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A qualitative assessment of the effects of climate change on bridges

En kvalitativ utvärdering av klimatförändringars inverkan på broar

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2020

Rapport TVBK-5277
ISSN 0349-4969
ISRN: LUTVDG/TVBK-20/5277

Examensarbete
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June 2020

Preface

This master thesis was carried out during the spring of 2020 for the Division of Structural Engineering at Lund's Faculty of Engineering LTH. The thesis accomplishes five years of studies and comprises 30 credits for the Master of Science in Civil Engineering. This thesis was attainable as accesses was granted to the Swedish Transport Administration management system BaTMan along with the Climate scenario database by the Rossby Centre, their data and input was highly appreciated.

I would like to thank my supervisor Amro Nasr for his patience with all my questions and for his guidance throughout the whole process. In addition, I would like to thank my co-supervisor Ivar Björnsson for his help during the initial as well as the final stages of my thesis.

Finally, I am very grateful for the support of my family and friends during my five years at LTH. Without you this would not have been possible.

Lund, June 2020

Amina Arnautovic

Abstract

Climate change is a fact and the potential climate change impacts on infrastructure are necessary to examine to ensure the safety and performance of societies. The evidence for climate change is overwhelming, the changes have been observed and the projected future based on models indicate further change. Several of the climate change impacts are predictable, though the magnitude of the changes is unknown. Bridges are a part of the infrastructure that have a substantially long service life, which make them important to consider when regarding the impacts of climate change.

In this thesis a recently developed risk-based prioritisation method was reviewed. The method qualitatively assesses the impacts of climate change on bridges, aiming to address the two following question related to operation and management. Firstly, which climate change impacts should be prioritised for a single bridge? Secondly, which bridge should be given precedence when considering the potential impacts of climate change, for a group of bridges? The main components of the method are hazard, exposure, vulnerability and consequence. These components are assessed and aggregated into two ranking indices, level-I ranking index addressing the first question and level-II ranking index addressing the second one. The review was conducted to examine the practical feasibility of the method, evaluating its strengths, weaknesses and possible improvements.

The potential climate change impacts selected for analysis of the method were increased deterioration rates and increased stress due to expansion. The bridge selection comprised out of seven roadway bridge located in different counties in Sweden. The relevant bridge information for the selection was obtained from the Swedish Transport Administrations database, BaTMan. The climate data used to evaluate the increase of the potential climate change impacts was acquired from the Climate scenario database created by the Rossby Centre at the Swedish Meteorological and Hydrological Institute.

The result of the review is that the risk-based prioritisation method is applicable, it addresses the aforementioned questions and prioritisation for the bridge selection is obtained. The method requires access to extensive data, both climate data and bridge data. It is also important to acknowledge that several assumptions and simplification were adopted to enable the assessment process.

Keywords: climate change; risk; bridges; qualitative assessment

Sammanfattning

Klimatförändringar är ett faktum och de potentiella klimatförändringarnas inverkan på infrastrukturen är nödvändigt att undersöka för att säkerställa samhällets funktion och säkerhet. Bevis för klimatförändringar är överväldigande, förändringarna har observerats samt tyder modelleringen av framtidens klimat på ytterligare förändringar. Flera av klimatförändringarnas inverkan på infrastruktur är förutsägbara, men storleken på dessa är okänd. Broar är en del av infrastrukturen som har en lång livslängd, vilket gör dem viktiga att ta hänsyn till när det gäller effekterna av klimatförändringar.

I examensarbetet granskades en nyligen utvecklad riskbaserad prioriteringsmetod. Metoden bedömer kvalitativt effekterna av klimatförändringar på broar, och syftar till att ta itu med de två följande frågorna. För det första, vilken av klimatförändringarnas effekter bör prioriteras för en enskild bro? För det andra, vilken bro bör ges företräde när man beaktar de potentiella effekterna av klimatförändringar för ett urval av broar? Metodens huvudkomponenter är fara, exponering, sårbarhet och konsekvens. Dessa komponenter utvärderas och sätts samma till två rankningsindex, level-I rankningsindex som besvarar den första frågan och level-II rankningsindex som tacklar den andra. Granskningen genomfördes för att undersöka metodens praktiska genomförbarhet, identifiera möjliga förbättringar samt utvärdera dess styrkor och svagheter.

De potentiella effekterna av klimatförändring som valts för analys av metoden var ökad nedbrytning av överbyggnad och ökade spänningar i bron på grund av expansion. Urvalet bestod av sju vägbroar belägna i olika län i Sverige. Den väsentliga informationen för urvalet erhölls från Trafikverkets databas, BaTMan. Klimatdata som användes för att utvärdera ökningen av de potentiella effekterna av klimatförändring samlades in från Klimatscenario databasen skapad av Rossby Center vid Sveriges meteorologiska och hydrologiska institut.

Resultatet av granskningen är att den riskbaserade prioriteringsmetoden är applicerbar, den besvara de ovannämnda frågorna och en prioritering för urvalet erhålls. Metoden kräver tillgång till omfattande data, både klimatdata och brodata. Det är också viktigt att konstatera att flera antaganden och förenklingar antogs för att möjliggöra utvärderingsprocessen.

Nyckelord: klimatförändring; risk; broar; kvalitativ bedömning

Notations and abbreviations

Some of the most used notations and abbreviations in the thesis are listed below

H	Hazard index
I	Exposure index
E	Strength of evidence index
V	Vulnerability index
C	Consequence index
i_r	Relative bridge importance index
I_o	Optimistic exposure
I_p	Pessimistic exposure
I_n	Normalised exposure
I_{on}	Normalised optimistic exposure
I_{op}	Normalised pessimistic exposure
$I_{p,\max}$	Maximum pessimistic exposure
e_c	Output from model with current climate data
e_o	Output from model with optimistic climate data
e_p	Output from model with pessimistic climate data
RI_1	Level-I ranking index
$RI_{1,o}$	Optimistic level-I ranking index
$RI_{1,p}$	Pessimistic level-I ranking index
RI_2	Level-II ranking index
$RI_{2,o}$	Optimistic level-II ranking index
$RI_{2,p}$	Pessimistic level-II ranking index
W_{I_n}	Weight assigned to the normalised exposure
W_E	Weight assigned to the strength of evidence
W_V	Weight assigned to the vulnerability
W_C	Weight assigned to the consequence
W_{i_r}	Weight assigned to the relative bridge importance
$AADT_{\max}$	Maximum annual average daily traffic
$DL_{\max}$	Maximum detour length

RCP	**R**epresentative **C**oncentration **P**athway
RF	**R**adiative **F**orcing
STA	The **S**wedish **T**ransport **A**dministration (Trafikverket)
IPCC	**I**ntergovernmental **P**anel on **C**limate **C**hange
GCM	**G**lobal **C**limate **M**odel
AADT	**A**nnual **A**verage **D**aily **T**raffic
DL	**D**etour **L**ength

Contents

1 Introduction

1.1 Background

The climate is changing, with the passage of time it has becomes more evident that significant climate changes are occurring. In addition to the overabundance of observational evidence of these changes, there are also numerous model projections which consistently indicate that the climate system is changing at a remarkable rate. While at the same time there are large uncertainties associated with the magnitudes of these changes, however the fact that the climate is changing is undeniable.

The climate change may prompt unforeseen impacts or increase currently existing ones for various sectors of our societies, one of these is sectors is the infrastructure. Bridges are a part of the infrastructure that have a substantially long service life, sometimes exceeding 100 years. To ensure safe and functional societies it is consequently vital to study the potential climate change impacts on infrastructure.

Up to date, only a small number of studies have attempted to address the risks imposed on bridges by climate change from a decision-making view in the context of infrastructure management. Nasr et al. (2019a) recently developed a method for comparatively assessing the impacts of climate change on bridges. The method aims to assess the effect of climate change for several potential impacts for a certain bridge of interest as well as generating a prioritisation system for a selection of bridges to determine which of these bridges should be given precedence when considering the effect of climate change. The proposed method has only been applied to hypothetical bridge examples to demonstrate its applicability. The climate change impacts assessed for the hypothetical examples were increased scour rates, increased deterioration rates, increased drainage problems and permanent inundation of bridge deck due to sea level rise.

1.2 Objectives

The overall aim of this thesis is to review the method developed by Nasr et al. (2019a) and to study the practical feasibility of the method on real case studies. The method could be a useful tool for risk assessment considering climate change impacts for bridges as well as for other infrastructures. The data for the case studies in this work was obtained from the BaTMan database which is the Swedish Transport Administrations (STA) Bridge and Tunnel Management system (STA, n.d.). The main objectives of this thesis are:

- To investigate the applicability of the method to real case studies, based on the data available on the BaTMan database.

- To identify the strengths, weaknesses and possible improvements of the proposed method as well as assess its compatibility with existing climate change projection from the SMHI database, (SMHI, 2018a).

1.3 Limitations

The bridge selection assessed in the study were limited to steel or concrete roadway bridges. The Swedish Transport Administrations database was the main source of information for the bridges which limited the selection to bridges located in Sweden.

The available climate data obtained from SMHI, narrowed down the selection of potential climate change impacts. The Climate scenario database accessible on SMHI, containing necessary climate data sets for the review of the method consists of number of different climate parameters, e.g. temperature, precipitation and wind. The main climate parameter utilized in the study was temperature.

1.4 Scope identification and overall methodology of the study

The initial steps before executing the prioritisation method involves choosing a bridge selection, a time frame and relevant climate change impacts for the time frame of interest. These choices are determined by the decision maker and outside the scope of the reviewed method.

The bridge selection assessed in this study consists exclusively of roadway bridges made of either steel or concrete. The database was studied to learn what information could be accessed. The account for BaTMan was not granted complete access to the entire database, though the essential bridge data was available.

The selection process of choosing the bridges for the assessment was done with consideration to the limitations (e.g., roadway bridge, steel or concrete as bridge material) as well as with some input from the Swedish Transport Administration. This amounted to the seven roadway bridges with difference locations all over Sweden. Assumptions and simplification of the bridge data were adapted to enable the assessment.

The time frame used in the assessment was a choice by the decision maker, partly governed by the amount of available data for the required climate parameters. This led to the current climate being represented by the 2010s and the investigated future climate represented by three different decades; the 2050s, 2070s and 2090s. The decadal comparison of climate (i.e. considering the climate parameters in a whole decade instead of a single year) was applied in order to obtain a better representation of the climate. Several decades of the future were investigated to see how the results of the review method would be affected.

The potential climate change impacts for the chosen time frame were investigated. Firstly, a wide literature review was conducted to gain knowledge of the subject as well as adjacent subjects, focusing mainly on climate change and the potential climate change impacts for bridge structures. Furthermore, research on where climate data could be obtained was conducted, more specifically scenario data. This led to the Rossby Centres research results which contained both historical and scenario climate data pertinent for the assessment.

To fully utilize the risk-based prioritisation method two impacts were assessed, these were chosen based on their relevancy for the time frame. In addition, the available climate data narrowed down the selection of the climate change impacts. The main climate parameter available and used in the study was the temperature which amounted to the two following potential climate change impacts; increased deterioration rates and increased stress due to thermal movements of the bridge deck.

1.5 Outline of the thesis

The core of this thesis is the risk-based prioritisation method. In order to present the method and its components, the thesis starts with an introduction to climate change impacts and the climate change parameters affecting them.

Chapter 2 presents the potential climate change impacts assessed in the study. In addition, the emission scenarios that have been selected for assessment are described and the Climate scenario database used to obtain the climate data is presented.

Chapter 3 presents the method, if no other references are presented in this chapter it should be concluded that the information is a part of the method.

Chapter 4 describes the bridges which were selected for the study and how the selection process was conducted. Moreover, the Swedish Transport Administrations BaTMan database used to obtain the bridge data in the assessment is described in short.

Chapter 5 presents the bridge data and climate data used in the assessment together with some of the assumptions and simplifications applied for the assessment.

Chapter 6 consist of a calculation example which describes all the steps in detail conducted when determining the ranking indices for a single bridge. While in Chapter 7 the results of the qualitative assessment for all bridge are presented. In Chapter 8 the results and the reviewed method are discussed. Lastly, in Chapter 9 the conclusions of the study are presented.

2 Climate

2.1 Climate change impacts

Identifying the hazards and the associated potential risks for a certain structure are the initial steps of risk assessment, this is then followed by analysing and evaluating the probability and severity of the risks. Nasr et al. (2019b) examined over 190 research articles, which resulted in identifying and categorising 31 potential climate change risks related to bridge structures.

Identification of the presented climate change risks was pursued in three ways. Firstly, some risks were identified in previous literature as potential climate change risks. Furthermore, some of the risks were identified by reviewing documented cases of bridge incidents, involving failure, malfunction or damage, and then trying to connect these incidents to the projected environmental hazards of the future. Lastly, additional risks were identified by contemplating scenarios induced through the projected change of climate parameters which could affect the performance and/or safety of bridges. The risks were categorised into seven main categories, namely durability, serviceability, geotechnical, increased demand, accidental loads, extreme natural event and operational risks.

For each category the related risks were grouped and the associated hazards were discussed. The probability or severity of the risks were not addressed in the aforementioned article as the main focus was solely to identify the potential climate change risks. In the article various projected changes of climate parameters and phenomena were considered such as temperature, heatwaves, precipitation, sea level, wind, relative humidity, etc. The two climate factors that can affect the largest number of potential risks are the higher temperature and the increase of precipitation (Nasr et al., 2019b). The research concluded that the two climate factors combined could affect 25 of the 31 investigated risks. Table 1 presents the potential climate change impacts assessed in this thesis, namely accelerated degradation of material and thermally induced stress and the change of climate parameters affecting them.

Table 1 The studied climate change impacts and the climate change parameters affecting them, identified by Nasr et al. (2019b).

Accelerated degradation of material		*Thermally induced stress*	
P↑	Higher precipitation	T↔	Higher temperature seasonal contrast
T↑	Higher temperature	T↑	Higher temperature
CC↑	Higher carbon concentration	HW↑	Increase in intensity/frequency of heatwaves
SR↑	Higher solar radiation	SR↑	Higher solar radiation
RH↑	Increase in relative humidity		

The identified risks consists of both direct and indirect impacts of climate change on bridges. Nasr et al. (2019b) emphasizes that for a bridge failure the reason for the incident is seldom identified as one single cause, which results in the importance of viewing potential climate change risks holistically instead of separately.

2.1.1 Accelerated degradation of material

A pertinent risk due to climate change relevant for bridges and infrastructure in general is the increased rate of material deterioration and degradation (Kumar & Imam, 2013). Numerous climate parameters affect the deterioration of the superstructure, the projected change of parameters like higher temperatures, increased precipitation, increase in relative humidity, and higher carbon concentrations in the atmosphere all induce accelerated deterioration (Nasr et al., 2019b). It should be acknowledged that the projection of increase for a climate parameter may only occur in some regions and under some scenarios.

An Australian study by Stewart et al. (2011) assessed the risk of corrosion initiation and damage to concrete structures under future climatic conditions in two cities, namely Sydney and Darwin. The climate parameters used in the assessment were carbon dioxide levels, temperature and humidity adopting several models as well. One of the conclusions of this study was that for some regions in Australia the risk of carbonation induced corrosion may increase by more than 400% by the year 2100. Regarding steel structures it is reasonable to assume that similar trends can be expected (Nasr et al., 2019b).

2.1.2 Thermally induced stresses

The projected increase of temperature in the future may lead to an increased demand on the deformation capacity of bridges; as a consequence, if the provided expansion joint is not sufficient to accommodate this increase in demand an increase of restrained thermal stresses is expected (Schwartz, 2010). Karl et al. (2009) points out that thermally induced stresses related to the projected climate change can impair bridge operations and increase maintenance costs, making it a risk worth considering. An additional climate parameter other than temperature that may induce increased stress is higher solar radiation which may increase the temperature gradient between the top and bottom of bridge decks (Nasr et al., 2019b).

Bridge structures endure complex thermal stresses that fluctuate continuously with time. The magnitude of the thermal stresses is contingent on different factors such as the climatological conditions, temperature variation inside the structure, geometry of the cross section and thermal properties of the material as well as the geographical location and the orientation of the bridge (Elbadry & Ghali, 1983).

2.2 Emission scenarios

The Intergovernmental Panel on Climate Change (IPCC) is a division of the United Nations established to assess the science related to climate change. IPCC (2013) presented four different emission scenarios in its most recent assessment report. Representative Concentration Pathway (RCP) scenarios consist of time series that specify concentrations and corresponding emissions related to greenhouse gases, aerosols and land use. The different scenarios are defined by specific radiative forcing characteristics, the scenarios are RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. The number that describe the scenarios indicates the approximate Radiative Forcing (RF) in W/m^2, that each scenario will give rise to in the year 2100 or at stabilisation after 2100, which is relative to pre-industrial RF values, see Figure 1. Radiative Forcing quantifies the change in energy flux per surface area, which entails that positive radiative forcing contributes to surface warming while surface cooling is the result of negative radiative forcing (IPCC, 2013).

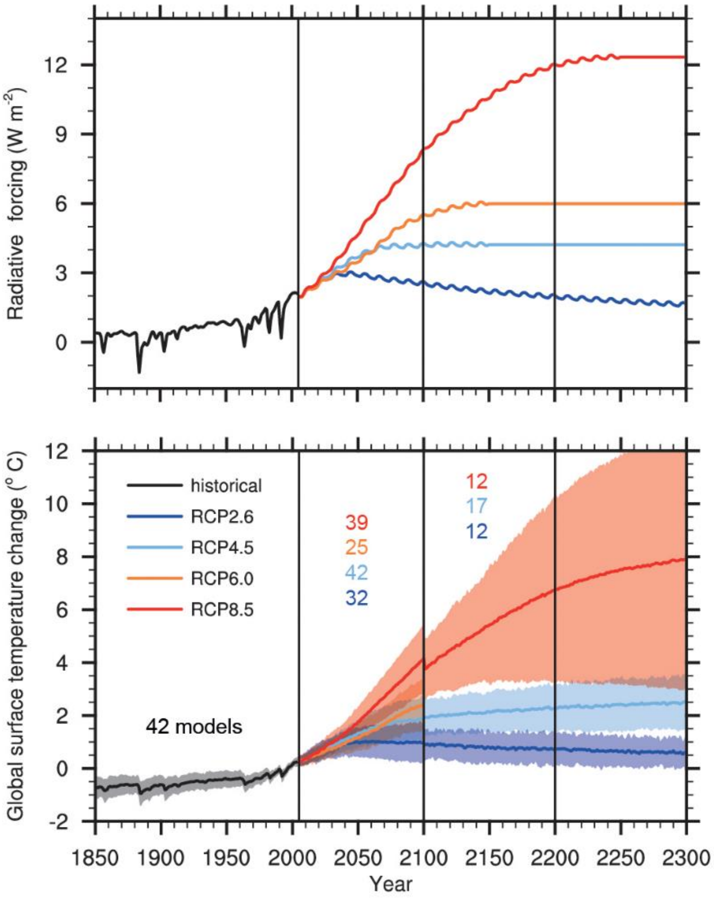


Figure 1 (Top) Total global mean radiative forcing for the four RCP scenarios. (Bottom) Changes in the global average surface temperature relative to 1986–2005 for the different emission scenarios (IPCC, 2013).

The lowest emission scenario is RCP 2.6 which is a relatively optimistic scenario, where climate policies are a significant aspect. This scenario is also referred to as RCP3-PD, peaks at approximately 3.0 W/m^2 and then declines to 2.6 W/m^2 in the year 2100 (IPCC, 2013). To achieve such low levels of radiative forcing, a substantial reduction of greenhouse gas emissions is required which could be enforced by implementing extremely stringent climate policies (Van Vuuren, et al., 2011). For this scenario the global mean temperature is projected to increase by the end of the century with 0.3°C to 1.7°C (IPCC, 2013).

The highest emission scenario is RCP 8.5 and can be seen as a relatively pessimistic scenario of the future, where climate policies are not implemented. The radiate forcing levels reaches 8.3 W/m^2 in the year 2100 and the RF afterward is on a rising trajectory (IPCC, 2013). This scenario assumes a rapid population growth which reaches about 12 billion by the year 2100 and technological developments at a lower rate which results in a highly energy-intensive scenario (Van Vuuren, et al., 2011). According to IPCC (2013) the projected increase for the global mean temperature by the end of the century for RCP 8.5 is 2.6°C to 4.8°C. Figure 2 presented the annual mean surface temperature change for the two investigated representative pathways, RCP 2.6 and RCP 8.5

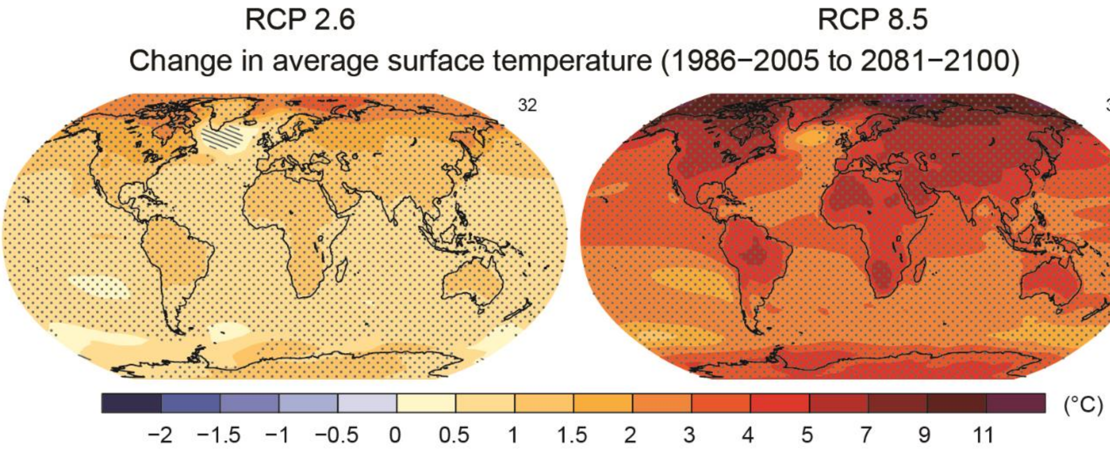


Figure 2 Change in the annual mean surface temperature for RCP 2.6 and RCP 8.5.

