Towards a holistic prioritization of climate-change risks for bridges

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ABSTRACT: Although the projected changes in the climate include considerable uncertainties, especially with downscaling, there is irrefutable evidence that the climate is changing at an unprecedented and alarming rate. In recent studies, some of the potential climate-change risks on bridges have been identified. The sheer number of these potential risks provokes two questions. Firstly, for a certain risk of interest (e.g. increased scour rate) which bridges should be prioritized from an inventory of bridges? Secondly, for a specific bridge, which of these risks are more critical? This paper proposes a method that can be used for addressing these two questions while considering the uncertainties intrinsic to the problem. Although this paper focuses on addressing the first question, a discussion on how the proposed method can be used for answering the second is also presented. The suggested method is based on four risk components; namely: hazard, exposure, vulnerability, and consequences. In spite of being specifically tailored for bridges, the developed method can be easily extended to other types of infrastructure. The proposed method is a step towards an improved climate-change risk management.

1. INTRODUCTION

Climate change can affect the performance of built infrastructure, in general, and bridges, in particular, in many different ways. Examples include bridge expansion joints which may not be sufficient to accommodate the projected higher future temperatures (Meyer, 2008 and Schwartz, 2010). These higher temperatures can drive many other risks relevant for infrastructure, e.g.: higher deterioration rates (Stewart et al., 2011); increased heat-induced damage to pavements and rails (Meyer, 2008 and Schwartz, 2010); higher creep deformations; and increased wildfire risks (Lozano et al., 2017). On the other hand, the higher precipitation intensity and/or frequency as projected for some regions can increase the deterioration rates of bridge materials (Stewart et al., 2011), affect pavement deterioration, increase scour rates, increase the risk of landslides and slope failures (Hultén et al., 2007 and Kristo et al., 2017) which may in turn damage bridges nearby, cause bridge drainage problems, and result in a higher risk of flooding (e.g. GDV, 2011; Hoeppe, 2016; and Batchabani et al., 2016). These and many other, potentially damaging, changes in climatic parameters are projected for the future climate (IPCC 2013).

Considering this large number of potential climate-change risks, two important questions demand attention:

- For a certain climate-change impact of interest, which bridges should be given priority from an inventory of bridges?
- For a specific bridge, which climate-change impacts warrant higher attention?

Considering that limited resources are available for adapting bridges to the impacts of climate change, these two questions become of major importance for guiding the efficient allocation of these resources.

Very few previous studies have attempted to incorporate climate change in the prioritization and/or decision making processes in the context of infrastructure (e.g. Yang et al., 2012; Lambert et al., 2013; You et al., 2014; and Espinet et al., 2017). While, to the authors' knowledge, the second question has not been explicitly addressed in previous literature, Ikpong and Bagchi (2015) have addressed the first question. In that work, the authors introduced a method for ranking bridges according to their climate change resilience. However, this method does not directly account for the uncertainties associated with specific climatic parameter changes nor those associated with the occurrence of a certain risk as a result of these changes.

This paper introduces a method that can be used to address both of the aforementioned questions while incorporating the uncertainties inherent to the problem. The paper outlines the main elements of the proposed method, referred to as prioritization indices, and demonstrates how these indices can be used to develop a ranking system for answering the first question. Finally, a discussion section that includes an explanation of how the proposed method can also be used for answering the second question is presented.

2. PROPOSED METHOD

2.1. Nomenclature

Several risk definitions exist in literature, see Thywissen (2006) and Aven (2012). A common feature among most these definitions is that they include a representation of both the likelihood of occurrence of an adverse event and the potential consequences of this event. The prioritization introduced in this study is based on the following structural engineering oriented risk definition (Ellingwood, 2001 and Decò & Frangopol, 2011):

$$R = P(H) \cdot P(F|H) \cdot C(F) \quad (1)$$

Where R is the risk value, $P(H)$ is the probability of occurrence of a hazard, $P(F|H)$ is the associated conditional failure probability, and $C(F)$ is the associated consequences.

