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Author(s):
Mehranfar, Hamed; Adey, Bryan T.; Chuo, Steven Yu-Pang; Moghtadernejad, Saviz

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Efficient early estimates of bridge interventions: Costs, required possession times and associated failure risks

H. Mehranfar, B.T. Adey & S. Chuo
Institute of Construction & Infrastructure Management, ETH Zurich, Switzerland

S. Moghtadernejad
Construction Research Centre, NRC Canada, Ottawa, Canada

ABSTRACT: Due to recent technological advances and the accumulation of historical information related to bridge conditions and bridge maintenance interventions, many managers are in the position to make efficient systematic early estimates of future bridge interventions. If this was possible, it would facilitate communication between different actors within the intervention planning process, e.g., asset managers, production managers, capacity managers, and network developers. Consequently, this paper proposes a methodology to efficiently and systematically make early estimates of bridge interventions, their costs, required possession times and associated risks. The methodology is used in a case study to make early estimates of the possible interventions in different planning periods for a 50m-long masonry bridge located in Switzerland. The results indicate that the methodology has the potential to provide efficient and complete over-views of possible upcoming interventions on all bridges within a bridge portfolio. Once implemented in a digital environment, the methodology is likely to provide bridge managers with an improved way to determine the timing of detailed bridge investigations by engineering offices.

1 INTRODUCTION

Currently, many bridge managers make early estimates of intervention requirements rather qualitatively, meaning that they use inspection reports and discuss with inspectors and engineers as to which interventions may be required on bridges in the future. A downside of the current process is its inability to provide a systematic and efficient overview over all the possible upcoming interventions, and without this systematic estimate it is also difficult to have a good overview of the intervention costs and the required possession times. The lack of a systematic overview may result in interventions being planned earlier or later than they ideally should be, resulting in additional intervention costs and greater than necessary service disruptions. An efficient and systematic approach to estimate the intervention requirements would help bridge managers to reduce costs and service disruptions. The use of digital tools has the potential to support bridge managers in taking advantage of their available data to address this gap in the current intervention planning.

Researchers and asset managers have developed multiple methodologies to improve bridge intervention planning by incorporating different concerns of the bridge managers. For example, (Adey et al., 2015; Adey & Hajdin, 2011) developed methodologies to determine asset-level intervention strategies and estimate financial requirements to execute the interventions. Although such methodologies provide bridge managers with an efficient and systematic overview, they require some improvements before they become useful. The improvements required are more detailed estimates, i.e., no longer focusing on the bridge level but on the component or element level, estimates of risk, and approximations of required track possession times. Examples of methodologies focused on making estimates at the component level include (Kim et al., 2022; Martani et al., 2021; Tserng et al., 2009). Examples of methodologies that have been developed to estimate the risk associated with bridges (Adey et al., 2012).

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Examples of studies that make estimates of intervention costs and/or possession times include (Adey & Hajdin, 2011; Burkhalter & Adey, 2022).

This paper fills the identified gaps by proposing an algorithm to estimate the component-level intervention requirements, related costs, and possession times systematically and efficiently for multiple planning periods at the early stages of bridge intervention planning considering:

- the condition evolution over time due to the multiple deterioration processes affecting the components,
- the failure risks as a function of the components being in different condition states,
- the possible preventive interventions on the different components of the bridge, and the associated costs and effects on service through the allocated possession times during their execution.

The methodology enables the use of both qualitative and quantitative information coming from different sources, e.g., results of visual inspections, approximate and detailed estimates of failure risks, and approximate and detailed estimates of the costs and impacts on service of executing interventions on the provided service. The methodology is used to estimate component-level intervention requirements, related costs, and possession times over future planning periods for a masonry arch bridge in Switzerland with a length of 50 m.

2 ALGORITHM

Figure 1 provides an overview of the algorithm for estimating the type, costs, and possession times of interventions that need to be executed over future planning periods.

