Life-Cycle Cost Approach to Bridge Management in the Netherlands

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The Dutch Directorate General for Public Works and Water Management is responsible for management of the national road infrastructure in the Netherlands. Structures such as bridges and tunnels are important structures in the road network and largely determine the functionality of the road network as well as necessary maintenance budgets. A methodology for a probabilistic life-cycle cost approach to bridge management was applied to the concrete highway bridges in the Netherlands. The Dutch national road network contains over 3,000 highway bridges, most of which are 30 years old or more. The annual maintenance cost of these bridges is a substantial part of the total maintenance cost. The question arises of when to carry out bridge replacements. A fundamental solution is to take a life-cycle cost approach with costs of maintenance and replacement and service lifetime as key elements. Maintenance strategies were drawn up for groups of similar elements, such as concrete elements, preserved steel, extension joints, and bearings. The structures were categorized into generic types, each with its own maintenance characteristics. For each structure, the maintenance cost was estimated on the basis of the life-cycle cost analyses of the underlying elements. After aggregation over the entire stock, this process eventually led to the maintenance cost on a network level. To calculate the life-cycle cost, lifetime distributions for concrete bridges were determined, and the expected cost of replacing the bridge stock was computed. The uncertainty in the lifetime of a bridge can best be represented with a Weibull distribution, which can be fit on the basis of aggregating the lifetimes of demolished bridges (complete observations) and the ages of current bridges (right-censored observations). Using renewal theory, the future expected cost of replacing the bridge stock can then be determined while taking into account current bridge ages and the corresponding uncertainties in future replacement times. The proposed methodology has been used to estimate the cost of replacing the Dutch stock of concrete bridges as a function of time.

The Dutch Directorate General for Public Works and Water Management is responsible for the management of the national road infrastructure in the Netherlands. Maintenance is one of the core tasks of this directorate. Structures such as bridges and tunnels are important objects in the road network. They largely determine the functionality of the road network as well as the necessary maintenance budgets. For the management of the structures, a bridge management methodology has been established. The aims of bridge management are

- Effectively managing operational programs,

- Giving a realistic budget estimate at a national level, and
- Tuning bridge management programs with other maintenance programs such as pavement management.

Structures such as bridges are characterized by large investments and a long service life of 50 to 100 years. Although the annual maintenance cost is relatively small compared to the investment cost (less than 1%), the sum of the maintenance cost over the service lifetime is of the same order of magnitude as the investment cost. Therefore, it is not recommended that decisions on maintenance be separated from decisions on investment. The question arises of when to carry out replacements. A fundamental solution to this problem is a life-cycle cost approach. Key elements of this approach are the costs of construction and replacement, the cost of maintenance, and the service lifetime. These three items must be addressed while taking into account the uncertainties involved.

This paper describes the methodology for a probabilistic life-cycle cost approach to bridge management that was applied to the concrete highway bridges in the Netherlands. The next sections describe the features of the Dutch national road network, the annual maintenance cost of the structures, and the replacement value of the structures and their lifetimes. After that, the probabilistic modeling of the total life-cycle cost of the concrete bridges and results are described.

NATIONAL ROAD NETWORK LEVEL IN THE NETHERLANDS

The Dutch national main road network consists of 3,200 km of road, including 2,200 km of motorway. It serves mainly one function, mobility, with traffic safety and environmental aspects taken into account. The network divides assets into four categories: pavements, structures, traffic facilities, and environmental assets. The total number of structures in the network is 3,283. The structures are categorized into generic types, each with its own maintenance characteristics. An overview of the types, their number, deck area, and replacement value (see section on replacement cost) is given in Table 1.

