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Lifetime and replacement cost analysis for concrete bridges and overpasses in the Dutch highway network

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ABSTRACT: Rijkswaterstaat (RWS), the executive agency of the Ministry of Infrastructure and the Environment in the Netherlands, maintains more than 3500 concrete bridges and overpasses in the country's main highway network. To calculate the life-cycle cost, information on the time and cost of replacement is required. Estimating the remaining lifetime becomes more important as the average age of the structures increases and at the same time the use intensifies. RWS is interested in the future budget requirements for the replacement and renovation of the structures. This paper's first objective is to review the age distribution of concrete bridges and overpasses in the Dutch highway network and to estimate their expected lifetime. A Bayesian analysis using the lifetimes of demolished structures and the ages of structures in use yields an update of the structures' lifetime distribution. Next, the expected replacement costs are computed based on the design lifetime, the best lifetime estimate and the lifetime distribution of the structures. Without taking into account the uncertainty in lifetimes, the future replacement costs of bridges and overpasses show a peak in the period 2040-2060. This makes sense, because most structures have been built in the early 1970s. The replacement costs level out when considering the lifetime uncertainty. However, a significant peak in budget requirements for the 2040-2060 remains and the uncertainty in the replacement costs cannot be neglected.

Keywords: service life estimation, replacement costs, concrete structures and probabilistic modelling

1 INTRODUCTION

Rijkswaterstaat (RWS), the executive agency of the Ministry of Infrastructure and the Environment in the Netherlands, maintains three networks in the country: the main highways, the main waterways, and the main bodies of water such as the large rivers and the coastal area of the North sea. The main highway network includes more than 3,500 concrete bridges and overpasses. Many of these structures date from the early 1970s. Their design lifetime is 80 years. In the last decades the average age of the structures has increased and at the same time the use has intensified. Moreover, in the coming years fewer structures will be built and the existing structures will be used longer. For these reasons estimating the remaining lifetime becomes more important.

Figure 1 shows the distribution of the structures' year of construction. While the oldest structure within this network dates back to 1920, the majority of these structures were constructed in the period between 1965 and 1980. To get a grip on the uncertain lifetime of the concrete structures, RWS periodically analyzes the age distribution. In 2003 a Weibull lifetime analysis of bridges and overpasses led to an estimate of 75 years (van Noortwijk and Kallen, 2004). In 2011 the Weibull analysis led to an estimate of 80 years, which equals the design lifetime. At that time the structures were about eight years older than in the 2003 analysis, but between 2003 and 2011 hundreds of bridges and overpasses had been built (see Figure 1).

Figure 1: Concrete structures' year of construction. Bridges in green. Overpasses in red.

Figure 2 shows the initial estimate of the replacement year by RWS based on 'year of construction'+ 'design lifetime'.

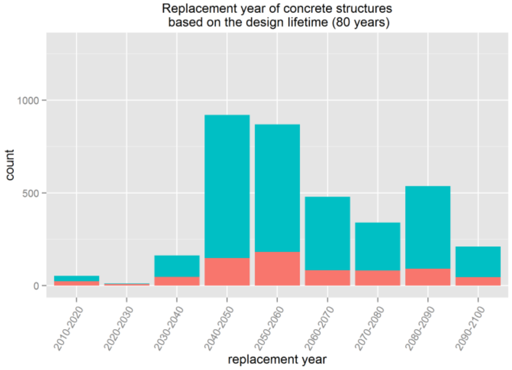

Figure 2: Replacement year of concrete structures based on the design lifetime of 80 years. Bridges in green. Overpasses in red.

The end-of-service life is defined as that moment when it is no longer economically efficient to maintain the structures or when they can no longer fulfil their functional requirements. The end-of-service life can be caused by deterioration for which technical requirements have been set. RWS monitors the structures' condition scores and relates these to the functional performance and technical requirements. The occurrence of the end of a structure's lifetime makes replacement or renovation necessary.

