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Long-term budget requirements for the replacement of bridges and hydraulic structures

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ABSTRACT: Bridges over waterways and hydraulic structures, such as sluices, locks, pumping stations, and storm-surge barriers may reach their end-of-service if they are no longer economically maintainable or if they can no longer fulfil their functional requirements. Rijkswaterstaat (RWS), the executive body of the Ministry of Infrastructure and the Environment in the Netherlands, maintains about 650 bridges and hydraulic structures in the country's main waterway network. Recently RWS has developed a Bayesian model to estimate the remaining service life of these 650 structures. Application of the model yields (i) best estimates of the expected service life for groups of similar structures and (ii) lifetime distributions for all structures individually. RWS wants to gain more insight in the long term budget requirements for the replacement of the structures. An easy way to do this is computing the replacement costs on the projected replacement years. However, both the replacement years as well as the replacement costs are uncertain estimates. In this article we show that probabilistic estimates of the replacement years and costs have added value to the asset manager who has to allocate sufficient funds to finance the replacement of infrastructure.

1 INTRODUCTION

Rijkswaterstaat (RWS), the executive body 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 latter two networks include about 650 bridges and hydraulic structures, such as sluices, ship locks, weirs, pumping stations, storm-surge barriers and docking areas. These structures are designed to last for a long time (80 or 100 years depending on the type of structure) and are costly to replace.

Figure 1 shows the distribution of the structures' year of construction. While the oldest structure within this network dates back to 1853, the majority of these structures were constructed in the period between 1920 and 1960. With a design lifetime of 80 to 100 years, a large number of structures in the Netherlands are nearing the end of their lifetime in the coming decades. The end of their lifetime is defined as that moment when it is no longer economically efficient to maintain these structures or when they can no longer fulfil their functional requirements. It 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. The fact that hydraulic structures operate in a complex network (comprised of both main and regional water systems) with many functions and stakeholders, makes the redesign of these infrastructural assets a complex task. On the other hand, the replacement of a key hydraulic structure offers stakeholders a

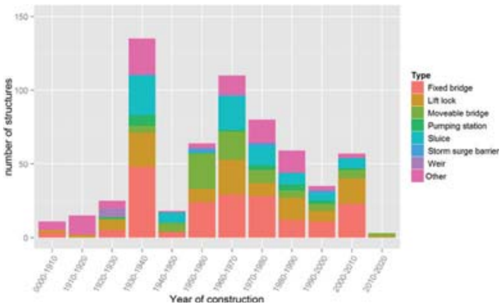

Figure 1. Distribution of the year of construction of bridges and hydraulic structures in The Netherlands.

valuable opportunity to re-think the water system as a whole by adding or subtracting functionality to structures.

Given the relatively old age of the current stock of structures in the Netherlands and the high cost of replacing each structure, it is necessary to get an indication of when a structure must be replaced. The age at which a structure needs to be replaced is uncertain and must therefore be estimated. These estimates must subsequently be used to predict the long term budget requirements for the replacement of the structures. Figure 2 shows the initial estimate of the replacement year by RWS based on 'year of construction'+ 'design lifetime'.

Since 2012 Rijkswaterstaat has been working on a methodology for the long term planning of the replacement and renovation of the major hydraulic structures within a project named "VONK". The main purpose of this project is to design an integrative framework to support policy makers and politicians with the necessary information for their decision-making process on the long term replacement and renovation of infrastructure. At the same time the framework should provide insight in the magnitude of the replacement task to justify the necessity of the financial reservations that have been made for the medium term.

The project VONK is still in progress. The outline of the integrative framework has been presented in Bernardini et al. (2014). A unified approach for estimating the remaining service life of the structures has been defined in Kallen et al. (2014). This approach distinguishes between functional and technical lifetime estimates. The work by Vuren et al. (2015) introduces an approach to help define long term reinvestment strategies for the replacement or renovation of hydraulic structures within existing water infrastructure networks. It focuses on the development of adaptation pathways to deal with future uncertainties in decision-making in a flexible and incremental way.

