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Simplifications for Decision-Making on Bridge Portfolios: Current Developments and Future Research Directions

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Infrastructure managers must make decisions that ensure the safe and efficient operation of their networks under conditions of limited resources and high uncertainty. However, planning large-scale interventions presents multiple challenges. In bridge management, for example, current planning practices focus on the progression of bridge deterioration and the effects of operational loads. However, other alarming conditions arising from extreme load cases, such as seismic, hydraulic, or accidental events, are not formally integrated into the decision-making process. This shortcoming is largely due to the difficulty of representing uncertainty in extreme load cases, particularly when analysing large asset portfolios. Consequently, there is a growing demand for simplified yet systematic and reliable approaches to prioritizing interventions in large bridge portfolios that account for a wide range of potential load conditions and enable managers to respond rapidly when necessary.

This paper reviews a selection of existing approaches that simplify the evaluation of bridge portfolios. It also analyses the use of fault tree analysis to systematically evaluate multiple extreme load cases that may lead to bridge failure. The results suggest that, despite numerous efforts to support bridge decision-making, a gap remains between current bridge management practices and research advances. Specifically, this relates to providing a bridge manager with a structured overview of potential bridge failure scenarios when assessing large bridge inventories. A bridge example is used to illustrate the systematic use of fault-tree structures for assessing bridges. Furthermore, this paper includes a brief discussion of future research directions in large-scale bridge management.

Keywords: Bridge management, bridge portfolios, fault tree analysis, risk assessment, systematic assessment.

1. Introduction

In bridge management, managers must plan interventions across extensive bridge portfolios, accounting for a wide range of potentially alarming conditions that could compromise their functionality. These management activities are supported by bridge management systems (BMSs), which have evolved with the inclusion of new technologies (Brighenti et al. 2024).

In current BMSs, historical data, particularly from visual inspections, are recorded to describe bridge deterioration mechanisms and establish deterioration patterns over time, thereby facilitating maintenance planning throughout the bridge's service life (Brighenti et al. 2024; Mirzaei et al. 2012). However, bridge failure mechanisms associated with extreme loads, such as natural hazards and accidents, are not formally incorporated into decision-making processes.

The consideration of such load cases has become increasingly important, as these events have contributed significantly to bridge failure in recent decades (Zhang et al. 2022). Researchers have addressed the inclusion of these extreme loads in bridge decision-making through risk models, which provide metrics offering bridge managers a coherent framework for assessing the probabilities and consequences of bridge failures.

However, most risk-based research has addressed in detail the response of bridges to individual sudden events and to certain combinations thereof (e.g., (Argyroudis e Mitoulis 2021; Adey et al. 2003)). Despite this, assessing all alarming conditions in bridges remains a challenge, particularly when analyses must be extended across multiple bridge types within a network.

Several studies have addressed the uncertainty of different risks at the network level by proposing advanced probabilistic approaches (e.g., (Hackl et al. 2018)). However, these methods can be difficult to implement in real-world decision-making contexts, and often require a level of technical expertise that asset managers may not possess (Adey et al. 2019).

To address this gap, there is a growing need for simplified yet systematic and reliable methods to support large-scale decision-making in transport infrastructure, whilst accounting for multiple extreme load conditions. Such approaches would provide managers with an initial and structured overview of risks, thereby improving the effectiveness of their decisions, such as allocating resources for in-depth engineering studies of bridges that require them.

Therefore, this paper analyses four existing simplification strategies proposed in the literature to help identify bridges requiring special attention within a portfolio. Furthermore, building on the previous study by Meie et al. (2025), this paper presents a methodology that uses fault tree structures to identify the causes of bridge failures systematically. These fault tree structures can be used to estimate the risks of bridge portfolios and identify assets requiring greater attention, even with limited data.

2. Supporting decision-making in bridge portfolios – A review

Decision-making is a fundamental component of contemporary BMSs (Brighenti et al. 2024; Mirzaei et al. 2012). In this process, bridge managers determine which bridges require intervention, which interventions are possible, and the feasibility of each (considering technical and economic implications). Decision-making can therefore be defined as the process of selecting the optimal interventions based on the bridge's service requirements and economic implications.