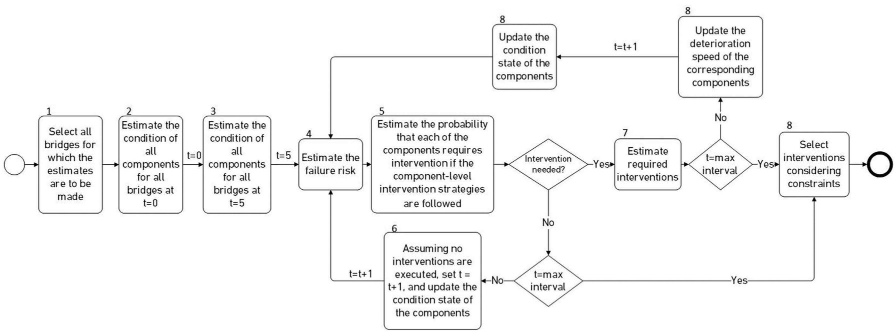

Figure 1. Flowchart for performing the intervention planning process in a digital platform.

Step 1: Select all bridges for which the estimates are to be made. No estimates need to be made for bridges that are already undergoing detailed investigations by engineering offices.

Step 2: Estimate the condition of all components for all bridges at t=0.

Step 3: Estimate the condition of all components for all bridges at the start of the planning period to be considered, e.g., t=5.

Step 4: Estimate the failure risks at t=5.

Step 5: Estimate the probability that each of the components will require intervention if the component-level intervention strategies are followed.

Step 6: Assuming no interventions are executed, set t = t+1 and repeat Steps 3 to 6 until the probabilities of components requiring intervention and the failure risks have been estimated for each of the years in the planning period.

Step 7: Estimate the required interventions: If the probability of requiring an intervention on at least one of the components is higher than the threshold value set, or the sum of the failure risks in the planning period is higher than a specific threshold value, it is considered that an intervention is to be executed on the bridge in this period, and indications are given as to which type of interventions are possible and the one that is the most likely, the possessions that are possible and most likely, and the likely intervention costs as a function of the type of intervention and possession times.

Step 8: Propose interventions to postpone if required: If it is known that not all interventions are possible within the planning period, e.g., due to a restricted budget even at this early stage, the indicator of the risk of failure is used to prioritize the bridge interventions, i.e., the bridges exhibiting the highest risk are first on the list. The bridges lowest on the list are postponed until the costs of the interventions included in the list are below the allocated budget.

3 EXAMPLE BRIDGE

The example masonry bridge was constructed in 1926 with a length of 50.8 m. This bridge is located in the canton of Bern, Switzerland and is characterized by three arches made of concrete blocks and resurfaced by rammed concrete (Figure 2).

3.1 *Components*

The main components of the example masonry bridge are remarked in Figure 2, i.e., foundations, piers, abutments, masonry arches, deck, spandrel walls, and railings and safety walkways.

Figure 2. An overview of different components of the example masonry bridge.

3.2 *Condition of components at t=0 and t=5*

Five discrete condition states are defined such that condition state 1 represents a situation with no or insignificant damage, while condition state 5 represents an alarming situation in which safety is at risk. The intermediate states indicate a worsening situation, with an increasing amount of damage. Table 1 shows an example of such definitions for the piers. Similar to the piers such condition states are defined for other bridge components.

Table 1. An example of condition state definition for the piers.

CS	Condition description	Damage description	Damage indicator
1	Good	None/ insignificant	No visible damage; only thin superficial cracks; no sign of corrosion; no or few humid zones.
2	Acceptable	Minor	Visible spot of rust and/or local spalling; thin cracks due to corrosion of the reinforcement; some humid zones; insignificant mechanical damage.
3	Damaged	Significant	Spalling with visible reinforcement; insignificant loss of section, less than 10% than visible reinforcement; cracks and/or humid zones with leaching of the concrete.
4	Poor	Extensive	Spalling of concrete with less than 25% of exposed reinforcement; significant loss of section, more than 10% of visible reinforcement; cracks with significant calcium deposits and/or large humid zones with the leaching of the concrete.
5	Alarming	Safety is endangered	Spalling of concrete with more than 25% of exposed reinforcement; significant loss of section area of the reinforcement; advanced pitting corrosion occurring; large humid zones with the leaching of concrete.

The condition state of all components is then estimated by matching the definition with the physical indicators mentioned in the latest inspection report. According to the records, the railings and safety walkways are in condition state 1, the foundations and abutments are in condition state 2, and the rest of the components are in condition state 3.

