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Integrating risk estimates into the planning of preventive maintenance for large portfolios of bridges

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Road managers must anticipate preventive maintenance intervention needs for all bridges in their network. This must be done years ahead of time, so that there is sufficient time to perform the appropriate detailed investigations of the structures by engineering offices, to combine with the interventions on other objects and schedule them, to obtain financing, and to prepare projects. Preventive maintenance interventions are, however, not always executed at the optimal time due to multiple factors, including variability in early overviews of upcoming intervention needs, lack of resources to conduct detailed investigations and lack of resources to carry out the interventions. Consequently, some interventions are executed earlier than required and some later, leading to either higher than necessary expenditures or higher than necessary risks. While existing bridge management systems do an admirable job in predicting when future interventions are required, there is potential to improve how they can help determine which investigations or interventions are to be postponed if necessary.

The work presented in this paper meets this challenge by demonstrating how standardized overviews of bridge related risks could be integrated into these systems, where the risk estimates are made using fault trees and standardized estimates of probabilities and consequences of base events. The top events of the fault trees are service-related events associated with the detection of situations related to bridges that would cause interruptions to service, e.g., the discovery of an excessively large crack that would cause a manager to reduce traffic loads on the bridge until at least detailed engineering investigations could be conducted. The consequences for each top event are approximated using parameters that enable quick estimation for all bridges in a network, e.g., the expected user costs because of increased travel time due to traffic deviations. The method is demonstrated on four highway bridges in Switzerland.

Keywords: bridge, preventive maintenance, emergency interventions, risk estimates, service risk.

1. Introduction

The maintenance of road infrastructure is carried out by infrastructure managers, who are responsible for the economic operation and upkeep of their network. It is their mandate to ensure that the infrastructure provides safe and efficient travel while maintaining the network with minimal capacity restrictions. Consequently, they must adopt a user-focused approach, balancing the needs of various stakeholders, including taxpayers who expect a cost-effective fiscal policy.

To fulfill the outlined goals and constraints, road infrastructure managers strive to implement a forward-thinking approach in their process, planning interventions ahead of time instead of reacting at the last minute with emergency (i.e., unexpected and immediate) interventions, for example by following the methodology presented by Adey and Hajdin (2011). Once the necessary preventive interventions are identified for the future, these interventions are organized into projects that form the intervention program (Adey, 2019). This program is then handed over to project managers to initiate detailed planning and execution.

Currently, the most advanced bridge managers use software (examples are shown in Mirzaei et al. (2012)) to estimate when preventive interventions will be required, together with the opinions of inspectors. This helps managers reduce variability in triggering detailed investigations, reducing reliance on inspector opinions, i.e., ensuring that interventions are taken at the right time. Avoiding premature or delayed interventions can result in a reduction of wasted resources or unnecessary risks to service. One area where the current software could offer more support to managers is, however, a view over the service risks related to the different bridges based on a standardized procedure. This would give managers an even better idea as to which bridges require intervention and would help them decide which detailed investigations to prioritize and which preventive interventions to postpone if necessary.

The work presented in this paper focuses on providing these **standardized overviews of bridge-related risks for managers**. This is achieved using fault trees and standardized estimation of probabilities and consequences of base events, where the base events represent situations that managers find unacceptable and would lead them to restrict the service provided by the bridge. The usefulness of this additional information is demonstrated through the analysis of four bridges on a highway stretch in Switzerland.

1.1. *Literature overview*

Risk analysis research for road networks is a broad and evolving field. Key areas of interest include hazardous events leading to link failure (Adey et al., 2010; Erath et al., 2009), bridge failure (Decò and Frangopol, 2011) and optimal preventive intervention strategies (Adey et al., 2003). Fault trees have been used to estimate risks due to bridge failures (Davis-McDaniel et al., 2013). A research gap, however, is explicitly using service-related risk in bridge decision making. Starting to fill this gap, Mehranfar et al. (2024) recently proposed using fault trees in a standardized procedure to provide an overview of service-related risks for railway bridges. This paper builds on this approach by adapting it for road bridges.

