interface "Technical platform" is an advantage or, more precisely, a prerequisite. The reason for this is that if performance requirements are set at "platform level", it gives the supplier the freedom to choose a technical solution within the platform's framework. Based on the above, the following research areas surfaced:

- Level of standardization, i.e. structure or component. Compared to the manufacturing industry, a technical platform is usually built on three main levels — a framework for the platform's performance regarding the products, modularization, and standardization of components.
- Given the organizational structure of the construction industry and the various stages, the issue of "ownership" of the platform is an important aspect to address.

Regarding the organizational placement of a "technical platform", the following alternatives emerged.

<u>The client as platform owner.</u> Considered inappropriate because it becomes too general, almost to be considered an industry practice. As a result, much of the innovation effect and business drive would disappear.

<u>The consultant as platform owner.</u> This is an utterly possible alternative. But it requires developing business models between consultant and contractor to achieve an effect. Long-term and strategic business relationships between primarily a consulting contractor are essential to investigate.

<u>The contractor as platform owner.</u> This is based on the same assumption and approach as consultants as owners, i.e. business models and business relationships. An advantage of this alternative is the close and natural coordination with "production". A first approach suggests that this alternative may be the first step in further development, but the question should remain open.

In addition to developing business models, it is crucial to describe what incentives there are for each party, client/consultant/contractor to contribute to implementing this approach and its methodology.

5.3 Need for a "Holistic multi-parameter verification/validation system"

A conceptual system architecture of a "Holistic multi-parameter verification and validation system" would in the digital transformation era that the industry is facing rely on digital working methods and techniques such as fiber-optics, artificial intelligence in the aspect of machine-learning and deep-learning, but also autonomy systems that can automate tasks. In Figure 3, an overview of a concept is presented. The system includes three pillars: Pillar 1 – Assessment, Pillar 2 – Predictions and Pillar 3 – Augmented Reality, and a data-retrieval based on deployed sensors such as fibre-optics and its related data-analysis.

Pillar 1 assesses the structural performance utilizing finite-element analysis enhanced by the collected structural data and uses AI to make statistical interpretations of the structural performance [3].

Pillar 2, opposite to Pillar 1, use AI to predict remaining service-life which require a deeper understanding of how to train prediction-models that enable real-time and reliable predictions of the condition state; an example of such a model is given in [6].

Pillar 3 relates to data reporting and the tools that make the condition of state accessible and available to the end-user [3].

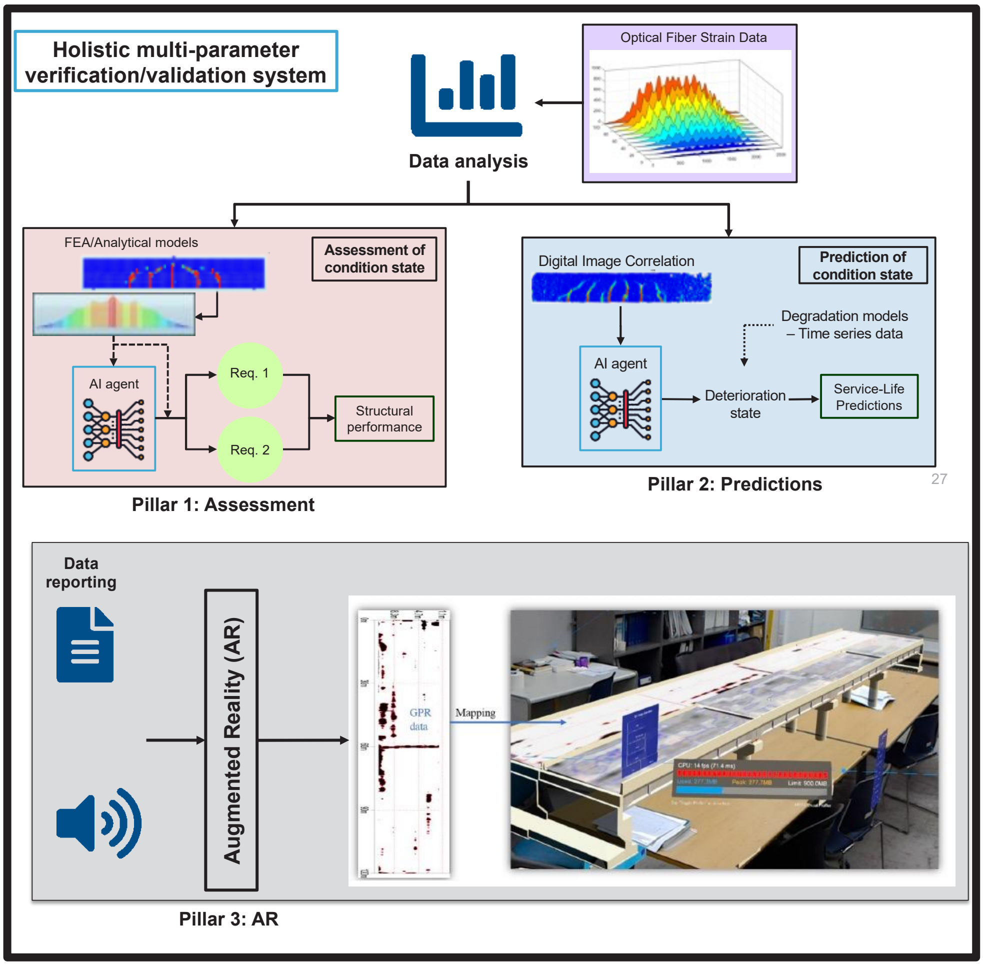

Figure 3. A proposal for a conceptual system architecture consisting of three pillars: Pillar 1 – Assessment, Pillar 2 – Predictions and Pillar 3 – Augmented Reality

6 Conclusions - Action plan and need for research

In the last part of the workshop series - visualising an action plan for implementation – the following main questions concluded the study:

1. Who should be responsible for the verification and validation?
2. Who is the potential owner of data?
3. Is there a need for a holistic multi-parameter verification/validation system?

6.1 Who should be responsible for the verification and validation?

Regarding the first questions there was a common conclusion that the verification chain must work in the management of assets, which implies that all actors are responsible for verification and validation. However, third-party certification may be required to obtain acceptance from the customer. The aspect "Who should follow up the function?" connects to "Who owns data?" and is important to understand.

Overall, the need for the competence of all actors to analyze and understand this type of information is increasing. The investments needed may, in turn, affect the business model of today. There is a certain amount of uncertainty about how a business model can be a driving force for creating space for investments in expertise in the area. Competence needs related to verification and validation include:

- Data-informed structural design and assessment
- Programming and Data security
- Digital business models
- Mathematical sciences with a focus on statistical analysis

6.2 Who is the potential owner of data?

Regarding the ownership of the data, it was seen as key-issue to be solved. Both ownership and data security are considered as a significant challenge, as access to information on the performance of construction works is crucial for the development and further development of concepts and platforms (building components or entire construction works). Data ownership includes:

- Accessibility (from sector)
- Data management and consistency
- Data timeframe (production - warranty stages – life cycle)
- Data security

6.3 Is there a need for a holistic multi-parameter verification/validation system?

Yes.

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