Between 2012 and 2015 RWS has developed a methodology for the long term planning of the replacement and renovation of major hydraulic structures (Bernardini et al., 2014). One of the components of this methodology is a Bayesian model called DISK Pro, which uses data on structures still in use, such as age (or year of construction), type and year of renovation, and the lifetimes of demolished structures to estimate the lifetime distribution of such structures.

The DISK PRO method has already been applied to five groups of hydraulic structures in The Netherlands. The lifetime estimates exceed the design lifetime, but the uncertainty in the lifetime is relatively high (Nicolai and Klatter, 2015).

The contribution of the present article is two-fold. Firstly, we feed the Bayesian model with lifetimes of demolished structures. Secondly, we take into account the lifetime uncertainties to get a grip on the long-term budget requirements for the replacement of concrete structures.

In section 2 we estimate the technical lifetime distribution of concrete structures through application of the DISK PRO method. In section 3 we use these estimates to compute the long term budget requirements for the replacement of bridges and overpasses. Section 4 concludes.

2 TECHNICAL LIFETIME ESTIMATES FOR CONCRETE STRUCTURES

2.1 *DISK PRO method*

The DISK PRO method introduced in Kallen et al. (2014) uses generic data to obtain a rough technical lifetime estimate for all structures. It is a Bayesian model, which reflects the uncertainty in the technical lifetime of a group of similar structures, such as sluices or fixed bridges. Initially, the lifetime of a group of structures is assumed to follow a Weibull distribution with known shape and uncertain scale parameter. The uncertainty about the value of the scale parameter is modelled with an inverse gamma distribution, being the prior distribution. Expert opinions on two percentiles of the lifetime are required to derive the prior predictive lifetime distribution of a group of structures. Data on structures still in use, such as age (or year of construction), type and year of renovation, and the lifetimes of demolished structures are input to the Bayesian update, which yields the posterior predictive lifetime distribution.

From the above it follows that the shape parameter of the Weibull distribution must be set to some value. We have set the parameter equal to the value found in the 2011 Weibull lifetime analysis of concrete structures. The shape parameter corresponds with a coefficient of variation (COV) of 0.27, which indicates that the uncertainty is relatively large.

2.2 *Data: existing and demolished structures*

Currently the main highway network includes 3592 bridges and overpasses. The age distribution of these structures in use are shown in Figure 3. Most structures are younger than 50 years. More than 1,000 structures are between 40 and 50 years old. In the last 10 years about 500 structures have been built.

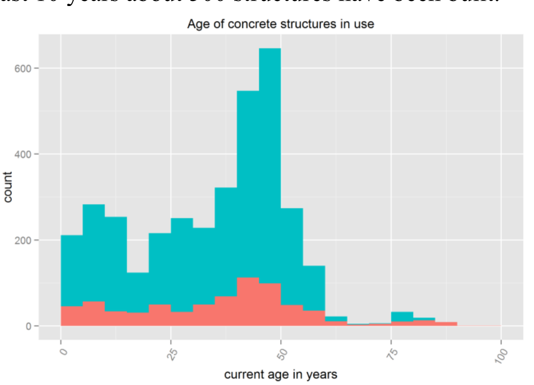

Figure 3: Age distribution of concrete structures in use. Bridges in green. Overpasses in red.

Figure 4 shows the age distribution of the structures at demolition. In the past decades 215 structures have been demolished. Many structures are demolished after 45 - 65 years. Some structures have been demolished before the age of 20 years. This raises the question of what are the reasons for demolition. Unfortunately RWS does not save the reason in the object database. The presumption is that the reason relates to the functional performance. An inquiry to the structures that have been demolished at an age younger than 20 years confirms the presumption. In all cases the demolition is part of the reconstruction of the highway or a highway junction.

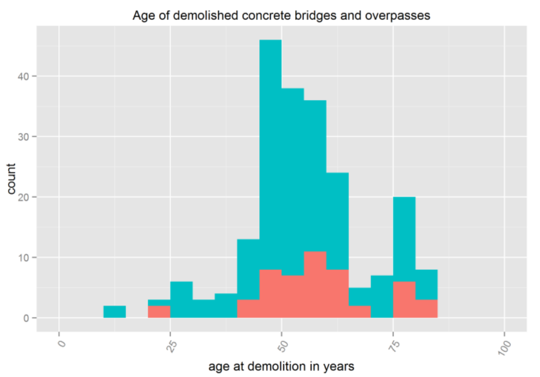

Figure 4: Distribution of structures' age at demolition. Bridges in green. Overpasses in red.