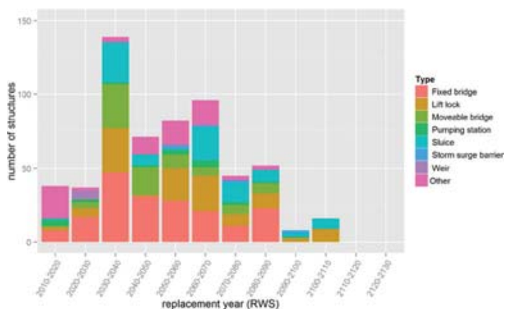

Figure 2. Year of replacement according to the "RWS basic method".

The contribution of the present article is two-fold. In section 2 we present the technical lifetime estimates following from the application of the Bayesian method introduced by Kallen et al. (2014). In section 3 we formulate probabilistic models for computing the long term budget requirements for the replacement of bridges and hydraulic structures. Section 4 lists the results of the application of the models to three groups of structures. Section 5 concludes.

2 TECHNICAL LIFETIME ESTIMATES FOR HYDRAULIC STRUCTURES

This article concerns the technical lifetime of structures, but unless otherwise stated, we shall use the term lifetime.

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 moveable 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.

The DISK Pro method first yields posterior lifetime distributions for groups of structures. Best estimates of the group lifetimes can easily be derived as the corresponding 50th percentiles. The blue line in Figure 3 shows the prior predictive lifetime distribution for a group of structures, the red one the posterior lifetime distribution. Next, the same output can be derived for a single structure by conditioning the group's posterior lifetime distribution on the structure's current age. The green line in Figure 3 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 assumption that the shape parameter of the Weibull distribution is known can easily be relaxed. Note that the shape parameter in Kallen et al. (2014) directly determines the Coefficient of

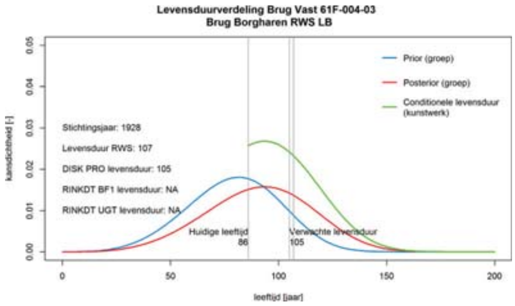

Figure 3. Lifetime distribution related to the fixed bridge near Borgharen. The blue (red) line represents the prior (posterior) predictive probability density of fixed bridges. The green line is the conditional posterior predictive probability density of the fixed bridge near Borgharen.

Table 1. Lifetime estimates following from DISK PRO analysis on five groups of structures.

Group	Types of structures (number)	Design lifetime (year)	Estimate (year)
1	Weir, sluice, lock, flood barrier (223)	100	109
2	Moveable bridge (82)	80	84
3	Siphon, underpass, mooring (101)	80	120
4	Pumping station (19)	80	86
5	Fixed bridge (187)	80	92
Total	All analyzed (612)		

Variation (COV). The related uncertainty can be modelled via a discrete probability distribution on values of the shape parameter (or the COV values). The DISK PRO method assumes that the COV takes values 0.1, 0.2 and 0.3, each value being equally likely. The exception is group 5, for which the COV-value is taken 0.27 based on previous research.

2.2 *DISK PRO results*

The approach by Kallen et al. (2014) has been applied to the data of five groups of structures shown in Table 1. Data of 612 structures in use have been analyzed as well as data from two demolished fixed bridges. Structures with missing year of construction and non-representative structures were left out the analysis.

Table 1 shows that all lifetime estimates are higher than the design lifetime. This is especially true for group 3, which consists of quite different, and also some quite old, structures. The most important source of information of DISK PRO is the current lifetime of the structures. The lifetime estimates of groups 1 and 3 are the result of a few structures that have been built before the year 1900.