ANNUAL MAINTENANCE COST

A maintenance strategy is drawn up for frequently used elements, such as concrete elements, preserved steel, extension joints, and bearings. Such a strategy requires a description of the minimal acceptable quality or condition, or a description of acceptable defects. Once the strategies are outlined, they can be applied to the stock of structures for the formulation of operational programs, and they can be used to estimate the total maintenance cost. An accurate

TABLE 1 Structures in Main Road Network

Object	Number	Deck Area (m^2)	Replacement Value (€ millions)
Concrete bridge	3,131	3,319,002	6,600
Steel bridge (fixed)	88	301,997	600
Movable bridge	43	347,876	1,100
Tunnel	14	475,228	1,700
Aqueduct	7	86,491	250
Total	3,283	4,530,593	10,250

estimate of the maintenance intervals and the cost of standardized measures are essential but difficult parts of the methodology. This information must be extracted from maintenance experts, since registered data are not yet available. In this process, subjective—and often conflicting—expert opinions must be combined to reach a level of consensus.

For each structure, the maintenance cost is estimated by means of the corresponding maintenance intervals and cost indicators. The results of this cost analysis can be updated by assessing the actual state of the structure through inspections. After aggregation of the maintenance plans of the entire stock of structures and prioritization of the available budgets, this process leads eventually to operational maintenance programs. A typical outcome of a maintenance plan for a single concrete highway bridge is given in Figure 1.

The prognosis of the maintenance cost for elements of structures can be applied to groups of structures. The maintenance cost on a network level can be determined by combining the maintenance costs of these groups of structures and their asset sizes. A similar approach is reported by Das (*1*). Table 2 gives the total annual maintenance cost per structure type.

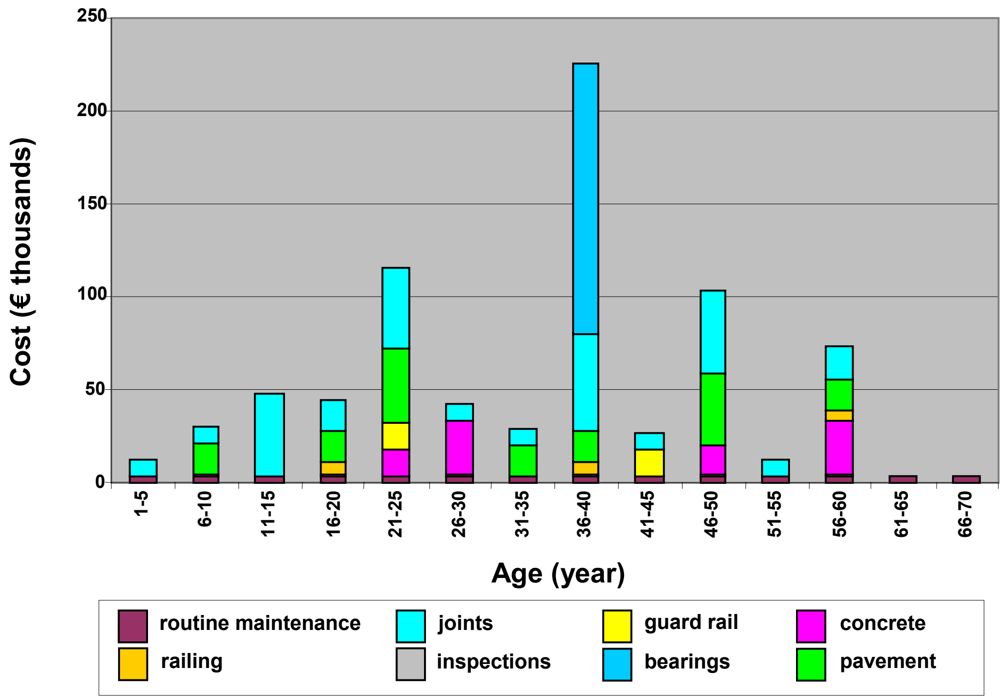

FIGURE 1 Maintenance cost of typical highway bridge summarized over units of time of 5 years.

