Societal Aspects of Bridge Management and Safety in The Netherlands

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ABSTRACT: The paper describes the decision-theoretic approach that is used for bridge management in the Netherlands to obtain optimal investment and maintenance decisions. First, the theoretic framework for optimising maintenance against lowest life-cycle costs is described. Second, the models and data on the structural behaviour, the deterioration processes, and the characteristics of inspection and repair are presented. The corresponding costs complete the data needed for performing a life-cycle costing analysis according to the framework proposed. Finally, the results are evaluated in a societal perspective.

1 INTRODUCTION

The main reason for the existence of civil infrastructures is public interest. Therefore, various societal aspects should drive an infrastructure program. Civil infrastructures are long-lived assets. Bridges and other structures are designed for lifetimes of 50 to 100 years. A bridge can last much longer from a technical point of view, providing the original functionality it is designed for does not change too much. The functional lifetime is often dominant. Bridges become obsolete, because they are functionally outdated. A careful choice of requirements for a bridge is crucial in fulfilling societal needs, not only now, but also in the future. Functional requirements in a decision-theoretic concept direct technical solutions to societal needs using reliability, availability, maintainability, and safety (RAMS) requirements. This will be explained in Section 2. The cost of maintenance is substantial in the long run and depends on design choices made. For these kinds of problems, a life-cycle costing (LCC) approach is an absolute necessity. The performance of bridges and bridge elements, their deterioration and its influence on the performance and effectiveness of maintenance can be evaluated from historical data. We should invest in ‘learning from the past’. Results of models and data in the Netherlands will be presented in Section 3. The last section of the paper evaluates the decision-theoretic results that have been obtained in the Netherlands so far.

2 RAMS AND LCC

This section discusses how a decision-theoretic approach is used by the Netherlands Ministry of Transport, Public Works, and Water Management (Rijkswaterstaat) to obtain optimal investment and maintenance decisions.

2.1 *Reliability, Availability, Maintainability, Safety (RAMS)*

Civil structures must be safe and reliable, and must satisfy legislation and environment conditions. These requirements can be expressed in terms of the so-called RAMS requirements as follows:

- Reliability (probability that a structure performs its required functions; this includes structural safety),
- Availability (expected ratio of the total time a structure is capable of performing its functions in a given time interval and the length of the interval),
- Maintainability (ease with which maintenance of a structure can be performed in accordance with prescribed requirements such as availability; in other words, the probability that a structure can be repaired, inspected and maintained in a given time interval),
- Safety (probability that a structure will not cause any harm – injury or death – to human beings, mainly traffic safety),

The RAMS approach is quite common in mechanical engineering and in rail infrastructure. The European requirements for rail infrastructure, EN 50126 (CENELEC, 1999), are based on these RAMS requirements. Public-owned infrastructure, rail and road systems, have to fulfil many additional requirements for human health and environmental issues. These issues are governed by national regulation and legislation and are not included in EN 50126. This problem is solved by extending RAMS to RAMSHE with Health (personnel safety, human health and well-being) and Environment (aesthetics, environment, risk perception, noise nuisance, and sustainability). Note that the requirement that a structure must be maintained against the lowest possible (life-cycle) cost is not included in RAMS.

2.2 *Maintenance*

During the last decade, the cost of maintenance has continuously increased. According to Dekker and Scarf (1998), the main reasons for this increase are the continuous expansion of the amount of structures and infrastructures, the intensified use and higher requirements (e.g. increase of traffic loads), and the outsourcing of maintenance. Furthermore, the age of the structures and infrastructures is increasing (most of the Dutch highway bridges are older than 30 years). The required annual budget for maintaining the Dutch stock of concrete structures of the road infrastructure is now 68 million Euro per year (Klatter and van Noortwijk, 2003). Given the replacement value of these structures being 10.25 billion Euro, the annual maintenance cost is 0.66% of the construction cost. There is currently a backlog in maintenance of 350 million Euro, which will be wiped off in the period 2005-2007.