However, in the context of climate change risks, a bridge is not directly affected by the hazard, i.e. change of a climatic parameter. Rather, the hazard (e.g. temperature increase) can drive an exposure (e.g. increased restrained thermal stresses) which in turn may affect the bridge. Therefore, an additional term is introduced to Equation 1 representing the conditional probability of an exposure given the occurrence of a hazard, $P(E|H)$. As a result, the failure probability becomes conditional on both the hazard and exposure. Additionally, to have a more versatile form of the equation, failure F in Equation 1 is replaced by damage D. Equation 1 then becomes:

$$R = P(H) \cdot P(E|H) \cdot P(D|E \cap H) \cdot C(D) \quad (2)$$

Figure 1 shows a schematic representation of Equation 2. However, for the sake of practicality, an index based approach where each of the four components in Equation 2 is reflected by representative prioritization indices is adopted instead of a probabilistic one. In this paper, **Hazard**, represented by $P(H)$, refers to the probability of a climatic hazard within a certain reference period; **Exposure**, represented by $P(E|H)$, refers to the potential adverse impact on the bridge caused, or increased, by the hazard; **Vulnerability**, represented by $P(D|E \cap H)$, refers to the potential damage inflicted by the exposure, and; **Consequences**, represented by $C(D)$, refers to the potential consequences of such damage to the system.

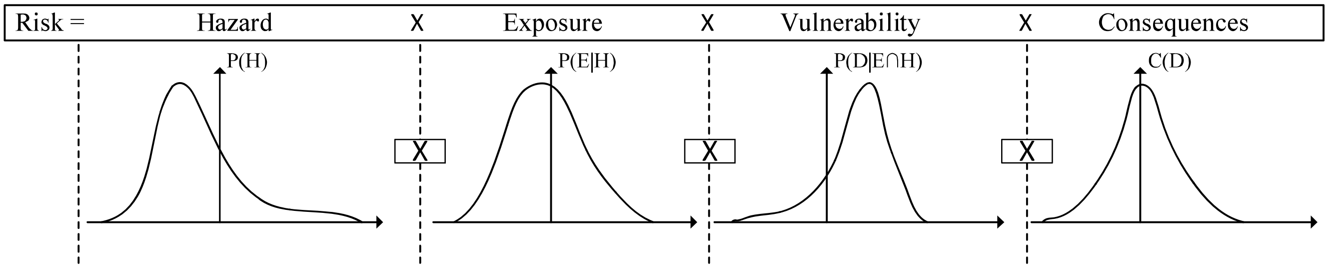

Figure 1: Schematic representation of Equation 2.

2.2. Scope identification

Preliminary steps for identifying the scope should precede the prioritization process. First, it is necessary to clearly define the reference period of interest. In other words, which climate changes are of interest; those projected for the 2030s; 2050s; or 2070s for example? Second, based on this choice, the relevant exposures at the defined reference period need to be identified and an exposure of interest should be selected.

2.3. Prioritization indices

In this section, 9 prioritization indices are introduced. The 9 indices consist of 4 indices reflecting the hazard component, 3 indices reflecting the exposure component, one index reflecting the vulnerability component, and one index reflecting the consequences component.

2.3.1. Hazard

To set comparable lower and upper bounds for the likelihood and extent of hazard(s) driving the considered exposure, two indices are introduced. The 25th percentile of a low emissions scenario (e.g. the IPCC RCP 2.6 scenario, see IPCC (2013)) is proposed for the lower bound (H_{low}), while the 75th percentile of a high emissions scenario (e.g. the IPCC RCP 8.5 scenario, see IPCC (2013)) is suggested for the upper bound (H_{high}). The suggested percentiles and scenarios are only illustrative. Ideally, the decision maker should determine which levels are appropriate.

Two other indices are proposed to account for two additional aspects. Firstly, some exposures can separately be driven by more than one possible hazard, or hazard combinations. For instance, the exposure of increased deterioration rates may separately be driven by the potential increase in future temperatures, increase in precipitation in some locations, change in relative humidity, increase in carbon concentrations, or increase in solar radiation. At a certain bridge location, the higher the number of projected hazards that can separately drive the exposure of interest, the higher priority this bridge should be given. This is accounted for by the index N_h, with suggested values as shown in Table 1. Secondly, the circulation models projecting changes in the climatic parameters can project these changes with varying certainty for each hazard. This is accounted for by the index C, also presented in Table 1. In the case that more than one hazard that can separately drive the exposure are projected at the bridge location, the lowest possible value for the index C may be considered.

2.3.2. Exposure

The first index representing the exposure component, referred to as (E), qualitatively assesses the strength of evidence supporting the occurrence, or increase, of the exposure of concern as a result of the hazard(s) projected at the bridge location. The values suggested for this index are shown in Table 1. Similar to C, the lowest possible value of E is considered when different evidence types support the exposure.