TABLE 2 Annual Maintenance Cost of Each Structure Type

Structure Type	Total Annual Maintenance Cost (€ millions)
Concrete bridge	37
Steel bridge (fixed)	7
Movable bridge	10
Tunnel	13
Aqueduct	1
Total	68

REPLACEMENT COST

The cost of replacing a structure largely depends on which elements must be replaced and which cost items are to be included. This can easily lead to a variation in replacement cost by a factor 2 to 4. The replacement cost is best based on the bridge length and its functionality. Is it a two-to-three-lane highway, for example. In calculating the expected cost, the bridge is replaced by a standard type of bridge that may not necessarily be the same as the original. The cost of replacement includes all direct and indirect cost items related to the structure itself. The costs of site preparation, demolition, and traffic measures are not included. The cost calculation is based on the same data used in cost calculations for construction projects. The replacement value of the entire stock of structures is presented in Table 1 and plotted against the year of construction in Figure 1. Figure 2 shows a peak in construction activities in the 1970s, which was characteristic for many Western European road networks (*2*).

SERVICE LIFETIME

The lifetime of structures can be assessed in a number of different ways, using the predefined design lifetime, the functional lifetime, and the economical lifetime, which are defined as follows:

- The design or technical lifetime is determined by the design method and the choices on loads and durability of materials and elements. The design codes used in the Netherlands require a design lifetime of between 50 and 100 years. Most highway bridges are designed for an 80-year lifetime.
- The functional lifetime is determined by the structure's use. The design anticipates a certain use, and the functional lifetime ends when the use changes.

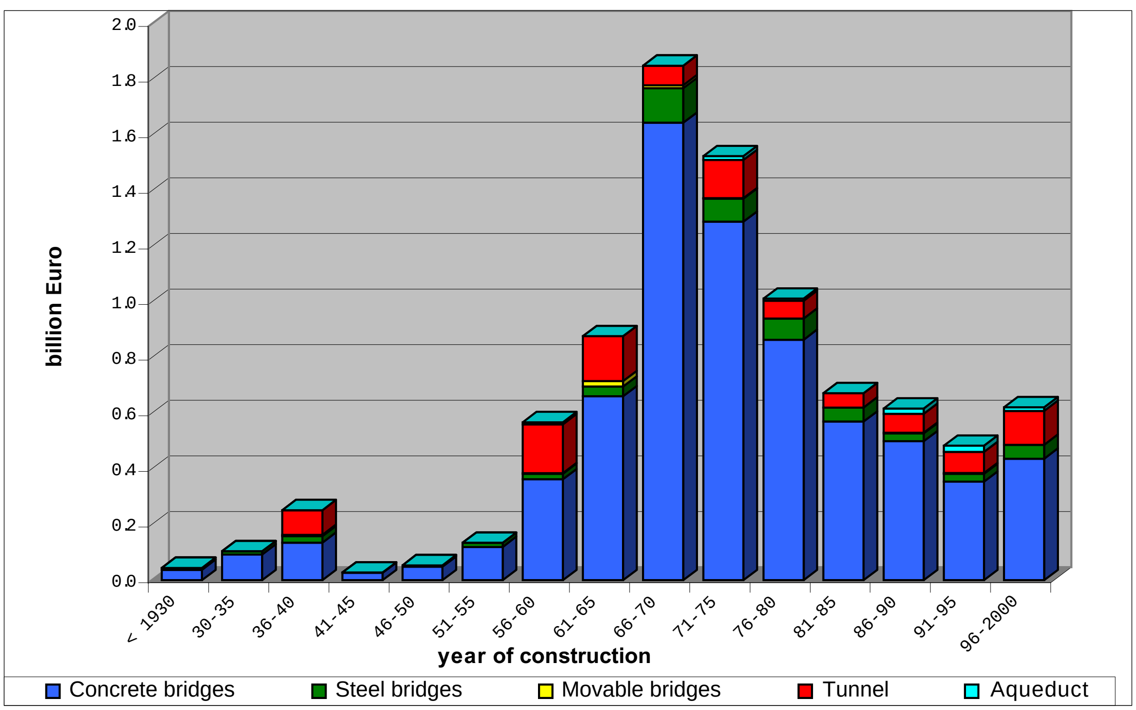

FIGURE 2 Replacement value of structures related to years of construction.

