Functional and technical end-of-service estimates for hydraulic structures

M.J. Kallen
HKV Consultants, Lelystad, The Netherlands.

R.P. Nicolai
HKV Consultants, Lelystad, The Netherlands.

W.D. van der Wiel, A. Willems & E.L.E van den Dungen
Iv-Infra, Papendrecht, The Netherlands.

H.E. Klatter
Rijkswaterstaat, The Netherlands.

ABSTRACT: Hydraulic structures, such as sluices, locks, pumping stations, bridges over waterways, and storm-surge barriers may reach their end-of-service if they are no longer economically maintainable or if they can no longer fulfill their functional requirements. Rijkswaterstaat, the executive body of the Ministry of Infrastructure and the Environment in the Netherlands, maintains about 650 hydraulic structures in the country's main waterway network. This paper describes a unified approach for estimating the remaining service life of hydraulic structures which is being developed and applied in the Netherlands.

1 INTRODUCTION

1.1 *Hydraulic structures in the Netherlands*

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 hydraulic structures. These are sluices, ship locks, weirs, pumping stations, bridges over rivers and canals, storm-surge barriers, docking areas, etc. 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 year of construction for these structures in the Netherlands. The oldest structure dates from 1853 and many were built right before and after the second World War.

Replacement of a structure may be necessary due to technical deficiencies that are not economically interesting to repair or due to functional requirements which can not or no longer be met. The different types of structures have different functional requirements. Climate and economic change may adversely affect the structure's ability to perform according to these requirements. For example, an increase in the number of ships may increase the waiting time at locks beyond an acceptable limit. Also, in the future we may need bigger ships to transport goods over rivers and canals and the current locks may be too small to accomodate these bigger ships.

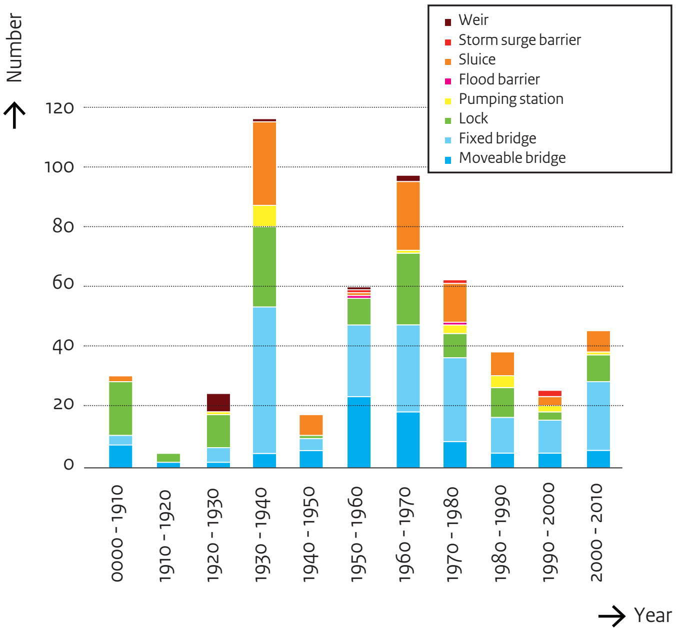

Figure 1: Distribution of the year of construction of hydraulic structures in the Netherlands. (Source: Delta Programmme/delta-atelier)

RWS has an annual budget to perform regular maintenance on these hydraulic structures. Maintenance is required to ensure that these structures can adequately fulfill their function in society today and in the future. For the purpose of planning maintenance activities, RWS uses forecasting to estimate the times at which renovations will likely need to be executed. These forecasts help the Dutch government to prepare for large investments in the future and to allocate sufficient funds to finance the replacement of infrastructure. In 2012, RWS made the first forecast by simply taking the design lifetime of each structure as the replacement age.

1.2 *Project goal*

Given the relatively old age of the current stock of hydraulic 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 using a combination of a probabilistic model and any data available to the modeller. Estimates must be given in the form of a lower and an upper bound, hereafter referred to as the timeframe for replacement.

A timeframe must be given for the two types of replacements: functional and technical. The goal of this project is to give bounds which correctly represent our uncertainty in the replacement age of each structure and which strike a balance between being well calibrated (i.e. the bounds contain the actual replacement age) and informative (i.e. the bounds are as narrow as possible). This is not an easy problem as, until now, no structure has been replaced due to technical deficiencies. This rules out a purely statistical approach and it gives little information for any other approach.