Further inquiry to the reason of demolition has to be done. For the lifetime analysis in this paper the data on demolished structures have not been adjusted. Hence the results shall underestimate the actual technical lifetime.

2.3 *Lifetime estimates and time of replacement*

The DISK Pro method first yields a generic posterior lifetime distribution for the entire group of concrete structures. The best estimate of the generic lifetime is derived as the corresponding 50th percentile: 80 years. This value equals the design lifetime and is somewhat higher than the 2011 Weibull analysis. The red line in Figure 5 shows the posterior lifetime distribution. The probability distribution of a single structure's lifetime is derived by conditioning the generic lifetime distribution on the structure's current age. The green line in Figure 5 is an example of a single structure's posterior lifetime distribution. Put differently, the green line is a predictor for the uncertain replacement age of a structure.

The lifetime estimates of single structures follow from the 50th percentiles of the conditional distributions (green line in Figure 5). For the structures younger than 40 years the best estimate is 80 years. For older structures the best estimate is higher than 80 years. Figure 5 shows that the lifetime of a 78-year old structure is 93 years. The explanation is that the conditional distribution of this structure has shifted to the right in comparison with the generic lifetime distribution.

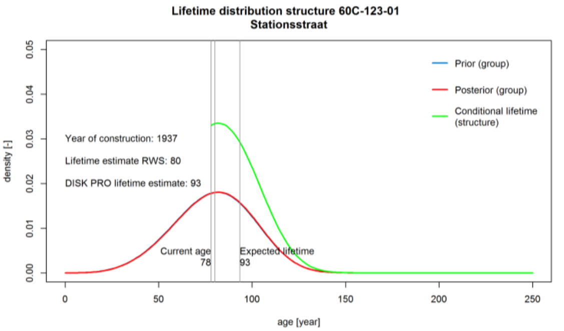

Figure 5: Generic lifetime distribution of concrete structures (red line) and (remaining) lifetime distribution of a particular bridge (green line).

What is the impact of the new estimation method on the time of replacement? Figure 6 shows the replacement years of the 3592 structures based on the DISK PRO lifetime estimates. According to this way of planning replacements, the first replacement is in 2024, the last in 2094. Most lifetime estimates do not deviate much from the design lifetime and hence the distribution of the replacement years resembles the distribution in Figure 2. The peak of replacements in the decade 2050-2060, however, is somewhat surprising. It appears that the DISK PRO lifetime estimate of 342 structures dating from 1968 and 1969 just exceed 82 years such that the corresponding replacement year shifts to the next decade. Taking into account the uncertain lifetime one would better assume a large number of replacements in the period 2040-2060. In the next paragraph we shall check this assumption by explicitly taking into account the lifetime uncertainty in the replacement costs (and replacement planning).

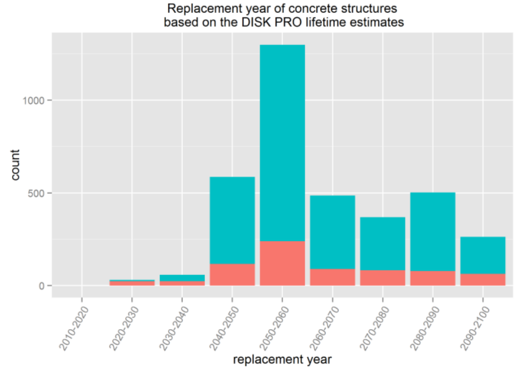

Figure 6: Replacement year of concrete structures based on the structures' DISK PRO lifetime estimates Bridges in green. Overpasses in red.

3 LONG TERM BUDGET REQUIREMENTS

3.1 *Data and models*

For analyzing the future replacement costs the four methods developed in Nicolai and Klatter (2015) have been applied to 3479 concrete structures with known replacement value. Unfortunately, the replacement value of 113 structures built between 2010 and 2015 are not available yet. Hence, the future replacement costs in the second part of the century shall be underestimated.