2.3 Climate scenario database

The Rossby Centre is a research unit at The Swedish Meteorological and Hydrological Institute (SMHI) that engages in research on the climate system's behaviour and the governing climate processes (SMHI, 2018b). The main tools for the research activities are the global and regional climate models developed within the Rossby Centre. For more than 20 years the research unit has worked on model development and evaluation of data to increase the knowledge of the future climate. The research consists of several aspects such as meteorological, oceanographical and hydrological.

The result from the climate research at the Rossby Centre was generated into an interactive database which is accessible on SMHI's website. The climate scenarios were created by combining emission scenarios, global and regional climate models for a specific modelled time period (SMHI, 2019). Modelled future climate data always contain uncertainties. There is not a climate model that is the best. For obtaining reliable results it is necessary to compare the projections of different models.

Global climate models comprise of a three-dimensional grid which give a representation of the whole atmosphere and the entire surface of the earth considering the land surface, oceans, lakes, ice and their interactions (SMHI, 2019). Climate indices are calculated over time for each grid, which represents a specific geographic location and elevation.

The grid spacing is generally quite large in a global climate model attaining a low resolution of detail at regional level, the reason is that it requires a lot of computer power which restricts the three-dimensional grid. Regional climate models are introduced when a smaller area of the earth is of interest, achieving a more detailed model with a smaller grid spacing. Interactions occurring in the surrounding area affecting the calculation area in a regional climate model are managed by the results from a global climate model.

For the climate scenario analysis for Sweden, the Rossby Centre's regional atmospheric model RCA which covers Europe was applied. This regional climate model consists of a grid resolution over the land surface amounting to 50x50 km. The historical data from observations is based on average values for a grid resolution of 4x4 km.

The database presents historical data and scenario data on several climate parameters for various geographical areas. The values in the result for the scenario data are presented relative to the mean values for the period 1961-1990. Scenarios and observations for Sweden are presented in the Climate scenario database which describes the observed climate up until the year 2018 and predictions for future climate development during the 21st century.

To obtain the relevant data from the database it is required to select a geographical area, emission scenario, season and climate parameter. Data was collected for each bridge by selecting the climate parameter of interest, the county corresponding to the location of the bridge, lastly choosing the scenario considering an optimistic and pessimistic approach, see Appendix 1.

3 Risk-based prioritisation method

3.1 Overview of the employed prioritisation method

The safety and performance of bridges can significantly be affected by climate change impacts. Climate change impacts can affect a bridge to a varying degree, some impacts are more severe and can initiate bridge failure whilst other impacts only disrupt the normal function of a bridge without endangering its structural safety. Considering the potential climate change impacts relevant to bridges, the proposed method aims to address the following questions:

- For a certain bridge of interest, which climate change impacts should be prioritised?
- For a group of important bridges, which of these bridges should be given precedence when considering the potential impacts of climate change?

The proposed method is an index-based risk method aiming at providing comparative assessments that are impartial and performed systematically. The proposed method is founded on the concept of risk and depends on assessing its different components. The four main risk components are hazard (H), exposure (I), vulnerability (V) and consequence (C). These components are represented with several indices and then combined into two different ranking indices, referred to as level-I ranking and level-II ranking which tackle the two aforementioned questions.

The purpose of level-I ranking is to prioritise the various climate change exposures for each bridge in the selection, addressing the first question. Level-II ranking is based on the results of level-I ranking, developing it to address the second question, achieving a prioritisation for the entire bridge selection considering the impacts of climate change.

The level-I ranking contains four indices that represent the four main risk components accompanied by an additional index representing the strength of evidence (E). For level-II ranking, an additional index which reflects the relative importance of the bridges in the selection (i_r).

The climate change impacts investigated are represented with models, to assess the increase in the future relative to the current climate, this is achieved by introducing historical climate data and scenario data in the assessment. Together with each model there is a need to identify the vulnerability indicators of the bridge, i.e. to define different characteristics of the bridge which demonstrate the susceptibility of the bridge to the impact of interest.

To represent the uncertainty in the assessment, each ranking index is evaluated twice which is accomplished through once adopting an optimistic approach and then adopting a pessimistic approach. This results in an optimistic and pessimistic value of level-I and level-II ranking indices and hence a lower and an upper limit are obtained for each ranking index.

3.3 Level-I ranking

3.3.1 Hazard

In the method, hazard is referred to as the potential change of an environmental parameter within a specific time period. Regarding the effects of climate change on bridges, the structures may not be directly affected by the hazard itself, instead the hazard can incite an exposure which subsequently may affect the bridge.

Exposures are instigated by the potential change of the environmental parameters, making these environmental parameters essential to analyse. The hazard is not a factor in the ranking, in the way that is contributes to value inserted in the ranking index equation, instead depending on the hazard level adopted it guides the climate data used in the assessment. In the analysis the hazard level is predefined by selecting a certain percentile of the probability distribution which is adapted for all exposures. Furthermore, applying an optimistic approach and then a pessimistic approach to the climate data. This results in a lower limit (H_o) and an upper limit (H_p) of the hazard index.

Normal distribution was the probability distribution used to analyse the climate data related to the environmental hazard. Normal distribution was adapted as there are no recommendations when processing climate data, while for other data there is a specific distribution that may be more suitable. The temperature data was the main environmental parameter utilized in this thesis. The 25th percentile values of RCP 2.6 were used for the optimistic approach while the 75th percentile values of RCP 8.5 were used for the pessimistic approach, see section 2.2 and Appendix 1 for more details. The percentiles used in the study were recommended in the article by Nasr et al. (2019a), which the authors based partly on the uncertainty associated with tail values of distributions.

3.3.2 Exposure

The exposure refers to the potential climate change impact on a bridge caused, or increased, by the hazard. The exposure index (I) describes the potential increase of the investigated climate change impact. This index is assessed twice, once optimistically (I_o) based on lower limit of the hazard index (H_o) and the second pessimistically (I_p) based on the upper limit of the hazard index (H_p). I_o and I_p are determined with Equations 1 and 2 respectively.

$$I_o = \max\left(\frac{e_o - e_c}{e_c}, 0\right) \tag{1}$$

$$I_p = \max\left(\frac{e_p - e_c}{e_c}, 0\right) \tag{2}$$

where e_o and e_p represent the exposure under H_o and H_p respectively and e_c represents the exposure under the current climate conditions.

The exposure cannot yield a negative value, a negative value indicates that there is no increase of the potential impact due to climate change when evaluating it with a specific model. If this would be the case, I_o and I_p are then assigned a value of zero according to Equations 1 and 2. For evaluating e_o, e_p, and e_c in Equations 1 and 2, models connecting the exposure to relevant environmental hazards are adopted.

3.3.2.1 Models

The selected potential climate change impacts for the study of the method were; increased deterioration rates and increased stress due to thermal movements of the bridge deck. The increase of deterioration rates was one of the climate change impacts assessed when investigating the practical feasibility of the proposed method for the hypothetical bridge examples. Considering it had been assessed previously, a viable model was attained from the article by Nasr et al. (2019a), presented in Table 2.

The increase of stress due to thermal movements of the bridge deck, was not documented in the article about the risk-based method. Therefore, research was conducted to obtain a model for this impact along with other indices. This led to the introduction of the model of thermal stress due to change in temperature. Furthermore, in this thesis the assessment is conducted on existing bridges that were built at a certain temperature in the past hence, i.e. construction temperature. It was determined that the assessment of the impact would be done with consideration to the construction temperature, comparing it to temperatures for the current and future climate.

Additionally, another choice was made to separate the increased stress due to contraction and increased stress due to expansion. To assess the increase of stress due to expansion, the maximum of the temperature index for the current and future climate would be compared, accounting for the construction temperature while for assessing the increased stresses due to contraction it would be the minimum of the temperature indices instead, see Figure 3.

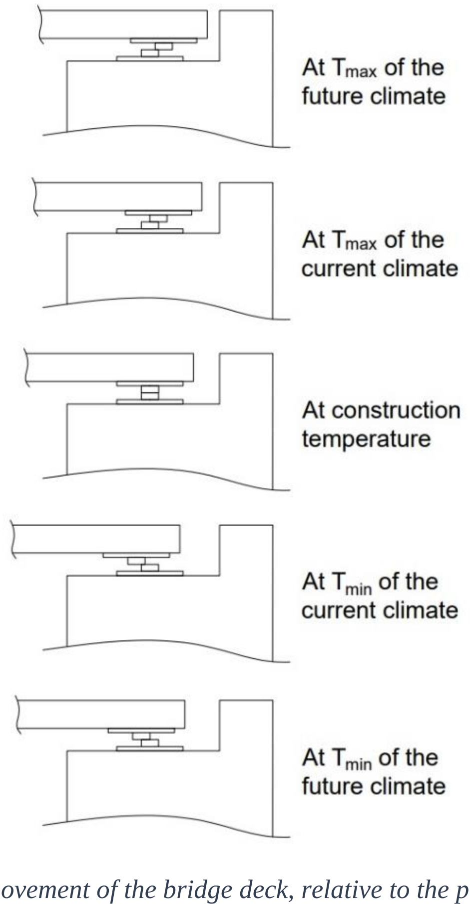


Figure 3 Illustrating the thermal movement of the bridge deck, relative to the position at construction.

Lastly, a choice was made to only assess expansion, excluding contraction from the assessment as it is not likely that it will become colder in the future resulting in increased contraction. Modifying the second climate change impact to comprise of increase of stress due to expansion. The exposure of increased stresses due to contraction could be assessed as well, though with the approach adapted in the thesis it would be considered a separate exposure. The models are choice by the decision maker. The models representing each of the potential climate change exposures are presented in Table 2.

Table 2 Models connecting the exposures of increased deterioration and increased stresses due to expansion to relevant environmental parameters.

Potential impact	Model
Increased deterioration rates	Corrosion rate (Duracrete, 2000) $i_{corr}(t)=i_{corr\text{-}20}\cdot\big(1+K\cdot(T(t)\text{-}20)\big)$ and $K=\begin{cases}0.025 \text{ if } T(t) < 20°\text{C}\\ 0.073 \text{ if } T(t) > 20°\text{C}\end{cases}$ (3) where $i_{corr}(t)$ is the corrosion rate at time *t*, $i_{corr\text{-}20}$ is the corrosion rate at 20°C, *T(t) is* the temperature (°C) at time *t* and *K* is a factor that has the values shown above.
Increased stress due to expansion	Thermal stress $\sigma = \alpha \cdot E \cdot \Delta T$ (4) where σ is the thermal stress, α is the coefficient of thermal expansion, *E* is the Young's modulus of the bridge material, Δ*T* is the differential between the maximum bridge temperature and the construction temperature of the bridge (°C).

Increased deterioration rates

The model by Duracrete (2000) is well known and depicts the effect of temperature on the corrosion rate, see Equation 3 in Table 2. The corrosion rate at 20°C, $i_{corr\text{-}20}$, is assumed to be constant for the different time periods analysed. The factor *K* is set to 0.025 as all the temperatures used in the assessment of the corrosion rate are less than 20°C. The remaining factor being the temperature at a specific time. The annual mean temperature was the temperature index used to describe the climate at a specific time. The optimistic and pessimistic change of the exposure of the increased deterioration rates, I_p and I_o, are calculated as shown below.

$$\mathrm{I_o} = \max\left(\frac{\mathrm{e_o} - \mathrm{e_c}}{\mathrm{e_c}}, 0\right) = \max\left(\frac{\mathrm{i_{corr}(t)_o} - \mathrm{i_{corr}(t)_c}}{\mathrm{i_{corr}(t)_c}}, 0\right)$$

$$I_p = \max\left(\frac{e_p - e_c}{e_c}, 0\right) = \max\left(\frac{i_{corr}(t)_p - i_{corr}(t)_c}{i_{corr}(t)_c}, 0\right)$$

where

$$e_c = i_{corr}(t)_c = i_{corr\text{-}20} \cdot \left(1{+}K\cdot(T(t)_c - 20)\right)$$

$$e_o = i_{corr}(t)_o = i_{corr\text{-}20} \cdot \left(1{+}K\cdot(T(t)_o - 20)\right)$$

$$e_p = i_{corr}(\mathrm{t})_p = i_{corr\text{-}20} \cdot \left(1{+}K\cdot\left(T(t)_p - 20\right)\right)$$

Also, where

$T(t)_c$	is the annual mean temperature for the current climate
$T(t)_o$	is the optimistic annual mean temperature for the future climate
$T(t)_p$	is the pessimistic annual mean temperature for the future climate

Increased stress due to expansion

The simplest way to determine displacement due to thermal expansion is to relate it directly to the bridge length using the linear equation, see Equation 5.

$$\Delta L = \alpha \cdot L \cdot \Delta T \qquad (5)$$

Moreover, thermal stress is determined as shown in Equation 4, see Table 2. These two expressions were the foundation for assessment of the second exposure. Thermal movement comprise of expansion and construction, in this thesis expansion is selected for further analysis. The initial position of a bearing or an expansion joint at construction, is compared to the current climate and to future climate to assess if there is any increase in thermal movements induce stress.

The material parameters are assumed to be constant, the remainder being the change in temperature. Emerson (1982) emphasises the gravity of accounting for the bridge temperature at the time of placement of joints and bearings when conducting an analysis. The proposed method accounts for the temperature the year of construction, which is presented by the annual mean temperature. The optimistic and pessimistic change of the exposure of increased stress due to expansion, I_p and I_o, are calculated as shown below.

$$I_o = \max\left(\frac{e_o - e_c}{e_c}, 0\right) = \max\left(\frac{\Delta T_{\max,o} - \Delta T_{\max,c}}{\Delta T_{\max,c}}, 0\right)$$

$$I_p = \max\left(\frac{e_p - e_c}{e_c}, 0\right) = \max\left(\frac{\Delta T_{\max,p} - \Delta T_{\max,c}}{\Delta \mathrm{T}_{\max,c}}, 0\right)$$

where

$$e_c = \Delta T_{\max,c} = \left(T_{\max,c} - T_0\right)$$

$$e_o = \Delta T_{\max,o} = \left(T_{\max,o} - T_0\right)$$

$$e_p = \Delta T_{\max,p} = \left(T_{\max,p} - T_0\right)$$

Also, where

$T_{\max,c}$ is the maximum daily mean temperature for the current climate

$T_{\max,o}$ is the optimistic maximum daily mean temperature for the future climate

$T_{\max,p}$ is the pessimistic maximum daily mean temperature for the future climate

T_0 is the construction temperature

3.3.3 Strength of Evidence

The strength of evidence index (E) accounts for the strength of evidence supporting the occurrence, or increase, of each exposure as a result of the climate change. This index is likewise assessed twice, once adopting an optimistic approach (E_o) and then adopting a pessimistic approach (E_p).

The description of the strength of evidence index applied in the assessment is presented in Table 3. The table is based on the classification of uncertainty obtained from Flage and Aven (2009), Goerlandt & Reniers (2016) points out that this is used for the assessments the strength of evidence, as it more advantageous than an uncertainty assessment.

Table 3 Values for the index E proposed by Nasr et al. (2019a)

Evidence strength	Strong	Average	Weak
E	1.0	1.0 - 0.2	0.2
Description	One or more of the following conditions are met: − Any assumptions made are judged as being very reasonable. − There exists a broad agreement/consensus among experts. − The phenomena involved are well understood.	Conditions between those describing strong and weak evidences.	One or more of the following conditions are met: − Some of the assumptions made involve obvious speculations. − There is a clear lack of agreement among experts. − Some of the phenomena involved are poorly understood.

Both the exposures analysed in the study are considered as relatively high strength of evidence supporting their occurrence due to climate change. Therefore, each exposure was assigned an index of 1.0 for both the pessimistic and the optimistic assessments.

3.3.4 Vulnerability

The vulnerability refers to the susceptibility of a bridge to being affected by an exposure triggered by the hazard. The vulnerability index (*V*) is determined by identifying relevant characteristics of a bridge that represent the susceptibility of the bridge affected by a certain exposure, in other words vulnerability indicators. Examples of vulnerability indicators are location, traffic volume, bridge geometry and material.

The different vulnerability indicators are constructed into a vulnerability scoring scheme for each investigated exposure. Every bridge in the selection is assigned a score based on its characteristics. The vulnerability index is calculated using Equation 6.

$$V_{ij} = \sum_{k=1}^{K} W_{jk} \cdot S_{ik} \qquad (6)$$

where V_{ij} is the vulnerability index of bridge i towards exposure j, W_{jk} is the weight of characteristic k in assessing the vulnerability of exposure j, S_{jk} is the score assigned to bridge i for characteristic k and K is the number of vulnerability indicators which are considered relevant for a certain exposure. As the previous indices, the vulnerability index is assessed twice, once optimistically and then pessimistically. The vulnerability scoring scheme for the exposure of increased deterioration rates is presented in Table 4.

Table 4 Vulnerability scoring scheme for the exposure of increased deterioration rates proposed by Nasr et al. (2019a); the table is inspired by NYSDOT (1997) and Ramey & Wright (1997).

Score	Bridge material	Age (A)	Zone	Traffic volume (Veh./day)
0	Reinforced or prestressed concrete	$A \leq 30$ *years*	Rural	$AADT \leq 4000$
0.1		$10 < A \leq 30$ *years*		
0.2	Properly painted steel		Urban	
0.3		$30 < A \leq 50$ *years* (recently rehabilitated)		$4000 < \mathrm{AADT} \leq 25000$
0.4	Properly impregnated timber			
0.5		$30 < A \leq 50$ *years* (not recently rehabilitated)	Industrial	
0.6	Not (properly) painted steel			
0.7		$A > 50$ *years* (recently rehabilitated)	Coastal	$AADT > 25000$
0.8	Not (properly) impregnated timber			
0.9		$A > 50$ *years* (not recently rehabilitated)		
1.0				
$W_{det,k}$	0.25	0.25	0.25	0.25

For the second exposure of increased thermal stress due to expansion several vulnerability indicators were noted in previous literature, i.e. the bridge deck material, geometry of the cross section, support conditions, capacity and condition of the bearings and expansion joints (Elbadry & Ghali, 1983; Moorty & Roeder, 1992; Branco & Mendes, 1993; SS-EN1991-1-5, 2003; Larsson, 2012). However, to the best of the author's knowledge, no previous literature ranking the identified indicators exist and hence only the bridge deck material was used for assessing the vulnerability of bridges to this exposure. The vulnerability indices for the second exposure of increased stress were based on a table C.1 from SS-EN 1991-1-5 (2003) utilizing the linear expansion for respective bridge deck material. Table 5 presents the coefficients of linear expansion obtained from Eurocode and the vulnerability scoring for the exposure of increased stress due to expansion assigned by the decision maker, namely the author of this study.

Table 5 Vulnerability score for the exposure of increased stress due to expansion, the table is inspired by SS-EN 1991-1-5 (2003)

Eurocode		Decision maker		
Material	Coefficients of linear expansion ($\cdot 10^{-6}$/°C)	Bridge deck material	Score	
			V_o	V_p
Concrete, lightweight aggregate	7	Reinforced concrete	0.1	0.6
Concrete, other	10			
Structural steel, wrought or cast iron	12	Structural steel	0.4	0.9
Stainless steel	16			

This resulted in a vulnerability index range of 0.1-0.6 for reinforced concrete and 0.4-0.9 for structural steel. Steel has a greater coefficient of linear expansion, indicating it more sensitive to temperature change therefore it is assigned a higher vulnerability score than concrete.

3.3.5 Consequence

The associated consequences with each exposure are accounted for with the consequence index. The scale used for assigning the index C with assessments of the potential exposures is presented in Figure 4. On the horizontal axis the various exposures are presented while the vertical axis provides a score depending on the degree of the consequence, failure is defined as total collapse. The scale provides an upper and lower limit for the index, representing an optimistic and a pessimistic evaluation of the consequences.