The evolution of the condition states over time is estimated using probabilistic discrete state modelling that approximates the probabilities of the transition of the components from one state to another in each unit of time, similar to the method being used in existing Bridge Management Systems (Mirzaei & Adey, 2015). An example of the transition probabilities for the piers is shown in Table 2. These transition probabilities are for one-year periods, which is the average time between the annual observations. In addition, the deterioration speed is considered as a function of the number of maintenance interventions executed on the component. This assumption is made since the execution of maintenance activities does not necessarily completely improve the physical and chemical properties of the components (Adey & Hajdin, 2011). For example, refilling the cracks in the piers and their rehabilitation can restore the condition state of the piers to condition state 1. There might still be an accumulation of aggregated alkali-silica in the pier, which accelerates the deterioration rate. In this example, it is assumed that following construction and a first maintenance intervention, the deterioration rate increases by 2% after each intervention. The maintenance intervention count resets after the replacement of the components. Similar logic is used to estimate the transition probabilities for other bridge components.

Table 2. An example of the transition probabilities for the piers.

	1*					2*				
CS	1	2	3	4	5	1	2	3	4	5
1	94%	6%	-	-	-	92%	8%	-	-	-
2	-	92%	8%	-	-	-	90%	10%	-	-
3	-	-	83%	17%	-	-	-	81%	19%	-
4	-	-	-	78%	22%	-	-	-	76%	24%
5	-	-	-	-	100%	-	-	-	-	100%

* Maintenance intervention count

An overview of the condition state of all components at t= 5 is provided in Table 3. These are estimated using the condition states at t= 0 and multiplying them with the probability of them transitioning from their initial state into the possible future states within 5 years.

Table 3. An overview of the condition state of the components at t=5.

	CS				
Component	1	2	3	4	5
Foundations	0%	93%	5%	2%	0%
Piers	0%	0%	48%	35%	17%
Abutments	0%	80%	16%	4%	0%
Masonry arches	0%	0%	46%	36%	18%
Spandrel-walls	0%	0%	50%	34%	16%
Deck	0%	0%	56%	32%	12%
Railing & Safety walkway	35%	56%	8%	1%	0%

3.3 *Component-level interventions and intervention strategies*

Interventions are executed on components to ensure they continue to function as expected. These interventions are defined individually for each component category in response to the severity of the observed damage. An example of intervention definitions for piers is shown in Table 4, which is defined using two sources (Adey & Hajdin, 2011; VICROADS, 2018). Three generic labels are given, i.e., rehabilitation, renewal, and replacement, to reflect the increasing effort and work required for interventions of each type (Adey & Hajdin, 2011).

Table 4. An example of the intervention definitions for the piers.

Intervention type	Activities
Rehabilitation	Fill out cracks and spalls with mortar or epoxy grouting; concrete protection coating.
Renewal	Renew concrete & reinforcement damaged; strengthen the pier; protection coating.
Replacement	Replacement of part or the whole pier.

The costs associated with these component-level interventions are estimated in terms of the owner and user costs. The owner unit costs are roughly estimated based on the values mentioned in Swiss Construction Price Index (Federal Statistical Office, 2021). The user costs are estimated in terms of the added travel time due to taking alternative connections. It is estimated that the closure of the bridge will increase the travel time by 8 minutes. The unit user cost is estimated based on the average wage, i.e., almost 43 mu/h (Federal Statistics Office, 2020). The total cost associated with an increment in the travel time varies as a function of the number of passengers. The average train occupancy in Switzerland, i.e., 50% occupancy, is considered to estimate the number of affected passengers. The total user costs are estimated as 86′232 mu/day (Equation 1).

$$\begin{aligned}\text{Daily user costs} = {} & \text{Average number of passengers per day} * \\ & \text{average wage}(\text{mu/h}) * \text{added travel time per passenger (h)}\end{aligned} \tag{1}$$

An overview of the intervention costs for the piers is shown in Table 5, which indicates, the more advanced and labour-intensive the activity, the more investment is needed. The owner and user costs for other components are estimated as with the pier interventions.

Table 5. An example of intervention costs for piers of the example masonry bridge.

Intervention type	Unit owner cost (mu/m^3)	Volume (m^3)	Duration of the service disturbance (weeks)	Owner cost (mu)	Service disturbance costs (mu)
Rehabilitation	290	11.3	0	3′289	172′465
Renewal	570	11.3	1	6′464	344′929
Replacement	1′100	11.3	2	12′474	603′626

The execution of these interventions does not necessarily restore the condition of the components to a like-new state. The intervention effectiveness for different components is estimated using different sources (Adey & Hajdin, 2011; Martins et al., 2004; VICROADS, 2018).

