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RISK BASED MAINTENANCE FOR SWISS RAILWAY BRIDGES: CONCEPT, IMPLEMENTATION AND FIRST EXPERIENCES

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Abstract.
The Swiss Federal Railway (SBB) has an inventory of approx. 6,000 bridges. So far, condition classes of the individual bridges have been used for maintenance management. To improve the efficiency of the maintenance management, a long-term change from the condition class-based approach to a risk-based approach is considered. Such a risk-based approach was developed and implemented during a two-stage process into software (Excel and Python). The software was also linked to the SBB databases to access the relevant data. The Python software now includes 12 parameters to adapt the initial failure probability to specific bridge conditions and 15 damage parameters. So almost 30 parameters are used to compute the risk for each bridge. The software is also linked to geographical maps to show the location of the bridges. Besides the development of the approach, also the first experience of the application of this methodology will be discussed. For example, the risk-based ranking of the bridges clearly showed that specific bridge types are dominating. Also, some original ideas and concepts were not applicable due to difficulties in providing the required input data. However, currently the risk-based bridge ranking complies well with former investigations carried out by hand.

Keywords: Bridges, collapse, condition class, damage, probability of failure, risk assessment.

1. Introduction

Switzerland has one of the densest and busiest rail networks in the world, but still achieves a top international ranking in punctuality. In 2010, rail transport accounted for 17 % of passenger traffic and almost 40 % of freight traffic [1].

The majority of the Swiss railway network dates back to the 19th century. The mean age of the bridges of the Swiss Federal Railway (SBB) is 71 years, the median is 64 years and about 1,300 bridges are older than 100 years (Figure 1). Also, major extensions of the railway network have been implemented in recent years, such as the Gotthard Base Tunnel or the Diameter Line in Zurich [1].

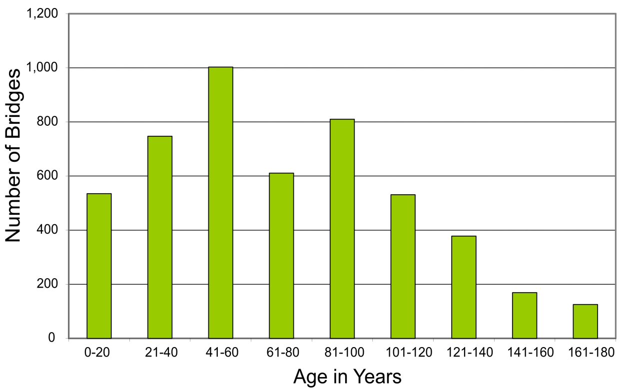

Figure 1. Age distribution of SBB bridges.

The Swiss government supports the operation and maintenance of the railway network with approximately 2 billion US-Dollar annually. In addition, major extension investments are financed through a special fund. The fund reached a volume of approx. 32 billion US-Dollar (1995 prices) [1].

The replacement value of the entire SBB network is given as 105 billion US-Dollar and the replacement value of the SBB network's engineering structures as 46 billion US-Dollar [2]. Table 1 gives the replacement values for various SBB engineering structures, with bridges alone accounting for approximately 12 billion US-Dollar [3].

SBB has set itself the goal of ensuring that mobility remains attractive and affordable for customers, cantons, and the federal government. Uncertainties in the management of the railway network have to be considered [4].

For this reason, knowledge of the network condition and thus also of the engineering structures, such as the bridges, is necessary. SBB therefore regularly prepares a network condition report [2].

The network condition report uses so-called condition classes for the evaluation of the engineering structures. Today, SBB determines the condition of bridges as part of inspections which include visual and other examinations. Based on observed condition classes and target condition classes, the maintenance of bridges can be managed. The network condition

Engineering Structures	Stock (approx.)	Replacement value (approx.)
Retaining Walls	11,000 sections	4 billion US-Dollar
Bridges	6,000	12 billion US-Dollar
Tunnel	300	12 billion US-Dollar

Table 1. Number and replacement value of various SBB engineering structures [3].