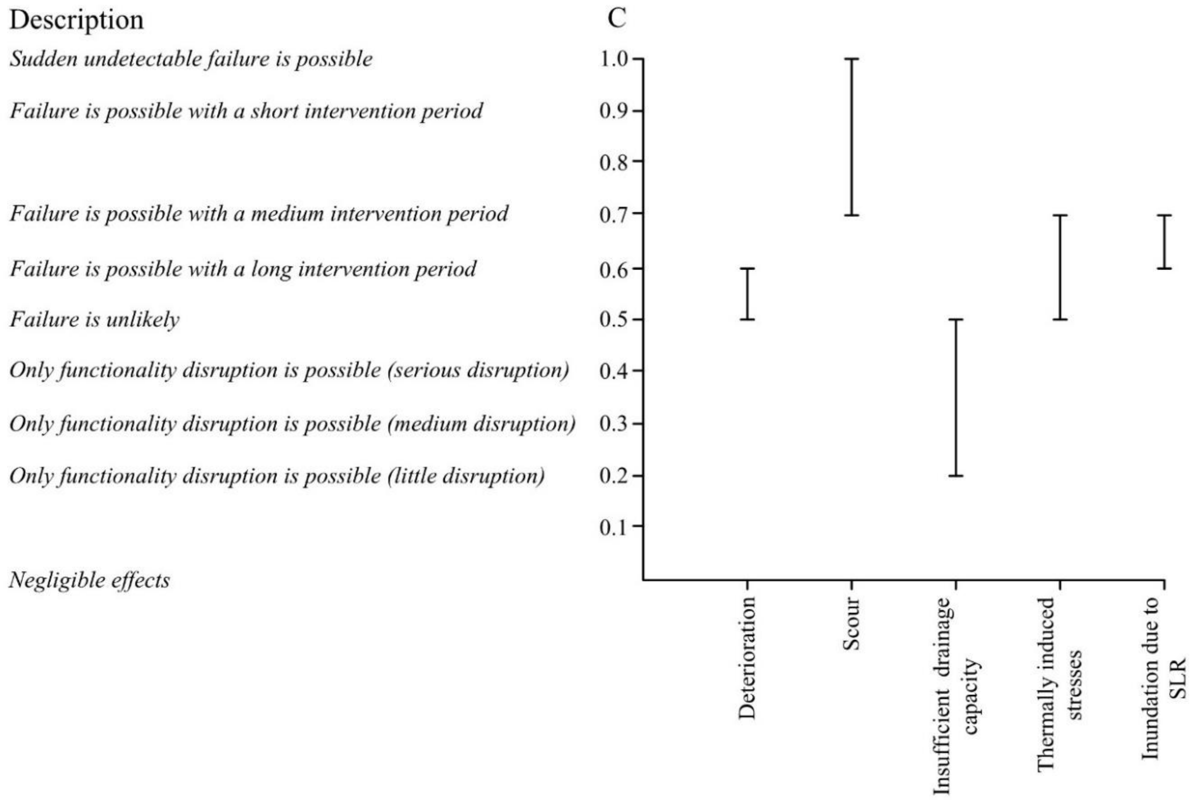


Figure 4 Scale for the index C, with assessments of five potential exposure modified after Nasr et al. (2019a).

3.3.6 Level-I ranking index

To obtain the level-I ranking index (RI_1), the weighted product aggregation method is used to combine the previously presented indices in one ranking index, see Equation 7. Nasr et al. (2019a) states that this method was selected for the ease of application and its simplicity.

The optimistic values of the indices generate the lower limit for the ranking index ($RI_{1,o}$) while the upper limit of the ranking index is determined with the pessimistic values of the indices obtaining ($RI_{1,p}$)

$$RI_1 = \left(I_n^{W_{I_n}} \cdot E^{W_E} \cdot V^{W_V} \cdot C^{W_C}\right) \cdot 100 \tag{7}$$

$$I_{on} = \frac{I_o}{I_{p,\max}} \tag{8}$$

$$I_{pn} = \frac{I_p}{I_{p,\max}} \tag{9}$$

where I_n is the normalised value of I_o or I_p calculated as shown in Equation 8 and Equation 9 while W_{I_n},W_E, W_V and W_C are the weights assigned to the different indices. In the assessment performed in this study, equal weights were assigned to the different indices when evaluating RI_1, this results in weights of 0.25 for the level-I ranking index. If a decision maker would deem an index more important, the index in question could be assigned a greater weight relative to the other indices in the ranking.

All exposure indices used in calculation are normalised, to ensure that the exposure indices have the same range of possible values from 0 to 1.0. For the level-I ranking index the normalisation in Equation 8 and Equation 9 is performed with respect to the maximum I_p over all exposures for each bridge identifying $I_{p,\max}$ as the purpose of ranking is to prioritise the different exposures for a certain bridge.

3.4 Level-II ranking

3.4.1 Bridge relative importance

When ranking the different bridges in the selection a comparative assessment of the relative importance of each bridge is required. For this purpose, an index representing the bridge relative importance is introduced according to Equation 10.

$$i_r = \frac{\frac{AADT_i}{AADT_{\max}} + \frac{DL_i}{DL_{\max}}}{2} \tag{10}$$

where $AADT_\mathrm{i}$ is the average annual daily traffic for a bridge i, DL_i is the detour length of a bridge i, $AADT_{\max}$ and DL_i are the maximum values of these indicators for the entire bridge selection.

In the method presented in Nasr et al. (2019a), a third factor is proposed for the bridge relative importance index, which is the replacement cost. As this information could not be obtained, the index is only composed of the *AADT* and *DL*. The evaluation of the relative bridge importance may be given a better representation if more factors could be included. Nasr et al. (2019a) also mentions there are other factors which are not reflected in these indicators such as military importance or if the bridge is an essential part of the road network in case of an evacuation.

3.4.2 Level-II ranking index

The level-II ranking index is created in the same way as level-I ranking index by aggregating the different indices into one ranking index (RI_2), with the use of the weighted product method resulting in Equation 11. The major difference being the additional index of the relative bridge importance and when normalising the exposures for level-II ranking, it is done with respect to the maximum I_p over all bridges for each exposure.

$$RI_2 = \left(I_n^{W_{I_n}} \cdot E^{W_E} \cdot V^{W_V} \cdot C^{W_C} \cdot i_r^{W_{i_r}} \right) \cdot 100 \tag{11}$$

where I_n is the normalised value of I_o or I_p calculated as shown in Equation 8, Equation 9 and W_{I_n}, W_E, W_V, W_C and W_{i_r} are the weights assigned to the different indices. Equal weights were assigned to the different indices when evaluating RI_2, this results in weights of 0.20 for the level-II ranking index. RI_2 is assessed twice, similar to RI_1, once adopting an optimistic attitude and then a pessimistic attitude. The average RI_2 values over all exposures are used to rank the bridges in the selection.

4 Bridge selection

4.1 BaTMan database

The Swedish Transport Administration (STA) uses a management system referred to as BaTMan (Bridge and Tunnel Management) which was developed to facilitate the management process for the entire lifespan of a structure. BaTMan is a digital web-based system containing a searchable database where users such as managers, consultants and planners can receive support with management work regarding both inspection, procurement and action (STA, n.d.). In the searchable database, users can find information on over 30,000 registered bridges, register new information on specific structures, and check previously performed actions.

The Swedish Transport Administrations methodology which forms the basis for management of structures is available in the BaTMan manual. In the manual the Swedish Transport Administration (2019) states the importance of using a management system as it benefits both the owner and the user. Through the implementation and documentation of conducted activities owners can optimize their costs and in turn ensure safety and accessibility for road users. The BaTMan manual describes the implementation of the various administrative steps and how these are documented. In addition, there are measurement methods, concepts and definitions, code lists etc. described in the manual.

The BaTMan database contains of information about numerous structures, covering different areas and parameters. All structures that are registered in BaTMan are assigned an identity number and information about the owner, manager, condition and geographical location are catalogued (STA, 2019). Besides this general information the following data is added continuously in the system; drawings, technical data, capacity, passages, inspections, performed maintenance and data of monitoring.

4.2 Selection process

The bridge selection that was assessed with the method was chosen on the basis that the bridges were well-known and located in different counties of Sweden. The bridge usage had to be road traffic, which meant that exclusively pedestrian bridges were not eligible. The material prerequisite of the bridge selection was that it had to be mainly constructed out of concrete and steel.

The Long Span Bridge database created by Caprani and De Maria (2019) was a tool used to narrow down the selection. Considering the criteria’s mentioned in the section above and the limitations, the following bridges were chosen: Älvsborg Bridge, Uddevalla Bridge, High Coast Bridge, North Traneberg Bridge and South Traneberg Bridge. In addition, two bridges were added to the selection, these were recommended by the Swedish Transport Administration. These two bridges are referred to as the West and East Bridge crossing the river Lagan. A total of seven bridges were assessed, their geographical positions are presented in Figure 5.

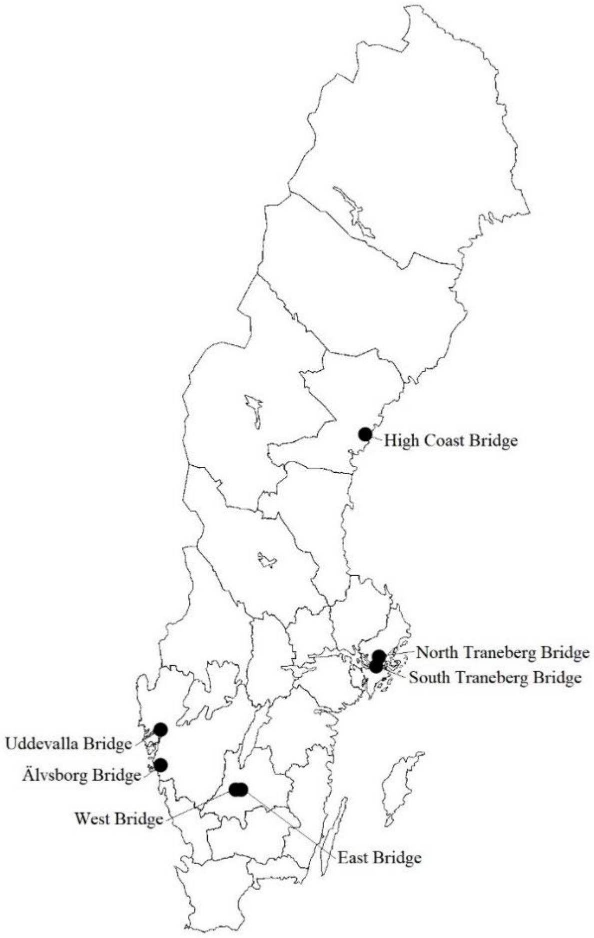


Figure 5 Map of Sweden with location of bridges marked out (Based on figure by Lokal Profil, CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=10214629)

4.2.1 Älvsborg Bridge

The Älvsborg Bridge is a suspension bridge located at the harbour entrance of Gothenburg, it took three years to complete and the bridge was operational in 1966. The bridge connects the north and south part of Gothenburg as it crosses the Göta Älv river. The bridge is located near the coast as well as in the centre of the city. At the north abutment there is a large industrial area.

The main span is constructed with a steel truss, while the end spans and pylons are made of concrete. All the steel in the main span was repainted during 2007 (STA, n.d.). To maintain the function and fulfil the safety requirements of the over 50-year-old bridge, continuous maintenance is performed, during 2020 new pavement will be installed on the bridge (STA, 2020). During the past years other maintenance activities have been performed, such as replacing the expansion joints at the abutments and installing a monitoring system to observe the movements of the bridge (Mageba, 2015; STA, n.d.).

Today, the bridge is the second busiest route crossing the river, the first one being the Tingstad Tunnel. The latest measurements performed of the traffic volume by the Swedish Transport Administration (n.d.) for the Älvsborg Bridge were performed during 2019 and amounted to 55520 AADT.

4.2.2 Uddevalla Bridge

The Uddevalla Bridge is a cable-stayed bridge with a semi-fan system crossing Sunninge Sound located west of the city Uddevalla. The deck of the bridge is a composite structure, combing steel and reinforced concrete while the pylons are reinforced concrete (STA, n.d.).

The route E6, originally passed through the city of Uddevalla, the planning of an alternative route was initiated due to increasing traffic demands and associated delays (Mageba, 2012). The result of the planning was a bridge as it was considered the best solution which could integrate with the environment with a minimal impact. The new route due to the Uddevalla Bridge shortened the previous route by 12.8 km (Mageba, 2012). The traffic volume on the Uddevalla Bridge is about 19000 AADT (STA, n.d.).

4.2.3 North and South Traneberg Bridge

The original Traneberg Bridge is a double arch bridge located in central Stockholm, it was constructed during 1932-1934. The bridge was the world's longest arch bridge cast in concrete when it was completed, with a span of 181 meters (Stockholm stad, 2013). Separate traffic was crossing over each bridge arch, a section of the bridge deck was utilized for road traffic while the other section was used for the trams, later on the trams were replaced by the metro (Dufwa, 1986).

The condition of the Traneberg Bridge was gradually deteriorating as the result of the increasing traffic volumes and extensive corrosion partially induced by road salt (Uusmann, 1997; Hassanzadeh, 2014) Restrictions limiting the heavy traffic were imposed as the roadway was in such a bad state. Under the prevailing circumstances the bridge underwent comprehensive renovation and retrofitting during 1998-2005. The bridge was retrofitted by keeping the double concrete arches and reconstructing the pillars and the deck (STA, n.d.). In addition, the third arch bridge was built south of the original Traneberg Bridge. The new arch bridge is a prefabricated steel arch that was cladded with concrete to merge with the original arches. The new roadway bridge was inaugurated in 2002 and as it opened for traffic the renovation started on the older structure.

The Traneberg Bridge is today a triple arch bridge consisting of three parallel parts, the first arch for the metro, the second arch for road traffic moving west and the last arch constructed is used for road traffic headed east. The arch bridge with the deck being operated by the metro is excluded from the assessment as only roadway bridges are of interest in this thesis. Henceforth, the other two bridge arches are referred to as the North and South Traneberg Bridge. The distinction is made as the south bridge was built later to facilitate the north bridge. The North and South Traneberg Bridge are highly trafficked bridges with approximately 60000 AADT for each bridge (STA, n.d.).

4.2.4 High Coast Bridge

The High Coast Bridge is a suspension bridge that crosses the Ångermanälv River, connecting the city Veda in Härnösands municipality in the south with the city Hornö in Kramfors municipality in the north. The bridge is located in a rural area as well as near the coast as the name of the bridge suggests.

The bridge was built 1993-1997 as a part of a larger project called the High Coast Project that aimed to improve the standard of the E4 road in Västernorrland county (Jörgensen, Petersen, & Pettersson, 1999) The old route featured several bottlenecks and the Sandö Bridge which was the previous bridge carrying the E4 road across the Ångermanälv River did not fulfil the requirements for live load.

The total length of the High Coast Bridge is 1867 meters, with a main span of 1210 meters. The bridge deck in the main span is a multiple-cell steel box girder and the end spans are constructed with prestressed concrete while the pylons are made of reinforced concrete (Jörgensen, et al., 1999; STA, n.d.). The traffic volume for the High Coast Bridge was measured in 2019 to 4900 AADT (STA, n.d.).

4.2.5 West and East Bridge crossing Lagan

The Bridge crossing Lagan consists of two concrete highway bridges that carry the E4 road across the river Lagan, located in a rural area of Vaggeryd municipality, Jönköping County. A distinction is made between the West Bridge and the East Bridge as they were built at different time periods and as different construction types.

The East Bridge is a slab frame bridge with a total length of 24 meters that was built in 1979. The West Bridge was built 15 years later, in 1994 as a continuous slab bridge with a total length of 34 meters. Each bridge has a roadway consisting of two lanes with traffic headed in one direction, the East Bridge carrying traffic moving north and the West Bridge carrying traffic moving south. The bridges are exposed to similar traffic volumes, with an AADT of 7600 for each bridge (STA n.d.).

5 Data

5.1 Bridge data

The characteristics of each bridge in the selection are used in the assessment of the vulnerability index for the exposures. How the different characteristics were obtained or determined as well as some assumptions and simplifications adopted are presented in the succeeding subsections. Table 6, presents the summary of the necessary bridge characteristic used to perform the qualitative assessment.

5.1.1 Bridge material

Bridges are advanced structures constructed out of several elements and materials. The material of the bridge is a parameter of importance for both climate change exposures analysed in this thesis. To apply the proposed vulnerability scoring schemes and values in the assessment, certain simplifications regarding the material of the bridge needed to be adapted.

For the exposure of increased deterioration rates, a representative bridge material for the whole bridge was selected. As the model for this exposure is based on corrosion rates, the more perceptive material to corrosion was chosen to represent the bridge. Therefore, if a bridge in question had e.g. pylons out of reinforce concrete and a steel truss deck in the main span, the chosen representative material for this bridge was determined to steel. This was the case for some of the bridges in the bridge selection which had a substantial amount of steel as a part of the superstructure. Some data was obtained from BaTMan regarding the condition of the steel elements, though not for all bridges in the selection therefore it is assumed that all the steel is properly painted.

The exposure of increased stress due to expansion, was assessed with consideration to the longitudinal thermal movements of the bridge deck. As a result, defining the material of the deck for each bridge was pertinent. For the bridges with more than one span, the structure of the deck and material varied between the main span and end spans. To move forward it was determined that for these bridges the material representing the bridge deck would be the material in the main span. Moreover, for the bridge with a composite structure, steel was chosen to represent the bridge deck due to the linear expansion coefficient being greater for steel than concrete. For the slab bridges and concrete arch bridges in the bridge selection, determining the representative material for the whole bridge and for the bridge deck was less challenging.

5.1.2 Age

Bridges deteriorate with age as they are affected by the environment and usage and therefore susceptibility increases with age. A definition of rehabilitation was set as it was necessary for the assessment of vulnerability for the first exposure. The bridge is considered rehabilitated if extensive maintenance has been performed during the past 20 years, examples of maintenance is repainting the structural steel elements against corrosion or exchanging worn out concrete elements.

5.1.3 Zone

Several of the bridges in the selection are located near the coast and at the same time either in an urban or rural area. Defining the specific zone for each bridge in the selection was challenging, as the proposed vulnerability scheme for the increased deterioration rates does not provide a detailed description of the zones mentioned. To facilitate the categorisation process a definition of a coastal bridge was adopted based on Stewart et al. (2011) which states if the bridge is located within 50 km from the coast it is seen as a coastal bridge.

5.1.4 Traffic volume

The AADT was obtained from the BaTMan database for each bridge, the latest measurements performed for each bridge were used accounting for the total traffic on the bridge in question. The traffic volume is assumed to be constant, no consideration to changes of the traffic volume in the future are accounted for in the assessment.

5.1.5 Detour length

The definition of detour length is the total additional distance travelled by a vehicle if the bridge is no longer operational. Generally, when crossing a bridge there is an origin and a destination for the vehicle, though in this case is neither is defined. The only thing that is predetermined is the desire to cross the bridge.

The detour length was determined with the use of Google Maps. To simplify the process of determining the detour length some guidelines were set. The definition of the starting point is the closest interchange before driving on to the bridge in question and the end point is defined as the next available interchange when driving off the bridge. The use of the traffic interchange as the start and end point is motivated by the fact that if the bridge would be closed this would be where the driver takes another exit for the alternative route. If the bridge in question had traffic in both direction which is the case for the majority of the bridges in the bridge selection, the detour length was determined for approaching the bridge in both directions and the average detour length was chosen to represent the bridge.

Table 6 Characteristics of the bridge selection.

Characteristics	Älvsborg Bridge	Uddevalla Bridge	North Traneberg Bridge	South Traneberg Bridge	High Coast Bridge	West Bridge	East Bridge
County	Västra Götaland	Västra Götaland	Stockholm	Stockholm	Västernorrland	Jönköping	Jönköping
Bridge material	Properly painted steel	Properly painted steel	Reinforced concrete	Reinforced concrete	Properly painted steel	Reinforced concrete	Reinforced concrete
Bridge deck material	Structural steel	Structural steel	Reinforced concrete	Reinforced concrete	Structural steel	Reinforced concrete	Reinforced concrete
Inaugurated	1966	2000	1934	2002	1997	1994	1979
Age (years)	54	20	86	18	23	26	41
Recently rehabilitated	Yes	No	Yes	No	No	No	No
Zone	Coastal	Coastal	Coastal	Coastal	Coastal	Rural	Rural
AADT (veh./day)	55520	18642	59577	56171	4909	7470	7644
Detour length (km)	8.20	12.9	7.50	7.50	24.4	3.00	4.40

5.2 Climate data

Obtaining climate data was a central point for the assessment of climate change impacts on the bridge selection. The climate data for the assessment was obtained from the Climate scenarios database created by the Rossby Centre, with the temperature being the main climate parameter utilized in this thesis.

5.2.1 Temperature

The time frame used in the thesis is a decadal approach, the current climate is represented by historical data from 2010-2018 and the future climate is represented by scenario data for the 2050s, 2070s and 2090s. A decadal comparison is chosen to obtain a good representation of the analysed climate.