In late 2012, RWS initiated a public tender for the development of such a modelling approach to be applied to the Dutch stock of hydraulic structures. After a round of presentations and interviews, HKV Consultants and Iv-Infra were awarded the contract for this project which is known under its acronym VONK.

1.3 *Available data*

There are several types of data which can be used to estimate the replacement age and which are available for this project. First, there is generic information such as the type of construction, the year of construction, the design lifetime (80 or 100 years), the geographical location, etc. Second, each structure is periodically given a quality score based on a visual inspection. These scores, on a discrete scale from 0 to 6, are the same as those for the Dutch bridge stock as reported on in Kallen & van Noortwijk (2005). Third, some structures have been studied using a fault-tree analysis which gives detailed information on failure modes. These were obtained during a project with the acronym RINK. Finally, experts may give estimates of the remaining life of individual structures.

The functional lifetime of a structure must be estimated using a scenario analysis. Several scenario's for climate change and economic development are available for this purpose. The primary source for these scenario's is the Deltaprogram, which is a national research program to safeguard the Netherlands against flooding in the long-term, and its modelling infrastructure. For example, the Deltamodel is used to calculate water levels under a given climate scenario and these results can be used to determine when a structure functionally deficient.

1.4 *Outline of approach*

The approach used in this project is aimed at estimating timeframes for all 650 structures using as much of the generic data as possible. This is the first step. The estimate for structures that have a fault-tree are further refined in a second step. Finally, as an optional third step, expert judgement may be used to obtain more information about the state of a structure. Each step consists of an analysis and the results of these steps is combined, using a Bayesian model, into a final estimate for the replacement timeframe.

The estimation of timeframes for replacement due to functional deficiencies is discussed in Section 2 and for replacement due to technical deficiencies in Section 3. The two steps to arrive at a timeframe for a technical replacement are called 'DISK Pro', which is a reference to the database which holds the generic data on the structures and which is called DISK, and 'RINK ΔT'. The latter being the existing RINK fault trees that are projected forward in time using time-dependent failure rates for the relevant failure modes. We end this paper with a discussion of future work in Section 4.

2 FUNCTIONAL LIFETIME

Each structure has one or more functions within the network that it's part of. RWS has functional performance requirements which are used to determine if a structure is capable of performing its function sufficiently well. For example, a ship lock must be able to raise and lower ships between sections of a river or canal with different water levels. Increasing ship sizes or traffic numbers due to economic growth may result in a performance reduction. The lock becomes too small or ships have too wait too long before they can enter the lock. Some structures also have a function to protect against flooding. Rising sea levels due to climate change may result in structures being of insufficient height.

The timeframes for 'functional replacements' are estimated using a scenario analysis. For four scenario's, the aforementioned Deltamodel gives results for the reference year (2015) and two years in the future (2050 and 2100). These results concern water levels that can be used to determine the required levels of protection against flooding, the possible shortage of water during summer, or the excess infiltration of saline water.

Figure 2 shows a schematic example of how a timeframe is obtained from these so-called Deltascenario's. It's lower and upper bound are given by the earliest and latest crossing of a boundary condition by the scenario's.

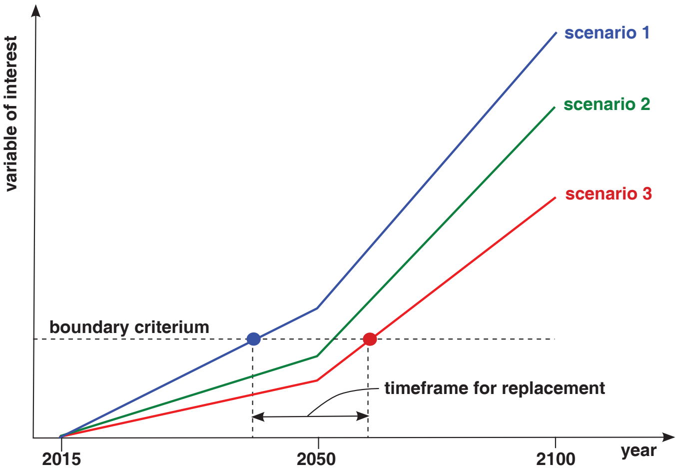

Figure 2: Schematic example of a replacement timeframe based on an analysis with three scenario's.

3 TECHNICAL LIFETIME

Two approaches to determine timeframes for replacement of structures due to technical deficiencies are presented here: 'DISK Pro' and 'RINK ΔT'. The first approach uses generic data to obtain a rough estimate for all structures. The second approach refines the first estimate using a time-dependent fault-tree analysis for a select number of structures.