- The economical lifetime ends when the operational cost has become so large that building a new structure is more economical. It should be noted that the term “economical” is not well defined.

Bridges’ observed lifetimes represent a sort of combination of these lifetime types. The approach of using observed lifetimes is more or less common practice for all sorts of structural elements. The application of this approach to bridges is rather innovative and is described in the next sections.

The service lifetime can largely depend on the approach used. In assessing lifetimes, it is important to note that they must be predicted a long time in advance. Uncertainties in future development of road traffic are many. Realizing this, the different approaches can be regarded as scenarios. Accounting for the uncertainty of the lifetime through probability distribution is therefore important.

ESTIMATION OF LIFETIME DISTRIBUTIONS

The uncertainty in the lifetime of concrete bridges can be quantified by performing a statistical analysis on lifetimes of demolished bridges and ages of existing bridges. However, the general opinion on estimating a lifetime solely on the basis of bridge replacement times is that the resulting expected lifetime is often considerably underestimated. Although this underestimation is confirmed by the results found by Dutch study, a statistical analysis is nevertheless useful. The underestimation problem can be resolved by fitting a probability distribution to both the lifetimes of demolished bridges (complete observations) and the current ages of existing bridges (right-censored observations). The estimates so obtained of the expected lifetime of a concrete bridge are more in accordance with the usual design life. Although the right-censored observations do not contain actual lifetimes, they are a valuable source of information. At least it is known that the lifetimes of existing bridges will be longer than their current ages.

The Weibull distribution is recommended for properly modeling the aging of bridges. Using the maximum-likelihood method, a Weibull distribution can be fitted to both complete and right-censored observations [see van Noortwijk and Klatter (*3*)]. An advantage of the Weibull distribution is that the conditional probability distribution of the residual lifetime given the current age can be analytically expressed as the so-called left-truncated Weibull distribution. The observed lifetimes and ages of concrete bridges and viaducts in and over the highway were aggregated. In total, 79 lifetimes of demolished bridges (the complete observations in Figure 3) and 2,974 ages of existing bridges (the right-censored observations in Figure 4) were gathered. Because the right-censored observations were only available in terms of units of time of 1 year, bridge replacement was modeled as a discrete-time renewal process [see van Noortwijk and Klatter (*3*)]. For 157 concrete bridges, the year of construction and/or the length and width are unknown leading to a total number of concrete bridges in the Netherlands of 3,131. These 157 bridges include 19 concrete-steel bridges that are not included in the statistical analysis because they have different aging characteristics than concrete bridges.

A statistical analysis was performed for complete lifetimes and also for the combination of complete and right-censored lifetimes. The general opinion of bridge maintenance managers is that a statistical analysis of replaced bridges is not useful, because the fitted lifetime distribution tends to underestimate the expected lifetime at about 40 to 50 years instead of the usual design life of 80 to 100 years. The main reason for this is that most demolished bridges are not replaced