In the literature, optimal intervention strategies are typically defined as those that minimize the bridge life-cycle cost while ensuring acceptable service levels over a predefined planning horizon (Adey et al. 2010). Consequently, decision-making models integrate deterioration forecasting, modeling of the effect of interventions, and optimization of the resources available for management, whether to maximize network performance or to ensure that each bridge operates at a minimum service level (Brighenti et al. 2024).

At the network level, the complexity of decision-making increases substantially. Managers must consider not only the condition of individual bridges but also the impact of bridge failures on network performance, including traffic disruptions. However, these interdependencies between bridge failures are not yet fully captured in current management practices. In many cases, bridge prioritization remains largely based on condition indices, although recent research has sought to incorporate risk-based approaches to provide a more comprehensive portfolio-level perspective.

Table 1 summarises a selection of four representative methodologies for bridge portfolio management. These studies were selected because they explicitly consider events beyond deterioration and use risk as a metric for prioritization within bridge portfolios. These approaches can be broadly classified into two categories: (i) index-based methods, and (ii) probabilistic approaches.

Index-based approaches combine multiple parameters into a single indicator to reflect the overall condition, importance, and vulnerability of a bridge. These methods are computationally efficient and well-suited for large-scale applications, enabling rapid screening and prioritization when data availability is limited.

For instance, Valenzuela et al. (2010) proposed an integrated bridge index that incorporates the structural condition of the bridge, its strategic importance, and its vulnerability to seismic risk and hydraulic vulnerability. Their methodology was calibrated and demonstrates strong predictive performance for application in the Chilean context. Similarly, Grieco et al. (2024) formulated a multi-risk index for traffic,

Table 1. Research approaches aimed at supporting bridge portfolio management

Reference	Methodology	Assessment of ...	Simplification used	Aiming to…	Case study
Valenzuela et al. (2010)*	Integrated Bridge Index (IBI)	Bridge condition, bridge strategic importance, hydraulic vulnerability, and seismic risk	A weight index calibrated using visual inspections, expert surveys, and regression analysis	Prioritize bridges and suggest maintenance strategies	6 bridges on a primary road in Chile
Proske e Standtke (2025)	Adjusted collapse frequency used in a risk assessment instead of failure probability	Bridge age, human error, bridge type, building material, construction technology, and seismic load, used as correction factors in the estimation of a corrected collapse frequency.	Collapse frequencies instead of failure probabilities, and correction factors to represent the effect of other load cases	Evaluate large inventories of bridges and prioritize them according to risk classes	Almost 14,000 railway and highway bridges in Switzerland
Grieco et al. (2024)	Multi-hazard risk-based procedure	Road traffic, vehicle impact on piers, seismic, and fire risks	A formulation of a multi-hazard risk index (0-1) based on a combination of single-hazard risk indicators rather than probabilistic models	Allow the prioritization of a large number of bridges with a limited level of information about them	30 highway bridges in the north of Italy
Meie et al. (2025)	Standardized fault trees with base events defined with probability values on a logarithmic scale	Deterioration, natural events (such as settlements and flooding), anthropogenic events (such as accidents, snowplow, impact load, and overloading), and structural safety	A combination of qualitative and quantitative logarithmic scales as probabilities for the occurrence of external events	Provide the manager with a standardized overview of the risks to their bridges	4 highway bridges in Switzerland

*This table should be read as follows: Valenzuela et al. (2010) describe a methodology based on an IBI for assessing the condition of bridges, their strategic importance, hydraulic vulnerability, and seismic risk. This methodology uses a weighted index, calibrated through visual inspection, expert surveys, and regression analysis, to prioritize bridges and maintenance strategies. The methodology is demonstrated across a portfolio with 6 bridges on a primary road in Chile.

vehicle impact, seismic, and fire events supported by statistical and sensitivity analyses, resulting in a robust quantitative framework for bridge prioritization. Despite their advantages, index-based approaches rely on predefined weighting schemes and simplified aggregation rules, which may limit their ability to represent uncertainty and the mechanisms underlying bridge failure explicitly.