3.1 *DISK Pro*

The goal of the first step is to define a probabilistic model which represents our uncertainty in the replacement age of a hydraulic structure and which can be updated with different types of data. For this purpose, a simple univariate Bayesian model is used. The model presented here has three distinct advantages:

1. the hyperparameters of the prior distribution can be easily determined using the design lifetime or by expert opinion,
2. the prior is conjugate to the likelihood such that updating the parameters is straightforward, and
3. the updating procedure handles both censored and uncensored data.

The model is defined in terms of Bayes' theorem:

$$p(\lambda\,|\,t) \propto p(t\,|\,\lambda)p(\lambda), \qquad (1)$$

where $p(\lambda)$ is the prior distribution over the parameter λ in the likelihood $p(t\,|\,\lambda)$ and $p(\lambda\,|\,t)$ is the posterior distribution given data t. The following Weibull distribution is used to represent the replacement age of hydraulic structures:

$$p(t\,|\,\lambda) = \frac{st^{s-1}}{\lambda}\exp\left(-\frac{t^s}{\lambda}\right), \quad t \geq 0, \qquad (2)$$

where $s > 0$ is the shape parameter and $\lambda > 0$ is the scale parameter. To obtain a univariate model, the value of the shape parameter is fixed by the modeller (see later). Not only does the choice for the Weibull distribution allow for a model with the aforementioned advantages, it also fits in with previous research on bridges in the Dutch highway network (van Noortwijk & Klatter 2004). Our uncertainty about the value of the scale parameter is represented by the inverse gamma distribution:

$$p(\lambda) = \mathrm{IG}(\lambda\,|\,\alpha,\beta) = \frac{\beta^{\alpha-1}}{\Gamma(\alpha)}\lambda^{-1-\alpha}\exp\left(-\frac{\beta}{\lambda}\right), \qquad (3)$$

where α and β are, respectively, the shape and scale parameters of the prior distribution and the hyperparameters of the model.

Given the likehood in Eq. (2) and the prior distribution in Eq. (3), it is now possible to derive a number of useful distributions. The first is the prior predictive distribution which, following Percy (2002), can be used to obtain an initial value for the hyperparameters in the model:

$$p(t) = \int p(t\,|\,\lambda)p(\lambda)\,d\lambda = \frac{\alpha\beta^{\alpha}t^{s-1}s}{(\beta+t^s)^{\alpha+1}}. \qquad (4)$$

The corresponding cumulative distribution function is given by

$$P(T \leq t) = 1 - \left(\frac{\beta}{\beta+t^s}\right)^{\alpha}. \qquad (5)$$

If two quantile values $P(t_1) = q_1$ and $P(t_2) = q_2$ are given then the value of α and β are obtained by (numerically) solving a set of two non-linear equations. Also note that if one quantile is given then the second quantile has to conform to the following restriction if a solution is to exist and be unique:

$$t_2 > \left[\frac{\ln(1-q_2)}{\ln(1-q_1)}\right]^{1/s} \cdot t_1. \qquad (6)$$

The second distribution that can be derived from (2) and (3) is the posterior for uncensored observations of the replacement age:

$$p(\lambda\,|\,t) \propto \mathrm{IG}(\lambda\,|\,\overline{\alpha},\overline{\beta}), \qquad (7)$$

where $\overline{\alpha} = \alpha + 1$ and $\overline{\beta} = \beta + t^s$ are the updated hyperparameters. The posterior predictive distribution in the case of a single uncensored observation of t, denoted by $p(\overline{t}\,|\,t)$, is the same as the prior predictive distribution in Eq. (4) with the updated hyperparameters. The posterior predictive distribution is essentially what we are looking for: a predictor for the uncertain replacement age of a hydraulic structure.

The third distribution that can be derived is the posterior distribution based on a censored observation, namely the current age of the structure. There are very few known cases of structures having been replaced due to technical deficiencies. The available data therefore mostly consists of censored observations. With a single censored observation only the shape parameter β of the prior distribution is updated in the posterior distribution, namely $\overline{\beta} = \beta + t^s$. The same result is obtained by Coolen (1996).