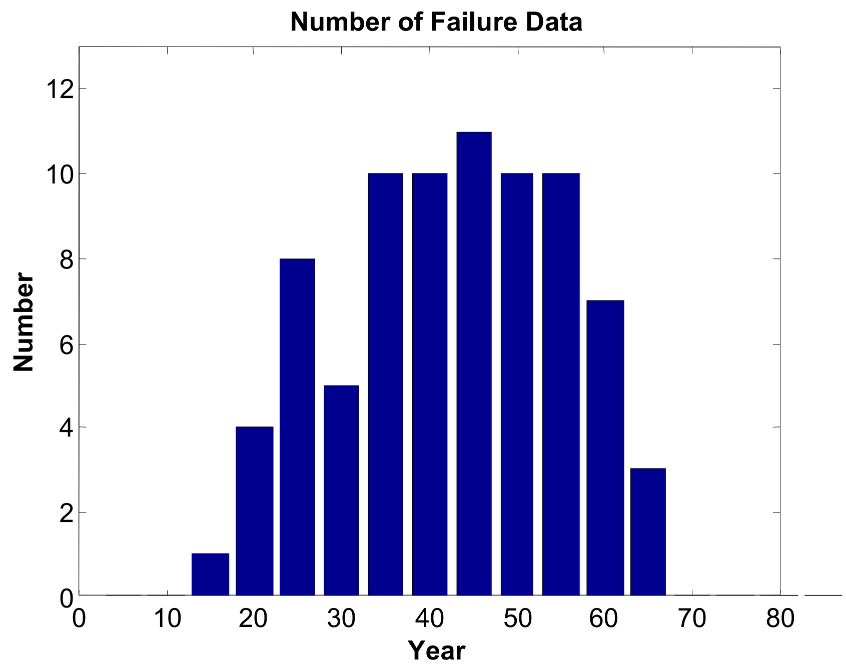

FIGURE 3 Histogram of complete lifetimes gathered in units of time of 5 years.

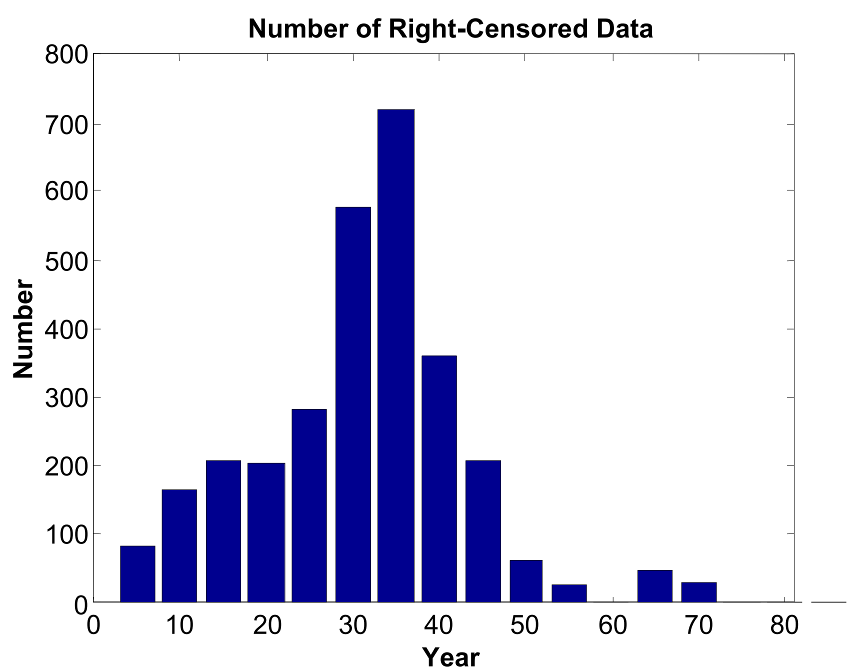

FIGURE 4 Histogram of right-censored lifetimes (current ages) gathered in units of time of 5 years.

as a result of technical failure, but because of a change in functional or economical requirements. Examples are bridges replaced because their load-carrying capacity cannot handle an unexpected increase of heavy traffic. Unfortunately, information has been insufficient to make a distinction between the design, functional, and economical lifetimes. Therefore, the observed lifetimes of demolished bridges can be either of these three, and the bridges were analysed as a whole. Furthermore, possible changes in bridge design over time could not yet be taken into account.

As expected, our statistical analysis of complete lifetimes resulted in an underestimation of the expected lifetime: a mean of 41 years with a coefficient of variation of 0.30. The corresponding maximum-likelihood estimators of the shape parameter and the scale parameter of the Weibull distribution are 3.8 and 45.1, respectively. The resulting Weibull probability density function based on complete observations is shown in Figure 5. However, when the current ages of the concrete bridge stock are included, the results change considerably. The expected lifetime increases from 41 to 75 years! The coefficient of variation changes little, with a value of 0.24. The maximum-likelihood estimates of the shape parameter and scale parameter are 4.7 and 81.8, respectively. The Weibull density function based on both complete and right-censored observations is shown in Figure 6.