The air temperature is assumed to be the same as the bridge temperature, which is a simplification of the reality as other climate parameter affect the bridge temperature (e.g. solar radiation, wind speed etc.). This simplification is adapted due to the available climate data, though in reality there is a difference between the air temperature and bridge temperature.

The temperatures used in the assessment of the exposure of increased deterioration rates and for the exposure of increased stress due to expansion are presented in Table 6 and Table 7 respectively. For the exposure of increased deterioration rates the annual mean temperature was used to while for the increased stresses due to expansion the maximum daily mean temperature was used mainly. The use of these temperature indices for the assessment of the increased of the exposures was a choice of the decision maker. The processed temperature data and the procedure of obtaining the values in Table 7 and Table 8 is explained in Appendix 1.

Table 7 The temperature change used for the exposure of increased deterioration rates; T: annual mean temperature.

Bridge	Current climate for the 2010s	Future climate					
		2050s		2070s		2090s	
		25th percentile of RCP 2.6	75th percentile of RCP 8.5	25th percentile of RCP 2.6	75th percentile of RCP 8.5	25th percentile of RCP 2.6	75th percentile of RCP 8.5
	T (°C)	T (°C)	T (°C)	T (°C)	T (°C)	T (°C)	T (°C)
Älvsborg Bridge	7.28	7.18	9.17	7.27	10.2	6.99	11.2
Uddevalla Bridge	7.28	7.18	9.17	7.27	10.2	6.99	11.2
North Traneberg Bridge	7.11	7.12	9.13	7.11	10.2	6.75	11.2
South Traneberg Bridge	7.11	7.12	9.13	7.11	10.2	6.75	11.2
High Coast Bridge	3.21	3.60	5.92	3.57	7.16	3.13	8.41
West Bridge	6.83	6.75	8.71	6.80	9.75	6.48	10.8
East Bridge	6.83	6.75	8.71	6.80	9.75	6.48	10.8

Table 8 The temperature indices used to assess the exposure of increased stress due to expansion; T_0*: annual mean temperature at year of construction,* $T_{max,c}$*: maximum daily mean temperature representing the current climate,* $T_{max,o}$*,*$T_{max,p}$*: optimistic and pessimistic maximum daily mean temperature representing the future climate.*

Bridge	Construction temperature	Current climate for the 2010s	Future climate					
			2050s		2070s		2090s	
			25th percentile of RCP 2.6	75th percentile of RCP 8.5	25th percentile of RCP 2.6	75th percentile of RCP 8.5	25th percentile of RCP 2.6	75th percentile of RCP 8.5
	T_0 (°C)	$T_{max,c}$ (°C)	$T_{max,o}$ (°C)	$T_{max,p}$ (°C)	$T_{max,o}$ (°C)	$T_{max,p}$ (°C)	$T_{max,o}$ (°C)	$T_{max,p}$ (°C)
Älvsborg Bridge	5.10	21.5	20.5	23.4	20.3	24.3	19.7	26.1
Uddevalla Bridge	8.00	21.5	20.5	23.4	20.3	24.3	19.7	26.1
North Traneberg Bridge	6.80	23.5	22.4	25.3	22.4	26.6	22.1	28.0
South Traneberg Bridge	7.20	23.5	22.4	25.3	22.4	26.6	22.1	28.0
High Coast Bridge	3.40	19.3	18.7	21.3	18.4	22.0	18.2	23.5
West Bridge	6.50	21.4	20.6	23.5	20.4	24.4	20.0	26.1
East Bridge	4.80	21.4	20.6	23.5	20.4	24.4	20.0	26.1

6 Calculation example

To easier comprehend the results, a calculation example is presented. The calculation example is performed for the High Coast Bridge, located in Västernorrland County. The selected future decade for the calculation example is the 2070s. The calculations are performed in the same way for the other bridges in the bridge selection, regardless of the investigated decades. The selected decade solely alters the temperature data used in the assessment. The temperature data obtained from SMHI is presented as the change of a specific temperature index, relative to a reference value. The reference values for the temperature indices relevant for the qualitative assessment are presented in Table 9.

Table 9 Corresponding reference value for the annual mean temperature and the maximum daily mean temperature based on data from 1961-1990 for the High Coast Bridge.

Bridge	County	Reference value	
		Annual mean temperature	Maximum daily mean temperature
High Coast Bridge	Västernorrland	1.9°C	18°C

The temperature values presented in the tables in this chapter are presented with consideration to the reference values unless stated otherwise.

6.1 Hazard

For the exposure of increased deterioration rates the main temperature index used in the assessment, was the annual mean temperature. For current climate, the annual mean temperature for the 2010s is presented in Table 10. The value that is used to represent the current climate for this exposure is obtained by taking the mean value over the decade which amounts to 3.21°C.

Table 10 The current climate for Västernorrland County during the 2010s, represented by the annual mean temperature, T_a: annual mean temperature (°C), $T(t)_c$: representative temperature (°C), mean value over the decade.

year	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*
T_a	0.80	4.00	2.70	3.30	4.40	4.00	3.30	3.10	3.30
$T(t)_c$	3.21								

For processing the future climate, accounting for the optimistic and pessimistic attitude, the probability distribution and the hazards levels are introduced. The predefined hazard levels were set to the 25th percentile values of RCP 2.6 for the optimistic approach while for the pessimistic approach the 75th percentile values of RCP 8.5 were adopted.

The Rossby Centre used numerous global climate models when projecting the future climate and generating the scenario data. The combinations of GCM’s and RCP scenarios used in the analysis are presented in Appendix 1. The scenario data consists of several value for a single year, depending on which of the RCP scenarios is investigated the amount of processed values differs. To obtain a single value for each year of the investigated future decade, the mean value and standard deviation are determined. Furthermore, with the use of inverse normal distribution and the specific percentile for each RCP scenario the value representing each year is calculated. Lastly to attain a single value to represent the entire decade, the mean value is determined for the values obtained with the probability distribution, see Table 11 and Table 12.

Table 11 The future climate for Västernorrland County during the 2070s, represented by the annual mean temperature for RCP 2.6. $\bar{x}$: mean value, σs: standard deviation, T3, T6, T7: projected annual mean temperatures (°C), Tn: temperature obtained for the 25th percentile (°C), $T(t)_o$: representative temperature (°C), mean value over the decade.

year	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
T_3	3.13	5.14	3.57	2.46	2.60	5.29	4.24	3.98	4.67	3.55
T_6	3.98	4.76	3.80	3.96	3.78	2.95	4.71	5.49	5.46	4.16
T_7	4.61	3.94	4.61	3.35	3.82	3.59	4.18	3.79	3.68	3.92
$\bar{x}$	3.91	4.61	3.99	3.26	3.40	3.94	4.38	4.42	4.60	3.88
σ_s	0.74	0.61	0.55	0.75	0.69	1.21	0.29	0.93	0.89	0.31
T_n	3.41	4.20	3.62	2.75	2.93	3.13	4.18	3.79	4.00	3.67
$T(t)_o$	3.57									

Table 12 The future climate for Västernorrland County during the 2070s, represented by the annual mean temperature for RCP 8.5. $\bar{x}$: mean value, σ_s: standard deviation, $T_{1\text{-}9}$: projected annual mean temperatures (°C). T_n: temperature obtained for the 75th percentile (°C), $T(t)_p$: representative temperature (°C), mean value over the decade.

year	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
T_1	6.44	5.32	6.77	7.40	6.38	7.48	7.45	6.31	7.95	6.05
T_2	5.62	5.78	6.69	6.13	5.43	6.99	6.69	6.56	6.48	7.24
T_3	5.92	6.67	6.04	5.69	6.20	6.33	7.12	4.84	6.30	6.26
T_4	7.62	7.26	7.76	8.08	6.24	7.53	7.90	7.93	7.71	5.94
T_5	5.31	6.92	8.09	7.51	7.16	7.15	7.54	6.83	7.82	7.95
T_6	6.20	8.01	7.02	7.65	7.82	6.51	7.32	6.01	6.70	8.31
T_7	6.66	6.02	7.62	6.31	5.61	6.44	5.88	7.07	6.67	5.46
T_8	5.29	5.77	7.37	6.52	7.02	5.40	5.55	6.48	6.30	5.57
T_9	4.78	4.72	6.76	6.89	5.50	5.88	4.96	4.69	6.52	6.08
$\bar{x}$	5.98	6.27	7.12	6.91	6.37	6.63	6.71	6.30	6.94	6.54
σ_s	0.86	1.03	0.64	0.80	0.82	0.72	1.02	1.03	0.68	1.04
T_n	6.56	6.97	7.56	7.45	6.93	7.12	7.40	6.99	7.40	7.24
$T(t)_p$	7.16									

The maximum daily mean temperature was the main temperature index used when assessing the exposure of increased stress due to expansion. For the 2010s the current climate is presented in Table 13. The value that is used to represent the current climate for this exposure is obtained by taking the maximum values over the decade which amounts to 19.3°C.

Table 13 The current climate for Västernorrland County during the 2010s, represented by the maximum daily mean temperature, T_m: maximum daily mean temperature (°C), $T_{max,c}$: representative temperature (°C), maximum value over the decade.

year	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*
T_m	19.3	19.0	18.2	19.0	18.9	19.3	18.6	19.3	19.2
$T_{\max,c}$	19.3								

The construction temperature was the second temperature index that was considered in the assessment of the exposure of increased stress. The construction temperature for High Coast Bridge is represented with the annual mean temperature from the year of construction which for 1997 was 3.40°C.

Similar steps as for the exposure of increased deterioration rates are performed to obtain a single value to represent the entire decade for the exposure of increased stress due to expansion. The major modification being the use of a different temperature index. Starting with calculating the mean value and standard deviation for each year of the decade. Moreover, a single value is obtained for each year by applying the predefined percentile for each RCP scenario and using the inverse normal distribution. Lastly to attain a single value to represent the entire decade, the mean value is determined for the values obtained with the probability distribution, see Table 14 and Table 15.

Table 14 The future climate for Västernorrland County during the 2070s, represented by maximum daily mean temperature for RCP 2.6. $\bar{x}$: mean value, σ_s: standard deviation, T_3, T_6, T_7: projected maximum daily mean temperatures (°C), T_n: temperature obtained for the 25th percentile (°C), $T_{max,o}$: representative temperature (°C), mean value over the decade.

year	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
T_3	20.0	17.4	16.8	19.7	17.4	19.6	18.9	16.8	18.5	19.2
T_6	22.0	19.3	18.2	20.7	21.6	18.1	21.4	24.2	22.3	19.9
T_7	19.0	18.3	19.7	20.8	19.3	20.8	19.2	18.9	17.9	21.2
$\bar{x}$	20.3	18.3	18.2	20.4	19.4	19.5	19.8	20.0	19.5	20.1
σ_s	1.53	0.98	1.41	0.60	2.08	1.39	1.34	3.83	2.36	0.99
T_n	19.3	17.7	17.3	20.0	18.0	18.5	18.9	17.4	18.0	19.4
$T_{\max,o}$	18.4									

Table 15 The future climate for Västernorrland County during the 2070s, represented by the maximum daily mean temperature for RCP 8.5. $\bar{x}$: mean value, σ_s: standard deviation, $T_{1\text{-}9}$: projected maximum daily mean temperatures (°C). T_n: temperature obtained for the 75th percentile (°C), $T_{max,p}$: representative temperature (°C), mean value over the decade.

year	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
T_1	20.1	19.6	21.3	20.1	21.8	21.8	21.8	22.7	20.6	23.1
T_2	20.2	19.2	22.4	21.1	20.4	21.0	21.5	20.8	18.8	21.2
T_3	22.5	19.4	19.7	20.2	19.5	19.8	21.7	19.2	21.0	20.7
T_4	20.6	23.0	23.3	21.5	21.9	23.9	21.8	22.2	21.6	19.1
T_5	20.6	19.3	20.5	22.0	20.5	20.7	22.7	20.7	22.5	20.9
T_6	20.6	22.7	21.3	21.2	22.8	23.1	25.0	21.6	22.5	22.9
T_7	19.9	22.7	19.0	20.4	19.3	21.4	19.8	20.0	22.3	21.4
T_8	19.5	21.5	24.0	21.8	23.2	19.8	25.3	20.0	20.2	20.6
T_9	20.3	20.8	19.3	19.8	17.9	22.4	17.3	20.1	21.4	18.1
$\bar{x}$	20.5	20.9	21.2	20.9	20.8	21.5	21.9	20.8	21.2	20.9
σ_s	0.84	1.61	1.77	0.80	1.75	1.41	2.46	1.14	1.23	1.59
T_n	21.1	22.0	22.4	21.4	22.0	22.5	23.5	21.6	22.0	22.0
$T_{\max,p}$	22.0									

6.2 Exposure

The expressions together with the values presented and described in section 3.3.2.1 are used to determine the exposure index. Equation 3 and Equation 4 are assessed three times respectively, once with the current climate, then with the optimistic future climate and lastly with the pessimistic future climate. The exposure indices are calculated by using Equation 1, Equation 2, Equation 3 and Equation 4, obtaining the following:

Increased deterioration rates

$$i_{corr}(t)_c = i_{corr\text{-}20}\cdot\big(1 + K\cdot(T(t)_c - 20)\big) = i_{corr\text{-}20}\cdot\big(1 + 0.025\cdot(3.21 - 20)\big) = \mathrm{i}_{corr\text{-}20}\cdot 0.580$$

$$i_{corr}(t)_o = i_{\mathrm{corr\text{-}20}}\cdot\big(1 + K\cdot(T(t)_o - 20)\big) = i_{corr\text{-}20}\cdot\big(1 + 0.025\cdot(3.57 - 20)\big) = i_{corr\text{-}20}\cdot 0.589$$

$$i_{corr}(t)_p = i_{corr\text{-}20}\cdot\Big(1 + K\cdot\big(T(t)_p - 20\big)\Big) = i_{corr\text{-}20}\cdot\big(1 + 0.025\cdot(7.16 - 20)\big) = i_{corr\text{-}20}\cdot 0.679$$

$$I_o = \max\left(\frac{i_{corr}(t)_o - i_{corr}(t)_c}{i_{corr}(t)_c}, 0\right) = \max\left(\frac{i_{corr\text{-}20}\cdot 0.589 - i_{corr\text{-}20}\cdot 0.580}{i_{corr\text{-}20}\cdot 0.580}, 0\right) = 0.015$$

$$I_p = \max\left(\frac{i_{corr}(t)_p - i_{corr}(t)_c}{i_{corr}(t)_c}, 0\right) = \max\left(\frac{i_{corr\text{-}20}\cdot 0.679 - \mathrm{i}_{corr\text{-}20}\cdot 0.580}{i_{corr\text{-}20}\cdot 0.580}, 0\right) = 0.170$$

Increased stress due to expansion

$$\Delta T_{\max,c} = \big(T_{\max,c} - T_0\big) = 19.3 - 3.40 = 15.9°\mathrm{C}$$

$$\Delta T_{\max,o} = \big(T_{\max,o} - T_0\big) = 18.4 - 3.40 = 15.0°\mathrm{C}$$

$$\Delta T_{\max,p} = \big(T_{\max,p} - T_0\big) = 22.0 - 3.40 = 18.6°\mathrm{C}$$

$$I_o = \max\left(\frac{\Delta T_{\max,o} - \Delta T_{\max,c}}{\Delta T_{\max,c}}, 0\right) = \max\left(\frac{15.0 - 15.9}{15.9}, 0\right) = 0$$

$$I_p = \max\left(\frac{\Delta T_{\max,p} - \Delta T_{\max,c}}{\Delta \mathrm{T}_{\max,c}}, 0\right) = \max\left(\frac{18.9 - 15.9}{15.9}, 0\right) = 0.171$$

6.3 Strength of Evidence

The investigated exposures are considered as relatively high strength of evidence supporting their occurrence due to climate change. The index E is therefore assigned a value of 1.0 for the pessimistic and the optimistic assessment of the index, see Table 16. These values for index E are valid for all the bridges.

Table 16 Value of the Strength of Evidence index for each exposure.

Bridge	Exposure	E_o	E_p
High Coast Bridge	Increased deterioration rates	1.00	1.00
	Increased stresses due to expansion	1.00	1.00

6.4 Vulnerability

To assess the vulnerability of the bridge for the investigated exposure, Equation 6, Table 4, Table 5 and Table 6 are utilized. Equal weights are assigned to the vulnerability indicators, implying a value of 0.25 for the exposure of increased deterioration rates. While for the exposure of increased stress due to expansion the only vulnerability indicator considered is the bridge deck which amounts to a weight of 1.00. The obtained vulnerability scores accounting for the characteristics of the High Coast Bridge relevant for the exposure of increased deterioration rates are presented in Table 17. Table 18, presented the vulnerability scores used in the assessment of the increased stress due to expansion.

Table 17 Vulnerability score for the exposure of increased deterioration rates.

Vulnerability indicators	High Coast Bridge	V_o	V_p
Bridge material	Properly painted steel	0.20	0.40
Age	$10 < A < 30$ years	0.10	0.30
Zone	Coastal	0.70	1.00
Traffic volume	$4000 < AADT < 25000$	0.30	0.70

Table 18 Vulnerability score for the exposure of increased stress due to expansion.

Vulnerability indicators	High Coast Bridge	V_o	V_p
Bridge deck material	Structural steel	0.40	0.90

The optimistic and pessimistic vulnerability index is determined according to Equation 6, obtaining the following:

Increased deterioration rates

$V_o = 0.25 \cdot 0.20 + 0.25 \cdot 0.10 + 0.25 \cdot 0.70 + 0.25 \cdot 0.30 = 0.33$

$V_p = 0.25 \cdot 0.40 + 0.25 \cdot 0.30 + 0.25 \cdot 1.00 + 0.25 \cdot 0.70 = 0.60$

Increased stress due to expansion

$V_o = 1.00 \cdot 0.40 = 0.40$

$V_p = 1.00 \cdot 0.90 = 0.90$

6.5 Consequence

To determine the values for index C, Figure 4 is used. For the exposure of increased deterioration rates and the exposure of increased stress the obtained values for the C index are presented in the Table 19.

Table 19 Consequence index score for the High Coast Bridge for each exposure.