1.2. *Goal of the paper*

Specifically, as managers are concerned with timing interventions to minimize unexpected service reductions, i.e., the risk of requiring emergency interventions, a method to incorporate these risk screenings into state-of-the-art management systems is proposed. As emergency interventions can lead to different levels of service reduction, three types of service-related events are considered:

- **Minor capacity reduction**, e.g., speed reduction over the bridge.
- **Moderate capacity reduction**, e.g., speed and capacity reduction over the bridge.
- **Major capacity reduction**, e.g., closure of the bridge.

These three levels are considered to represent the smallest meaningful distinction between the likely service reductions to be estimated when considering service-related risk. How these categories are used is explained in the subsequent Methods section and shown on four example bridges in the Case Study section.

2. Background

To understand how a method for the estimation of service-related risks for an entire bridge portfolio is useful, it is important to have a basic understanding of the process that computer systems currently follow when estimating an overview of the upcoming preventive interventions and where the activity of risk estimation fits into that process. As this work was done for the Federal Road Office of Switzerland (FEDRO) their system was used (FEDRO, 2021). A high-level description of the modified intervention estimation algorithm is given in Figure 1 and Table 1, based on the summary in Adey and Hajdin (2011). The enhancements are in italics.

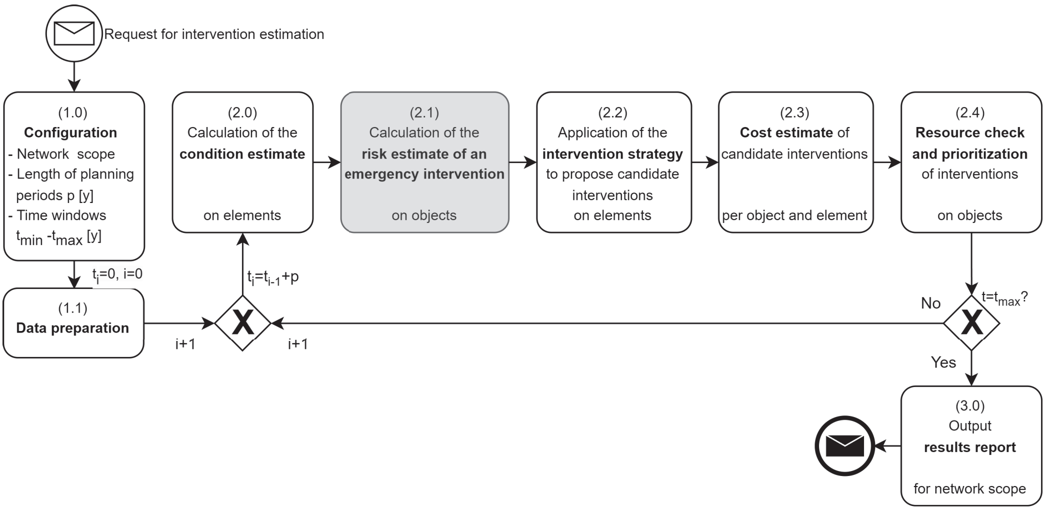


Fig. 1.: Algorithm to propose timing of future preventive interventions.

Table 1.: Modified preventive intervention estimation algorithm.

Task	Description
1.0	Set the extent of the bridges to be included as well as the time period of, and intervals in, the investigation.
2.0	At $t = 0$, estimate the condition states of all elements of each bridge. At $t > 0$, estimate future condition states using discrete transition probabilities, selected as a function of the deterioration processes being considered.
2.1	*Estimate risk for each bridge considering the condition of its elements in the investigated interval. Details provided in Section 3.*
2.2	Identify the required interventions in the investigated interval as a function of the element condition and the bridge *risk*, using agreed-upon intervention strategies.
2.3	Estimate costs for the interval being investigated.
2.4	Propose timings of interventions considering managerial, budget, and *risk* constraints, including reasons for prioritization.
3.0	Determine which detailed investigations to start to ensure the interventions can happen in the desired time interval and update the base data if necessary.