CALCULATION OF REPLACEMENT COST

When the lifetime distribution is based on both complete and right-censored observations, the expected replacement cost over a bounded horizon can be computed by means of renewal theory. It is assumed that the replacement cost of a concrete bridge is independent of time. Although an old bridge is seldom replaced by the same type of bridge, it is difficult to accurately assess the cost of a new bridge. The replacement value of the stock of concrete bridges with known years of construction is €6,380 million [€ = US$1.02644 (December 2002)]. The replacement value of the concrete–steel bridges and the concrete bridges with unknown years of construction and/or unknown lengths and widths is €220 million.

In Figure 7, the expected cost per year is shown as a function of time and the bridges' ages (while the ages are gathered in units of time of 5 years). Summing over all the concrete bridges, as well as their corresponding ages and replacement costs, gives the expected cost per year as derived in van Noortwijk and Klatter (*2*) and shown in Figure 8. As expected, the uncertainty in the second replacement time is greater than the uncertainty in the first replacement time. As the time horizon approaches infinity, the expected long-term average cost per year approaches €85 million. Indefinitely far in the future, our delayed renewal process becomes a stationary renewal process for which the expected cost per unit time finds an equilibrium value. To account for the replacement cost of the 157 concrete bridges with unknown years of construction and/or unknown lengths and widths, the expected replacement cost per unit time shown in Figures 7 and 8 should finally be multiplied by a factor 6600 / 6380 = (6380 + 220) / 6380 = 1.03.

The cost of maintenance is not included in Figures 7 and 8. The life-cycle cost can be estimated by combining the cost of replacement with the cost of maintenance. The cost of maintenance can be regarded as constant, averaged over the large number of structures. This assumption will only be valid for an aging bridge stock. The annual cost of replacement after a long time will be approximately €85 million—about twice the annual cost of maintenance of €37 million. The first peak in the expected cost of replacement is three times the annual cost of maintenance. These results can be regarded as a first step in developing a replacement strategy based on life-cycle cost. Different scenarios for replacement, such as preventive replacement or postponed replacement, by extending the lifetime can be assessed on the basis of life-cycle cost.

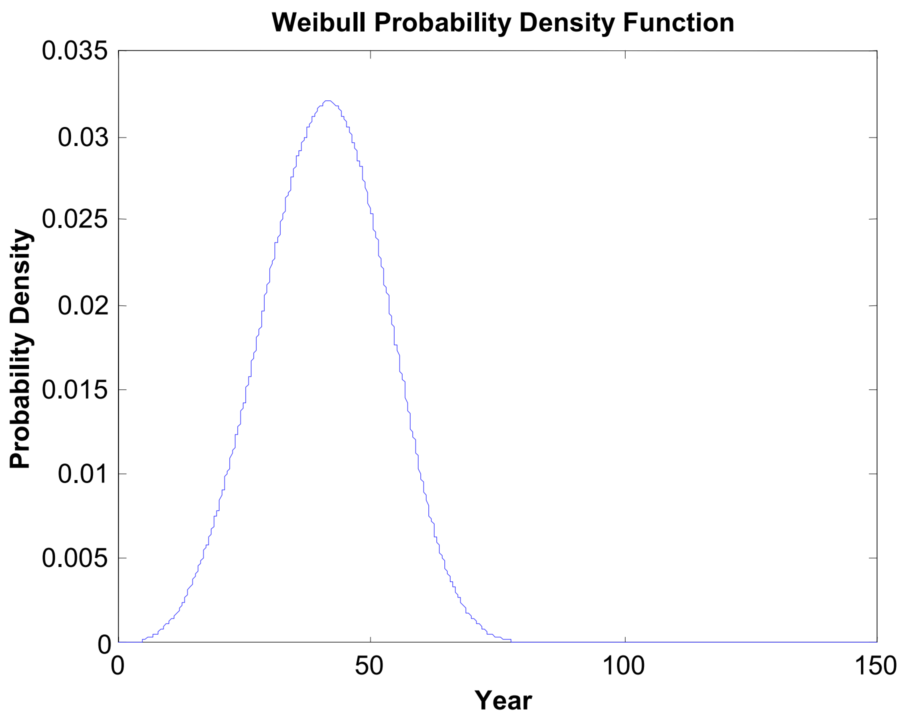

FIGURE 5 Weibull distribution estimated on the basis of complete lifetimes.