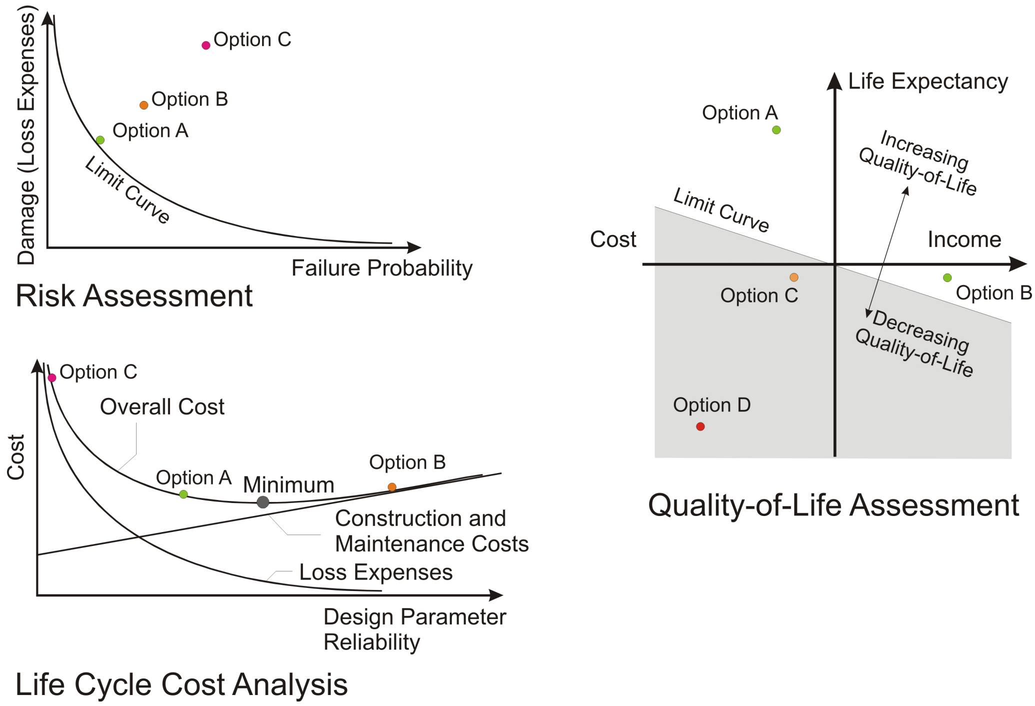

Figure 2. Potential procedures for risk-based asset management of SBB bridges.

report thus forms the basis for the asset management of the bridges. In principle, only the structure itself is considered in this condition-based assessment, not the SBB network. The condition-based planning of maintenance measures can therefore not consider any information on the importance of the bridge structure in the SBB network.

In contrast, the risk-based assessment can consider the importance of the structure for the SBB network and thus for the fulfilment of the above-mentioned global goals of SBB [4]. To do so, the risk-based assessment includes numerous performance and functional parameters of the railway. This assessment therefore allows better prioritisation of computational investigations and maintenance measures on the bridges from an overall perspective.

Based on these considerations, SBB launched a project on the development of risk-based bridge management in 2019. The project consisted of various working steps:

- Collection and preparation of the state of the art in risk-based maintenance management for possible application at SBB (2019)
- Implementation of a proof-of-concept for the SBB bridges (2019)
- Software implementation and linking with the SBB databases (2020)
- Practical application and feedback of experience to improve the procedure (2021 – 2022).

In addition to the implementation for bridges, an implementation for other engineering structures is planned and partly prepared.

2. Methodology

In order to prioritize bridges and maintenance measures on the given SBB network, a mathematical procedure should be applied. From the point of view of risk-based maintenance management, three procedures are possible:

- Risk assessments (time-independent),
- Life cycle cost analyses (time-dependent, includes risk assessments) and
- Quality-of-life assessments (considering macroeconomic indicators).