The intervention strategy selected for the components, along with the effectiveness of the interventions is shown in Table 6. No intervention is needed when the component is in condition state 1 and 2, whereas a replacement is needed when the component is in condition state 5. For condition states 3 and 4, rehabilitation and renewal interventions are carried out respectively, and the values in the table correspond to the effectiveness of these interventions. For example, when a rehabilitation intervention is executed on a component in condition state 3, there is an 85% chance that the component will be in condition state 1 at the beginning of the next year.

Table 6. An example intervention strategy for a bridge component with the effectiveness of interventions.

Condition state	Intervention type	CS1	CS2	CS3	CS4	CS5
1	Do nothing	-	-	-	-	-
2	Do nothing	-	-	-	-	-
3	Rehabilitation	85%	15%	-	-	-
4	Renewal	80%	20%	-	-	-
5	Replacement	100%	-	-	-	-

3.4 *Failure risks between t=6 and t=10 and t=11 and t=15*

As long as the component-level intervention strategies are followed, and there are no changes to the expected loading of the bridge, it can be assumed that failure risks are within the acceptable thresholds that are set by the asset managers, and the consideration of these thresholds can be omitted from the analysis for planning future interventions. If, however, interventions are going to be postponed beyond the time suggested by the component-level intervention strategies the probability and consequences of the bridge not functioning as intended. Two fault trees are developed to approximate the consequences associated with the failure of the bridge to provide the required level of service, while components are in different condition states. The associated top events, i.e., restricted service and interrupted service, are defined based on the severity of the bridge failure which is a function of the severity of component failures. In the former, rehabilitation interventions are executed during night closures, and in the latter, replacement interventions are conducted during a period that includes total closure of the bridge for a certain time. The basic events are defined to include gradual and sudden deterioration events. These events can occur due to a combination of external loads, e.g., traffic loads and excessive loads due to natural hazards.

Figure 3 shows the fault trees developed for the interrupted service.

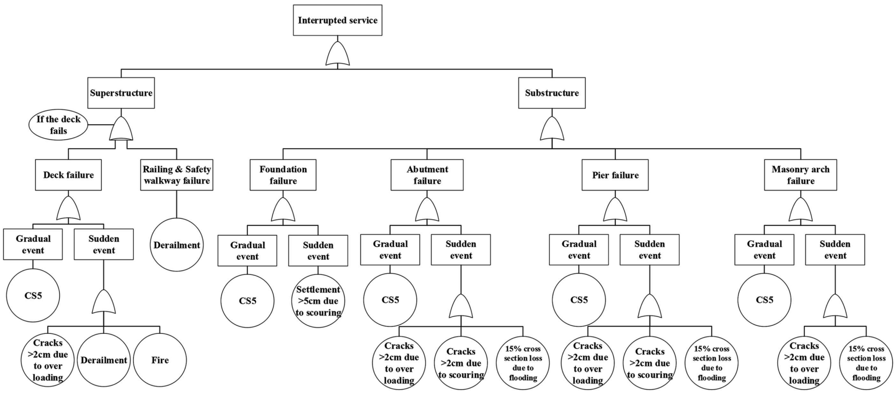

Figure 3. An example fault tree for interrupted service on the masonry bridge.

The probability of failure of each component is estimated as a function of the occurrence probability of each basic event, which in turn is estimated as a function of the probability of imposition of external loads and the resistance of the components. The probability of the imposition of the excessive loads does not depend on the condition state of the components and their annual occurrence probability was estimated using expert opinion. The resistance of the component, however, depends on its geometric and material properties. This resistance changes over time as a function of its condition state. Table 7 shows the considered occurrence probabilities of basic events, where it is less likely that basic events occur when a component is in condition state 1 and it is very likely to occur when the component is in condition state 5. These estimations were used to quantify the probability of failure of each component. The occurrence probability of each top event is estimated using the failure probability of the components.

Table 7. An example of occurrence probabilities of basic events.