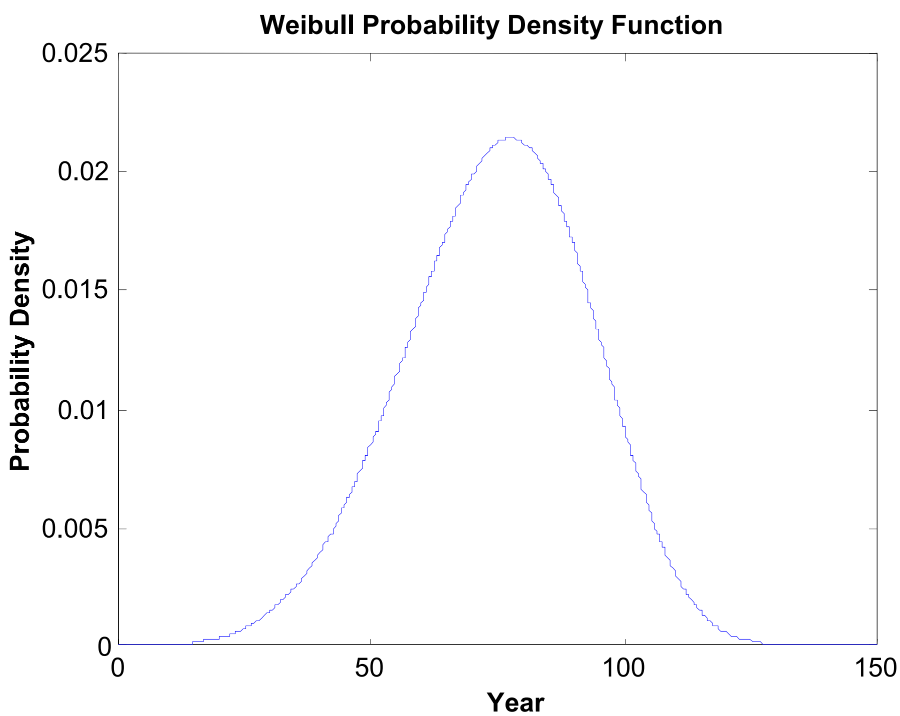

FIGURE 6 Weibull distribution on the basis of both complete and right-censored lifetimes.