Usually, maintenance is defined as a combination of actions carried out to restore a structure to, or to “renew” it to, a specified condition in which the structure can perform its required functions. Rijkswaterstaat refers to this specified condition as the basic maintenance level (BML) for structures (Klatter, 2003). In defining the BML, Rijkswaterstaat identifies the following five functions: mobility, traffic safety, life quality, user comfort, and aesthetics. The BML covers all the above-mentioned RAMSHE requirements as follows: mobility includes ‘RAM’, traffic safety is the ‘S’, life quality the ‘H’, and life quality, comfort and aesthetics concern ‘HE’.

Inspections, replacements, perfect repairs, and lifetime extensions (also called partial repairs) are possible maintenance actions. Through lifetime-extending maintenance (LEM), the deterioration can be delayed as such that failure is postponed and the lifetime is extended. Examples of LEM are spot repair of steel coatings and the protection of structures against de-icing salts (e.g. by sealing joints). In civil engineering, a failure is often condition failure (disability of a structure to perform its required functions within constraints of legal safety margins), whereas in mechanical engineering failure is often physical failure (breakdown). In structural engineering, condition failure generally means that the probability of a collapse is unacceptable high. Rijkswaterstaat is currently investigating what the risks are with respect to a structure’s disability to satisfy the BML during a pre-specified reference period.

2.3 *Life-cycle costing (LCC)*

In minimizing maintenance costs, the total costs should ideally be considered over the life of a structure. Generally, the following life-cycle phases can be identified: design, construction, use, and demolition. All costs should be considered, regardless of the funding source. Therefore, life-cycle costs should not only include the direct costs of construction, maintenance, and demolition, but also the indirect costs for the society and environment. Examples of life-cycle costing (LCC) are balancing the initial cost of investment against the future cost of maintenance, and balancing the costs of preventive maintenance against the costs of failure.

In optimising life-cycle costs, it has become increasingly important that measures assure a sustainable development. Probably the most popular definition of sustainable development is the one stated in the Brundtland Report (WCED, 1987): “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. As opposed to sustainability, durability focuses more on the reliability and is defined as the “permanence by virtue of the power to resist stress or force”. An example of durable and sustainable development is coating maintenance.

Rijkswaterstaat is responsible for the maintenance management of approximately 6 million m^2 of coated steel (Heutink et al., 2004). Due to more tight environmental legislation, the cost of coating maintenance has rapidly increased over the last 15 years and maintenance optimisation is therefore of considerable interest. This legislation prescribes that the surface water nearby steel structures should be protected against polluting emissions (e.g., from coal tar epoxy coatings) during maintenance. This can be achieved by applying a protective shield, which completely seals off the maintenance activities from the local environment. However, an environmental protective shield is very expensive and should often be placed if essential maintenance (EM) is performed. A protective shield can be avoided by applying lifetime-extending maintenance (LEM) by means of spot repair of the coating. Therefore, about 40 % cost reduction can be realized by combining LEM and EM. The LEM interval with lowest life-cycle costs is 11 years for which the lifetime of the steel coating can be extended with about 10 years. The condition is defined as the part of the surface of a steel gate that has been corroded (see Figure 1). The LCC was performed using the LEM model developed by Rijkswaterstaat (van Noortwijk and Frangopol, 2004).

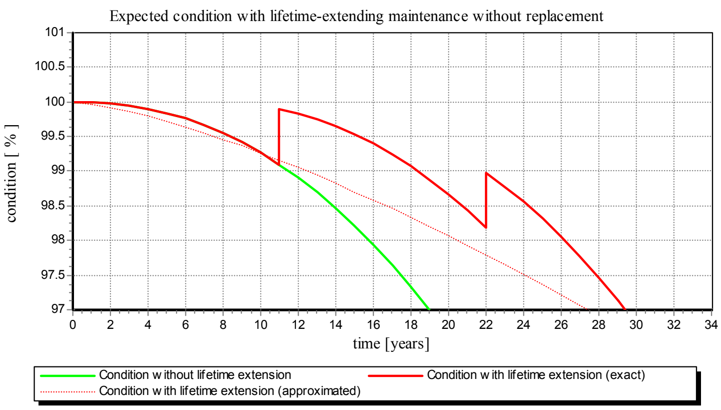

Figure 1: Expected condition of the coating with and without LEM for the cost-optimal LEM interval.