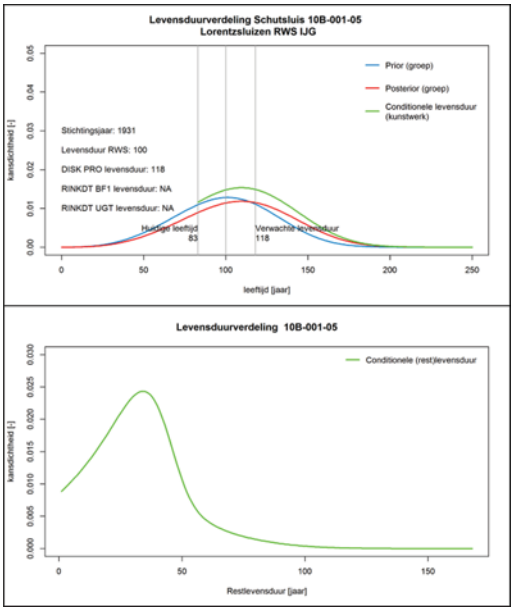

Figure 4. The above plot shows the lifetime distribution related to a lock at IJmuiden for COV = 0.3. Below the combined conditional posterior predictive remaining lifetime density is shown (on a different time-scale).

The DISK PRO method also yields lifetime estimates of individual structures. Figure 3 illustrates that the lifetime estimate of a 86 year old structure can be higher than the group lifetime estimate (105 vs. 92 years). Figure 4 shows as an example the remaining lifetime distribution for a single sluice (green lines), which is the result of the combination of lifetime distributions for three values of the coefficient of variation. The uncertainty in the individual structure's remaining lifetime is still quite large.

3 PROBABILISTIC MODELS FOR LONG-TERM BUDGET REQUIREMENTS

3.1 *Considerations on models for probabilistic replacement planning*

The initial RWS estimate of the structures' replacement years, shown in the Figure 2, is quite different to the DISK PRO replacement years shown in Figure 4. The former figure shows deterministic values given by 'year of construction + design lifetime'. The latter figure displays probabilistic technical end-of-service estimates, resulting from the application of the DISK PRO method. These methods are only two of many that can be applied to gain more insight in the long-term budget requirements for the replacement and renovation of structures. For example, one could also sample every structure's lifetime from the conditional remaining lifetime distribution (green lines in Fig. 3 and Fig. 4). By doing so, one creates a probabilistic replacement time series of all structures (and associated costs), which takes into account the uncertainty in the remaining lifetime of structures. However, such a series makes it difficult to retrieve the individual replacement times.

We shall introduce and compare four models for computing the replacement costs over time. The basic considerations on these models are:

- The technical end-of-service estimate is based on the deterministic RWS basic method, which does not take into account any uncertainties at all.
- The expected value following from the Bayesian DISK PRO method is input to the replacement planning. The expected value takes into account the statistical uncertainty in the lifetimes of structures, but it is a single possible realisation of the lifetime.
- Instead of directly integrating out the statistical uncertainty, the posterior distribution of the remaining technical lifetime can serve as an input to the replacement planning.
- The replacements costs of the structures are either deterministic or stochastic variables.

Four models for making the replacement planning and computing the budget requirements are presented here.

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 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.

Table 2 summarizes the specifications of the four models.

Table 2. Model specification.

Model	Remaining lifetime	Replacement cost
1. Deterministic	Deterministic	Deterministic
2. Semi-probabilistic	Expected value	Deterministic
3. Probabilistic	Posterior distribution	Deterministic
4. Fully probabilistic	Posterior distribution	Stochastic

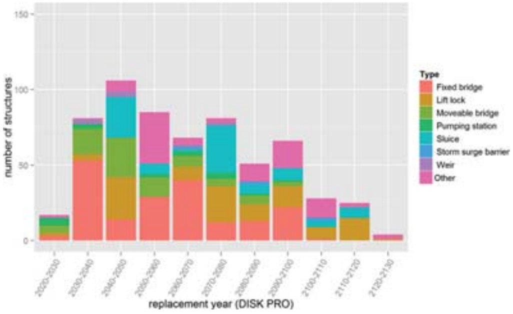

Figure 5. Distribution of the replacement year of bridges and hydraulic structures (DISK PRO).