On the other hand, probabilistic approximation methods aim to reduce the complexity of fully probabilistic assessments by using representations of failure probabilities. For example, Proske e Standtke (2025) used collapse frequencies rather than failure probabilities to assess the risk of 14,000 bridges in Switzerland. They also incorporate a corrected factor to account for bridge characteristics and some extreme load effects. While Meie et al. (2025) propose the use of logarithmic scales to define the probability assessment of load cases associated with natural hazards and anthropogenic events, combined with fault tree structures to represent multiple failure mechanisms.

While both probabilistic approaches provide a more explicit representation of uncertainty, the methodology proposed by Proske e Standtke (2025) requires the analysis of extensive historical data that is not always available, and the one presented by Meie et al. (2025) remains at a conceptual level, requiring further methodological development to support practical implementation.

In general, the literature analyzed in this paper reflects a consistent interest in developing approaches to assess large bridge portfolios and thus help managers prioritize interventions. However, important limitations remain. In particular, there is a lack of systematic frameworks that enable the consistent identification and integration of multiple alarming conditions and failure mechanisms into a unified analysis. Addressing this limitation is essential to improve decision-making, especially in the early stages of decisions where bridge prioritization is required.

In this context, this paper aims to present a potential methodology that employs fault tree analysis and probabilistic evaluation to support portfolio-level decision making. While fault tree analysis can provide an overview of bridge failure modes, as presented by Meie et al. (2025), the contribution of this work lies in the development of a structured approach for defining the probabilities of the events leading to bridge failure.

3. Fault trees in a risk-based model for managing bridge portfolios

The use of logic tree analysis dates back decades and is widely used across various fields of knowledge. These logic trees encompass event tree and fault tree structures, which visually represent the logical relationships among events and their causes. Despite the advantages of logic trees as graphical and analytical tools, few documented studies use them to support transport infrastructure management.

Existing applications include the use of event trees to assess risks for different railway assets (Papathanasiou e Adey 2021)), and to analyze the interdependencies of multiple bridge failure modes (Mondoro e Frangopol 2018). Fault tree analysis (FTA), in contrast, have been used to assess bridge failure probabilities, considering various events ranging from deterioration to sudden events such as earthquakes and floods (Meie et al. 2025; Davis-McDaniel et al. 2013; Mehranfar et al. 2023).

Based on the use of FTA and the gap identified in Section 2, a methodology is proposed that adopts fault trees with a parametric probabilistic assessment of load cases beyond deterioration. The following six steps compound it:

(i) Identification of bridge failure modes;
(ii) Definition of a fault tree structure representing each bridge failure mode;
(iii) Parametric probabilistic assessment of base events;
(iv) Estimation of bridge failure probability using a FTA;
(v) Assessment of consequences
(vi) Risk estimation.

An explanation of each step is presented with an example demonstration.

4. Example demonstration

To demonstrate the methodology proposed in Section 3, a fictitious bridge is used as an example (see Fig. *1*).

The bridge in Fig. *1* corresponds to a reinforced concrete bridge with a continuous deck structure with two lanes (one in each direction) connecting sides A and B. The main elements of the bridge are also shown in Fig. *1*.

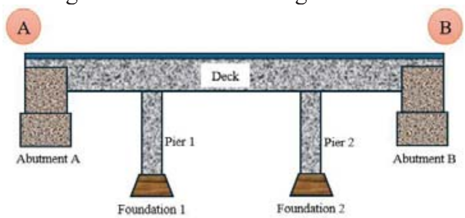

Fig. 1 Bridge used to demonstrate the methodology

This example is intended solely to demonstrate workflow consistency, not to provide a numerical assessment.

4.1. *Identification of bridge failure modes*

In this methodology, "bridge failure" is defined as a service interruption resulting from administrative decisions that either partially reduce the bridge's traffic capacity or impose a full closure.