Bridge	Exposure	C_o	C_p
High Coast Bridge	Increased deterioration rates	0.50	0.60
	Increased stresses due to expansion	0.50	0.70

6.6 Bridge relative importance

To determine the bridge relative importance information about the traffic volume and detour length is obtained in Table 6, for more details about the relative importance, see section 3.2.1. For the assessed bridge selection, the South Traneberg Bridge had the highest traffic volume which was 59577 AADT. The High Coast Bridge had the longest detour length which was 24.4 km and an AADT of 4909. Equation 10 is used to determine the bridge relative importance for the High Coast Bridge.

$$i_r = \frac{\frac{AADT_i}{AADT_{\max}} + \frac{DL_i}{DL_{\max}}}{2} = \frac{\frac{4909}{59577} + \frac{24.4}{24.4}}{2} = 0.54$$

6.7 Level-I ranking index

To calculate the level-I ranking index, the exposures need to be normalised as shown in Equation 8 and Equation 9. The normalisation is performed with respect to the maximum I_p over all exposures for each bridge identifying $I_{p,\max}$ as the purpose of ranking is to prioritise the different exposures for a certain bridge. The normalised exposures are calculated by using Equation 8 and Equation 9, obtaining the following:

Increased deterioration rates

$$I_{on,1} = \frac{I_o}{I_{p,\max}} = \frac{0.015}{0.171} = 0.09$$

$$I_{pn,1} = \frac{I_p}{I_{p,\max}} = \frac{0.170}{0.171} = 0.99$$

Increased stress due to expansion

$$I_{on,1} = \frac{I_o}{I_{o,\max}} = \frac{0}{0.171} = 0$$

$$I_{pn,1} = \frac{I_p}{I_{p,\max}} = \frac{0.171}{0.171} = 1.00$$

Equation 7, representing the level-I ranking index can be rewritten for the optimistic and pessimistic attitude, see Equation 7a and Equation 7b.

$$RI_{o,1}=\left(I_{on,1}^{W_{I_n}}\cdot E_o^{W_E}\cdot V_o^{W_V}\cdot C_o^{W_C}\right)\cdot 100 \tag{7a}$$

$$RI_{p,1}=\left(I_{pn,1}^{W_{I_n}}\cdot E_p^{W_E}\cdot V_p^{W_V}\cdot C_p^{W_C}\right)\cdot 100 \tag{7b}$$

In the assessment, equal weights were assigned to the different indices when evaluating RI_1. The defined indices from subchapter 6.2-6.5 along with Equation 7a and Equation 7b are used to calculate the optimistic and pessimistic level-I ranking index:

Increased deterioration rates

$$RI_{o,1}=\left(0.09^{0.25}\cdot 1.00^{0.25}\cdot 0.33^{0.25}\cdot 0.50^{0.25}\right)\cdot 100=34.8$$

$$RI_{p,1}=\left(0.99^{0.25}\cdot 1.00^{0.25}\cdot 0.60^{0.25}\cdot 0.60^{0.25}\right)\cdot 100=77.3$$

Increased stress due to expansion

$$RI_{o,1}=\left(0^{0.25}\cdot 1.00^{0.25}\cdot 0.40^{0.25}\cdot 0.50^{0.25}\right)\cdot 100=0$$

$$RI_{p,1}=\left(1.00^{0.25}\cdot 1.00^{0.25}\cdot 0.90^{0.25}\cdot 0.70^{0.25}\right)\cdot 100=89.1$$

6.8 Level-II ranking index

The level-II ranking index builds on the results from the level-I ranking index, including the bridge relative importance in the assessment as well as conducting the normalisation in a different way. The normalisation is performed with respect to the maximum I_p over all bridges for each exposure. For the exposure of increased deterioration rates the maximum pessimistic exposure is obtained from the High Coast Bridge, which amounts to the value of 0.170. While for the exposure of increased stress due to expansion the Uddevalla Bridge attained the maximum pessimistic exposure corresponding to a value of 0.209. The normalised exposures are calculated by using Equation 8 and Equation 9, obtaining the following:

Increased deterioration rates

$$I_{on,2}=\frac{I_o}{I_{p,\max}}=\frac{0.015}{0.170}=0.09$$

$$I_{pn,2}=\frac{I_p}{I_{p,\max}}=\frac{0.170}{0.170}=1.00$$

Increased stress due to expansion

$$I_{on,2}=\frac{I_o}{I_{p,\max}}=\frac{0}{0.209}=0$$

$$I_{pn,2}=\frac{I_p}{I_{p,\max}}=\frac{0.171}{0.209}=0.82$$

Equation 11, representing the level-II ranking index can be rewritten in a similar way as for the level-I ranking index, once for the optimistic attitude and secondly the pessimistic attitude, see Equation 11a and Equation 11b.

$$RI_{o,2} = \left(I_{on,2}^{W_{I_n}} \cdot E_o^{W_E} \cdot V_o^{W_V} \cdot C_o^{W_C} \cdot i_r^{W_{i_r}}\right) \cdot 100 \tag{11a}$$

$$RI_{p,2} = \left(I_{pn,2}^{W_{I_n}} \cdot E_p^{W_E} \cdot V_p^{W_V} \cdot C_p^{W_C} \cdot i_r^{W_{i_r}}\right) \cdot 100 \tag{11b}$$

When evaluating $RI_{2,}$ equal weights were also assigned to the different indices. The defined indices from subchapter 6.2-6.6 along with Equation 11a and Equation 11b are used to calculate the optimistic and pessimistic level-II ranking index:

Increased deterioration rates

$$RI_{o,2} = \left(0.09^{0.20} \cdot 1.00^{0.20} \cdot 0.33^{0.20} \cdot 0.50^{0.20} \cdot 0.54^{0.20}\right) \cdot 100 = 38.0$$

$$RI_{p,2} = \left(1.00^{0.20} \cdot 1.00^{0.20} \cdot 0.60^{0.20} \cdot 0.60^{0.20} \cdot 0.54^{0.20}\right) \cdot 100 = 72.1$$

Increased stress due to expansion

$$RI_{o,2} = \left(0^{0.20} \cdot 1.00^{0.20} \cdot 0.90^{0.20} \cdot 0.70^{0.20} \cdot 0.70^{0.20}\right) \cdot 100 = 0$$

$$RI_{p,2} = \left(0.82^{0.20} \cdot 1.00^{0.20} \cdot 0.90^{0.20} \cdot 0.70^{0.20} \cdot 0.70^{0.20}\right) \cdot 100 = 77.5$$

To rank the bridges in the selection, the average RI_2 values over all exposures are used:

$$RI_{2,av,o} = \frac{38.0 + 0}{2} = 19.0$$

$$RI_{2,av,p} = \frac{72.1 + 77.5}{2} = 74.8$$

7 Results

The results from the qualitative assessment of the seven bridges are shown in Tables 20-22 for the investigated decades and the visualisation of the results of level-I ranking and level-II ranking, are presented in Figures 6-8 and Figures 9-11, respectively.

Nasr et al. (2019a) proposed method of visualisation used for the results of level-I ranking, in Figures 4-6, which is derived from the probability consequences diagrams with uncertainty boxes proposed by Duijm (2015). In Duijm (2015) the presented diagram separates the uncertainty of the probability and consequences. Instead the modified method for visualisation of the level-I ranking results, distinguishes between the uncertainty resulting from the climate side namely the hazard along with the exposure and the uncertainty resulting from the vulnerability and consequences side. The benefit of this method of visualisation is that it assists the decision maker by means of indicating whether climate change mitigation in itself can affect the different exposures or if attention should be directed to the bridge structure and the related consequences of each exposure. The more critical an exposure is for a certain bridge, the closer it is located to the top right corner, which indicates a higher value of level-I ranking.

The results of level-I ranking and level-II ranking are not affected by the investigated decade and as small differences in the values of the ranking indices are viewed as negligible, the same prioritisation is obtained for all the decades when considering the addressed questions in the method. Namely, for a single bridge which is the most critical climate change impact? Furthermore, for a group of bridge which bridge is the most critical one considering the potential climate change impacts?

The results of the level-I ranking for the investigated decades indicate that for all the bridges the exposure of increased stress due to expansion is the more critical exposure. Considering the results of level-I ranking regarding the exposure of increased stresses, the bridges in the selection would benefit significantly from climate change mitigation, this applies to all bridges. The results of the level-I ranking imply that the exposure of increased stresses can also be affected by decreasing the bridge vulnerability to this exposure and the potential consequences.

For the following three bridges; High Coast Bridge, North and South Traneberg Bridge, the results of level-I ranking indicate an increase of the exposure of deterioration for the optimistic future climate for the 2070s and/or 2050s. Although, this does not affect the final conclusions of level-I ranking index. Regarding the exposure of deterioration, the three bridge would benefit from climate mitigation. The climate mitigation would have a greater impact on the distant future, than the near future.

Several of the bridges are similarly ranked when analysing the results of the level-II ranking index, this leads to the bridges sharing places in the prioritisation. For the exposure of increased stress, the following prioritisation is obtained based on the results of the level-II ranking index: Älvsborg Bridge, High Coast Bridge and Uddevalla Bridge ranked highest (most critical) followed closely by North and South Traneberg Bridge which are all similarly ranked. The East and West Bridge are the least critical bridges for this exposure. In the same way a ranking of the bridge selection is established for the exposure of deterioration. Starting with the following four bridge in first place; Älvsborg Bridge, High Coast Bridge, North and South Traneberg

Bridge, then Uddevalla Bridge on second place and a shared third place for the East and West Bridge. When considering both exposures the same ranking is obtained as for the exposure of increased deterioration.

Table 20 Results of applying the method to the bridge selection for the 2050s; Det.: Deterioration, Str.: Stress; $I_{on,1}$, $I_{pn,1}$: *Optimistic and pessimistic normalised exposure indices for level-1 ranking;* $I_{on,2}$, $I_{pn,2}$: *Optimistic and pessimistic normalised exposure indices for level-2 ranking;* $RI_{2,av.}$: *Average level-2 ranking index over all exposures for each bridge.*

2050s		Exposure						Evidence		Vulnerability		Consequence		i_r	RI_1		RI_2		$RI_{2,av.}$	
Bridge		I_o	I_p	$I_{on,1}$	$I_{pn,1}$	$I_{on,2}$	$I_{pn,2}$	E_o	E_p	V_o	V_p	C_o	C_p		$RI_{1,o}$	$RI_{1,p}$	$RI_{2,o}$	$RI_{2,p}$	$RI_{2,av.o}$	$RI_{2,av.p}$
Älvsborg Bridge	Det.	0	0.07	0	0.61	0	0.59	1.00	1.00	0.58	0.75	0.50	0.60	0.63	0	72.3	0	70.1	0	75.1
	Str.	0	0.11	0	1.00	0	0.82	1.00	1.00	0.40	0.90	0.50	0.70		0	89.1	0	80.1		
Uddevalla Bridge	Det.	0	0.07	0	0.50	0	0.59	1.00	1.00	0.33	0.60	0.50	0.60	0.42	0	65.1	0	61.8	0	69.2
	Str.	0	0.14	0	1.00	0	1.00	1.00	1.00	0.40	0.90	0.50	0.70		0	89.1	0	76.6		
North Traneberg Bridge	Det.	0	0.07	0	0.66	0	0.64	1.00	1.00	0.53	0.75	0.50	0.60	0.65	18.0	73.9	23.1	71.6	11.5	72.8
	Str.	0	0.11	0	1.00	0	0.81	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	74.0		
South Traneberg Bridge	Det.	0	0.07	0	0.65	0	0.64	1.00	1.00	0.38	0.63	0.50	0.60	0.63	16.4	70.2	21.4	68.4	10.7	71.0
	Str.	0	0.12	0	1.00	0	0.83	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	73.7		
High Coast Bridge	Det.	0.02	0.12	0.13	0.93	0.15	1.00	1.00	1.00	0.33	0.60	0.50	0.60	0.54	38.5	76.0	41.8	72.1	20.9	75.6
	Str.	0	0.13	0	1.00	0	0.90	1.00	1.00	0.40	0.90	0.50	0.70		0	89.1	0	79.0		
West Bridge	Det.	0	0.07	0	0.50	0	0.60	1.00	1.00	0.10	0.35	0.50	0.60	0.12	0	57.0	0	43.5	0	49.4
	Str.	0	0.14	0	1.00	0	0.99	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	55.3		
East Bridge	Det.	0	0.07	0	0.56	0	0.60	1.00	1.00	0.20	0.45	0.50	0.60	0.15	0	62.4	0	47.8	0	52.2
	Str.	0	0.12	0	1.00	0	0.89	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	56.6		

Table 21 Results of applying the method to the bridge selection for the 2070s; Det.: Deterioration, Str.: Stress; $I_{on,1}$, $I_{pn,1}$: Optimistic and pessimistic normalised exposure indices for level-1 ranking; $I_{on,2}$, $I_{pn,2}$: Optimistic and pessimistic normalised exposure indices for level-2 ranking; $RI_{2,av.}$: Average level-2 ranking index over all exposures for each bridge.

2070s		Exposure						Evidence		Vulnerability		Consequence		i_r	RI_1		RI_2		$RI_{2,av.}$	
Bridge		I_o	I_p	$I_{on,1}$	$I_{pn,1}$	$I_{on,2}$	$I_{pn,2}$	E_o	E_p	V_o	V_p	C_o	C_p		$RI_{1,o}$	$RI_{1,p}$	$RI_{2,o}$	$RI_{2,p}$	$RI_{2,av.o}$	$RI_{2,av.p}$
Älvsborg Bridge	Det.	0	0.11	0	0.62	0	0.62	1.00	1.00	0.58	0.75	0.50	0.60	0.63	0	72.6	0	70.8	0	75.4
	Str.	0	0.17	0	1.00	0	0.82	1.00	1.00	0.40	0.90	0.50	0.70		0	89.1	0	80.1		
Uddevalla Bridge	Det.	0	0.11	0	0.51	0	0.62	1.00	1.00	0.33	0.60	0.50	0.60	0.42	0	65.4	0	62.3	0	69.5
	Str.	0	0.21	0	1.00	0	1.00	1.00	1.00	0.40	0.90	0.50	0.70		0	89.1	0	76.6		
North Traneberg Bridge	Det.	0	0.11	0	0.59	0	0.66	1.00	1.00	0.53	0.75	0.50	0.60	0.65	0	71.9	0	72.1	0	73.9
	Str.	0	0.19	0	1.00	0	0.91	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	75.8		
South Traneberg Bridge	Det.	0	0.11	0	0.58	0	0.66	1.00	1.00	0.38	0.63	0.50	0.60	0.63	0	68.3	0	68.9	0	72.2
	Str.	0	0.20	0	1.00	0	0.93	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	75.5		
High Coast Bridge	Det.	0.02	0.17	0.09	0.99	0.09	1.00	1.00	1.00	0.33	0.60	0.50	0.60	0.54	34.8	77.3	38.0	72.1	19.0	74.8
	Str.	0	0.17	0	1.00	0	0.82	1.00	1.00	0.40	0.90	0.50	0.70		0	89.1	0	77.5		
West Bridge	Det.	0	0.11	0	0.54	0	0.64	1.00	1.00	0.10	0.35	0.50	0.60	0.12	0	58.0	0	44.1	0	49.6
	Str.	0	0.20	0	1.00	0	0.97	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	55.0		
East Bridge	Det.	0	0.11	0	0.60	0	0.64	1.00	1.00	0.20	0.45	0.50	0.60	0.15	0	63.4	0	48.4	0	52.3
	Str.	0	0.18	0	1.00	0	0.87	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	56.3		

Table 22 Results of applying the method to the bridge selection for the 2090s; Det.: Deterioration, Str.: Stress; $I_{on,1}$, $I_{pn,1}$: Optimistic and pessimistic normalised exposure indices for level-1 ranking; $I_{on,2}$, $I_{pn,2}$: Optimistic and pessimistic normalised exposure indices for level-2 ranking; $RI_{2,av.}$: Average level-2 ranking index over all exposures for each bridge

2090s		Exposure						Evidence		Vulnerability		Consequence		i_r	RI_1		RI_2		$RI_{2,av.}$	
Bridge		I_o	I_p	$I_{on,1}$	$I_{pn,1}$	$I_{on,2}$	$I_{pn,2}$	E_o	E_p	V_o	V_p	C_o	C_p		$RI_{1,o}$	$RI_{1,p}$	$RI_{2,o}$	$RI_{2,p}$	$RI_{2,av.o}$	$RI_{2,av.p}$
Älvsborg Bridge	Det.	0	0.14	0	0.52	0	0.64	1.00	1.00	0.58	0.75	0.50	0.60	0.63	0	69.5	0	71.3	0	75.7
	Str.	0	0.28	0	1.00	0	0.82	1.00	1.00	0.40	0.90	0.50	0.70		0	89.1	0	80.1		
Uddevalla Bridge	Det.	0	0.14	0	0.43	0	0.64	1.00	1.00	0.33	0.60	0.50	0.60	0.42	0	62.6	0	62.8	0	69.7
	Str.	0	0.34	0	1.00	0	1.00	1.00	1.00	0.40	0.90	0.50	0.70		0	89.1	0	76.6		
North Traneberg Bridge	Det.	0	0.15	0	0.55	0	0.68	1.00	1.00	0.53	0.75	0.50	0.60	0.65	0	70.6	0	72.4	0	73.3
	Str.	0	0.27	0	1.00	0	0.81	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	74.1		
South Traneberg Bridge	Det.	0	0.15	0	0.54	0	0.68	1.00	1.00	0.38	0.63	0.50	0.60	0.63	0	67.1	0	69.2	0	71.5
	Str.	0	0.28	0	1.00	0	0.83	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	73.8		
High Coast Bridge	Det.	0	0.22	0	0.85	0	1.00	1.00	1.00	0.33	0.60	0.50	0.60	0.54	0	74.5	0	72.1	0	74.4
	Str.	0	0.26	0	1.00	0	0.78	1.00	1.00	0.40	0.90	0.50	0.70		0	89.1	0	76.7		
West Bridge	Det.	0	0.15	0	0.48	0	0.66	1.00	1.00	0.10	0.35	0.50	0.60	0.12	0	56.3	0	44.4	0	49.4
	Str.	0	0.31	0	1.00	0	0.92	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	54.5		
East Bridge	Det.	0	0.15	0	0.53	0	0.66	1.00	1.00	0.20	0.45	0.50	0.60	0.15	0	61.6	0	48.8	0	52.2
	Str.	0	0.28	0	1.00	0	0.83	1.00	1.00	0.10	0.60	0.50	0.70		0	80.5	0	55.7		

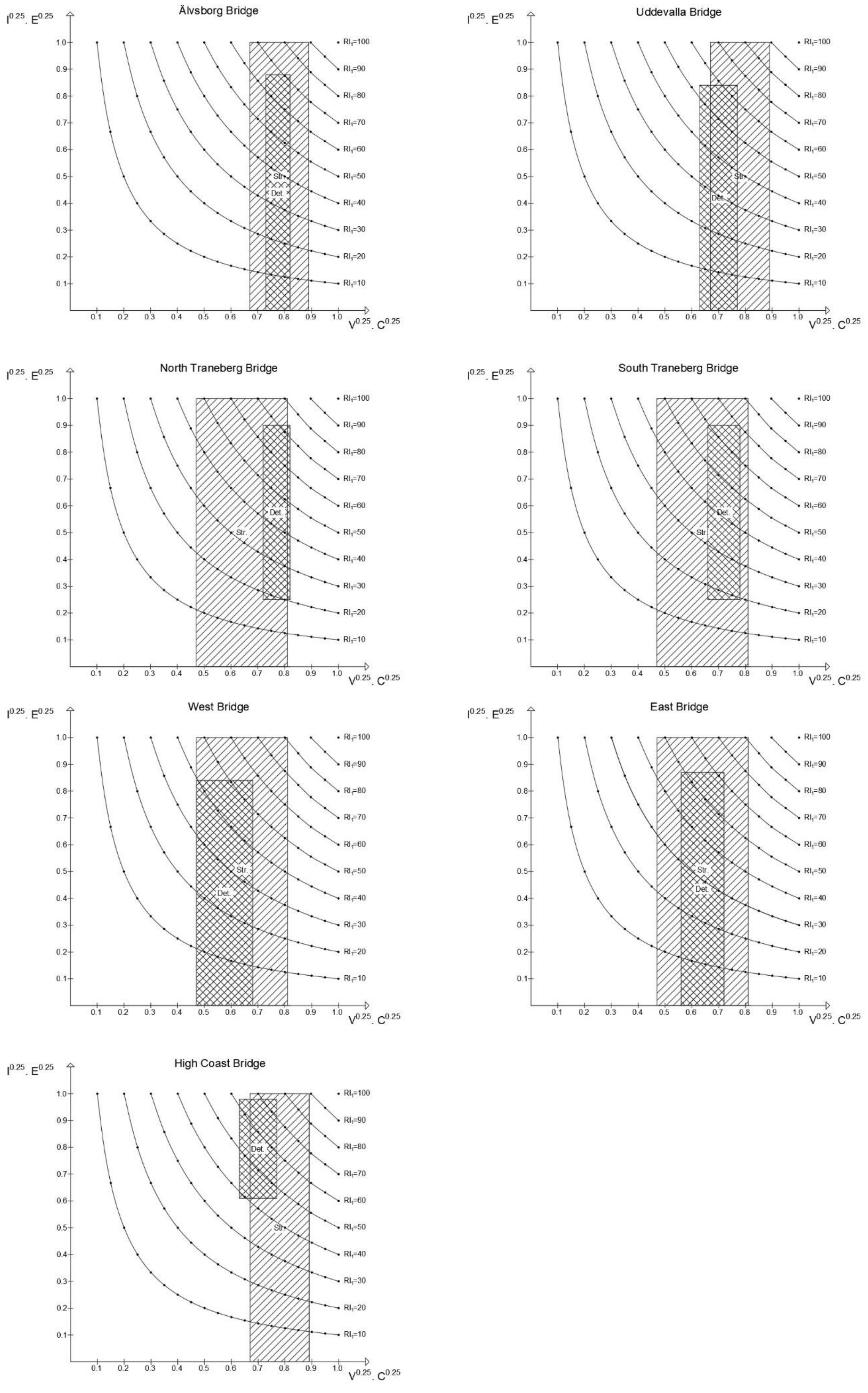


Figure 6 Visualisation of level-I ranking results for the 2050s; Det.: Deterioration, Str.: Stress.