The goal of all procedures is the evaluation of possible measures based on rational criteria. Figure 2 shows the evaluation of measures in these three models. As can be seen in Figure 2, the $x-$ and $y-$axes of the three diagrams are labelled differently. Each of

Example of SBB data plotting

Import classes

```
%matplotlib inline
import matplotlib.pyplot as plt
import pandas as pd
import numpy as np
```

Load data

```
data = pd.read_csv('20181210_DfA.csv', sep=';', decimal=',' )
data2 = pd.read_csv('globale_auswertung.csv', sep=';', decimal=',')
```

Merge data

```
result = pd.concat([data, data2], axis=1, sort= False)
```

select versagenswarscheinlichkeit columns

```
col_contains_versagen = [col for col in result.columns if
'Versagenswahrscheinlichkeit' in col]
print(col_contains_versagen)
['Versagenswahrscheinlichkeit SIA 269:2007 (o. Korr.)',
'Versagenswahrscheinlichkeit SIA 269:2007 (mit Korr.)',
'Versagenswahrscheinlichkeit Badewannenkurve (o. Korr.)',
'Versagenswahrscheinlichkeit Badewannenkurve (mit Korr.)',
'Versagenswahrscheinlichkeit Taricska (o. Korr.)', 'Versagenswahrscheinlichkeit
Taricska (mit Korr.)', 'Versagenswahrscheinlichkeit Zustandsklasse (o. Korr.)',
'Versagenswahrscheinlichkeit Zustandsklasse (mit Korr.)',
'Versagenswahrscheinlichkeit Konstant (o. Korr.)', 'Versagenswahrscheinlichkeit
Konstant (mit Korr.)']
```

Compute Risiko

```
for col_name in col_contains_versagen:
    name = col_name.replace('Versagenswahrscheinlichkeit', 'Risiko')
    result[name] = result[col_name] * result['Schadensfolgekosten']
```

FIGURE 3. Python programming (Jupyter Notebook).

these models takes different parameters into account and can therefore lead to different results. In principle, the models become more and more universal from risk assessment to life cycle analysis to quality-of-life assessment, i.e., they consider an increasing number of parameters. For this reason, quality-of-life parameters are also referred to as the highest form of risk assessment.

Simplified life cycle cost models are currently applied in SBB's asset management, but without considering detailed risk assessments. It is planned to embed the risk assessment later in the existing life cycle cost models.

The general model for the life cycle cost (LCC) is:

$$LCC = G(d) - C(d) - I(d) - R(d) \qquad (1)$$

where G is the operating profit, C the construction costs, I the maintenance costs, R the risk of loss and d the vector of design variables.

Risk assessment represents a trade-off between traceability of results, number of parameters required and data management. The implementation of quality-of-life assessment models requires additional parameters, which are currently not available. It is therefore not pursued further in this study.

In principle, risk parameters R always consist of two factors: probability of occurrence E and extent of damage S:

$$R = E \times S \qquad (2)$$

The determination of these two factors is explained in the following sections.

3. Probability of Collapse

In order to calculate realistic risk values R, the use of realistic collapse probabilities of bridges is mandatory, otherwise one obtains risk values that are only of limited practical relevance and that may lead to a misallocation of SBB resources in the long run.

The term collapse probability E used here symbolises the mixture of calculated failure probabilities and corrections based on statistically evaluated collapse frequencies:

$$E_B = P_f(a) \cdot \prod_i k_i \qquad (3)$$

with E_B as the collapse probability for each bridge, $P_f(a)$ as the age-dependent failure probability and k_i as correction factors. The factors k_1 to k_{12} for the calculation of the individualised corrected collapse probability are listed below. The factors consider