1 A deterministic model. The replacement year equals the outcome of the RWS basic method.
The replacement costs are deterministic.
2 Semi-probabilistic model. The replacement year is based on the DISK PRO method's technical end-of-service life estimate, being the best estimate of the structure's expected lifetime.
The replacement costs are deterministic.
3 Probabilistic model for the technical end-of-service life. The replacement year is a random variable. It's realisations are sampled from the posterior predictive lifetime distribution.
The replacement costs are deterministic.
4 Fully probabilistic model. The replacement year is the random variable specified in model 2.
The replacement costs are stochastic having a triangular distribution, where the lowest (highest) value is 75% (150%) of the deterministic estimate. The mean of this distribution is about 108% of the deterministic value in model 3.

Table 1 summarizes the specifications of the four models.

Table 1: Model specification.

Model	Lifetime estimate	Replacement cost
1 Deterministic	Deterministic	Deterministic
2 Semi-probabilistic	Expected value	Deterministic
3 Probabilistic	Posterior distribution	Deterministic
4 Fully probabilistic	Posterior distribution	Stochastic

The key assumptions of this case-study are:

– The planning horizon is 2015–2100. The length of the planning periods is 10 years.
– The current replacement planning by RWS is not taken into account.
– A structure shall be replaced only once in the planning horizon.
– A structure's replacement cost does not depend on the structure's lifetime or year of replacement.
– Costs are not discounted.

3.2 *Future replacements costs*

Figure 7 shows the future replacement costs according to models 1 and 2. The pattern of the bars resemble the patterns of the replacement years in Figures 2 and 6. Due to the large number of structures the differences in the replacement values level out.

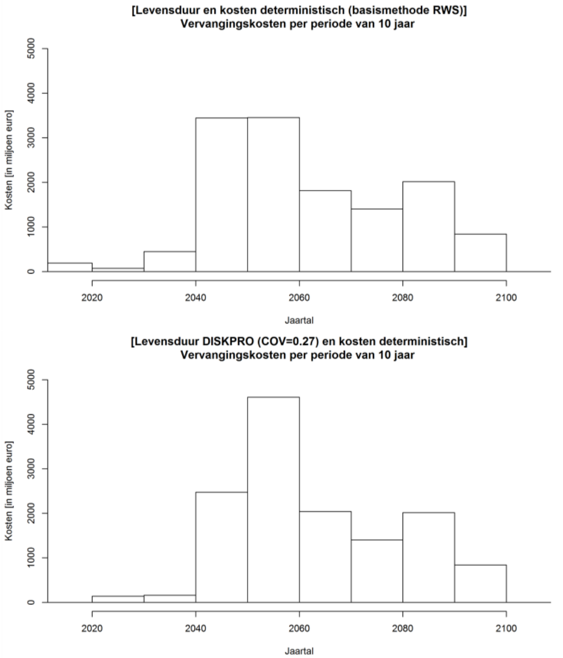

Figure 7: Expected future replacement costs of concrete structures as a function of time based on methods 1 and 2 (from top to bottom).

The bar plot in Figure 8 shows the distribution of the replacement years in models 3 and 4, which include the lifetime uncertainty. The peaks in the (expected) number of replacements in the period 2040-2060 have flattened in comparison with figures 2 and 6. The expected number of replacements ranges between 250 and 500 per decade. The large uncertainty in the lifetimes also results in replacements after the year 2100.

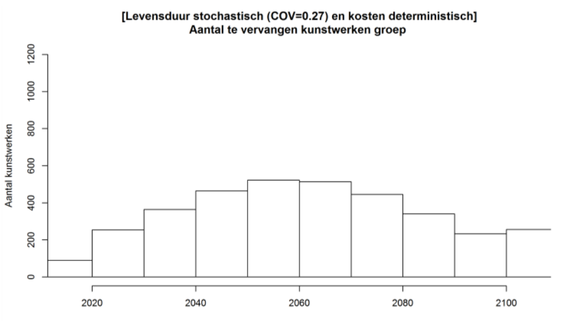

Figure 8: Distribution of the replacement year of concrete structures based on the structures' posterior lifetime distributions (models 3 and 4). Replacements beyond the year 2100 are added together.