Accordingly, failure modes are formulated in terms of service interruption duration (expressed in days). These failure modes constitute the top events in the fault tree structures and reflect varying levels of operational disruption severity.

Table 2 presents three examples of bridge failure modes considered in this study.

Table 2. Bridge failure modes

Bridge failure mode (Top Event)	Days
Major interruption	180
Moderate interruption	60
Minor interruption	30

The duration of the interruption may be defined by bridge managers based on available resources and expected recovery time.

4.2. *Fault tree representation of bridge failure*

For each failure mode defined in Table 2, a corresponding fault tree is constructed. The identification of relevant base events and the definition of their logical relationships rely significantly on managerial expertise.

As an example, *Fig. 2* presents the fault tree associated with a moderate bridge interruption that considers a partial closure of the bridge (e.g., one lane of the bridge) for 60 days. Each base event represents a condition that could justify a temporary partial closure, such as advanced deterioration of key structural elements that requires immediate intervention.

4.3. *Parametric probabilistic assessment*

Once the fault tree structure is defined, the probability of each base event must be estimated. A major challenge in current FTA applications for bridge assessment is the probabilistic modeling of these events, primarily due to uncertainties in the occurrence of sudden events such as floods and earthquakes.

To address this limitation, an index score is proposed to assess the probability of each base event defined in *Fig. 2*. These indices represent the bridge's exposure and fragility and are calculated following the route that reflects each bridge's characteristics.

As an illustrative example, the parametric assessment of an impact load is presented (see Fig. *3* and Fig. *4*). The selected parameters are based on established findings in the literature regarding factors influencing bridge response to this event.

For each possible route in Fig. *3* and Fig. *4* a resulting score ranging from 1 to 5 is obtained. This score can be mapped onto a probability matrix, where I_x represents exposure, and I_y represents fragility. This matrix may subsequently be translated into quantitative probabilities, for instance, defining values through expert judgment.

4.4. *Estimation of bridge failure probability*

Once the probabilities of the base events are defined, the probability of each failure mode can be computed using standard fault tree analysis rules.

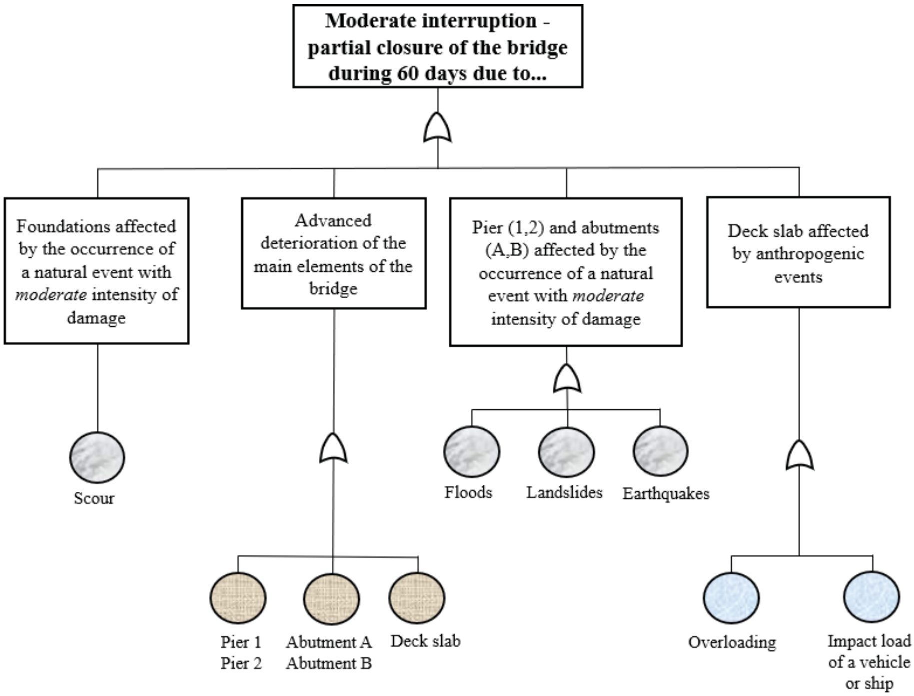

Fig. 2 Fault tree structure for a moderate partial closure of the example bridge.