3.2 *Model application*

The replacement years and costs for model 1 and model 2 follow directly from the definitions. The outcomes of models 3 and 4 are stochastic by nature. The expected value and variance of the replacement costs in each years can be computed analytically. To gain insight in the variation of the replacement years and costs, the replacement planning is created via Monte Carlo simulation of the replacement years and replacement costs (model 4).

The models are applied to the structures in groups 1, 2 and 5, i.e. 223 hydraulics structures, 82 moveable bridges and 187 fixed bridges. The replacement costs of the structures in group 1 are on average most expensive, being 5 (10) times larger than the replacement costs of the structures in group 2 (5). 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 can be replaced only once in the planning horizon.
- The replacement cost of a structure is not dependent on the structure's lifetime or replacement year.
- Costs are not discounted.

- Some unique structures, such as the Eastern-Scheldt and Maeslant storm surge barriers, are left out the analysis. Their replacement costs are extremely high (one or two orders of magnitude higher) and would distort the results.
- A sensitivity analysis is done by means of estimating the technical lifetimes of groups 1 and 2 for COV-values 0.1, 0.2 and 0.3. Note that the combined posterior distribution for these groups mimics the distribution found with COV = 0.3.

4 CASE-STUDY APPLICATION TO BRIDGES AND SLUICES

4.1 *Analysis*

Figure 6 shows the results of the deterministic model (RWS basic method) applied to group 1. The replacement costs of all three groups of structures follow the pattern of the deterministic replacement years shown in Figure 2. Only a few structures are planned for replacement after the year 2100. Figure 7 shows that the semi-probabilistic model plans the replacements later in time than the deterministic model (Fig. 1 and Fig. 5). In some planning periods the costs are much higher than in others.

Figure 6. Replacement costs deterministic model (1) for periods of 10 years.

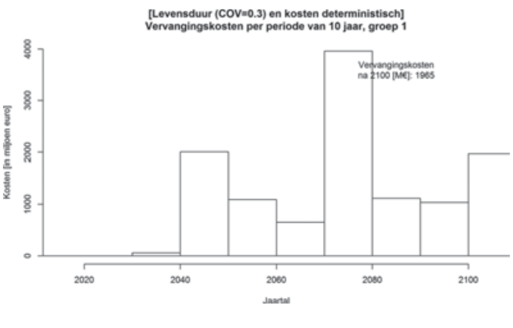

Figure 7. Expected replacement costs semi-probabilistic model (2) for periods of 10 years.

The probabilistic model spreads the expected replacement years and replacement costs comparatively equally over time (see Fig. 8). This is due to the large variation in the lifetimes. The expected value of the total budget requirements beyond the year 2100 is quite high for group 1, which consist of about 30 structures younger than 20 years with an expected lifetime of over 100 years. Model 4 yields similar results to model 3. However, the expected replacement costs are approximately 8% higher, because the replacement costs are stochastic with mean 108% of the deterministic estimate. Models 3 and 4 yield higher expected replacement costs beyond the year 2100 than model 1 and model 2. Due to the high uncertainty in the lifetime the replacement years and costs are spread over time.

The replacements costs per period appear rather sensitive to the COV value. The higher this value is, the higher the variance of the lifetime. Consequently, the expected budget requirements for COV = 0.1 are more spiky than those for COV = 0.2 and COV = 0.3 (not shown here).

The variability in the budget requirements resulting from model 3 is shown in Figure 8. The red dashes are 5th and 95th percentiles, the green dashes are 10th and 90th percentiles, and the blue 'pluses' are the 50th percentiles. The replacement costs in a period of 10 years can be a factor two lower or higher than the expected value. For example, model 3 (COV = 0.3) gives a 90%-range of about 50 to 200 million euros for the structures in group 2 in the 10-year periods between 2020 and 2070. As the lifetimes are highly uncertain (see Fig. 4) and the probability that the lifetime exceeds 100 years is high, the total expected costs after the year 2100 are quite high. The results for model 4 are similar. The replacements costs in different periods of times can be regarded communicating