Condition states (CS): 1 – good, 2 – acceptable, 3 – damaged, 4 – poor and 5 - alarming (Adey and Hajdin, 2011).

3. Risk Estimate

The risk per bridge is the sum of the risk of each service event. The risk of each service event is estimated using probabilities of base events that are estimated as a function of key structural and situational characteristics and consequences of failure, i.e., the costs of restoration and the user costs of disruption that are estimated using characteristics pertaining to network use during normal operation and during the service restrictions. Eq. (1) shows how the service risk is calculated considering the service events minor, moderate and major capacity reduction. The values used for the case study are given in the explanatory notes for Eq. (1). The consequences are all monetized. An overview of impacts on road stakeholders of service reduction can be found in Adey et al. (2020).

$$R = \sum_{e \in E} P_e \cdot (C_{e,\text{User}} + C_{e,\text{Operator}}) \qquad (1)$$

where:

- R is the risk for a bridge based on all events $E = \{e_{\text{minor}}, e_{\text{moderate}}, e_{\text{major}}\}$.
- P_e is the probability of event e.
- $C_{e,\text{User}}$ are the user costs of event e.
- $C_{e,\text{Operator}}$ are the operator costs of event e.
- $e_{\text{minor}} \in E$ is a minor capacity reduction, i.e., a 50% speed reduction, with a duration of 90d.
- $e_{\text{moderate}} \in E$ is a moderate capacity reduction, i.e., a 50% speed reduction and a one-lane capacity reduction in both directions, with a duration of 180d.
- $e_{\text{major}} \in E$ is a major capacity reduction, i.e., full closure, with a duration of 360d.

3.1. *Probability of a service reduction*

The probability of a service event occurring is quantified by using standardized fault trees with base events mapped to standardized probability values. An example fault tree for e_{moderate} is shown in Figure 2. The others are similarly structured but have different base events. The fault trees should be sufficiently simple so that they can be replicated easily for all similar structures within a portfolio of thousands of bridges, and that the results directly compare. They can be expanded per bridge on an as need basis.

Three intermediate events, connected with an "OR" gate lead to the top event "Moderate capacity reduction". The intermediate event "Alarming condition states of elements belonging to" covers all base events that would cause a manager to trigger an emergency intervention that would result in a moderate capacity reduction, e.g., an element in an alarming condition state (here CS 5). The intermediate event "External events" covers all external events that can cause a manager to immediately impose a moderate capacity reduction, where the source can be either anthropogenic or natural. External events can be thought of as extreme events. The intermediate event "Unverified limit states" covers reasons that managers may reduce service that are not directly related to condition or the occurrence of external events. For example, they happen when engineers have reassessed the bridge and found for one reason or another that it doesn't meet the limit states criteria. Such analyses are triggered for various reasons, such as traffic load increases, changes in codes or engineering / managerial intuition.

The base event probabilities can be estimated from models, data or expert opinion. With the lowest common denominator being expert opinion, for which a scale to convert qualitative to quantitative probabilities must be developed (an example is shown in Table 2). Each organization must determine their own scales and conversion rates, as these vary as a function of traffic, environment, element age and construction quality, and experts.

Table 2.: Example link between qualitative and quantitative values for the base event probabilities.

Qual.	Quant.	Qual.	Quant.
Very high	10^{-2}	Low	10^{-8}
High	10^{-4}	Very low	10^{-10}
Medium	10^{-6}		

3.1.1. *Operator costs*

Estimating the operator costs requires an approximate estimation of the emergency intervention cost that is representative of the costs that would incur for each of the reasons the service event would occur. It is expected that there is variability between the specific emergency intervention costs caused by each combination of base events that would trigger it. The estimations also need to be adapted considering the extent of the bridge. This can be done using values of a few key parameters, such as the extent of elements (e.g., m, m^2, m^3), bridge type, bridge length, and topography.

For example, the operator costs for an emergency intervention may be estimated using the cost for the emergency intervention per cubic meter of bridge deck, multiplied by the extent of the bridge deck, and a cost reduction factor f_r to help consider the severity between service events. An example of how the costs can be estimated is shown in Eq. (2).