In optimising maintenance against lowest life-cycle costs, the following four questions must be answered:

What type of maintenance should be applied?
Roughly, there are two types of maintenance (see, e.g., van der Toorn, 1994): corrective maintenance (after failure) and preventive maintenance (mainly before failure). Corrective maintenance can best be chosen if the risk of failure is low; preventive maintenance if this risk is high. Up to the fifties of the last century mainly corrective maintenance was applied, because industry was not highly mechanized and downtime did not matter much (Moubray, 1997). Preventive maintenance can be further subdivided into: time-based maintenance (carried out at regular in-

tervals of time), use-based maintenance (carried out after a fixed cumulative use, operation or load), condition-based maintenance (carried out at times determined by inspecting or monitoring a structure's condition), and opportunity-based maintenance (carried out when a certain time or use threshold is exceeded and an opportunity occurs). Industrial maintenance changed from corrective to preventive in the fifties; initially time-based maintenance in the sixties (such as equipment overhauls at fixed intervals) and from the seventies on more condition-based maintenance (such as condition monitoring). Ideally, the type of maintenance should be chosen on the basis of LCC.

What is the uncertain time to failure (probability)?
Structures generally deteriorate relatively slowly (except for the mechanical components of a movable bridge). The deterioration is mainly determined by weather and environment conditions, not so much by usage (except for parts sensitive to fatigue). The uncertainties related to these processes are large. An example is the lifetime uncertainty of concrete viaducts and bridges having 5 and 95% quantiles of 43 and 103 years, respectively (van Noortwijk and Klatter, 2004). See also Frangopol et al. (2001) and Kallen and van Noortwijk (2006).

What are the costs of construction, maintenance and failure?
In the Netherlands, maintenance strategies are drawn up for groups of similar elements such as concrete elements, preserved steel, extension joints, and bearings. For these strategies, so-called Reference Documents have been written in which standardized maintenance costs (per unit, per unit length or per unit area) and maintenance intervals can be found. These maintenance costs and intervals were determined using expert judgment. Once the maintenance strategies are defined, they can be applied to formulate operational programmes for the stock of structures and to estimate the expected total maintenance cost. The construction cost is estimated on the basis of the bridge length and its functionality. Because bridge failure is defined as condition failure, failure cost doesn't have to be included. For more details, see van Noortwijk and Klatter, 2003.

What is the optimal investment and maintenance decision with the lowest risk?
Maintenance optimisation against lowest life-cycle costs can be performed in the design phase for new structures and in the use phase for existing structures. In the design phase of new structures, the initial investment cost must be balanced against the future maintenance cost. Let r be the discount rate compounded annually, d the decision (type of construction and type of maintenance including corresponding characteristics such as, e.g., inspection interval), then the expected discounted costs over a bounded time horizon of length n can be written as

$$E[L(n;d)] = E[C_{\text{investment}}(0;d)] + \sum_{t=1}^{n} \frac{E[C_{\text{maintenance}}(t;d)] + E[C_{\text{failure}}(t;d)] + E[C_{\text{renewal}}(t;d)]}{(1+r)^t} \tag{1}$$

where

$L(n;d)$	=	cumulative discounted cost over period of n years (loss),
$C_{\text{investment}}(t;d)$	=	cost of investment in year t given decision d,
$C_{\text{maintenance}}(t;d)$	=	cost of maintenance in year t given decision d,
$C_{\text{failure}}(t;d)$	=	cost of failure in year t given decision d,
$C_{\text{renewal}}(t;d)$	=	cost of renewal in year t given decision d.

The expected value is defined with respect to all the relevant uncertainties such as the uncertainties in costs and times to failure. The expected discounted costs over an unbounded horizon can be determined by letting $n \to \infty$. Although Equation (1) looks simple at first sight, it should be noted that the actual computation of the expected costs is not trivial and requires computational effort. The main reason for the complexity is that all expectations at time t are conditional on maintenance, failures and renewals in the period before t. The costs of maintenance may include the costs of inspections, replacements, perfect repairs, and lifetime-extending maintenance. The cost of renewal represents the cost of replacing an old structure with a new one. If the existing structure is replaced with an identical one, then the renewal cost may be assumed equal to the investment cost. In the use phase of existing structures the investment cost should be omitted. In general, the decision problem can be formulated as follows. The decision-maker can best choose a decision d^* whose expected loss is minimal. A decision d^* is called an optimal decision when

$$E(L(n,d^*)) = \min_{d\in D} E(L(n,d)). \qquad (2)$$

In this decision-theoretic framework, optimal maintenance decisions can be determined under uncertainty. Examples are determining optimal age-replacement intervals for time-based maintenance and optimal combinations of inspection intervals and maintenance levels for condition-based maintenance.