With the model in place, the workflow for obtaining a timeframe for an individual structure is now as follows:

1. select a value for the shape parameter s in Eq. (2),
2. calculate the initial value for the hyperparameters α and β in Eq. (3) with quantile values from one of the following sources:
    - the design lifetime as the median (i.e. 50% quantile) and a second quantile (e.g. the 90% quantile),
    - two quantiles obtained using the RINK ΔT approach as presented in Section 3.2 below, or
    - two quantile estimates obtained through expert opinion.
3. calculate the posterior distribution of the shape parameter λ and the posterior predictive distribution,
4. obtain a timeframe for the replacement age using a suitable confidence interval.

The shape parameter s follows directly from the coëfficient of variation so it is possible to prepare a small number of values for this coëfficient that can be selected by the modeller and which represent a range of ‘spreads’ in the replacement age of structures.

It should be noted that a right-censored observation (i.e. the current age of the structure) contains relatively little information. Figure 3 shows an example of a prior predictive distribution with a coëfficient of variation equal to 0.2 and hyperparameters such that $P(80) = 0.50$ and $P(120) = 0.95$. The latter means that we assume a 50% probability of the replacement age being either before or after the age of 80 years and a probability of only 5% that the structure will be replaced after the age of 120 years. If a structure is 40 years old, then this information will have very little effect on the hyperparameters. It is only when the current age of a structure is greater than the mean of the prior predictive distribution that the posterior distribution will shift to the right as is the case in Figure 3.

One downside of using right-censored observations is the fact that younger ages are trumped by the oldest age. In other words, if we have three observed ages for which $t_1 > t_2$ and $t_1 > t_3$ holds, then $P(T > t_1, T > t_2, T > t_3) = P(T > t_1)$. We therefore use the current age of a structure only to obtain a posterior predictive distribution for the structure in question and not for the whole group. In essence, we are assuming that the lifetimes of the structures are not correlated, but independently and identically distributed (i.i.d.). In the Bayesian framework, the observed lifetimes are exchangeable.

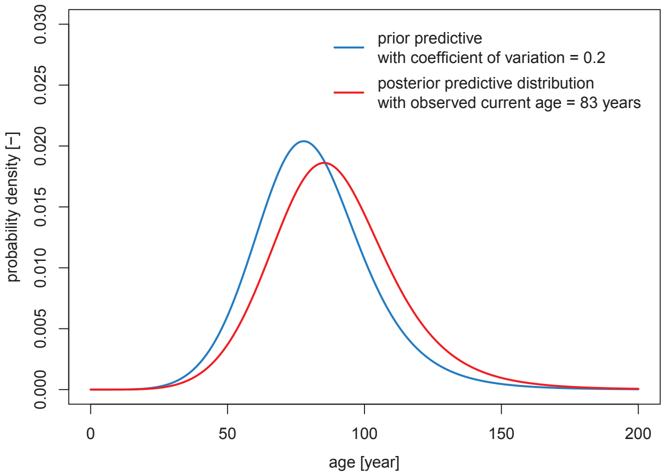

Figure 3: Example of updating a prior estimate with a single right-censored observation.

3.2 *RINK ΔT*

The RINK ΔT approach offers a more refined estimate for the end of technical lifetimes of a select number of hydraulic structures. This approach is based on minimal cutsets resulting from fault-tree analysis executed within the RINK project. These cutsets contain quantitative information about failure modes and thus the performance of critical components in terms of failure rate and mean times to repair (MTTR). Fault tree analysis typically results in reliability and unavailability figures for a specific moment in time. The RINK ΔT approach aims to extrapolate these figures in time, resulting in an insight in the future technical performance of (subsystems of) an object.

Firstly, relevant subsystems are identified, i.e. the civil structure, the steel structures (such as lock gates), the operating and control system, electromechanical and electrohydraulic components. All minimal cutsets will be categorized as part of a subsystem. Outliers and external failure modes (such as failure as a result of lightning, fire, human error etc.) will be identified and excluded from further analysis.

Secondly, normative failure types (e.g. fatigue, overload, ageing) are identified for every subsystem. Each failure type typically depends on a certain variable (eg. time (ageing), number of cycles (fatigue) or water level difference (overload)). Based on expert opinion, failure frequency curves are constructed. An example of such a (in this case exponential) curve is shown in Figure 4. It depicts the failure frequency of a civil structure as a function of the load (represented by a factor of the design load).