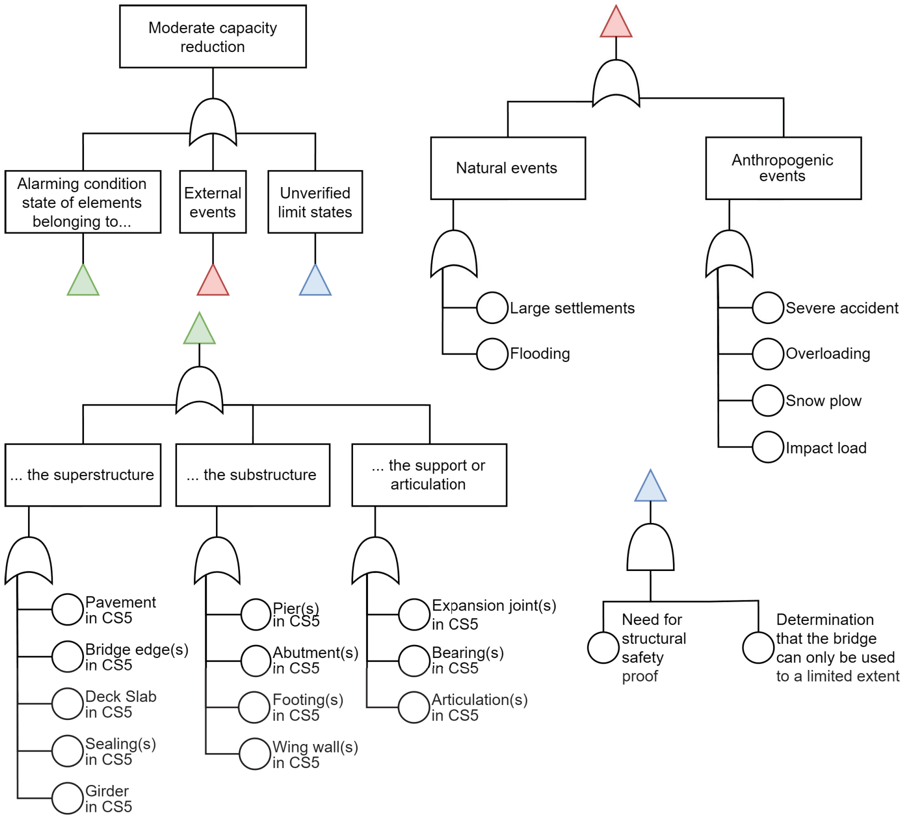


Fig. 2.: Example fault tree for a girder bridge with element level data.

$$C_{e,\text{Operator}} = \sum_i (A_i \cdot uc_{e,i}) \cdot f_{e,r} \cdot (1 + f_{\text{UnAccElements}}) \cdot (1 + f_{\text{Installation}}) \cdot (1 + f_{\text{Traffic}} + f_{\text{Oversight}}) \quad (2)$$

where:

- $C_{e,\text{Operator}}$ are the operator costs of service event e.
- A_i is the extent of element i.
- $uc_{e,i}$ is the unit cost per element type i for service event e.
- $f_{e,r}$ is the cost modification factor to adjust the cost for each service event e. The values used were: $f_{e_{\text{minor}},r} = 0.1$, $f_{e_{\text{moderate}},r} = 0.25$, $f_{e_{\text{major}},r} = 0.5$
- $f_{\text{UnAccElements}}$ accounts for elements that are not part of the calculation, e.g., due to missing data. The value used was 0.2.
- $f_{\text{Installation}}$ accounts for the costs of the construction site installation. The value used was 0.1.
- f_{Traffic} accounts for the costs of establishing traffic assignments, signaling, marking, etc. The value used was 0.1.
- $f_{\text{Oversight}}$ accounts for planning and overseeing the intervention. The value used was 0.15.

3.1.2. *User costs*

The user costs due to an emergency intervention result directly from the top event. Therefore, the approximation required when calculating the operator costs is not necessary.