The other two indices describing the exposure component, I_{low} and I_{high} respectively, are intended for setting comparable lower and upper bounds for the potential increase in the exposure as a result of the previously introduced hazard bounds, i.e. H_{low} and H_{high}. I_{low} and I_{high} can be calculated using Equations 3 and 4 respectively:

$$I_{low} = \min\left(100\%,\ \frac{e_{low} - e_i}{e_i}\right) \tag{3}$$

$$I_{high} = \min\left(100\%,\ \frac{e_{high} - e_i}{e_i}\right) \tag{4}$$

Where e_{low} and e_{high} represent the exposure under H_{low} and H_{high} respectively and e_i represents the initial exposure without the effect of climate change. For evaluating the fractions in Equations 3 and 4, models connecting the exposure to the relevant hazard should be used if available. Otherwise, these fractions can be assessed qualitatively either by a group of experts, through e.g. expert elicitation (Ayyub, 2001), or individually by the decision maker. An exposure increase of 100% or more is regarded to belong to the highest exposure increase group and therefore Equations 3 and 4 are limited to 100%.

Table 1: Proposed values for the indices C, N_h, E.

Value	*Index description*		
	C	N_h	*E*
1.00	*High uncertainty*	*≥ 3*	*Personal opinion of the decision maker (DM)*
0.67	*Average uncertainty*	*2*	*Opinion of a group of experts (GE)*
0.33	*Low uncertainty*	*1*	*Well-established and supported by scientific evidence (SE)*

2.3.3. Vulnerability

The next prioritization index, referred to as Vulnerability Index (*VI*), is proposed for assessing the vulnerability component in Equation 2. This index is based on identifying a set of bridge attributes that reflect the bridge vulnerability to the exposure of interest, i.e. vulnerability indicators. The different possible alternatives for each indicator are then given a score from 0 to 1, 0 being not at all vulnerable and 1 being highly vulnerable. If the bridge scores a 0 on any indicator a *VI* of 0 is assigned, otherwise *VI* is to be calculated as the average of bridge scores on all indicators.

Table 2 gives a suggestion for the vulnerability indicators of four possible exposures; increased scour rates, increased liquefaction potential during earthquakes, increased drainage problems, and increased deterioration rates, as previously mentioned in 2.3.1. While the increased scour rates may result from the hazards of sea level rise, melting permafrost at some locations, and the projected increase in precipitation in some regions (Nasr et al., 2018), the second exposure can be caused by the possible rise in ground water tables, see e.g. Nath et al. (2018), as a result of the projected increase in precipitation which can also drive the third exposure. A proposition of the scoring scheme of some of the suggested scour vulnerability indicators is presented in Table 3. In case such indicators cannot be identified or a scoring is not possible, e.g. due to the lack of information about the bridge attributes and/or the lack of scientific knowledge about the exposure, the *VI* can be assigned qualitatively. In these cases, information concerning the frequency of past incidents where the bridge was damaged by the considered exposure can be used together with the knowledge/experience of the decision maker or other experts.

Table 2: Suggestions of possible vulnerability indicators for four potential climate-change exposures.

Exposure	*Suggested indicators*
Scour	*Foundation type, bed slope, depth of footing below bed level, causes of flow turbulence near bridge (yes/no), existing scour protection measures, pier width, soil type (NYSDOT, 2003 ,Shan et al., 2015)*

Liquefaction	*Design ground acceleration, soil type, thickness of unliquefiable soil crust, thickness of liquefiable soil layer, normalized standard penetration test blow counts (Ishihara,1985, Seed et al., 2003, CEN, 2004)*
Drainage	*Cross-slope, longitudinal gradient, vertical sag (yes/no), actual area of drainage inlet in comparison to the calculated area, diameter of drainage pipes, type of inlet (NZ Transport Agency, 2001)*
Deterioration	*Bridge material, age, span type (single or multi-span), zone (marine, industrial, exposed to deicing salt etc.) (Ramey & Wright, 1997)*

Table 3: A possible vulnerability scoring for scour; NE: Non-erosive; LE, ME, HE: Low, medium, and high erodibility respectively.

Score	*Foun-dation type*	*Scour protection measure*	*Pier width*	*Soil type*
0.00		*Sheet pile or cofferdam*		*NE*
0.10	*Long RC or steel piles (>6m)*		*<1m*	
0.30	*Long timber piles (>6m)*	*Other properly designed and well-functioning*	*1-1.5m*	*LE*
0.60	*Short piles (<6m)*	*Some protection*	*1.5-2.5m*	*ME*
1.00	*Shall-ow*	*No protection*	*3.0≤*	*HE*

2.3.4. Consequences

The VI can give a reasonable comparative assessment of the potential damage state of each bridge. However, the severity of the consequences will strongly depend on the importance of the bridge being considered. For instance, the collapse of a bridge of low importance may be less consequential than a moderate damage to a bridge of very high importance. Therefore, an index i_r is introduced to reflect the relative importance of the different bridges.

