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Toward a Digital Twin Framework for Railway Bridge Maintenance: Indicators, Predictive modelling and Risk–Reliability Considerations

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Railway infrastructures are critical infrastructure whose condition evolves over time due to traffic, material degradation and environmental effects, affecting reliability, safety and service availability. Effective maintenance management relies on performance indicators and predictive models to support decision-making under uncertainty. This paper outlines the initial steps toward the creation of a Digital Twin framework for railway infrastructures maintenance. It focuses on the input data and the procedures needed to process and update them, which are then used to generate prediction scenarios. These scenarios enable the evaluation of potential consequences and support risk- and reliability-based prioritization of maintenance strategies.
Conceptual considerations of cost and RAMS are included, highlighting their relevance for infrastructure management. This paper presents a foundation for integrating performance indicators, monitoring data and scenario-based analysis into a Digital Twin, providing support for forward-looking and evidence-based maintenance decisions for railway bridges.

Keywords: Roadway bridges; Railway bridges; Performance indicators; Maintenance management; Risk-based prioritization; Reliability; Digitalization.

1. Introduction

Railway infrastructures are subject to continuous deterioration due to traffic loads, environmental exposure and ageing processes (Morais et al. 2021a). Maintaining the required levels of reliability, safety and availability therefore requires regular condition assessment and appropriate maintenance interventions. However, maintenance decisions are often made under uncertainty and must consider technical, operational and economic constraints.

The management of railway infrastructure increasingly relies on information obtained from inspections, monitoring systems, measurements, maintenance records and operational databases (Morais et al. 2021a; Morais et al. 2021b). Although large amounts of information are available, using data from different sources in a consistent manner to support maintenance decisions remains a significant challenge (Morais et al. 2021b; Morais et al. 2026). Data are often heterogeneous, collected at different times and frequencies, and not systematically integrated into maintenance management processes.

To support maintenance decision-making, collected data must be transformed into information that can describe infrastructure condition, identify degradation trends and estimate future performance. Performance Indicators and predictive models can contribute to this process by providing a structured representation of infrastructure performance and its expected evolution over time (Morais et al. 2021a; Morais et al. 2021b). However, maintenance decisions also require the evaluation of alternative maintenance actions and their potential consequences.

In recent years, Digital Twin concepts have received increasing attention in infrastructure management. Their potential value is frequently associated with the integration of data, models and information from multiple sources within a common environment (Tchana et al. 2019). However, for maintenance applications, the relevance of a Digital Twin depends not only on its ability to collect and update information but also on its ability to support maintenance assessment, prioritization and planning.

This paper presents the initial steps toward a Digital Twin framework for railway bridge maintenance. The objective is not to present a fully implemented Digital Twin, but rather to propose a framework that links performance assessment, predictive modelling, scenario analysis, risk, RAMS and maintenance decision support. The proposed framework aims to establish a structured information flow from data acquisition to maintenance decision-making by linking performance assessment, predictive modelling, scenario analysis, maintenance prioritization and decision support.

2. Railway Bridge Performance Assessment

2.1. *Input Data and Performance Indicators*

The assessment of railway bridge condition requires information describing the current state of the asset and the factors influencing its performance over time. Such data may be obtained from inspections, monitoring systems, measurements, tests, maintenance records and operational databases (Morais et al. 2021a; Morais et al. 2026).

However, maintenance decisions are not based directly on individual observations or measurements. The collected data must first be processed into information that supports performance assessment and maintenance management. For this purpose, Performance Indicators (PIs) can be used to represent relevant aspects of bridge performance (Morais et al. 2021a; Morais et al. 2026).

Depending on the available data and on the aspects of infrastructure performance being assessed, PIs may be defined for bridge components, operational conditions, environmental effects, costs, reliability, safety or other relevant characteristics of the infrastructure (Morais et al. 2021a; Morais et al. 2021b; Morais et al. 2026).

By providing a consistent representation of infrastructure performance, PIs support the assessment of current performance, the identification of degradation trends and the comparison of maintenance needs between assets.

2.2. *Predictive Modelling*

While PIs describe the current infrastructure performance, predictive models can be used to estimate their evolution over time. Such models may use inspection results, monitoring information, maintenance records and other relevant data to support the assessment of future bridge performance (Morais et al. 2021a).

Depending on the available data and on the intended use of the predictions, different modelling approaches may be adopted, including statistical, probabilistic, stochastic or data-driven models. The resulting forecasts may support the identification of future maintenance needs and the evaluation of alternative maintenance actions (Morais et al. 2021a).

3. Conceptual Digital Twin Framework for Railway Bridge Maintenance

3.1 *Scenario Analysis*

Different maintenance actions and future operating conditions may lead to different bridge performance levels, costs and operational consequences. For this reason, alternative scenarios can be evaluated before implementation to support maintenance planning and decision-making.