1. Human error
2. Correlation of the limit states

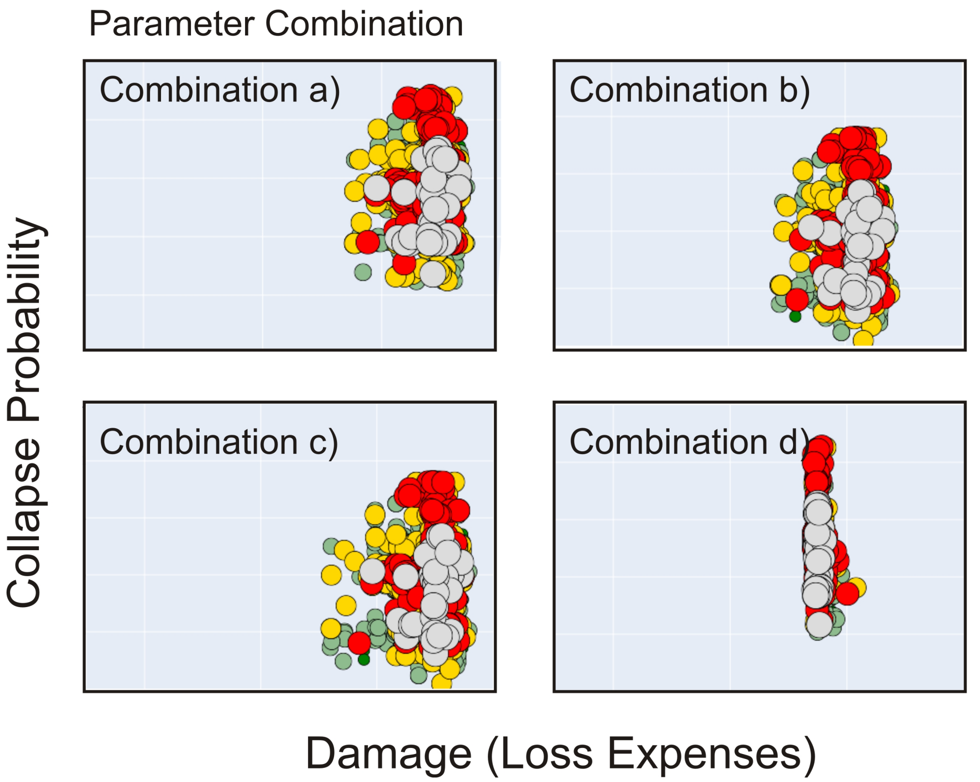

Figure 4. Sensitivity analysis I (the colour indicates the condition class).

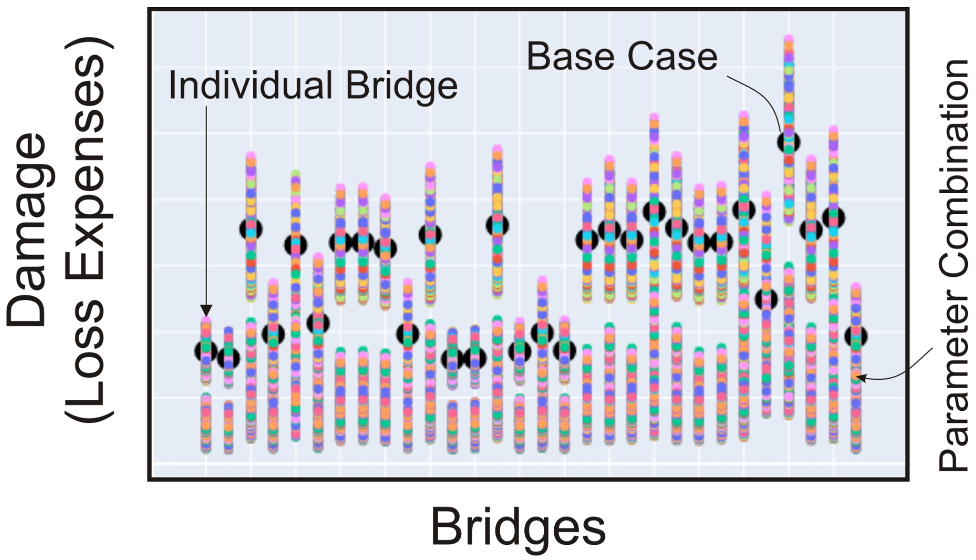

Figure 5. Sensitivity analysis II.

3. Static determinacy
4. Early failure recognition
5. Type of overpass
6. Quality of the static calculation
7. Bridge type
8. Building material
9. Construction technology
10. Robustness
11. Serviceability
12. Load tests results available

Furthermore, different models for the age-dependent failure probability were integrated, such as the bathtub curve, the model according to SIA 269, the model according to Taricska [5], a model depending on the condition classes and a model without ageing. The SBB degradation curves were also considered.

The development of the correction factors was shown in [6] and the approach was implemented for each SBB bridge. The necessary data for determining the age-dependent probability of failure and correction factors are taken from the SBB bridge databases.