For assessing this index, different parameters indicating the relative importance of each bridge, i.e. importance indicators (i_i); e.g. based on traffic volume and utilization, can be used as shown in Equation 5. Otherwise, this index can be set qualitatively from 0 to 1.0, 1.0 being of the highest relative importance, by the decision maker.

$$i_r = \frac{i_i}{i_{i\ \max}} \quad (5)$$

Where i_i and $i_{i\ max}$ are the values of the importance indicator for the bridge being considered and for the bridge with the highest importance respectively.

3. PROPOSED RANKING INDICES

Based on the prioritization indices presented in the previous section, the prioritization of bridges in a bridge inventory considering a specific climate-change impact is possible. For this purpose, 2 ranking indices are introduced in this section; risk index and uncertainty index.

3.1. Risk index

Using the prioritization indices introduced in section 2, the lower and upper limits of a risk index that can be used for prioritizing bridges considering a certain climate-change impact, *LL* and *UL*, are calculated using Equations 6 and 7 respectively. The method used for aggregating the different prioritization indices in both equations is the weighted product method. It is considered more suited for the purpose than other aggregation methods, e.g. the weighted sum method, due to its resemblance to the chosen risk definition, represented by Equation 2, ease of application, and simplicity.

$$LL = N_h^{0.25} \cdot I_{low}^{0.25} \cdot VI^{0.25} \cdot i_r^{0.25} \quad (6)$$

$$UL = N_h^{0.25} \cdot I_{high}^{0.25} \cdot VI^{0.25} \cdot i_r^{0.25} \quad (7)$$

In Equations 6 and 7, a neutral attitude is adopted for assigning the weights to the different indices, 0.25 for each of the four indices. This attitude is based on the fact that in Equation 2 each of the four components contributes equally to the risk value. These weights can be changed depending on the decision maker's preference.

3.2. Uncertainty index

LL and *UL* defined in the previous section reflect the uncertainty in the risk value for each bridge. Another index, referred to as the Uncertainty Index (*UI*), is introduced to represent the uncertainty associated with climate projections and the strength of evidence supporting the risk of interest at the location of the bridge considered. *UI* can assume the values shown in Table 4 and is calculated as follows:

$$UI = C \cdot E \quad (8)$$

Table 4: Possible values for UI; SE, GE, DM: see Table 1

C \ *E*	*SE*	*GE*	*DM*
Low uncertainty	*0.1089*	*0.2211*	*0.3333*
Average uncertainty	*0.2211*	*0.4489*	*0.67*
High uncertainty	*0.3333*	*0.67*	*1.00*

3.3. Prioritization of bridges

With the aid of the proposed LL, UL, and UI, the decision maker can reach a more objective decision on which bridges are more critical considering a certain climate-change risk. If the risk of interest has more than one driving hazard, the proposed equations for *LL*, *UL*, and *U*I can directly be used. Otherwise, N_h, *C* and *E* become irrelevant. In the latter case, only *LL* and *UL* are used in the prioritization and Equations 6 and 7 are modified by removing N_h and changing all weights to 0.33, if neutral attitude is adopted.

Risk visualization may be particularly useful for the prioritization. Figure 2 suggests a visualization method that can be used to facilitate the ranking of the different bridges. A flowchart of the steps necessary for the prioritization is shown in Figure 3.

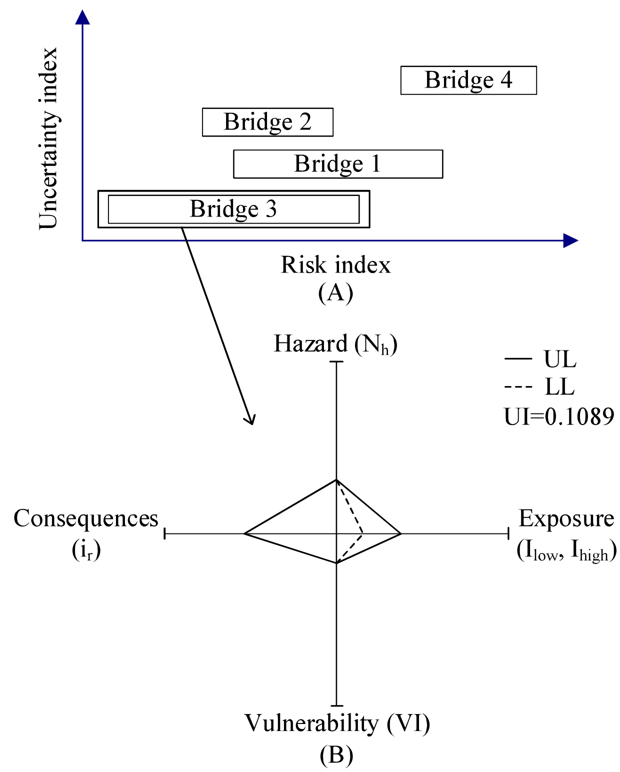

Figure 2: The proposed risk visualization methods for (A) comparatively viewing LL, UL, and UI (B) viewing the different prioritization indices.