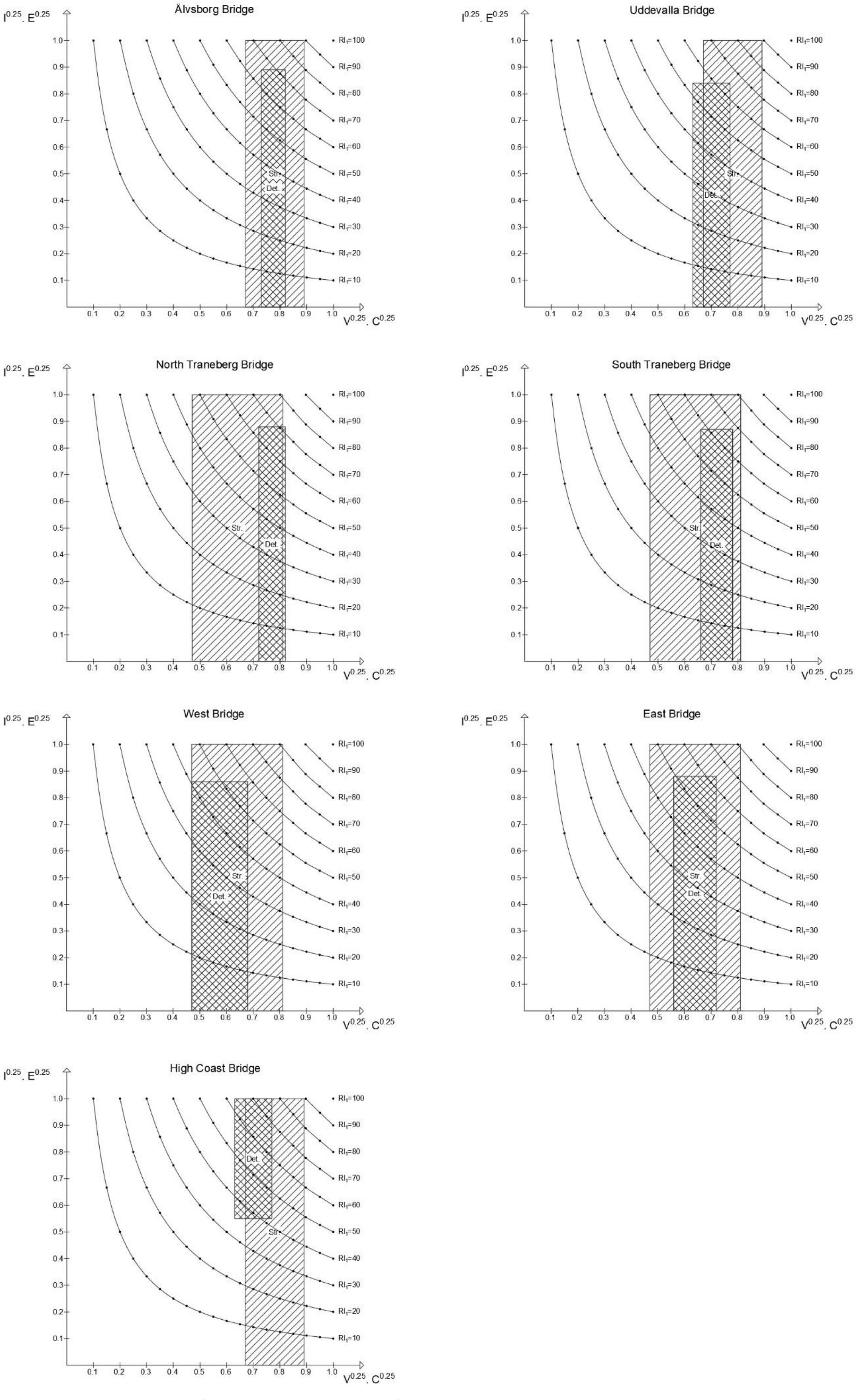
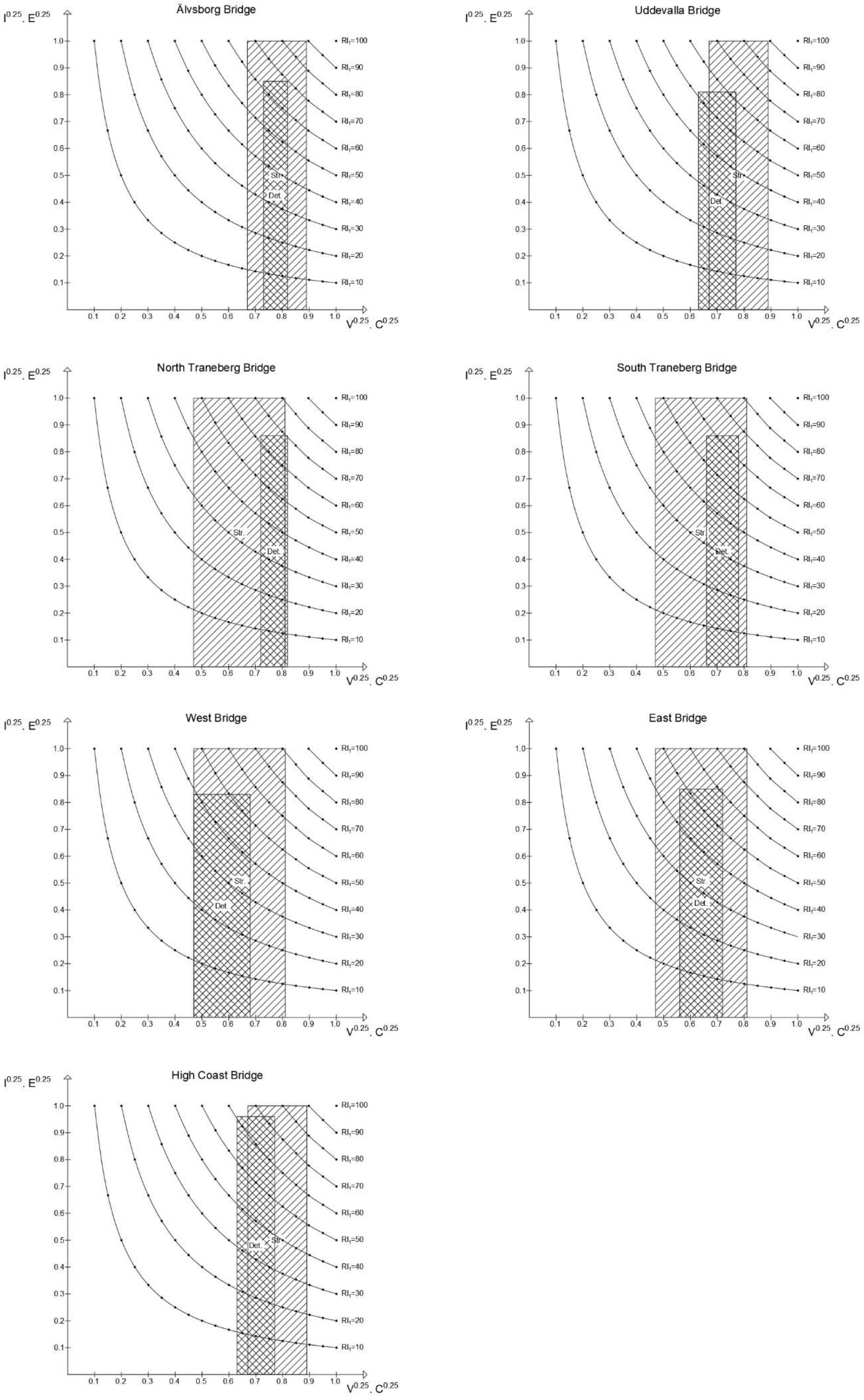


Figure 7 Visualisation of level-I ranking results for the 2070s; Det.: Deterioration, Str.: Stress.


Älvsborg Bridge

Uddevalla Bridge

North Traneberg Bridge

South Traneberg Bridge

West Bridge

East Bridge

High Coast Bridge

Figure 8 Visualisation of level-I ranking results for the 2090s; Det.: Deterioration, Str.: Stress.

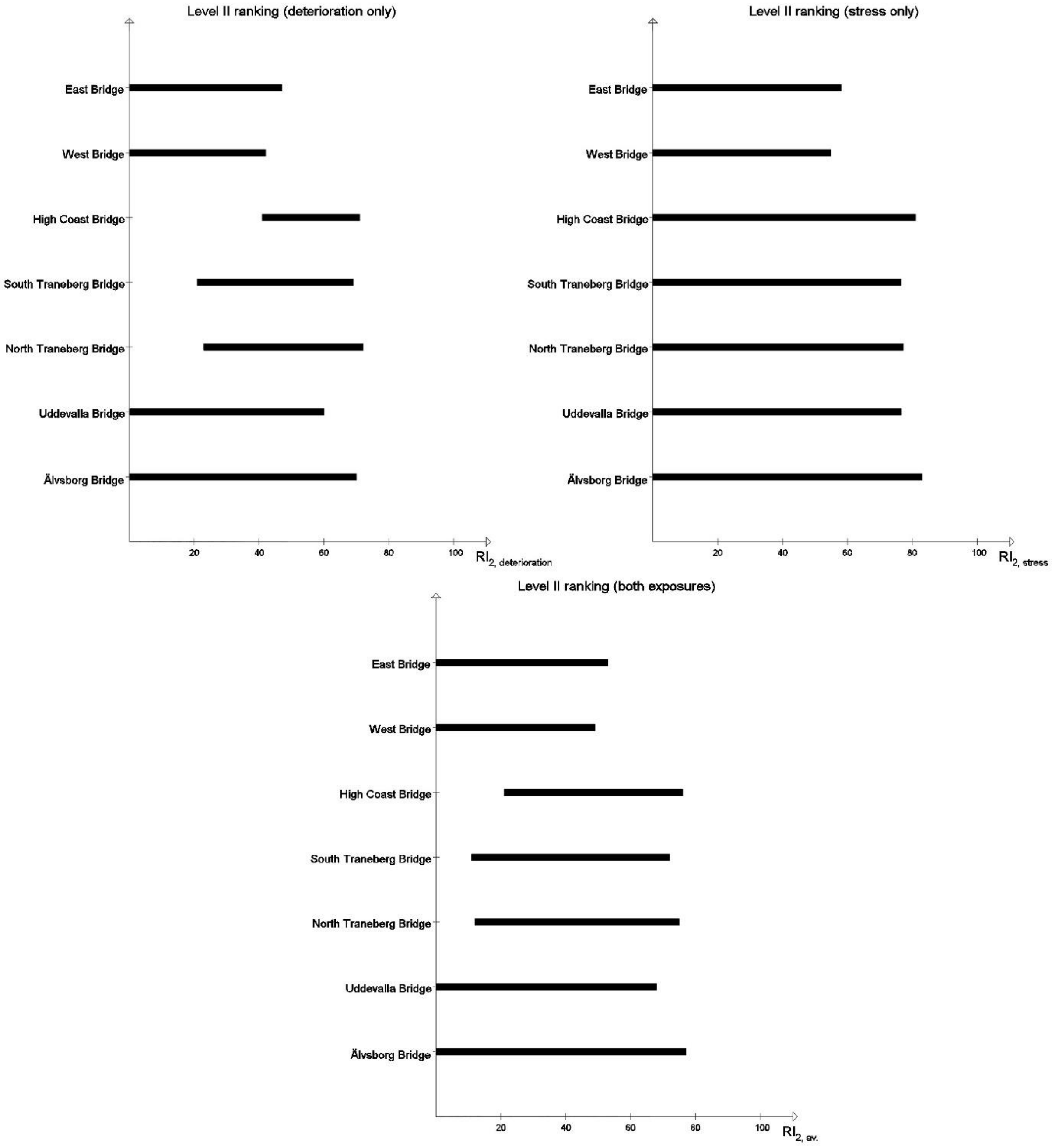


Figure 9 Visualisation of level-II ranking results for the 2050s.

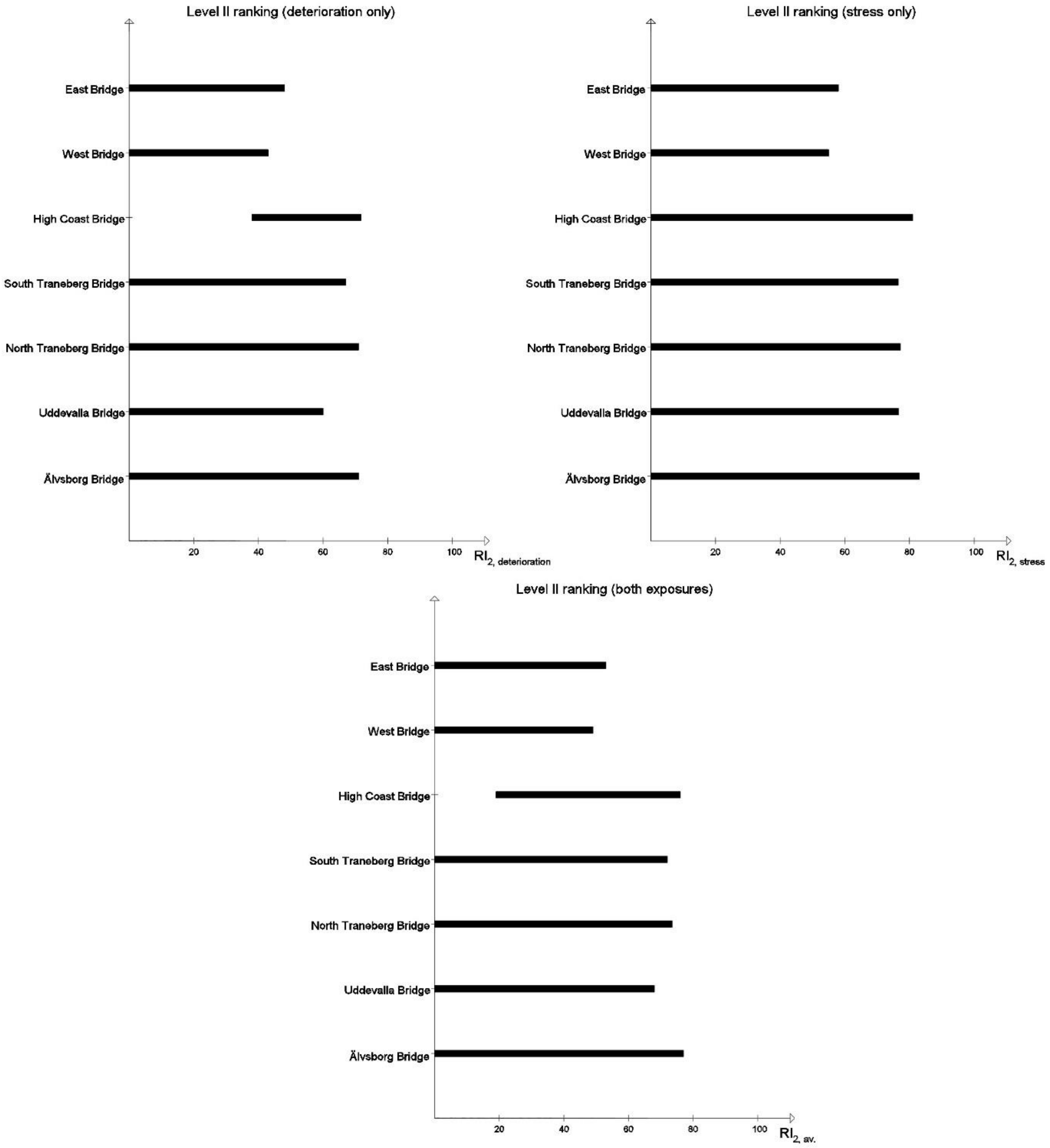


Figure 10 Visualisation of level-II ranking results for the 2070s.

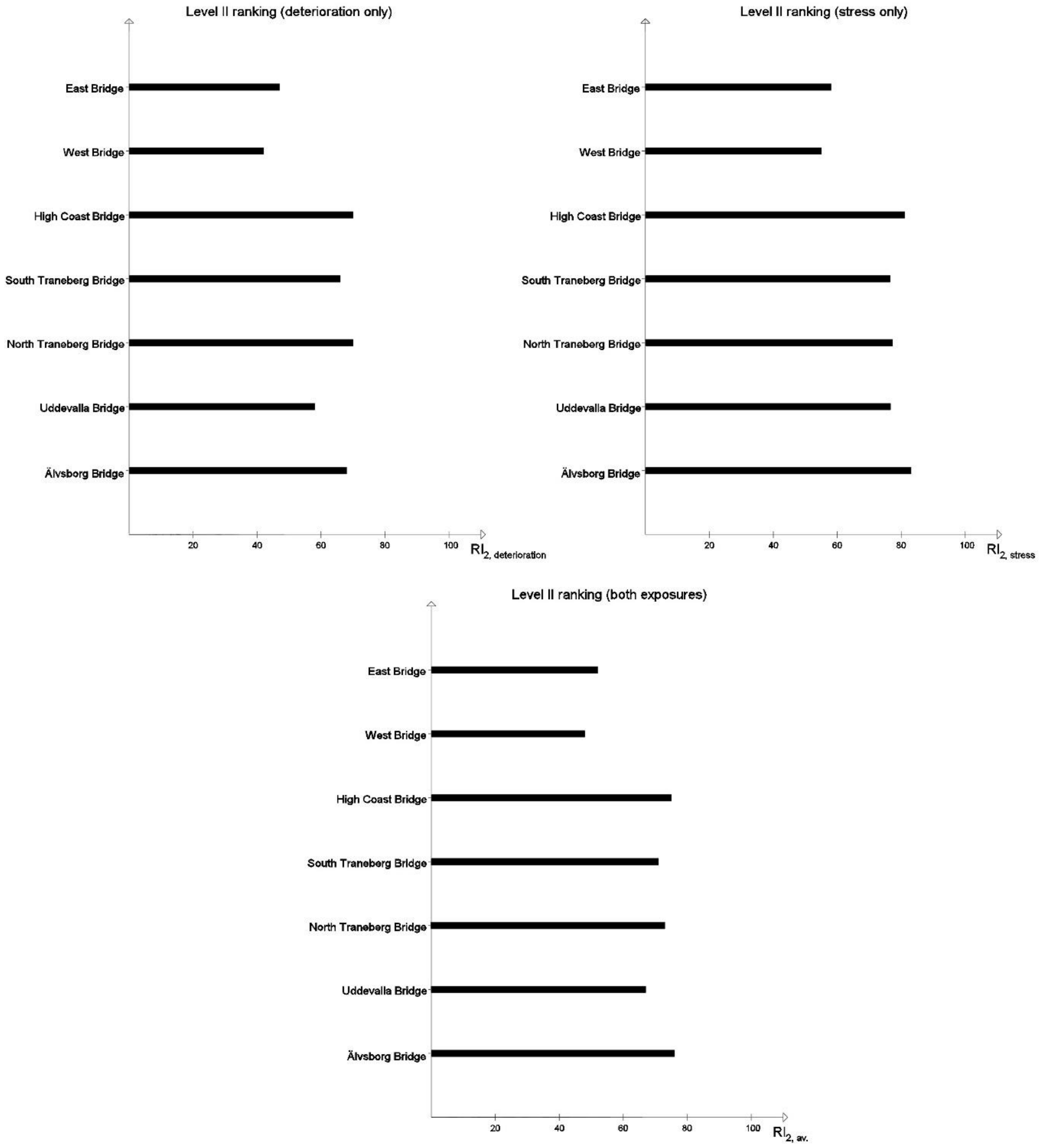


Figure 11 Visualisation of level-II ranking results for the 2090s.

8 Discussion

When analysing the obtained results from the assessment of the bridge selection, it must be acknowledged that even though the proposed method aims to be unbiased, there is an inherent subjectivity and uncertainty in the assessment. Furthermore, it is necessary to consider that the exposures have been normalised and several assumptions have been adopted. Thus, the ranking indices should not be considered as quantitative measures of risk and the results should not be interpreted outside of the purpose of the method as this may lead to misguided conclusions. Additionally, minor differences in the values of the ranking indices for the different alternatives should be regarded to be insignificant.

The subjectivity is for example reflected in the choice of the values for the indices E, V, and C. Furthermore, the subjectivity also resides in the selection of the different vulnerability indicators used to assess the vulnerability index. The decision maker makes subjective choices of the weights throughout the whole assessment, the weights for the vulnerability indicators as well as choosing the weights for the different indices for level I ranking index along with level II ranking index. Another source of subjectivity is associated with models chosen for evaluating the increase of each exposure as well as the assumptions adopted when applying these models.

The proposed method requires a model for each climate change impact. The models chosen to describe the exposures only consider one factor, the temperature. There are other factors such as relative humidity, precipitation or solar radiation which also can influence the climate change impact on the bridge structure. It would be interesting to assess the same potential impact with different models to see how the choice of the model can affect the values of the ranking. The future climate was represented by the 2050s, 2070s and 2090s, another aspect would be to see how the results of the assessment change if another time frame would be adopted e.g. the near future such as the 2030s or 2040s. The results from the method of the investigated future decades were similar over all the decades obtaining the same prioritisation, though for the 2050s compared to the 2070s and 2090s slight deviations were noted in the results. In addition, the current models were assessed relative to the 2010s. Noting that the temperature in 2010s is already affected by climate change (higher than the preindustrial climate) another interesting aspect would be to see how the results be affected if the average climate from, e.g. 1961-1990, would be considered instead of the 2010s.

For the exposure of increased stress due to expansion, the vulnerability index was only based on a single vulnerability indicator, the bridge material. This leads to unreliable assessment of the vulnerability for this exposure. The most critical exposure for all the bridges in the selection was the increased stress, though if more indicators would have been considered the results may have been different.

The proposed method requires substantial amount of data. Outside of the scope of the method, a vital step is to determine a suitable model for evaluating the increase of an exposure, the choice of model is related to the data. Both historical and future climate data associated with the different scenarios are necessary for the assessment which may be difficult to obtain. Nonetheless, acquiring climate data is an inherent prerequisite to assessing the impacts of climate change on infrastructure.

Furthermore, bridge data is essential for the assessment, along with relevant literature about vulnerability indicators related to the exposure in question and additional information to rank these to construct a vulnerability scoring scheme. The necessary bridge data was obtained from BaTMan, the database was sufficient for the exposures assessed in this thesis, though it may not be for all potential climate change impacts. In this study only two climate change impacts were considered for seven bridge, it would be interesting to see how feasible the method could be on a larger scale, with numerous potential climate change impacts, for a larger bridge selection or considering both aspects.