Since the Deltamodel produces future loads/cycles

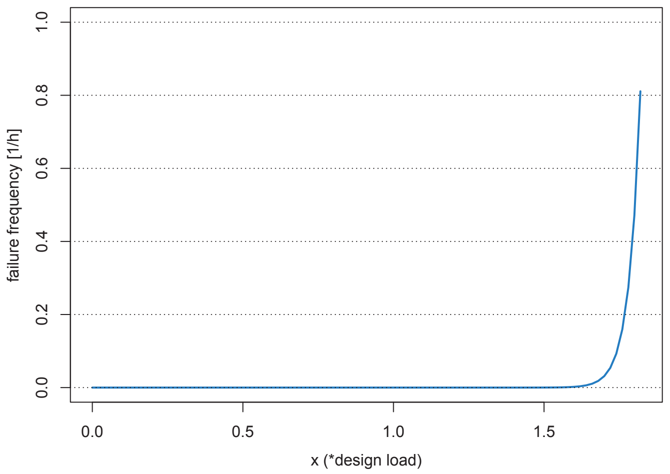

Figure 4: Example of an exponential failure frequency.

in four different future scenarios, future failure frequencies of the critical components (as identified by the fault tree analysis) can now be varied in time based on its subsystem and the corresponding failure frequency curve for each scenario.

As failure frequencies of all cutsets that are part of a certain subset are 'updated' to a future scenario, and since the MTTR is known, the unavailability of that cut set may be calculated. Consequently, combining the unavailability of the updated cutsets will lead to the unavailability of the subsystem at some future moment in time and for the given scenario.

As an example, Figure 5 shows the unavailability of the electromechanical subsystem of a lock complex, where fatigue is assumed to be the normative failure type, the failure rate increases exponentially as a function of the number of cycles and the number of cycles increases linearly in time. In such conditions we find an S-shaped curve, while other subsystems may show different behavior, highly dependent on both the failure frequency curve and the load scenario.

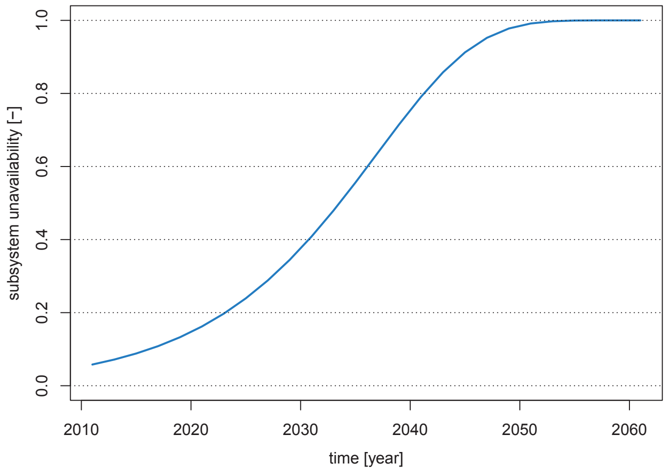

Figure 5: Example of an S-curve for the unavailability of a subsystem in a structure.

Unavailability curves can now be created for all relevant subsystems and for each one of the four Deltascenario's. For a single scenario, this will lead to a result as shown in Figure 6. This figure includes the 20-year time intervals at which the operating system needs replacements. Such systems are not characterized by an increasing unavailability, since they are widely assumed to have a constant failure rate.

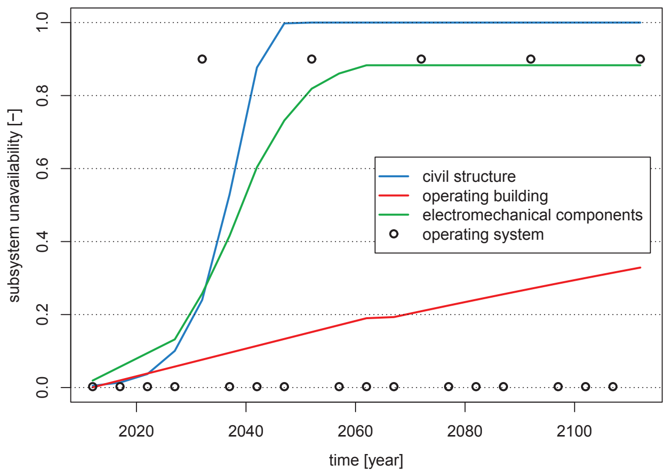

Figure 6: The unavailability curves of all subsystems are combined and a replacement year is determined by a predefined performance criterium.