In (2) an optimal decision is chosen such that the costs of construction, maintenance, failure and renewal are minimal. If failure is interpreted as physical failure, then the failure probability is subject to optimisation as well; that is, the more reliable the structure, the higher the investment cost and the lower the corresponding probability of failure. An example is the economic decision problem of heightening a dike such that the sum of the investment cost and the expected flood damage cost is minimal (van Dantzig, 1956). Note that a reliability constraint can be included as well by formulating a constraint such that the actual failure probability is less than the target failure probability. Therefore, this type of maintenance is called 'reliability-based' (Frangopol et al., 2004). If failure is interpreted as condition failure, then a failure implies that the probability of collapse is unacceptable high. In this situation, maintenance optimisation is performed such that the expected costs are minimal under the constraint that the failure condition should be avoided. As soon as condition failure occurs, maintenance should be performed. This type of maintenance is called 'condition-based' (Frangopol et al., 2004). In addition to possible failure cost, the cost due to unavailability of the structure (such as bridge-user cost due to traffic jam, detour, vehicle-weight restriction, closure, etc) can also be included. Note that the cost of failure is often non-recurrent, whereas the cost of unavailability depends on how long failure prolongs.

Cost optimisation with respect to all kinds of decision variables is computationally expensive. A very helpful approach can be applied when we are able to identify 'renewals' in modelling maintenance (Barlow and Proschan, 1965). Maintenance can be modelled as a renewal process if we can identify independent renewals that bring a structure back into its original condition or "good as new state". After each renewal, we start – in a statistical sense – all over again, where each renewal cycle includes the costs of a single renewal, maintenance actions and possible failure (see the paragraph following Equation (1)). Though renewal theory attracted a huge amount of applications in the fields of mechanical and electrical engineering, it penetrated the field of structural engineering just very recently. Mathematical derivations of analytic life-cycle models on the basis of continuous-time and discrete-time renewal processes can be found in Rackwitz (2001) and van Noortwijk (2003), respectively. Rijkswaterstaat more and more requires that structures and infrastructures should be built and maintained against lowest life-cycle cost while taking RAMSHE into account. An example of a LCC tool of Rijkswaterstaat is the LEM model, which is also based on a renewal model (van Noortwijk and Frangopol, 2004).

3 DETERIORATION AND COST MODELS AND DATA

In order to perform the LCC calculation according to Equation (1), we need models and data on the structural behaviour, the deterioration processes, characteristics and constraints of inspection and repair and–last but not least–costs. One option is to have a look at costs only. Improvements can be made by adding models for degradation and inspection.

3.1 *Cost-driven models*

In many cases inspection and maintenance costs are reasonably well documented. Based on those cost data sources, for instance, the following simple cost model may be derived (van Gorp, 1995ab; van der Toorn, 1994):

$$c = A\, b\, f \qquad (3)$$

where c is the yearly costs for maintenance activities, A is the bridge surface area, b the building cost per unit of surface area and f the maintenance factor. For bridges it was found in The Netherlands that b varies from about 1000 €/m^2 for large bridges to 2000 €/m^2 for small bridges (Wijnants, 2001). If we neglect the movable parts of bridges, the maintenance factor f has a rounded off mean value of about 1% per year (for an example, see Section 2.2). Such a model can be used to give a first prediction for a large stock of bridges, provided that stock constellation and maintenance strategies don't change.

The cost model (3) may be improved, for instance by making f a function of characteristics like age and surface area. Based on the data in Figure 2 it may be concluded that for large bridges up to t = 40 and 50 years the yearly costs are almost constant, but that between 40 and 50 year a peak in maintenance is to be expected. For smaller bridges there seems to be a more gradual increase in costs. Experience learns further that for t > 50 yr there are two options: either the bridge is maintained at a higher level than before or it is given up for the long run and may serve quite some time at a relatively small cost level. Roskam (1996) extended the above cost model by differentiating to the type of structural system like steel bridge, reinforced concrete, prestressed concrete, plate-girder bridges, box-type bridges, and so on. It turned out that there are large differences, for instance the maintenance for box-girder bridges turned out to be at least a factor 5 higher than the maintenance for simple plate-girder bridges.