Condition state	The annual occurrence probability of each basic event	Assumed probability of occurrence of basic event
1	Very low	0.001%
2	Low	0.01%
3	Medium	0.02%
4	High	0.05%
5	Very high	0.1%

The occurrence of each top event has different consequences. The consequences vary as a function of the amount of work needed to recover the required level of service. The values of required service disruptions and intervention costs are calculated using the information in section 3.3.

The estimates of failure risks as a function of the component behaviour enable the setting of a threshold on the value of additional failure risk that would trigger an intervention, especially in case component-level strategies are for some reason not set. Considering such a threshold also enables obtaining a meaningful overview of the component-level intervention requirements and eliminates the possibility of requiring intervention on different components every year. In this study, the tolerable failure risk threshold was set as the value of failure risks when all components are in CS4. Figure 4 shows the evolution of the failure risks over time for the studied bridge. It is shown how triggering interventions can be dependent on the level of failure risks, given the tolerable failure risk threshold.

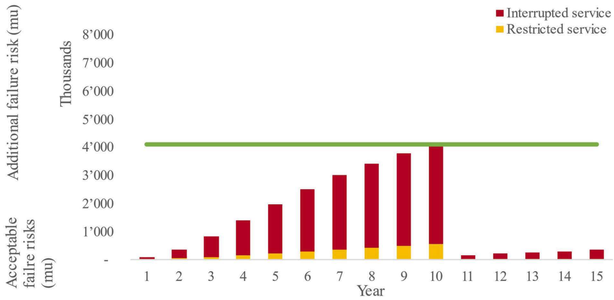

Figure 4. The evolution of the failure risks over time considering a failure risk threshold.

4 MOST LIKELY INTERVENTIONS

The intervention requirements are estimated for the initial phases of the intervention planning process, i.e., 6-15 years ahead of the execution time. Therefore, three planning periods are defined, i.e., 1-5, 6-10, and 11-15, where it is assumed that no interventions are planned for years 1-5 since decisions related to this planning period have already been made. The intervention requirements for the future planning periods are predicted using the intervention strategies determined in section 3.3 and the deterioration rate estimated in section 3.2. Interventions are scheduled to be executed on a component when the failure risks approach the defined failure risk threshold. Table 8 represents detailed information associated with the intervention requirements with the highest probability in the second planning period along with the expected costs and impacts on the service. The execution of this intervention on the

Table 8. The most probable intervention in the future planning periods.

Planning period (expected execution year)	Component	Likelihood of requiring intervention (%)	Intervention type	Expected duration	Expected effects on service (weeks) if done alone* None	Restrictions on the traffic	Closure	Expected intervention costs (×103 mu)
11-15 (year 11)	Piers	46	Replacement	51	30	14	7	616
	Abutments	25	Rehabilitation	23	14	7	2	293
	Deck	36	Replacement	64	30	14	20	1′861
	Masonry arches	48	Replacement	57	30	7	20	1′939
	Spandrel-walls	44	Replacement	18	14	4	0	433
	Railings + Side walkway	25	Rehabilitation	3	2	1	0	101

* This table is to serve as a starting point for discussions as to what exactly will be required for the bridge.

piers of this bridge will require 51 weeks to be complete such that the traffic needs to be disrupted for a week, followed by two weeks of service restriction during the execution.

5 CONCLUSIONS

This paper proposed a systematic and digital methodology to make early estimates of future bridge interventions their costs, required possession times and associated risks. The methodology was tested in a case study to provide a detailed overview of intervention requirements for a masonry bridge with a length of 50.88 m in Switzerland. The main novelty of the methodology proposed in this study is in focusing on components instead of assets, and the use of fault trees to estimate the condition state dependent failure risks, since the systematic consideration of failure risks associated with the level of service is missing in existing bridge management systems (Mirzaei et al., 2014). The proposed methodology considers the aspects that are important to bridge managers.

To ensure compatibility with existing practice, the current condition state, the condition evolution, and plausible intervention strategies were estimated to be used in a five-state model with probabilities of transitioning between states over time. The failure risks of the bridge were estimated using fault trees considering two top events associated with the severity of the traffic disturbance. The failure probabilities were estimated as a function of the condition state of the components. The consequences of top events were calculated considering the owner cost of interventions and user costs due to service disruption.

Future studies should focus on the implementation of the proposed methodology to plan the component-level interventions for all assets in a network in both simulated and real planning processes to assess the improvements in efficiency and effectiveness of the proposed digital methodology.

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