All relevant costs to users, e.g., accidents, travel time noise, comfort and vehicle operation can be part of the estimation. There can also be costs to the directly and indirectly affected public. It is, however, useful to concentrate only on the most impactful ones as this is only a rough approximation to be used for comparison purposes. Travel time often governs user cost (Adey et al., 2012).

The approximate user costs due to a service event can be estimated using expert opinion or detailed simulations, such as those done by Erath et al. (2009). The example values used are given in Table 3.

Table 3.: Users cost [kCHF/d] per impact category.

Top events	Impact categories [kCHF/d]			
	Very small	Small	Medium	High
Minor	25	50	100	250
Moderate	50	100	250	500
Major	100	250	500	1000

3.2. *Reference risk ratio estimate*

Bridges have inherently different risk levels, e.g., a large bridge will have significantly higher risks than a small bridge on the same road if they have the same probability of failure because it will take significantly more resources (time, material, personal, machines) to conduct an emergency intervention on the large bridge than the small bridge. This means that comparing all bridges using just their absolute risk levels might not provide a manager with sufficient risk information. In addition to the absolute risk level the reference risk ratio R_R, (see Eq. (3)) i.e., the ratio between the acceptable risk for the bridge, R_{LV}, and the absolute risk R_{AV}, should be estimated (a measure directly related to the percentual delta risk). One possible way to approximate varying risk levels for bridges of different sizes is to use the risk associated with the bridge when all elements are in a poor condition state (here CS 4).

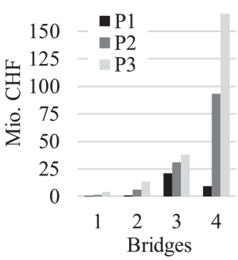
$$R_R = \frac{R_{AV}}{R_{LV}} = 1 + \frac{R_{AV} - R_{LV}}{R_{LV}} \tag{3}$$

4. Example

The example shows the risk estimates for four bridges located on the national road in Switzerland for a time span of five to twenty years, at five-year intervals (i.e., period 1 to 3). No name, length or location of the bridges, which were all built between 1965 and 75, are provided due to data protection rules. The key characteristics of the four bridges are shown in Table 4, where bridges 1 and 4 are concrete box girder bridges and bridges 2 and 3 are concrete girder bridges with an open cross section. The overview of the risk and the reference risk ratio estimates for the four bridges are shown in Figure 3 and 4. As shown in Table 4, most of the elements on the four bridges are to have preventive interventions in period 1 based on the CS estimations. This means that all four bridges should now be subject to a detailed investigation to help determine if indeed the bridges need an intervention and if so what it will be. The risk estimates can be used, for instance, to help determine which bridges should undergo detailed investigation - likely before intervention - and which ones can be postponed if it is not possible to investigate all at once. If one of the four detailed investigations needs to be postponed, consideration should first be given to postponing bridge 1. In every period, bridge 1 has the lowest overall risk level (0.0, 1.7 and 4.3 Mio. CHF) and its risk is the farthest away from an acceptable risk level (0%, 18% and 44%). Of the four bridges, it is indicated that bridge 3 should have priority, as it has the highest reference risk ratio and absolute risk (65%, 21.1 Mio. CHF) in period 1, followed by bridge 2 (4%, 1.1 Mio. CHF) and 4 (4%, 9.6 Mio. CHF), where bridge 4 should perhaps have priority over bridge 2, as the risk grows quickly in period 2 (38%, 93.3 Mio. CHF) and 3 (67%, 166.2 Mio. CHF). Without this information, decision makers would have no objective way to ascertain the gravity of postponing one or the other detailed investigations / interventions. The information becomes even more useful in large bridge portfolios, as an overview of, e.g., prioritization based on risk is available.

Table 4.: Overview of the four example bridges.