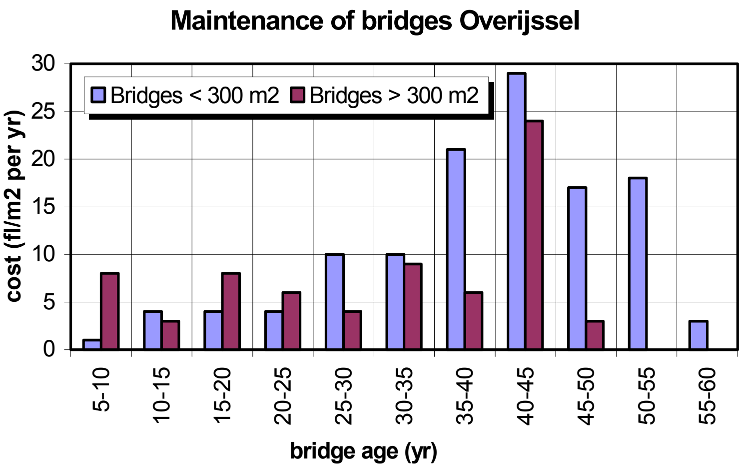

Figure 2: Maintenance costs versus age for bridges (less and larger than 300 m^2) in the Province of Overijssel (The Netherlands).

The above models are based on smoothed yearly averages. An alternative is to base a model on discrete points in time where some specific maintenance is carried out. For different elements of the bridge (deck, asphalt, kerbs, piers, abutments, railings, joints, bearings, etc) or different maintenance types (painting, replacement), different cycles should be chosen. Starting from average values we may introduce a scatter, both in the repair times and in the repair costs. The cost predictions may be made for a single bridge as well as for a stock of different type and age. Van Noortwijk and Klatter (2004) estimated the expected costs of bridge maintenance and replacement on the basis of the uncertainties in the times of maintenance and replacements. Optimisation by combining maintenance activities could be included. A next step in a prediction model could be the inclusion of recent inspection results, which could lead to a formal or heuristic updating of the expected repair costs for the next period. In this way, the effect of possible backlogs in maintenance could be visualised.

3.2 *Physical and statistical models*

Although a direct research into the life-cycle costs is of great value, there is a great disadvantage. The point is that we may only produce predictions and little or no optimisation. In general, it is not known what could be the effect of for instance a change of the geometrical dimensions of material properties. For that case we need models that describe the structural condition as a function of the ongoing deterioration processes. One of the most classical examples is the reduction of the structural reliability due to fatigue (Dijkstra and van Straalen, 1997; Chryssanthopoulos and Vrouwenvelder, 2004). More recently, useful models have been developed for corrosion (Melchers, 1999; Heutink et al., 2004), and carbonation, chloride-ingress and ASR for concrete (Duracrete, 1998; Gaal, 2004; Li, 2004; Vu and Stewart, 2002). In developing models, we may start from the description of the physical processes (crack growth, diffusion, etc) or tune suitable statistical models like Markov processes, Gaussian processes or gamma processes to experimental or analytical results.(for an overview, see Frangopol et al., 2004). These models enable one to calculate the effects of all kinds of measures and in combination with cost estimates a search for minimal maintenance costs may be performed. Some illustrative examples are:

Fatigue of steel gates in the Eastern-Scheldt storm-surge barrier
Dijkstra et al. (1996) made an optimisation using a failure and decision tree schematisation of the fatigue problems for the steel gates of the Eastern-Scheldt storm-surge barrier. Failure probabilities due to various possible defects and failure costs were included.

Spalling of concrete bridges
By careful modelling the Dutch bridge stock, including items like cover continuing hardening and chloride surface concentration as a function of time, Gaal (2004) produced a fair description of the spalling of concrete on Dutch Bridges (Figure 3, left).