Scenarios may represent, for example, no intervention, preventive maintenance, delayed intervention or alternative maintenance strategies. They may also consider changes in operational or environmental conditions, such as variations in traffic loads, operating conditions or other factors that may influence infrastructure performance.

The objective is to compare the consequences associated with these alternatives and support maintenance prioritization (Morais et al. 2026).

3.2 *Risk, Reliability and RAMS Considerations*

Assets presenting similar condition states may have different operational importance, exposure levels or consequences of failure and therefore different maintenance priorities (Morais et al. 2021b).

Risk and RAMS-related information can support the evaluation of these consequences. Together with performance assessment results, these elements contribute to maintenance prioritization by incorporating aspects related to reliability, availability, maintainability, safety and the potential impacts of bridge degradation (EN 50126-1; EN 13306).

Cost information may also be incorporated into the assessment process. This allows technical, operational and economic consequences to be considered together when comparing alternative maintenance actions and defining maintenance priorities (Morais et al. 2021a; Morais et al. 2026).

3.3 *Maintenance Decision Support*

The proposed framework is intended to support maintenance decisions regarding where and when interventions should be performed and which maintenance actions should be prioritised.

For this purpose, information related to bridge performance, predicted evolution, scenario consequences, risk, RAMS and costs can be considered together within the maintenance assessment process. This provides a structured basis for comparing assets and supporting maintenance prioritization.

Such an approach may be particularly relevant when resources are limited and multiple maintenance needs coexist. In these situations, the framework can support a more informed evaluation of maintenance alternatives and intervention priorities (Morais et al. 2026).

3.4 *Framework Integration and Updating*

Within the proposed framework, the Digital Twin is considered as the environment where information related to performance assessment, predictive modelling, scenario analysis and maintenance decision support can be integrated and updated over time (Tchana et al. 2019). Inspection results, monitoring information and maintenance records may be incorporated as they become available, allowing assessments, predictions and maintenance priorities to reflect the most recent knowledge regarding infrastructure performance (Morais et al. 2026).

The contribution of the proposed framework lies in the definition of a structured information flow linking data acquisition, performance assessment, predictive modelling and maintenance decision support within a Digital Twin environment for railway bridge maintenance.

The overall framework proposed in this work is summarized in Fig. 1, illustrating the relationships between data acquisition, performance assessment, predictive modelling, scenario analysis and maintenance decision support within a Digital Twin environment.

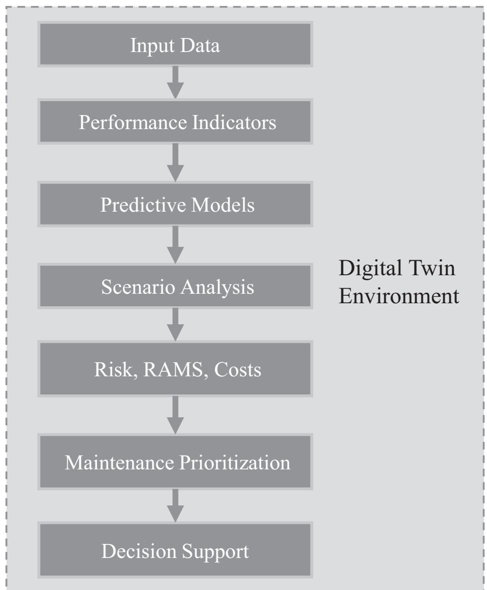

Fig. 1. Conceptual framework linking data acquisition, performance indicators, predictive modelling, scenario analysis, risk, RAMS, costs, maintenance prioritization and decision support within a Digital Twin environment for railway bridge maintenance.

4. Final considerations

This paper presented the initial steps toward a Digital Twin framework for railway bridge maintenance. The proposed framework combines performance assessment, predictive modelling, scenario analysis, risk, RAMS and maintenance information within a common structure intended to support maintenance decision-making.

The contribution of the work is not the development of a Digital Twin itself, but the definition of a framework that links data acquisition, performance assessment and maintenance decision support. In this context, the Digital Twin provides the environment in which information from different sources can be brought together to support maintenance assessment, prioritization and planning.

Maintenance decisions require more than information regarding the current condition of an asset. They also require an understanding of how infrastructure condition may evolve, the consequences associated with different maintenance actions and the priorities that emerge from technical, operational and economic considerations. Bringing information from different sources together in a consistent manner remains a significant challenge for maintenance management. The proposed framework provides a structured basis for addressing this challenge by linking data acquisition, performance assessment, predictive modelling and maintenance decision support within a Digital Twin environment intended to support railway bridge maintenance decision-making.

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