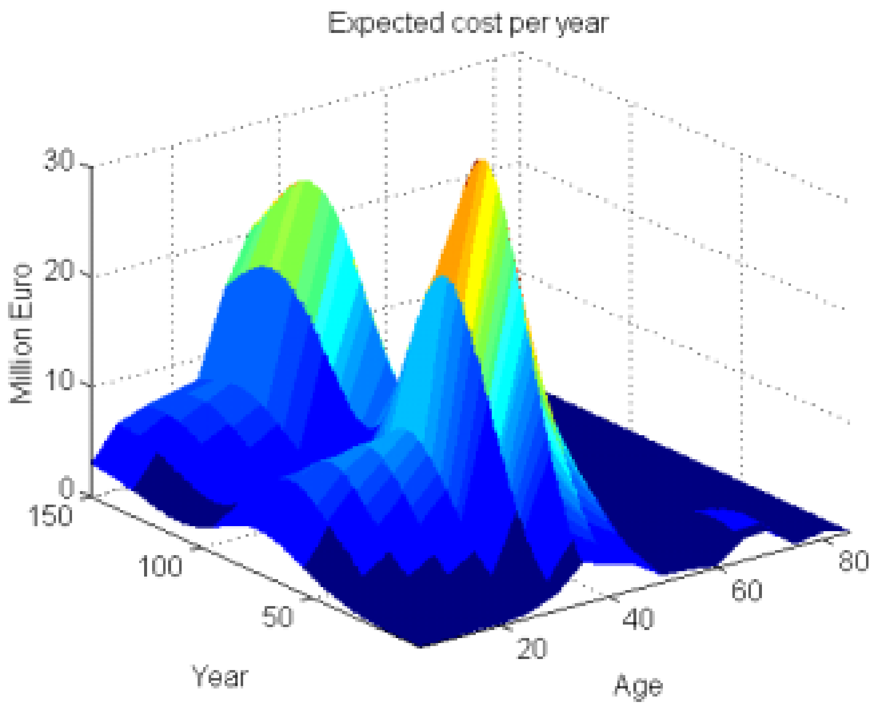

FIGURE 7 Expected cost per year as a function of age, where ages are gathered in units of time of 5 years.

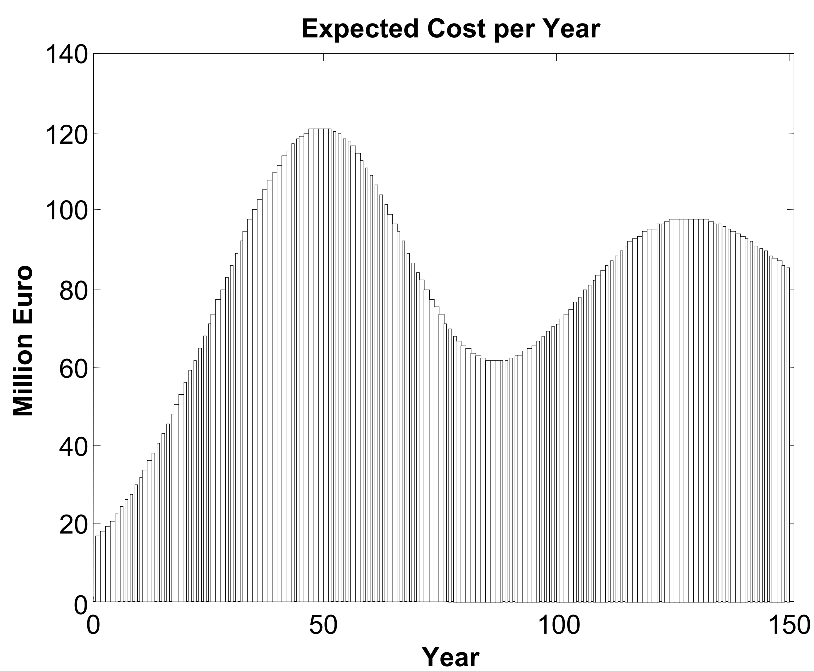

FIGURE 8 Expected cost per year summed over all ages.

CONCLUSIONS

The results presented in this paper demonstrate that cost of replacement and maintenance can be combined into a life-cycle cost approach. For this a systematic assessment of cost data, asset data, and lifetimes is needed. Creating a consistent set of data needs great care.

The service lifetime of a bridge is a parameter that is difficult to predict, but it has major influence on replacement cost. Several scenarios have been developed in assessing bridge lifetime. To account for the uncertainty in the lifetime by a probability distribution is therefore important.

A statistical analysis was used for determining the lifetime distribution of concrete bridges in the Netherlands. A Weibull distribution was fitted to both complete lifetimes of demolished bridges and current ages of existing bridges. Unlike the average value of the observed complete lifetimes, the expected value of the Weibull lifetime distribution was in agreement with the usual design life. Advantages of representing the uncertainty in the lifetime of bridges with a Weibull distribution are the possibility of properly modeling aging and of analytically deriving the conditional probability density function of the residual lifetime when the current age is given.

The so-obtained Weibull distribution was used to determine the future expected cost of replacing the bridge stock. In calculating this cost, the ages and replacement costs of the individual bridges were taken into account. In a case study, the expected future cost of replacement of the Dutch concrete bridges was estimated. Taking into account the uncertainties in the replacement times has the advantage that the cost is more spread out over time than in the deterministic case.

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