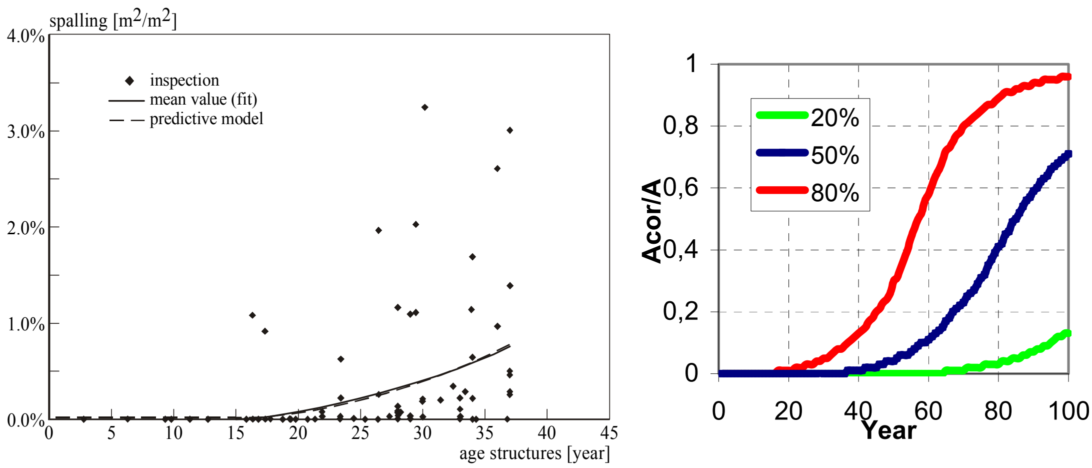

Figure 3 (left): Comparison of theoretical prediction and inspection results for spalling (Gaal, 2004); (right): Part of the area where reinforcement bars have been corroded due to chloride ingress (A_{cor}/A) as a function of time (Li, 2004).

Corrosion due to chloride ingresss
Li (2004) and Vu and Stewart (2002) incorporated the spatial variability enabling to get parts of the structure to be contaminated after some time and other parts not ((right)3, right). In this way, the scatter in Figure 3 left can be explained. Further, we can simulate the efficiency of various repair options like partial repair, perfect repair or total replacement as well as the optimal point in time.

Corrosion of the steel gates of the Haringvliet barrier
In optimising LEM and EM for the coating of the steel gates of the Haringvliet barrier, Heutink et al. (2004) defined the deterioration as the percentage of the surface of a steel gate that has been corroded and modelled its temporal variability with a gamma process (see Figure 4). Note that the failure level is a corroded surface of 3%. For details on the maintenance optimisation, see Section 2.3.

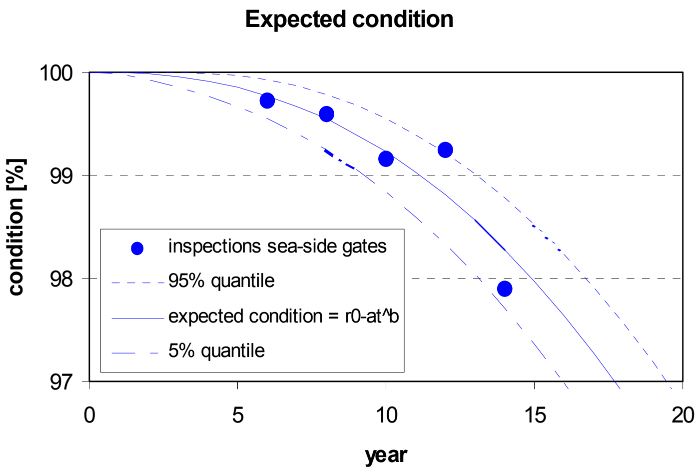

Figure 4: Expected deterioration in terms of the fraction of non-corroded area including uncertainty and inspections from 5 different steel gates (Frangopol et al., 2004).

3.3 *Condition classification systems*

If no reliable deterioration models are available, a *condition classification system* may be helpful. Bridges in the Netherlands are subject to periodic visual inspections. At each inspection, the inspector records individual damages and uses a discrete damage rating scheme with condition states ranging from “excellent” (no damage) to “bad” (damage posing extreme safety threat) to indicate their severity. For convenience, transitions from one condition state to the other usually are modelled as a Markov process, but other options are possible as well. Kallen and van Noortwijk (2006) used Dutch bridge condition data to fit a Markov deterioration model (see Figure 5). For a set of reinforced concrete beams and slabs in a sea environment, Li (2004) has made a comparison between a Markov model developed by Komure et al. (2002) and a physical model of chloride ingress followed by corrosion. It turned out that both models behaved well, the tuned Markov model being slightly better. However, as in the case of the cost-driven models, these tuned models give little insight in the effects of changes in design or maintenance strategies. On the other hand, a great advantage of Markov models is that they are very well suited to incorporate information from visual inspections.