Once the unavailability curves for all subsystems are determined, it becomes clear at what time in the future the first of these subsystems drops below a predefined availability requirement. Due to the long design lifetime of these structures, it is very often the operating system or the electromechanical components which cause the low availability of the whole system. At this point RWS may decide to replace only these subsystems or the whole structure depending on what is most economical from a life-cycle point of view. In this way, a year of replacement is chosen for each one of the four Deltascenario's and the timeframe of replacement is bounded by the earliest and latest replacement age.

3.3 *Combined results*

Figure 7 shows the nature of the results (this is a fictitious example) of the described method for a structure and for a certain function. As a reference the outcome of the first basic prediction of 'end of life' of RWS in 2012 (2056, no distinguishment between end of technical and functional lifetime) is depicted (green).

The probability density of the 'end of technical lifetime' (blue), which is a combined result from the DISK Pro approach as described in Section 3.1 and the RINK ΔT approach described in Section 3.2, varies roughly between 2062 and 2078. This means that somewhere in that period it is expected that it is no longer economically justified to repair the deficiencies in the total of the civil/steel structure, including the installations.

The functional requirements are expected to exceed the functional performance of the structure somewhere between 2050 and 2068 (red), based on the calculation of deterministic Deltascenarios.

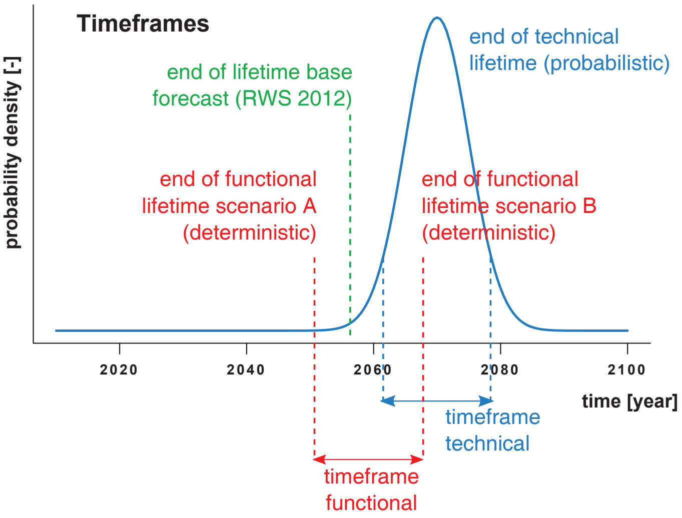

Figure 7: Schematic representation of the two timeframes: technical and functional.

Figure 7 shows the desired outcome of this project, the actual combination of the results of these two approaches is the subject of current research. There are several options to be considered:

- The lower and upper bounds of the timeframe from the RINK ΔT method may be considered as two quantiles which can be used to determine the hyperparameters of the prior distribution in the DISK Pro method.

- The lower bound of the timeframe may be used as a right-censored observation in the updating procedure of the DISK Pro method. This would assume that the structure will survive this lower bound at the minimum.

4 FURTHER DEVELOPMENTS

The described methods for determining the timeframe for replacement of the hydraulic structures have largely been developed conceptually and a proof of concept has been delivered. The application of the method to the 650 structures requires substantial automation in order to be able to easily connect with those data sources of RWS that contain specific information on each structure.

Three important aspects will be further developed:

1. The prediction of the failure behaviour in time of important failure mechanisms will be further elaborated on in order to obtain more accurate predictions in the RINK ΔT-method.

2. If a structure is (more or less) representative for a larger group of structures, then any information relating to this structure or its end-of-life prediction may be used for estimating the replacement timeframes for the other structures in the group.

3. The resulting timeframes of this method will be presented to experts of RWS who know the specific structures and are responsible for their functioning. This will give a final opportunity to adjust the timeframes or to make changes to the prior information used in this method.

5 CONCLUSIONS

This paper presents a methodology for obtaining timeframes during which hydraulic structures in the Netherlands are expected to require replacement or major renovation. These timeframes are for replacements due to the failure to meet technical requirements (Section 3) or functional requirements (Section 2).

The model for obtaining a timeframe for the technical ‘lifetime’ of a structure uses a simple univariate Bayesian model to make full use of the little information that is available about the remaining life of the structures. By using an informative prior distribution, the infrastructure manager can start his analysis with default information (such as the design life) or an expert’s opinion on the lifetime of a structure.

The model for the functional ‘lifetime’ uses the Deltamodel, which is includes a hydraulic model to obtain water levels under different climate scenarios, to estimate the time at which a structure will no longer be able to fulfill its functional requirements.

Both models are still under development and areas of further research are provided at the end of the paper.

6 ACKNOWLEDGMENTS

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