Bridge Nr.	Characteristics	Abutment(s)	Retaining/Wing wall(s)	Pier(s), Pylon(s)	Wall(s), Panel(s)	Plate girder(s)	Box girder(s)	Deck slab(s)	Kerb(s), Parapet(s)	Bearing(s), Hinge(s)	Transition joint(s)	Arch(es), Vault(s)	Waterproof seal(ings)	Surfacing	Barrier(s), Railing(s)	Pipe(s), Culvert(s)
		Generalized element types														
1	Nr. of elements	4	2	4	18	-	-	8	8	8	4	-	2	2	-	-
2		4	-	30	11	2	-	8	4	15	14	4	-	2	-	-
3		4	-	6	10	-	6	6	4	30	4	-	2	2	6	-
4		13	33	44	114	37	-	16	5	28	13	-	2	2	4	4
1	Average CS at t=0 of elements	2.3	2.3	2.3	2.3	-	-	2.3	2.3	2.5	2.5	-	2.6	2.5	-	-
2		2.3	-	2.3	2.3	2.3	-	2.3	2.3	2.5	2.8	2.3	-	2.5	-	-
3		3.3	-	2.3	2.7	-	2.7	3.0	4.0	3.8	4.0	-	2.6	4.0	4.0	-
4		2.5	2.6	2.9	2.4	2.4	-	2.6	3.0	2.7	3.0	-	3.0	3.0	3.0	2.3
1	Nr. of elements requiring preventive intervention in period 1	4	2	4	18	-	-	8	8	8	4	-	2	2	-	-
2		4	-	30	11	2	-	8	4	15	14	4	-	2	-	-
3		4	-	6	10	-	6	6	4	30	4	-	2	2	6	-
4		12	27	44	114	33	-	16	5	25	13	-	2	2	4	4
4	… in period 3	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-



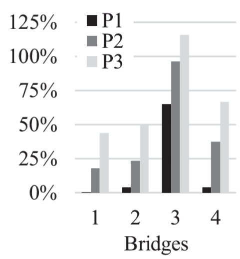


Fig. 3.: Risk [Mio. CHF] of a service disruption (left).

Fig. 4.: Reference risk ratio [%] of a service disruption (right).

5. Discussion

The presented method is an initial attempt to provide infrastructure managers with a standardized overview of their bridge-related risks that fit with the computer systems they use to support the planning of preventive maintenance interventions. Although the initial results are promising, further investigation is required.

The first question to be answered is whether it is possible in practice to identify the base events that will lead to service reductions. This requires considerable foresight, and managers currently do this on an ad hoc basis.

The second question is whether it is possible to tie the base events to the top events as done in the example in a meaningful way. It may not be possible to determine the specific base events of different types to trigger the specific top events, e.g., a pier in condition state 5 might lead to owner costs and user costs that are too different than those caused by any small earthquake. If this is true, individual fault trees may be required for every type of situation that can cause service disruption.

The third question is how comfortable managers will be with a standardized overview of the risk created from qualitative estimates of the likelihood of occurrence of the base events. Although they currently often don't use any, they may still prefer having none than having qualitative estimates. Additionally, more sophisticated risk definitions exist that incorporate elements such as vulnerability metrics, triplets with an associated value for background knowledge, and possibility distributions for the damage (Aven et al., 2018), which might offer further insights if a more nuanced risk quantification is pursued.

The fourth question pertains to the use of risk and the reference risk ratio in decision making. Although, the reference risk ratio may be the better risk measure to use in decision making, as long as risk aversion is the same for all bridges, because it negates the effect of variations in extent of the bridges, the idea of estimating risk and establishing an acceptable risk level may prove too complicated to be of use in regular managerial decision making.

6. Conclusion

This paper shows that there is a potential way to provide bridge managers with an overview of the risks related to their bridges that may improve their decision making as to which detailed investigations or interventions to postpone if all the ones to be done cannot, e.g. due to resource constraints. Such a method, which would be updated automatically with every inspection and every analysis would also allow bridge managers to respond immediately to questions pertaining to their bridge risks from both internal and external stakeholders. Combined with the decision support software that is often used by bridge managers this addition will help further decrease the heterogeneity in decision making and thereby reduce interventions being triggered too early or too late, helping to avoid excess intervention costs and minimize excess risk. More work, however, is required to ensure how feasible the idea is in practice.

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