4. Damage Parameters

The calculation of damage costs S of a bridge collapse, failure or closure can become very extensive and detailed. In some cases, up to 50 parameters are considered in the literature, ranging from the number of victims to environmental damage [7]. For the SBB model, however, only 15 damage parameters have been included:

$$S_B = \sum_i s_i \, f_i \qquad (4)$$

where SB are the damage costs for each individual bridge and s_i individual damage cost shares. Some of the shares s_i and the correction factors f_i, respectively are listed below:

1. Replacement value of the bridge
2. Price of a goods train
3. Price of a passenger train
4. Mean number of fatalities and injuries
5. Value to avoid one fatality (VOSL)
6. Ratio of passenger to goods trains
7. Number of trains per day
8. Restrictions on the detour route
9. Additional expense due to detour route
10. Duration of the line closure

Parts of the development of such factors have also already been published, see for example [8]. Most of the damage cost values and the necessary data for determining the factors were provided by SBB

5. Software Implementation

First, the SBB exported the bridge data into Excel. In Excel, the calculation procedure was implemented as a "proof-of-concept" according to the formulas shown above. However, the calculation must access a large number of dynamic SBB databases, for example detailed train data.

For this reason, the entire calculation was implemented into Python (Jupyter Notebook, see Figure 3) and migrated to the SBB computer system. As a result, confidential data does not leave SBB. In total, almost 30 parameters are read from the SBB databases per bridge. The Python software is also linked to a dynamic GIS model. Due to licensing restrictions, however, no images of the GIS link are shown within the scope of this article.

6. Sensitivity Analysis

For the almost 30 parameters, testable and robust values must be provided. Therefore, all parameters should have a significant influence on the calculation. To test the sensitivity of the model and the calculations, various sensitivity calculations were carried out.

The sensitivity calculation of the overall model was carried out in two steps. Firstly, four parameter combinations were calculated for approx. 4,000 bridges and secondly, approx. 30 parameter combinations were calculated for 30 bridges.

Figure 4 shows the position of approx. 4,000 SBB bridges in a risk diagram in the context of the first sensitivity calculation. The sensitivity calculations consider four variations of the computation of 11 of the individual bridge input parameters, such as the probabilities of failure, replacement values of bridges, price of freight trains and passenger trains, ratio of freight to passenger trains, number of trains per day, costs of downtime and the number of fatalities and injured. The $x-$axis shows the extent of damage in US-Dollars and the $y-$axis the probability of collapse. One can see clearly both, the change of the bridge results in $y-$direction (combination a and b) and in the $x-$direction (combination c and d) by the different value combinations.

Figure 5 shows a second sensitivity study for 30 bridges. Each column is a bridge and each point per column is a parameter combination. The black dot is the anchor point (base case).

As a result of the sensitivity studies, the weighting of the different input parameters is also obtained. Figure 6 shows the importance of four damage cost variables for risk determination. These results are in accordance with other works on risk assessment of bridges [7, 9, 10].

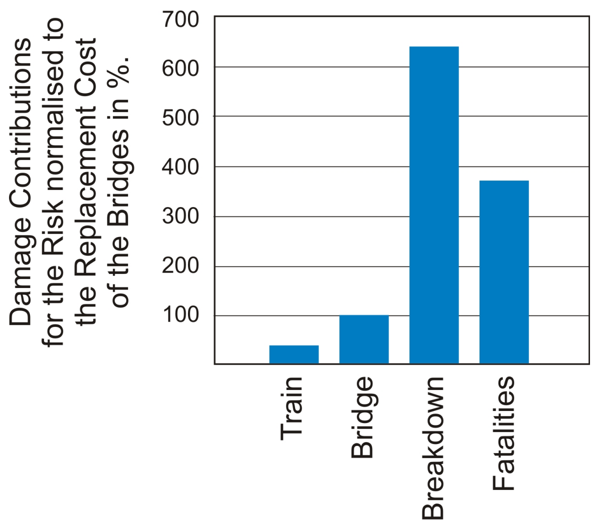

Figure 6. Normalised damage contributions.

7. Results

The results of the risk assessment of all SBB bridges can be presented either in tabular form as a TOP-100 risk list or geographically. Figure 7 shows a geographical representation of the location of 4,237 SBB bridges and the associated risk class. One can clearly see the sensitivity of the calculation models and thus also indirectly the effects of maintenance measures. However, some bridges are dominating the risk in most models.