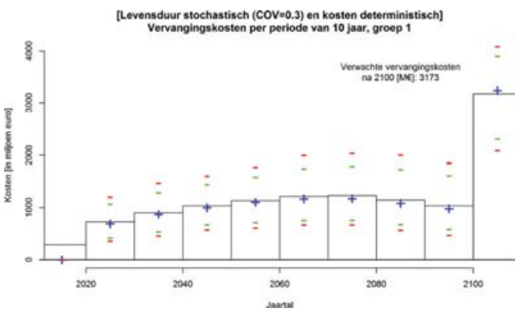

Figure 8. Replacement costs probabilistic model (3) for periods of 10 years. The red dashes (–) are 5th and 95th percentiles, the green dashes (–) are 10th and 90th percentiles, and the blue pluses (+) are the 50th percentiles.

vessels; by assumption the total expected replacement costs are fixed in models 3 and 4.

4.2 *Discussion on the applicability of the models to long-term reinvestment strategies for the replacement of structures*

One of the research questions is to what extent the probabilistic models yield useful results for the long-term replacement problem. The case-study shows that the probabilistic models spread the replacement costs over time due to the high uncertainty in lifetimes. At group level the resulting replacement costs per period of time yield useful information to the asset manager (RWS) who has to allocate sufficient funds to finance the replacement of infrastructure.

Firstly, the expected lifetimes are higher than the first estimates of RWS and the end-of-service years are further in time as well. RWS bases the replacement years of individual structures in the next two decades on inspections and condition assessments. Secondly, the peaks in the replacement budget are about a factor 2–4 higher than the averages. These peaks can be considered insignificant and RWS has decided not to take these peaks into account in their long-term replacement strategy.

It is not possible to retrieve the replacement years of individual structures from the probabilistic planning models. The planning of inspection or investigation of structures could benefit from the application of model 2 (the semi-probabilistic model), which bases the planning on the expected remaining lifetime of structures.

5 CONCLUSIONS AND FURTHER RESEARCH

The executive body of the Ministry of Infrastructure and the Environment in the Netherlands works on a methodology for the long term planning of the replacement and renovation of 650 hydraulic structures and bridges in the country's main waterway network. This article focuses on the technical lifetime estimation and the long-term budget requirements for the replacement of these structures.

A Bayesian model is applied to estimate the technical lifetime of the structures. The model makes full use of the little information that is available about the remaining life of the structures. The model is applied to several groups of structures and to all individual structures. The resulting probability distributions show large uncertainty in the lifetimes.

We have formulated deterministic and probabilistic models for making a long term replacement planning of major structures in The Netherlands. One of the models uses the expected remaining lifetime as the replacement year. Two probabilistic models take into account the uncertainty in the lifetimes (and the replacement costs). In a case-study the models have been applied to groups of bridges and sluices in The Netherlands.

The results of the case-study on three groups of structures show that the probabilistic models spread the replacement years and costs almost equally over time. This is a result of the relatively wide lifetime distributions of the structures. The deterministic model yields a spiky replacement planning. We conclude that the probabilistic models primarily yield useful information on the budget requirements for groups of structures. The expected lifetimes are higher than the first estimates of RWS and thus the end-of-service or replacement years are further in time. Also, the peaks in the replacement budget are a factor 2–4 higher than the averages. These peaks can be considered insignificant and RWS has decided not to take these peaks into account in their long-term replacement strategy.

Due to their stochastic nature the probabilistic models, which take into account uncertainty in the lifetimes and the replacement costs, are not very well suited for inspection and maintenance planning of individual structures. The semi-probabilistic model, which is based on the expected lifetime estimate, is a better candidate as one can directly retrieve the individual structures from the replacement costs.

Further research shall focus on controlling the variation in (yearly) replacement costs, which is effected heavily by the large uncertainty in lifetimes. Increasing the amount of data can reduce the variation to a small extent. In a new case-study the Bayesian model and probabilistic planning models shall be applied to about 4000 fixed bridges and viaducts in the main highway network. Also, the Bayesian lifetime model shall be applied to similar groups of components.

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