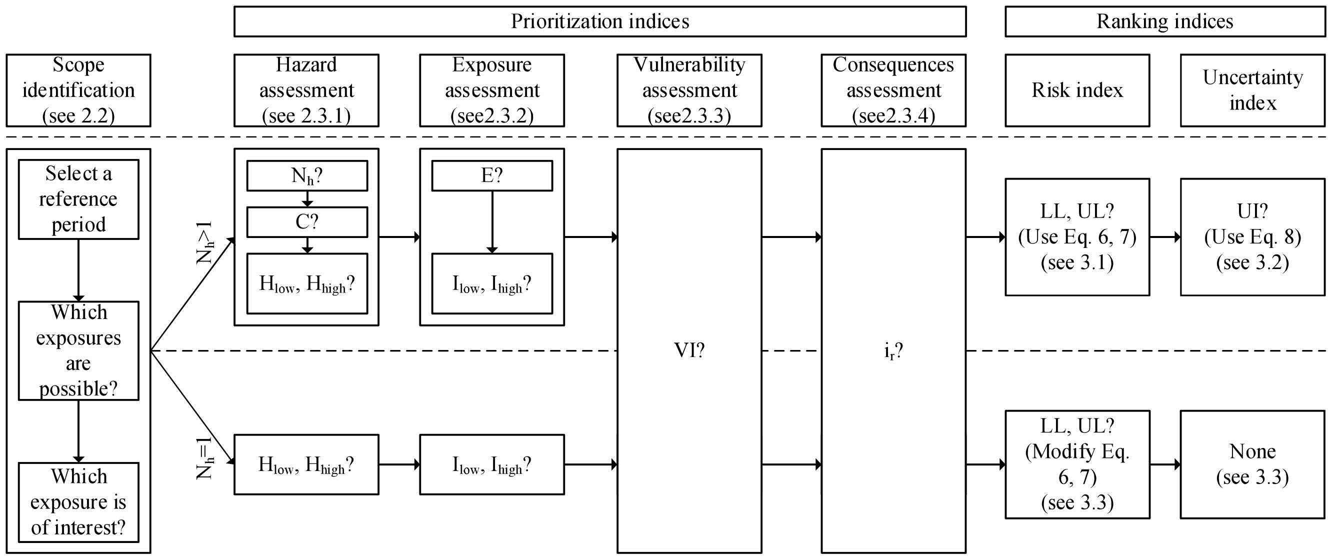

Figure 3: A flowchart demonstrating the necessary steps for the proposed method.

4. DISCUSSION

The proposed method can also be used for prioritizing different potential climate-change impacts for a specific bridge of interest. However, unlike in the case of prioritizing bridges considering a certain risk, the *VI* does not provide a reasonable comparative assessment of the potential damage states resulting from different risks. For instance, if a certain bridge scores *VI* of 0.3 for scour and 0.7 for the risk of drainage problems, this does not necessarily mean that the potential damage state of the latter risk is higher than that of the former. Therefore, a direct assessment of the potential damage state of each risk is needed.

Furthermore, a distinction between the different types of consequences, i.e. repair and replacement costs; user costs related to traffic loss; and life loss costs, is needed for this prioritization. The higher the importance of the considered bridge, the more consequential traffic and life costs will be in comparison to material costs and vice versa.

5. CONCLUSIONS

In this study, a method that can be used for prioritizing bridges under a specific climate-change risk that is of interest was outlined. Furthermore, a discussion of how this method can also be employed to prioritize different potential climate-change risks for a certain bridge was presented. The proposed method is based on four components characterizing risk, namely hazard; exposure; vulnerability; and consequence. However, some limitations of the proposed method exist. For instance, using different climate change scenarios may affect the prioritization results. Moreover, the proposed values for the different indices are subjective and are not based on statistical analysis. However, the problem at hand is of such a high degree of uncertainty that any ambition of total objectivity can be counterproductive.

6. ACKNOWLEDGEMENTS

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