The method relies on the decision maker partly making the right or more correct choices regarding models and assigning of indices. For the decision maker or the person that conducts the assessment there is a need for wide knowledge or expert elicitation which is vital to obtain a reasonable assessment. For the exposure of increased stress due to expansion, the results reflect the quality of the assessment of the exposure may not have been optimal. Several choices were made during the assessment process and there are numerous aspects which could impact the final results, from the choice of model to the temperature index used. The assessment of this exposure needs to be investigated and developed further.

9 Conclusions

The proposed method is practically feasible on real case studies, it addresses the aforementioned questions which is the aim of the method, supplying the decision maker with a qualitative assessment of the bridge selection. The obtained results from the assessment can assist the decision maker to assign the restricted resources with consideration to climate change. Further examining the visualisation of the results of level I ranking which demonstrates which aspects can influence the exposure in question; whether climate change mitigation is advantageous or if focus should be on the bridge structure along with the related consequences. Although like any risk method, implementing the method includes making assumptions and using data and models that have varying degrees of uncertainty.

The choice of models for the potential climate change impacts are outside the scope of the method. It is up to the decision maker to make a choice of which impacts to assess as well as with which models to assess these with. Various climate change risks have been identified in previous literature, to facilitate the assessment process it would be favourable if the method came with an appendix with proposed models for potential climate change impacts. This is not an improvement for the method, merely a proposal of development of it as an entirety.

If the method would be used by others, it could be favourable to clarify and explain the different aspects of the method further and possibly supply some guidelines, as there are many choices to be made by the decision maker. Noting that the presented guidelines are not a requirement rather there as assistance. Things that could be clarified is e.g. the hazard index, as it is not an index treated like the others. The hazard index is not inserted in the main equations for the ranking indices, namely Equation 7 and Equation 11. Instead the lower limit and upper limit of the hazard index is used to determine the optimistic and pessimistic exposure. Another matter is the equations for level-I ranking and level-II ranking index, it is explained in text that the indices are assessed optimistically and pessimistically, though for the reader it could be to an advantage to have the equations be presented as Equation 7a/7b or Equation 11a/11b. The risk-based prioritisation method has potential though needs to be developed and examined further.

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Appendix 1

The temperature data processed and the procedure to obtain the final values is presented in this appendix. The climate data for each bridge is dependent on its location, the geographical area used to obtain the temperature data was the counties of Sweden. All the temperature data was obtained from the Climate scenario database (SMHI, 2018a), which is based on research by the Rossby Centre. The temperature data in the database is presented as the change in temperature index relative to a reference value which is the mean value of the temperature index for 1961-1990.

The main temperature indices used in the assessment of the exposures was the annual mean temperature and the maximum daily mean temperature. The reference values for the maximum daily mean temperature were not presented in the database, instead the values were obtained from SMHI (2014). The relevant counties for the bridge selection and the corresponding reference values used in the calculation are presented in Table 23.

Table 23 Relevant County for each bridge and corresponding reference value for the annual mean temperature and for the maximum daily mean temperature based on data from 1961-1990.

Bridge	County	Reference value	
		Annual mean temperature (°C)	Maximum daily mean temperature (°C)
Älvsborg Bridge	Västra Götaland	6.1	20
Uddevalla Bridge			
North Traneberg Bridge	Stockholm	5.8	22
South Traneberg Bridge			
High Coast Bridge	Västernorrland	1.9	18
West Bridge	Jönköping	5.6	20
East Bridge			

The different temperature indices used in the assessment are presented with consideration to the reference value unless stated otherwise, this implies that the values shown in the following tables are the change in the temperature indices added to respective reference value.

Increased deterioration rates

For the exposure of increased deterioration rates, the temperature index used was the annual mean temperature. The current climate is based on historical data for the 2010s, the annual mean temperature for the current climate is presented in the Table 24. The final value that is used in the assessment for each county is the average of the annual mean temperature for the decade.

Table 24 The current climate during the 2010s, represented by the annual mean temperature.

Current climate									
Annual mean temperature (°C)									
County	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*
Västra Götaland	4.90	7.70	6.60	6.90	8.40	7.90	7.50	7.50	8.10
Stockholm	5.10	7.50	6.50	6.90	7.90	7.90	7.20	7.20	7.80
Västernorrland	0.80	4.00	2.70	3.30	4.40	4.00	3.30	3.10	3.30
Jönköping	4.70	7.20	6.10	6.40	7.90	7.40	7.00	7.00	7.80

The time periods analysed in the future are the 2050s, 2070s and 2090s, which are presented by scenario data. For the optimistic approach the RCP 2.6 was adopted while for the pessimistic approach the RCP 8.5 was used instead. The Rossby Centre applied several global climate models generating the scenario data. Table 25, presents the utilized combinations of GCM's and RCP scenarios used in the analysis. The scenario data consists of several value for a single year, depending on which of the RCP scenarios is investigated the amount of processed values differs.

Table 25 The global climate models used by the Rossby Centre in the analysis of the Climate scenarios.

Denoted	*Country/Institute*	*Model name*	*RCP 2.6*	*RCP 8.5*
y1	Canada	CCCma-CanESM2		x
y2	France	CNRM-CERFACS-CNRM-CM5		x
y3	EU	ICHEC-EC-EARTH	x	x
y4	France	IPSL-IPSL-CM5A-MR		x
y5	Japan	MIROC-MIROC5		x
y6	UK	MOHC-HadGEM2-ES	x	x
y7	Germany	MPI-M-MPI-ESM-LR	x	x
y8	Norway	NCC-NorESM1-M		x
y9	USA	NOAA-GFDL-GFDL-ESM2M		x

In Tables 26-37, the optimistic and pessimistic scenario data for the annual mean temperature is presented for the different counties and decades. Normal distribution is used for the scenario data, the mean value and standard deviation are determined for each year. With these parameters established and the predefined hazards levels for the respective RCP scenario a single value can be obtained for each year. The hazard levels being the 25th percentile for the optimistic approach while for the pessimistic approach the 75th percentile is adopted. Furthermore, acquiring the annual temperature for the assessment valid for both optimistic and pessimistic approach involved calculating the mean value for each investigated future decade.

Table 26 The future climate for Västra Götaland County during the 2050s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Västra Götaland County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y3	8.29	8.50	7.62	7.01	7.05	7.80	7.08	8.09	7.88	7.75
y6	7.95	8.34	8.41	7.99	6.85	8.00	7.14	7.69	7.38	7.70
y7	7.66	7.04	6.93	7.18	7.99	8.17	6.91	4.94	7.92	7.29
Annual mean temperature for RCP 8.5 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y1	7.70	9.06	8.60	9.04	9.17	8.79	8.53	9.21	9.98	8.04
y2	8.89	8.18	9.24	7.82	8.43	9.49	9.02	9.26	8.75	8.76
y3	9.23	9.58	8.94	8.71	7.61	9.14	8.81	9.89	8.71	8.63
y4	8.32	9.16	7.36	8.56	10.0	10.7	9.35	9.91	8.37	6.98
y5	8.12	8.94	8.71	8.34	9.82	9.50	8.34	7.91	8.90	9.48
y6	8.35	8.85	9.68	9.58	8.92	9.17	8.13	8.99	9.64	10.2
y7	7.45	7.27	7.90	7.89	8.25	8.22	7.19	8.44	8.46	8.82
y8	8.01	6.91	7.83	8.85	8.48	8.38	8.61	7.56	7.64	8.42
y9	9.50	8.94	9.33	8.30	8.37	8.15	7.64	8.86	8.23	8.32

Table 27 The future climate for Stockholm County during the 2050s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Stockholm County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y3	8.17	8.24	6.95	7.25	7.31	7.64	7.01	7.83	8.10	7.48
y6	7.95	8.33	8.15	7.84	6.83	7.74	7.14	7.83	7.58	7.65
y7	7.63	7.09	7.14	6.88	7.65	8.25	6.91	4.80	7.60	7.24
Annual mean temperature for RCP 8.5 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y1	7.52	9.02	8.44	9.04	9.04	8.56	8.39	8.89	9.89	8.02
y2	8.77	8.74	9.38	8.03	8.90	9.59	9.42	9.57	8.90	8.97
y3	8.79	9.52	8.97	8.76	7.64	9.03	8.75	9.78	8.67	7.91
y4	8.43	9.19	7.24	8.56	10.06	10.71	9.39	9.95	7.96	6.36
y5	7.69	8.87	8.98	8.26	9.34	9.37	8.42	8.16	8.82	9.61
y6	7.91	8.67	9.42	9.40	8.67	9.12	8.12	8.73	9.35	9.62
y7	7.33	7.27	7.77	7.78	8.26	8.03	7.41	8.32	8.43	8.95
y8	7.68	6.60	7.65	8.66	8.69	8.40	8.78	7.64	7.83	8.72
y9	9.42	8.92	9.48	8.41	8.03	7.85	7.85	8.78	8.42	8.27

Table 28 The future climate for Västernorrland County during the 2050s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Västernorrland County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y3	5.00	5.33	3.59	3.90	4.30	4.26	3.37	3.90	4.75	4.44
y6	4.50	5.14	5.10	4.12	2.95	4.02	3.69	4.09	4.10	4.46
y7	4.05	3.23	3.12	3.82	3.67	4.43	3.57	1.46	3.89	4.06
Annual mean temperature for RCP 8.5 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y1	3.91	6.38	4.82	5.83	5.58	5.48	5.66	6.22	6.77	5.20
y2	5.03	5.51	5.96	4.49	5.25	6.30	5.98	6.07	5.80	6.08
y3	5.07	6.56	5.75	5.80	4.95	5.75	5.84	6.06	5.61	4.90
y4	4.98	6.49	3.81	5.67	7.61	8.60	6.25	6.86	4.62	3.51
y5	3.45	5.36	5.25	4.71	6.01	5.78	4.73	5.20	5.36	5.72
y6	4.74	5.35	5.49	6.46	6.11	6.34	5.33	5.73	5.95	6.42
y7	3.46	4.34	4.48	3.97	4.80	4.55	3.85	5.00	5.22	5.02
y8	4.30	3.57	3.86	5.24	5.50	5.03	5.54	3.72	3.96	5.09
y9	5.98	5.35	6.42	4.72	4.64	4.37	5.05	5.41	4.66	4.36

Table 29 The future climate for Jönköping County during the 2050s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Jönköping County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y3	7.65	7.89	7.10	6.58	6.69	7.30	6.67	7.72	7.25	7.26
y6	7.47	7.89	8.07	7.49	6.75	7.67	6.85	7.30	6.94	7.46
y7	7.22	6.61	6.48	6.59	7.59	7.81	6.59	4.45	7.43	6.87
Annual mean temperature for RCP 8.5 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y1	7.31	8.62	8.25	8.61	8.69	8.22	8.03	8.72	9.40	7.56
y2	8.41	7.72	8.84	7.38	8.20	9.03	8.72	8.85	8.36	8.24
y3	8.77	9.17	8.55	8.20	7.05	8.53	8.38	9.41	8.28	7.97
y4	7.98	8.95	7.06	7.94	9.54	10.1	8.89	9.52	8.06	6.59
y5	7.80	8.41	8.38	7.71	9.11	8.85	8.05	7.30	8.42	8.88
y6	7.91	8.43	9.23	8.99	8.56	8.69	7.52	8.50	9.15	9.62
y7	7.06	6.71	7.36	7.51	7.81	7.74	6.89	7.91	7.97	8.50
y8	7.49	6.39	7.43	8.37	8.05	8.00	8.21	7.25	7.38	8.05
y9	9.03	8.46	8.85	8.11	7.66	7.76	7.07	8.18	8.06	7.83

Table 30 The future climate for Västra Götaland County during the 2070s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Västra Götaland County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y3	7.29	7.91	7.37	6.44	5.93	8.52	7.77	7.52	7.91	7.91
y6	7.62	7.78	7.48	7.69	7.53	6.81	8.47	9.16	9.12	7.88
y7	7.82	7.79	7.53	7.48	7.78	7.28	7.87	7.20	7.00	7.69
Annual mean temperature for RCP 8.5 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y1	9.62	8.69	9.79	9.57	9.67	10.5	10.7	8.91	10.1	9.47
y2	8.65	8.87	9.64	8.59	9.36	10.2	9.32	10.2	9.38	9.58
y3	9.67	9.12	9.43	8.64	8.52	9.30	9.62	7.85	9.08	9.17
y4	9.90	10.2	10.2	10.5	9.35	10.9	10.1	10.7	10.2	9.59
y5	9.37	10.5	10.7	10.6	10.3	9.99	10.6	10.5	11.4	11.2
y6	9.25	11.3	9.46	9.80	11.0	9.16	9.89	10.2	9.93	11.3
y7	9.55	9.32	10.4	9.02	8.11	9.29	9.42	10.4	9.18	8.55
y8	8.20	9.32	9.87	9.89	9.72	8.75	8.84	9.59	9.37	9.53
y9	8.81	7.90	9.79	10.6	8.98	8.97	8.35	8.05	10.2	9.56

Table 31 The future climate for Stockholm County during the 2070s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Stockholm County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y3	6.91	8.00	6.96	5.84	5.84	8.70	7.82	7.41	7.85	7.77
y6	7.55	7.99	7.30	7.53	7.44	6.81	8.32	8.91	9.12	7.63
y7	7.90	7.56	7.44	7.21	7.63	7.51	7.89	7.21	6.80	7.35
Annual mean temperature for RCP 8.5 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y1	9.30	8.61	9.92	9.71	9.46	10.4	10.6	8.85	10.1	9.24
y2	8.74	9.19	10.0	9.06	9.22	10.1	9.87	10.51	9.67	9.77
y3	9.66	9.19	9.30	8.43	8.53	9.07	9.76	7.92	8.93	9.13
y4	10.0	10.1	10.2	10.4	9.38	10.7	10.2	11.1	10.3	9.56
y5	9.32	10.2	10.7	10.6	10.3	10.3	11.1	10.3	11.3	11.1
y6	9.59	11.3	9.65	9.83	11.1	9.28	10.2	9.46	9.85	11.4
y7	9.41	9.22	10.3	8.91	8.36	9.35	9.32	10.1	9.48	8.48
y8	8.00	9.12	9.97	10.1	9.83	8.73	8.65	9.48	9.20	9.03
y9	8.73	8.03	9.56	10.6	8.99	8.87	8.46	8.39	9.83	9.73

Table 32 The future climate for Västernorrland County during the 2070s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Västernorrland County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y3	3.13	5.14	3.57	2.46	2.60	5.29	4.24	3.98	4.67	3.55
y6	3.98	4.76	3.80	3.96	3.78	2.95	4.71	5.49	5.46	4.16
y7	4.61	3.94	4.61	3.35	3.82	3.59	4.18	3.79	3.68	3.92
Annual mean temperature for RCP 8.5 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y1	6.44	5.32	6.77	7.40	6.38	7.48	7.45	6.31	7.95	6.05
y2	5.62	5.78	6.69	6.13	5.43	6.99	6.69	6.56	6.48	7.24
y3	5.92	6.67	6.04	5.69	6.20	6.33	7.12	4.84	6.30	6.26
y4	7.62	7.26	7.76	8.08	6.24	7.53	7.90	7.93	7.71	5.94
y5	5.31	6.92	8.09	7.51	7.16	7.15	7.54	6.83	7.82	7.95
y6	6.20	8.01	7.02	7.65	7.82	6.51	7.32	6.01	6.70	8.31
y7	6.66	6.02	7.62	6.31	5.61	6.44	5.88	7.07	6.67	5.46
y8	5.29	5.77	7.37	6.52	7.02	5.40	5.55	6.48	6.30	5.57
y9	4.78	4.72	6.76	6.89	5.50	5.88	4.96	4.69	6.52	6.08

Table 33 The future climate for Jönköping County during the 2070s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Jönköping County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y3	6.74	7.45	6.87	5.88	5.41	8.09	7.22	7.09	7.49	7.61
y6	7.19	7.51	7.00	7.26	6.93	6.41	8.10	8.65	8.63	7.38
y7	7.35	7.26	6.95	7.13	7.34	6.78	7.35	6.86	6.53	7.27
Annual mean temperature for RCP 8.5 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y1	9.21	8.14	9.41	9.18	9.28	10.0	10.3	8.52	9.67	8.91
y2	8.03	8.36	9.13	8.31	8.93	9.79	9.09	9.85	9.04	9.11
y3	9.28	8.65	9.15	8.02	8.15	8.84	9.24	7.56	8.60	8.73
y4	9.44	9.78	9.71	10.1	9.01	10.5	9.62	10.5	9.79	9.30
y5	9.06	10.0	10.2	10.1	9.80	9.81	10.4	10.0	10.9	10.6
y6	8.99	10.9	8.98	9.32	10.6	8.79	9.58	9.54	9.57	11.0
y7	9.01	8.96	9.95	8.44	7.74	9.03	8.96	9.78	8.70	8.04
y8	7.58	8.97	9.48	9.53	9.32	8.33	8.36	9.24	9.01	9.00
y9	8.41	7.69	9.32	10.2	8.56	8.66	7.91	7.60	9.74	9.26

Table 34 The future climate for Västra Götaland County during the 2090s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Västra Götaland County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y3	6.23	7.40	7.55	7.89	8.33	8.14	6.11	6.24	7.08	7.35
y6	6.95	7.97	8.07	8.14	7.08	7.73	8.88	7.06	7.92	7.36
y7	7.23	7.15	7.47	6.69	6.44	6.76	8.53	7.92	7.77	7.69
Annual mean temperature for RCP 8.5 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y1	9.81	10.5	11.2	12.1	11.0	10.8	12.0	11.2	11.3	10.8
y2	8.90	9.21	10.3	10.0	10.3	10.5	10.1	11.0	9.65	10.8
y3	10.5	10.8	10.4	9.81	11.4	10.5	11.0	9.92	10.4	10.2
y4	10.9	10.8	10.2	11.2	10.5	10.9	10.4	11.7	11.6	11.4
y5	10.7	11.5	11.0	11.6	10.9	12.3	10.5	12.1	12.3	12.6
y6	9.41	12.0	12.9	11.2	11.8	11.0	12.2	11.5	11.3	11.6
y7	8.72	10.9	10.3	9.81	9.69	8.64	9.65	9.73	9.89	10.0
y8	9.07	10.7	10.7	10.0	9.23	8.97	9.36	10.0	10.7	9.41
y9	11.6	10.8	11.0	9.64	8.99	9.73	10.0	10.0	9.82	9.78

Table 35 The future climate for Stockholm County during the 2090s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Stockholm County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y3	6.20	7.05	7.09	7.79	8.11	8.04	5.77	5.99	5.97	7.10
y6	7.08	7.51	7.73	8.16	7.07	7.85	8.70	7.34	8.00	7.44
y7	6.99	7.18	7.31	6.59	6.06	6.45	8.58	8.05	7.73	7.30
Annual mean temperature for RCP 8.5 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y1	9.94	10.2	10.9	11.9	10.9	10.6	11.8	11.0	11.1	10.7
y2	9.37	9.55	10.8	9.67	10.3	10.7	10.4	11.2	10.2	11.1
y3	10.3	10.7	10.6	9.83	11.4	10.4	10.9	10.1	10.6	10.5
y4	11.0	11.0	10.2	11.1	10.6	10.8	10.4	11.6	11.7	11.4
y5	10.6	11.3	10.9	11.7	11.0	12.4	10.8	12.4	12.5	12.8
y6	9.86	11.8	12.6	11.2	11.7	11.3	12.2	11.4	11.4	11.5
y7	8.79	10.6	10.3	9.5	9.47	8.84	9.77	9.62	9.93	10.0
y8	9.24	10.4	10.9	10.1	9.17	9.00	9.45	10.0	10.8	9.20
y9	11.4	10.9	11.2	9.68	9.09	9.64	10.0	9.71	9.78	9.82

Table 36 The future climate for Västernorrland County during the 2090s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Västernorrland County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y3	1.59	2.89	3.12	4.42	4.96	4.23	2.48	1.88	2.55	3.94
y6	4.04	4.50	4.17	5.03	3.99	4.44	5.53	4.71	4.53	3.70
y7	3.28	3.33	3.72	3.14	2.75	3.34	5.22	4.50	4.48	3.47
Annual mean temperature for RCP 8.5 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y1	7.29	7.31	8.27	8.57	8.07	7.85	8.81	7.90	7.78	7.45
y2	6.38	6.83	8.02	6.13	7.09	7.43	7.46	8.12	7.68	8.53
y3	7.72	7.36	8.16	7.09	8.83	7.83	8.21	7.21	7.94	8.16
y4	8.37	8.41	7.35	8.60	8.30	8.11	7.28	9.11	9.01	9.23
y5	7.86	8.25	8.19	9.04	8.25	9.24	7.49	9.97	9.04	9.63
y6	7.36	8.77	9.64	8.93	8.73	8.97	9.41	8.55	8.94	8.70
y7	5.77	7.92	7.17	6.51	6.54	5.79	6.93	6.65	7.30	6.65
y8	6.62	7.87	8.00	6.71	6.68	6.42	6.82	6.90	8.15	6.54
y9	8.15	8.15	7.67	6.13	6.06	6.11	6.77	6.28	6.18	6.74

Table 37 The future climate for Jönköping County during the 2090s, represented by the annual mean temperature for RCP 2.6 and RCP 8.5.