3.4 *Mixing physical and statistical models*

Physical models may be preferred for many reasons; reality however is that reliable and mature physical models simply are not available for all relevant materials and environments. Probably, it is the best – at least for the time being – to combine physical models with statistical models. We could start with pure cost-driven models and combine them with physical models, classification models or statistical models as far as possible. An example of a mix of a physical and statistical model is a gamma process for which the expected deterioration is (partly) assessed according to a physical deterioration law and updated on the basis of inspections (Bakker and van Noortwijk, 2004). Such a mix could give the best possible guarantees to reach optimum maintenance schemes, including all data and knowledge that is available today.

4 EVALUATION

In the previous sections, a decision-theoretic approach for bridge management and safety has been defined and the first firm steps in filling it in have been shown. Important steps are evaluating the results achieved by past and present maintenance practice and developing scenarios and predicting the effects in costs and performance of infrastructure. On the network level, these results have been evaluated in the audit on the White Paper on Mobility of the Netherlands Ministry of Transport, Public Works and Water Management regarding the economic effectiveness

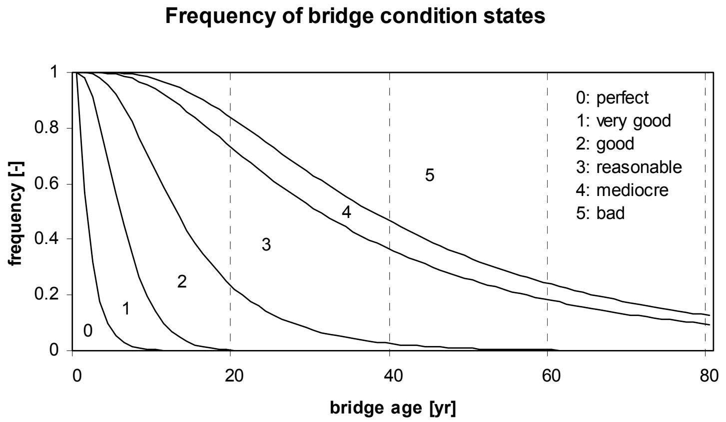

Figure 5: Relative frequency of condition states as a function of bridge age (Kallen and van Noortwijk, 2006).

of investments in road maintenance in the years 2011-2020 (Besseling et al., 2004). The life-cycle approach is a key element in this report. Although maintenance became more transparent, its effectiveness is yet to be proven. Especially, the effect of maintenance on the performance of infrastructures in socio-economic terms on a network level must be investigated.

To serve the public, it will not be sufficient to focus on the technical aspects only; communication on all the aspects involved is crucial for public acceptance of the agency's work. A key objective is establishing open communication with the public and politics about the RAMS/LCC efforts needed to meet the functional user requirements. The position of a governmental road authority placed in a societal context is rather complex. Her main goal is, or at least should be, to serve the public in transportation needs in getting the best value for the tax-payer's money. At the same time, the agency acts as executioner of policy decided by politics. Generally this sets constraints for public transportation needs, because of necessary reduction of adverse effects and funds being scarce. In practice, electoral interests at stake for politicians don't make this task easier. The road agency in the Netherlands contracts out all of the execution of work on roads and bridges. The preparation of this work is contracted out to an increasing extent as well. To serve the public means in practice to assure that industry serves the public. To achieve this, the agency must be able to explain industry how the public has to be served. She has to specify service levels, built-in incentives for innovation to develop future solutions to nowadays' and tomorrow's problems and incentives to optimise performance at lowest costs. The goal of the agency is to create a balance in costs and scope that fits into available budgets, as well as to set standards that can be maintained in the future.

Summarising, a development where the decision-theoretic approach will be combined with 'telling and selling' this story will lead to a broader acceptance. In this respect, important items to be addressed on the engineers' agenda are the performance of infrastructure and a risk-based approach expressed in public understandable language.

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