The bar plot of the expected replacement costs in Figure 9 resembles the distribution of the number of replacements in Figure 8. The replacement costs range between about 1 and 2 billion Euros per decade. The maximum is attained in the period 2040-2060, but this is much smaller than the maximum expected replacement costs in models 1 and 2 (see Figure 7). As the replacement value of younger, mostly larger, structures is about 20% higher than the average replacement value, a similar increase in the expected replacement cost per structure is found for the decades from 2090 as compared to the first decades in the 21th century.

Figure 9 also shows the variability in the replacement costs as a result of the uncertainty in the lifetime estimates. The red dashes are 5th and 95th percentiles, the green dashes are 10th and 90th percentiles, and the blue 'pluses' are the 50th percentiles of the replacement costs. The uncertainty in the replacement costs cannot be neglected. For example, the 5th and 95th percentiles of the replacement costs in the decades 2040-2050 and 2050-2060 are given by 1.7 and 2.5 billion Euros, respectively.

Model 4 yields similar results as model 3 with replacements cost levels being 8% higher (not shown here). Note that the replacements costs in different decades can be regarded communicating vessels; by assumption the total expected replacement costs are fixed in models 3 and 4.

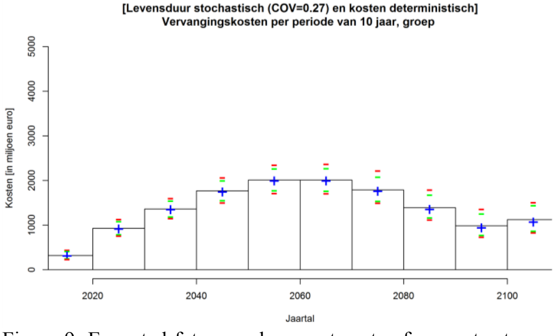

Figure 9: Expected future replacement costs of concrete structures as a function of time based on model 3. The red dashes (-) are 5th and 95th percentiles, the green dashes (-) are 10th and 90th percentiles, and the blue pluses (+) are the 50th percentiles.

4 CONCLUSIONS AND RECOMMENDATIONS

Rijkswaterstaat (RWS), the executive agency of the Ministry of Infrastructure and the Environment in the Netherlands, maintains more than 3,500 concrete bridges and overpasses in the country's main highway network. Many concrete structures date from the early 1970s. Estimating the remaining lifetime becomes more important as the average age of the structures increases and at the same time the use intensifies. Moreover, in the coming years fewer structures will be built and the existing structures will be used longer.

Rijkswaterstaat initiated a study to answer the following research questions:

- what will be the expected service life of these structures;
- what will be the future budget requirements when these structures have to be replaced when they reach end of their service life;
- what are the uncertainties and what is their influence on the answers to the two questions above.

A Bayesian model is applied to estimate the technical lifetime of 3592 concrete bridges and overpasses in the main highway network. The model makes full use of the little information that is available about the remaining life of the existing structures and. Moreover, the model is also fed with the age at demolition of 215 demolished structures. The resulting probability distributions show large uncertainty in the lifetime. The lifetime estimates are about equal to the initial design lifetime (80 years). However, the technical lifetime is underestimated, since many of the 215 structures are demolished for functional reasons. Therefore, we recommend further analysing the reason for demolition.

The lifetime estimates have been used to analyse the long-term budget requirements of the concrete structures with four models (deterministic and stochastic). Whereas the planning models with deterministic replacement years result in large peaks in replacement costs between 2040 and 2060, the probabilistic models yield a less spiky cost profile with a maximum in this time interval. The asset managers at RWS should take into account a steady increase in budget requirements for the replacement of concrete structures in the next 50 years. Due to the large number of concrete structures the variability in the total replacement cost level is relatively small, but it can lead to 20% higher peaks. Hence, it is a factor that RWS should keep in mind.

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