Jönköping County										
Annual mean temperature for RCP 2.6 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y3	5.83	6.97	7.21	7.57	7.99	7.65	5.45	5.81	6.34	6.77
y6	6.53	7.58	7.56	7.50	6.64	7.48	8.43	6.62	7.53	6.91
y7	6.68	6.75	6.88	6.19	5.88	6.23	7.95	7.52	7.30	7.25
Annual mean temperature for RCP 8.5 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y1	9.44	10.0	10.8	11.6	10.5	10.4	11.4	10.8	11.0	10.4
y2	8.55	8.93	10.0	9.57	10.0	10.2	9.61	10.5	9.38	10.6
y3	10.1	10.3	10.0	9.31	10.9	10.2	10.5	9.62	10.1	9.87
y4	10.5	10.4	9.77	10.6	10.2	10.7	10.0	11.3	11.1	10.9
y5	10.3	11.1	10.5	11.1	10.5	11.9	10.2	11.6	12.1	12.3
y6	9.16	11.5	12.4	10.5	11.3	10.7	11.6	11.1	10.9	11.3
y7	8.25	10.6	9.81	9.45	9.19	8.34	9.37	9.38	9.51	9.71
y8	8.60	10.2	10.4	9.71	8.72	8.56	8.80	9.72	10.2	9.1
y9	11.1	10.4	10.7	9.38	8.73	9.40	9.62	9.77	9.50	9.37

Increased stress due to expansion

For the exposure of increased stress due to expansion the maximum daily mean temperature was the temperature index used for the exposure. The maximum daily mean temperature is the greatest value of the daily average temperature during a year. The same time period as for the previous exposure is adopted, meaning the 2010s for the current climate and the 2050s, 2070s and 2090s for the future climate.

The historical maximum daily mean temperature was not available for the 2010s, the current climate was instead presented by scenario data obtained from the Rossby Centre. The procedure to determine a single value to represent the decade, was conducted by firstly averaging the value for the optimistic and the pessimistic scenario data for every single year. The result of the average maximum daily mean temperature representing the current climate is presented in the Table 38. The final value that was used in the assessment for the current climate was taken as the maximum of the maximum daily mean temperature for the decade.

Table 38 The current climate during the 2010s, represented by the average maximum daily mean temperature based on pessimistic and optimistic scenario data.

Current climate									
Maximum daily mean temperature (°C)									
County	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*
Västra Götaland	20.8	21.1	19.7	20.9	20.7	20.8	20.1	21.5	20.9
Stockholm	23.2	22.7	22.0	22.9	22.9	23.2	22.9	23.5	22.5
Västernorrland	19.3	19.0	18.2	19.0	18.9	19.3	18.6	19.3	19.2
Jönköping	21.0	21.3	19.8	20.9	21.1	20.9	20.5	21.4	21.0

Considering that the bridges are existing bridges, the temperature at construction was included for the second exposure. This was represented with the annual mean temperature from the year of construction for each bridge. Though for the North Traneberg Bridge which was finished in 1934, the historical data of the annual mean temperature could not be obtained as the accessible data starts from 1961. To include the North Traneberg Bridge in assessment of the second exposure the temperature data from 1961 was used instead.

In Table 39, the change of the annual mean temperature for the different construction years, which subsequently amounts the constructions temperature by adding the change of annual mean temperature to the reference value noted for each county presented in Table 23.

Table 39 The change of the annual mean temperature for the construction year.

Bridge	Construction year	Change in the annual mean temperature (°C)
Älvsborg Bridge	1966	-1.00
Uddevalla Bridge	2000	1.90
North Traneberg Bridge	1934	1.00
South Traneberg Bridge	2002	1.40
High Coast Bridge	1997	1.50
West Bridge	1994	0.90
East Bridge	1979	-0.80

In Tables 40-51, the optimistic and pessimistic scenario data for the maximum daily mean temperature is presented for the different counties and decades. Similar calculation procedure as for the annual mean temperature is adopted for the maximum daily mean temperature. The predefined hazard levels are the same, i.e. 25th percentile for RCP 2.6 and 75th percentile for RCP 8.5. Normal distribution is used along with the hazard levels and a single value is obtained for each year. The average of the values over the future decade of interest is the representative value for the maximum daily mean temperature used in the assessment.

Table 40 The future climate for Västra Götaland County during the 2050s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Västra Götaland County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y3	22.5	24.4	23.2	21.3	20.7	19.9	20.1	22.2	23.8	20.7
y6	24.1	20.8	21.8	22.7	21.1	19.1	20.5	23.8	21.3	19.6
y7	22.7	20.0	21.1	21.4	20.0	22.6	19.3	21.1	19.1	21.7
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y1	22.3	20.9	23.6	26.1	21.4	21.1	22.7	23.6	29.6	21.3
y2	23.3	18.5	20.6	21.4	23.2	21.6	23.6	20.8	20.6	21.4
y3	24.1	22.3	20.5	20.1	19.3	21.8	23.4	24.3	23.1	19.6
y4	23.0	22.7	19.3	24.5	22.3	22.7	23.0	22.9	20.7	23.3
y5	21.5	24.4	23.4	20.4	24.0	23.4	21.4	22.0	18.7	22.3
y6	23.0	20.8	22.5	25.4	20.9	22.6	21.1	20.9	25.2	26.6
y7	23.8	21.9	17.7	20.1	21.8	22.3	20.3	20.7	20.7	22.9
y8	21.6	21.0	20.3	26.6	20.8	20.8	23.4	21.8	21.5	21.5
y9	21.7	19.9	23.6	21.0	24.1	23.1	20.6	26.5	20.4	22.4

Table 41 The future climate for Stockholm County during the 2050s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Stockholm County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y3	26.7	25.8	23.4	23.2	23.6	23.2	22.2	23.0	26.0	22.3
y6	25.9	22.9	22.6	24.4	21.2	22.5	23.6	24.9	23.4	22.1
y7	23.0	21.8	22.6	24.3	21.7	26.4	21.6	22.1	21.3	22.2
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y1	24.1	24.5	25.2	26.5	24.0	24.1	24.2	27.2	30.4	22.9
y2	24.1	21.3	22.9	22.4	25.9	23.9	25.6	22.0	22.2	23.0
y3	25.6	23.9	22.4	23.5	21.0	23.7	26.0	27.0	23.7	21.4
y4	24.2	25.6	22.3	26.3	24.7	24.3	25.8	25.2	23.0	24.7
y5	23.1	25.8	24.9	23.3	23.3	25.4	23.9	23.2	21.6	24.8
y6	25.4	22.9	26.2	23.7	23.3	25.0	23.0	23.8	26.3	27.6
y7	24.7	23.7	21.4	23.2	24.0	24.5	22.4	23.1	24.4	28.3
y8	23.5	22.6	22.6	27.6	25.0	22.3	24.4	24.5	24.7	25.6
y9	25.0	22.2	24.6	23.3	25.7	24.9	23.1	26.2	22.7	24.0

Table 42 The future climate for Västernorrland County during the 2050s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Västernorrland County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y3	19.0	21.5	19.6	18.3	17.7	17.4	17.2	19.1	21.0	20.5
y6	21.3	20.9	20.5	20.3	19.2	18.3	22.3	23.3	19.8	19.2
y7	19.9	19.3	20.1	19.9	17.4	20.0	18.3	19.5	17.5	19.6
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y1	20.9	20.0	20.8	22.2	20.5	21.7	21.2	21.2	25.3	19.9
y2	21.4	18.9	20.1	20.6	21.2	20.5	21.5	19.5	19.0	20.3
y3	21.4	21.3	18.4	20.1	17.8	19.0	20.8	20.0	21.4	19.7
y4	20.6	21.6	18.6	22.7	23.2	19.8	20.8	21.8	20.4	20.8
y5	20.1	22.0	19.7	18.7	21.1	21.3	19.4	19.4	19.1	22.6
y6	19.8	20.1	20.6	21.5	20.8	20.1	19.9	19.4	23.6	22.8
y7	22.1	20.4	17.6	17.6	19.4	19.7	18.0	19.1	20.5	20.5
y8	20.9	19.2	18.6	23.5	18.7	19.8	20.7	20.3	21.3	19.7
y9	19.4	18.2	21.4	20.6	21.1	19.7	20.8	21.8	18.4	21.2

Table 43 The future climate for Jönköping County during the 2050s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Jönköping County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y3	22.3	23.2	23.2	20.6	20.2	20.5	19.9	23.0	23.8	20.3
y6	23.9	20.9	20.9	22.5	20.0	19.7	21.2	23.1	22.1	20.5
y7	23.7	19.4	20.6	21.2	19.9	23.5	20.4	20.4	20.0	20.5
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2050*	*2051*	*2052*	*2053*	*2054*	*2055*	*2056*	*2057*	*2058*	*2059*
y1	21.9	20.7	22.9	26.2	22.0	21.1	22.4	25.2	29.5	22.5
y2	22.4	18.7	19.9	21.1	23.8	21.1	23.8	20.1	20.7	21.2
y3	22.6	21.2	20.5	20.2	19.7	21.8	25.0	23.3	22.6	19.4
y4	23.4	23.3	21.6	24.4	22.5	22.7	22.9	22.8	20.1	23.4
y5	20.4	23.6	22.5	19.8	22.9	23.2	23.0	21.6	18.9	21.3
y6	23.9	21.1	22.5	23.0	21.1	22.8	21.1	21.4	24.9	27.2
y7	23.3	22.2	17.6	21.1	21.7	23.2	20.1	21.5	20.7	23.4
y8	20.4	21.3	20.3	26.5	20.4	20.4	23.4	23.7	21.9	22.7
y9	22.4	20.2	24.9	21.3	24.0	24.3	21.0	26.1	21.2	22.5

Table 44 The future climate for Västra Götaland County during the 2070s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Västra Götaland County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y3	22.3	20.1	18.6	20.7	19.0	22.9	20.1	19.5	19.5	23.3
y6	21.8	21.9	18.4	21.0	24.4	19.0	22.7	25.4	22.5	22.8
y7	21.1	20.3	22.4	24.2	22.2	25.0	21.0	19.9	20.6	23.9
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y1	21.6	22.7	23.2	21.1	24.3	22.9	23.5	22.3	21.8	25.7
y2	21.0	19.9	24.5	21.9	22.9	22.5	24.3	24.8	20.7	22.9
y3	26.9	22.0	19.8	21.6	20.2	22.6	21.9	21.1	23.4	25.2
y4	20.9	25.1	24.8	23.8	21.8	26.3	20.7	24.9	21.4	22.5
y5	22.6	21.4	23.9	24.9	21.7	21.0	25.0	20.6	25.6	23.1
y6	23.4	26.6	21.4	23.6	24.2	25.1	27.6	22.3	23.9	24.7
y7	24.1	28.0	25.5	22.9	21.9	23.1	23.3	22.4	25.3	22.9
y8	22.3	22.1	26.1	25.8	24.3	21.0	25.4	22.9	23.7	23.6
y9	22.5	22.9	21.2	23.0	19.9	23.0	20.8	21.5	21.9	19.6

Table 45 The future climate for Stockholm County during the 2070s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Stockholm County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y3	27.0	23.4	21.1	23.0	20.9	26.9	23.3	21.3	22.1	26.3
y6	24.2	22.3	21.2	22.4	25.1	20.1	24.7	26.6	26.8	22.7
y7	24.4	22.8	25.8	23.8	23.4	27.9	22.3	23.0	22.6	26.1
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y1	23.9	24.9	25.3	23.3	25.8	24.6	25.4	25.2	23.8	28.5
y2	22.9	23.3	29.2	24.4	24.2	24.1	25.2	27.9	23.2	25.2
y3	29.7	23.9	23.0	23.4	23.4	23.9	24.4	23.0	26.1	29.2
y4	23.9	26.2	27.6	27.3	25.0	27.8	23.7	27.7	24.0	24.1
y5	24.5	23.8	26.0	28.7	24.3	23.7	27.8	24.3	27.2	24.2
y6	26.5	30.1	23.3	26.1	26.5	25.4	29.3	24.3	25.5	27.6
y7	25.6	30.1	25.3	24.6	21.7	25.1	25.6	23.5	25.0	24.4
y8	23.5	25.3	27.4	28.2	29.3	23.4	28.5	25.5	24.3	24.7
y9	24.6	25.7	22.9	24.8	22.6	24.5	22.3	22.5	23.7	23.5

Table 46 The future climate for Västernorrland County during the 2070s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Västernorrland County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y3	20.0	17.4	16.8	19.7	17.4	19.6	18.9	16.8	18.5	19.2
y6	22.0	19.3	18.2	20.7	21.6	18.1	21.4	24.2	22.3	19.9
y7	19.0	18.3	19.7	20.8	19.3	20.8	19.2	18.9	17.9	21.2
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y1	20.1	19.6	21.3	20.1	21.8	21.8	21.8	22.7	20.6	23.1
y2	20.2	19.2	22.4	21.1	20.4	21.0	21.5	20.8	18.8	21.2
y3	22.5	19.4	19.7	20.2	19.5	19.8	21.7	19.2	21.0	20.7
y4	20.6	23.0	23.3	21.5	21.9	23.9	21.8	22.2	21.6	19.1
y5	20.6	19.3	20.5	22.0	20.5	20.7	22.7	20.7	22.5	20.9
y6	20.6	22.7	21.3	21.2	22.8	23.1	25.0	21.6	22.5	22.9
y7	19.9	22.7	19.0	20.4	19.3	21.4	19.8	20.0	22.3	21.4
y8	19.5	21.5	24.0	21.8	23.2	19.8	25.3	20.0	20.2	20.6
y9	20.3	20.8	19.3	19.8	17.9	22.4	17.3	20.1	21.4	18.1

Table 47 The future climate for Jönköping County during the 2070s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Jönköping County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y3	21.8	21.0	18.6	20.0	19.2	22.1	19.7	20.2	19.8	23.3
y6	22.2	21.7	18.8	20.9	24.4	19.0	22.2	25.4	23.1	21.4
y7	21.8	21.0	22.8	23.9	21.4	24.3	21.9	20.8	21.3	25.4
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2070*	*2071*	*2072*	*2073*	*2074*	*2075*	*2076*	*2077*	*2078*	*2079*
y1	22.7	23.2	23.0	21.1	24.2	22.6	23.6	22.2	21.8	24.8
y2	21.1	20.2	24.1	22.0	22.1	23.2	24.0	25.8	21.6	23.7
y3	27.1	22.4	20.5	21.1	20.7	21.1	21.7	21.1	23.7	24.8
y4	21.1	25.5	25.3	25.0	21.8	25.9	20.4	26.8	21.4	22.9
y5	21.8	21.5	22.8	25.1	23.1	21.0	25.5	20.8	24.4	22.9
y6	25.2	27.0	21.0	23.3	25.7	24.6	27.5	21.4	24.3	26.1
y7	23.8	28.1	25.3	23.4	22.4	23.7	23.2	21.7	24.4	23.2
y8	21.4	22.5	25.4	25.3	25.3	20.9	25.3	23.4	23.1	23.0
y9	22.6	23.3	21.0	22.6	20.7	22.3	20.9	21.5	22.0	21.0

Table 48 The future climate for Västra Götaland County during the 2090s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Västra Götaland County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y3	21.9	19.7	20.0	20.7	19.2	23.0	20.2	18.5	19.6	20.5
y6	18.4	20.2	21.2	20.6	19.0	23.8	19.9	21.8	22.9	24.2
y7	19.9	20.9	21.2	18.3	21.0	20.8	23.3	21.7	18.7	21.0
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y1	27.2	24.6	25.2	31.2	23.8	24.5	29.0	25.5	28.7	32.0
y2	23.2	21.5	23.5	23.2	21.3	21.2	23.6	21.8	23.1	21.7
y3	23.6	26.7	21.9	23.6	24.5	21.9	24.1	22.5	24.3	21.6
y4	22.5	20.9	22.2	24.7	22.7	26.4	22.0	24.2	25.4	24.8
y5	20.9	25.4	24.5	24.2	22.5	25.9	23.7	22.7	25.9	28.8
y6	24.3	26.6	30.9	24.8	24.1	27.0	27.5	26.4	23.5	25.2
y7	30.2	23.9	28.6	22.7	23.2	24.8	25.7	24.9	21.5	23.4
y8	22.8	27.0	24.1	27.1	23.2	24.1	23.0	22.7	28.2	23.5
y9	24.7	23.3	25.2	24.1	23.4	25.9	24.2	24.1	25.0	21.9

Table 49 The future climate for Stockholm County during the 2090s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Stockholm County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y3	23.4	22.6	21.8	22.4	21.0	24.7	23.5	22.7	22.1	23.0
y6	21.5	22.1	23.0	25.1	20.8	27.4	22.5	25.3	26.0	25.2
y7	21.7	23.5	24.8	21.7	22.6	23.1	24.5	24.2	20.4	22.4
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y1	28.9	26.9	27.4	32.0	26.8	26.1	29.9	26.7	29.6	32.1
y2	26.2	23.5	25.8	24.4	23.9	24.0	25.2	24.0	25.8	24.5
y3	25.9	28.8	24.0	27.1	27.8	24.3	28.3	27.0	27.4	25.8
y4	26.4	23.9	25.2	27.1	26.7	29.5	24.2	26.1	28.0	26.8
y5	24.4	27.9	26.1	26.1	24.8	28.8	26.2	26.6	27.7	33.2
y6	28.2	30.1	32.9	26.9	26.4	27.2	28.2	26.5	26.7	26.4
y7	27.6	25.3	30.2	23.7	25.5	25.7	26.7	28.7	24.2	24.2
y8	25.7	26.7	27.3	29.6	24.6	24.8	25.7	25.4	29.9	25.8
y9	24.0	24.4	27.5	25.0	24.4	27.5	25.8	25.7	26.5	25.0

Table 50 The future climate for Västernorrland County during the 2090s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Västernorrland County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y3	19.2	17.5	18.3	18.6	17.9	21.2	18.0	15.9	17.0	19.3
y6	17.9	20.4	18.9	19.0	19.2	22.6	19.9	21.1	21.6	21.9
y7	17.7	19.3	20.9	17.7	19.3	19.3	20.3	20.5	16.5	19.7
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y1	24.1	23.2	23.7	26.0	22.1	22.2	23.6	23.1	24.2	23.5
y2	21.5	20.9	23.3	21.0	19.8	21.4	21.5	21.7	23.3	21.0
y3	22.1	19.5	20.2	20.9	22.9	20.8	26.1	21.7	22.0	21.5
y4	23.7	20.0	22.6	24.6	23.0	25.2	20.5	23.1	24.7	23.2
y5	20.1	22.5	22.4	22.4	21.3	22.0	21.4	22.9	22.9	24.1
y6	23.0	24.7	26.4	22.7	22.9	27.1	25.8	22.7	22.7	21.7
y7	22.3	22.6	23.6	20.9	22.5	21.5	21.6	22.7	20.3	20.9
y8	22.8	23.9	22.4	23.8	21.1	23.0	22.1	22.1	24.3	23.7
y9	21.5	20.4	21.9	21.7	21.1	22.1	20.4	21.7	21.3	21.9

Table 51 The future climate for Jönköping County during the 2090s, represented by the maximum daily mean temperature for RCP 2.6 and RCP 8.5.

Jönköping County										
Maximum daily mean temperature for RCP 2.6 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y3	21.7	20.8	19.9	20.6	18.6	22.0	20.5	20.2	19.4	20.8
y6	19.0	19.6	21.0	21.6	19.1	25.1	20.9	23.2	23.5	24.2
y7	20.5	21.2	21.0	18.3	22.9	21.0	22.8	21.6	19.3	21.2
Maximum daily mean temperature for RCP 8.5 (°C)										
model	*2090*	*2091*	*2092*	*2093*	*2094*	*2095*	*2096*	*2097*	*2098*	*2099*
y1	26.6	25.0	25.2	31.5	24.2	24.4	28.2	25.0	29.1	31.9
y2	25.0	21.6	23.0	22.9	21.4	21.4	23.2	22.4	22.6	21.9
y3	23.8	26.4	22.5	24.4	24.4	22.6	23.4	23.6	24.5	22.2
y4	23.1	21.6	22.5	24.8	23.0	26.1	22.1	24.9	24.6	25.5
y5	21.2	24.3	23.9	24.3	22.7	26.5	24.4	22.4	25.6	29.1
y6	24.7	26.1	30.8	24.9	24.0	25.7	27.1	26.2	24.3	25.5
y7	29.3	25.2	27.9	22.6	21.6	22.9	27.0	25.2	21.7	24.4
y8	23.2	25.9	24.4	28.3	24.3	23.0	22.6	24.5	27.2	23.4
y9	24.4	23.3	25.3	24.5	23.4	26.3	24.8	24.5	24.9	21.7