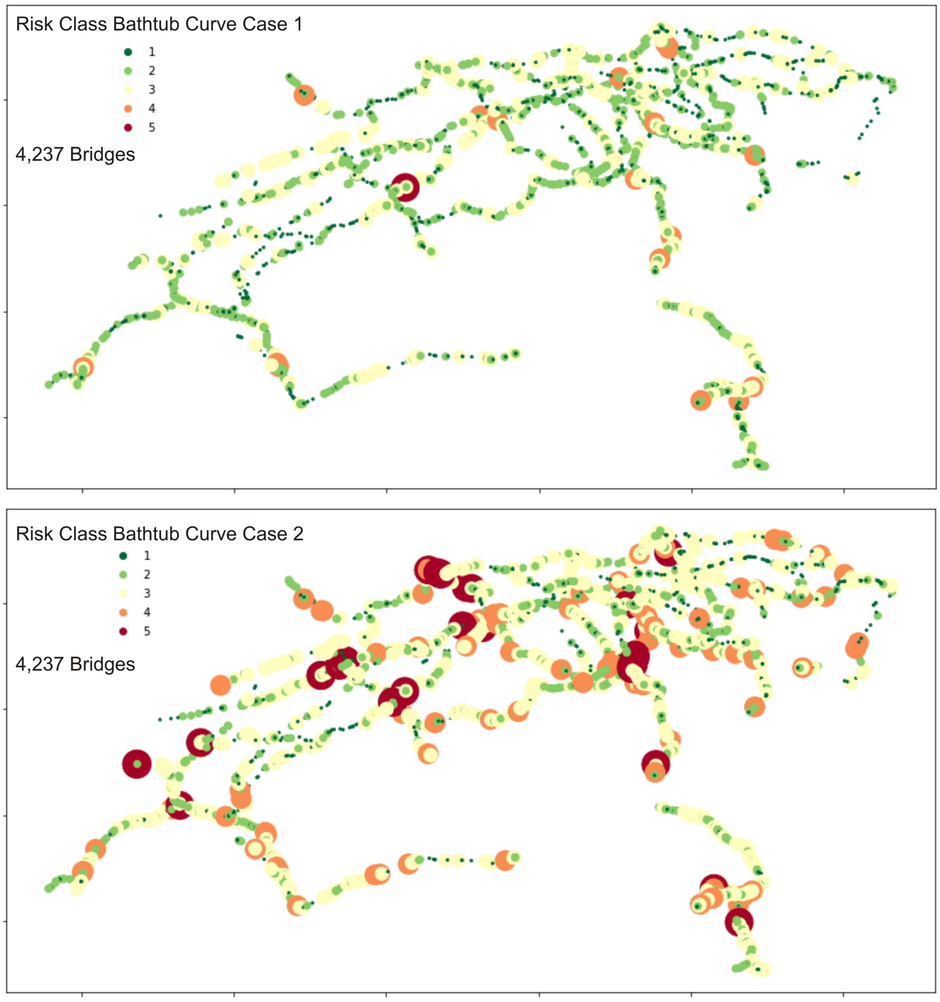

Figure 7. Geographical location of the SBB bridges and representation of the respective risk class for two models.

The location of the bridges can be shown much more comprehensively in GIS maps but is not shown here due to copyright restrictions.

8. Practical Experience and Outlook

The practical application of risk-based maintenance management did not take place without intensive discussions and challenges. For example, it became apparent at an early stage that the choice of the number of risk classes effects considerably the acceptance of the procedure among inspectors and civil engineers [11]. Furthermore, discussions about the comparability of the condition classes and risk classes also arose. Figure 8 shows such a comparison. This figure clearly indicates a difference in the relative frequency of bridges in condition classes and risk classes respectively. Whereas the final consequences in terms of required maintenance measures may be clear, the interpretation of the causes of the different frequencies requires detailed inside into the computations. In general, the distribution of risk classes indicates a better overall situation than the distribution of conditional classes. This may indicate that in practice already engineers and managers consider costs and risks for the selection of maintenance measures by a non-mathematical approach.

Furthermore, the calculation was also extended to bridges over SBB lines. Here, however, not all data are available, as other owners are involved. The extension of the bridge population also applies to the SBB itself, since in principle culverts can also be considered.