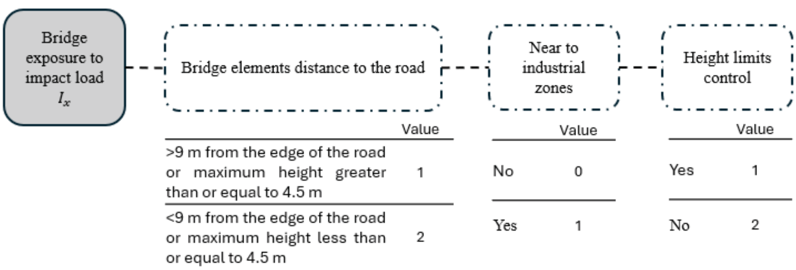

Fig. 3 Definition of exposure index I_x for impact load analysis

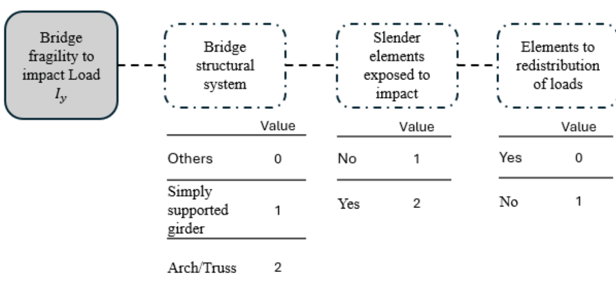

Fig. 4 Definition of fragility index I_y, for impact load analysis

4.5. *Assessment of consequences*

The consequences associated with each failure mode are evaluated from both the user and the owner perspectives. User consequences are quantified as delays resulting from bridge service interruptions, while owner consequences are estimated using predefined bridge repair costs for each failure mode.

4.6. *Risk estimation*

The risk is obtained by multiplying the failure probability from section 4.4 and the consequence assessment in section 4.5.

5. Discussion

The literature reviewed in Section 2 shows a growing body of academic work aimed at helping managers prioritize bridges in large inventories. Index-based approaches are computationally efficient but provide only a limited view of failure mechanisms. In contrast, fully probabilistic methods often require data and computational resources that are not available in practice.

The methodology proposed in this paper seeks to provide a structured and scalable approach for integrating multiple extreme load cases that cause bridge failures. Fault tree structures offer a consistent basis for assessing the risks of bridge portfolios. This, combined with a parameter-based probabilistic methodology, can help address the shortcomings of current fault tree analysis implementations. In this context, the goal is not to obtain precise absolute failure probabilities but rather to support the classification and relative prioritization of bridges by risk level.

Despite recent advances in academic research, further work is needed to strengthen the methodological basis of decision-making in bridge management systems, particularly by more effectively integrating these advances into real-world planning processes, such as those described by Hässig et al. (2026). Simple yet robust bridge prioritization tools are essential, specifically in large bridge portfolios where detailed information is often limited, resources must be allocated efficiently, and some scenarios demand rapid decision-making.

6. Conclusions

This article presents a structured analysis of four selected research studies that propose strategies to facilitate the prioritization of bridges within large inventories. These studies range from index-based formulations to simplifications of the probabilistic assessment required for risk analysis. The review shows that while these approaches differ in complexity and data requirements, none fully integrates multiple loading cases that lead to alarming conditions of large bridge inventories.

To address this gap, this paper introduces a methodology that uses FTA with parametric probability assessments for base events. The main contribution is intended to be an intermediate-level modeling approach between purely qualitative screening tools and fully probabilistic risk assessments. Its primary objective is to support consistent relative risk ranking across large bridge inventories, thereby assisting managers in identifying assets that require more detailed investigation.

Future research will focus on several key aspects, including defining parametric probabilistic assessments for other base events, calibrating probability scales, and accounting for dependencies among base events.

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