In addition, further effects have been shown in practical application:

- Certain bridge types (single-span steel girders) and certain constellations (bridges over water) occur more frequently or dominate the TOP 100 risk list. This observation cannot be independently verified at the moment because all known collapse and damage events have already been used for the modelling (burned data).
- Individual control calculations showed inconsistencies in the input data. Individual case checks are then necessary. For the bridges, however, the error rate in the databases is below 5 %. There are considerations to identify and automatically replace such erroneous entries by means of Artificial Intelligence

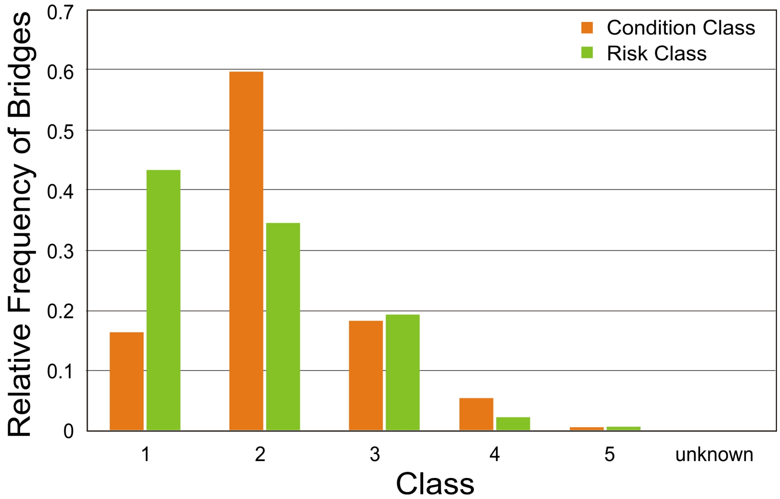

Figure 8. Comparison of the frequency of bridges in the condition and risk classes (class 1 means either good condition or low risk, class 5 means very bad condition or very high risk).

or other advanced software.

- A prioritisation list of the bridges, created independently and with a different method, shows an overlap of 50 % with the TOP 100 risk list. Whether this is a good value cannot be assessed at this stage, as different input parameters are considered.
- The feedback from the bridge managers was very positive when the bridges relevant to them were confirmed by the risk list.
- The Ossingen bridge, which was closed in January 2021 due to safety concerns, was ranked 90th on the TOP 100 risk list. The SBB considers all bridges in the TOP 100 as "potentially risky" and plans further investigations or measures.
- The communication of the results of the risk-based assessments requires an increased effort, since the condition class of a bridge is easier to communicate than the risk value which includes a variety of input variables from different fields, e.g., structural engineering, economy, rail network organisation. Therefore assumptions, simplifications, methods, values, and consequences must be explained in detail to achieve acceptance of the method at various organisational levels.
- The use of the results for inspection and maintenance depends also on other factors. Organisational and technological effects also play a major role, such as possibility of closure, required closure time of a route, the accessibility of bridges, etc.
- The procedure is more sensitive to changes in the general conditions, such as the changed traffic volume associated with COVID-19 pandemic. Here, the condition classes are more stable, but of course, concluded maintenance measures are also subject to budgetary constraints.
- For some input parameters, values are not yet available. For example, it is unknown what effects construction technologies have on the collapse probability of bridges. Further work is needed here. So far, the factor 1 has been used in the computation.
- An extension of the existing model to include time-dependent influences is planned. The data have already been prepared. This would be the transition from the solely risk-based to the life-cycle-based models. Since such models are available here at SBB, the two models would have to be linked and adapted only.
- Natural hazard models are available at SBB [12, 13]. These could also be linked with the risk model.

With the methodological development and software implementation of the risk-based asset management of SBB bridges, both structural analysis, inspections of bridges and maintenance measures can be prioritised. From the authors' point of view, the concept of condition classes is retained and thus allows the person responsible for the structure to influence the risk calculation and, under certain circumstances, to veto them (e.g., condition class 5 always beats risk list).

The risks calculated serve as an additional information or decision variable to optimise the utilisation of the portfolio and the investment in the infrastructure. The long-term impact of the risk analysis should also allow an appropriate and transparent use of financial resources and control of the risk to society.

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