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Thoft-Christensen, Palle

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CHAPTER 122

A SIMPLIFIED PREVENTIVE MAINTENANCE STRATEGY FOR CONCRETE BRIDGES [1]

P. Thoft-Christensen
Aalborg University, Aalborg, Denmark

ABSTRACT

In the paper, a simple model for estimating the optimal time between preventive maintenance (PM) activities is presented. It is based on a number of simplified assumptions, but the model is believed to be able to model the most important factors related to the problem. The effect of a PM activity is modelled by a simplified model based on three average parameters, namely the effect of a PM action on the rate of deterioration, on the reliability and on the time of delay of deterioration. Using the central limit theorem, all three variables may be modelled as normally distributed stochastic variables. It is shown in the paper that the optimal time between maintenance activities as a function of the difference between the initial reliability and the critical reliability may easily be estimated using Monte-Carlo simulation. Likewise, the total discounted preventive costs as functions of the time interval and the discount rate may be estimated by Monte-Carlo simulation.

1. INTRODUCTION

A bridge management system consists of a large number of bridges. The objective of a bridge maintenance strategy is to minimize the cost of maintaining such a group of bridges in the service life of the bridge stock. Estimation of the service life costs is very uncertain so that a stochastic modelling is clearly needed. This can be expressed mathematically as; see Thoft-Christensen [1]

$$\min E[C] = \min\left(E[C_M] + E[C_U] + E[C_F]\right) \tag{1}$$

[1] Proceedings (CD) IABMAS'04, October 19-22, Kyoto, Japan. Taylor & Francis Group, ISBN 04 1536 336 X.

where

$E\left[C\right]$ is the expected total cost in the service life of the bridge stock,

$E\left[C_M\right]$ is the expected maintenance cost in the service life of the bridge stock,

$E\left[C_U\right]$ is the expected user cost e.g. traffic disruption costs due to works or restrictions on the bridges in the bridge stock,

$E\left[C_F\right]$ is the expected cost due to failure of bridges in the bridge stock.

For a *single* bridge *i* in the bridge stock the expected cost of the bridge in its service life $E\left[C_i\right]$ can be written

$$\begin{aligned} E\left[C_i\right] &= E\left[C_{Mi}\right] + E\left[C_{Ui}\right] + E\left[C_{F_i}\right] \\ &= \sum_{t=1}^{T} \{(1+\gamma)^{-1}\left[E[C_{Mi}(t)]P(M_{it}) + E[C_{Ui}(t)]P(U_{it}) + E[C_{Fi}(t)]\,P(F_{it}(t)\right]\} \end{aligned} \tag{2}$$

where

γ is the discount rate (factor), e.g. 6 %,

$E\left[C_i\right]$ is the expected total cost for bridge *i*,

$E\left[C_{Mi}(t)\right]$ is the expected maintenance cost for bridge *i* in year *t*,

$E\left[C_{Ui}(t)\right]$ is the expected user cost for bridge *i* in year *t*,

$E\left[C_{Fi}(t)\right]$ is the expected failure cost for bridge *i* in year *t*,

$P(M_{it})$ is the probability of the event "maintenance is necessary" for bridge *i* in year *t*,

$P(U_{it})$ is the probability of the event "user costs relevant" for bridge *i* in year *t*,

$P(F_{it})$ is the probability of the event "failure" for bridge *i* in year *t*,

T is the remaining service life or reference period (in years).

Let the number of bridges in the considered bridge stock be *m*. The expected total cost for the bridge stock can then be written

$$\begin{aligned} E\left[C\right] &= \sum_{i=1}^{m} \left\{E\left(C_{Mi}\right) + E\left(C_{Ui}\right) + E\left(C_{Fi}\right)\right\} \\ &= \sum_{i=1}^{m}\sum_{t=1}^{T} \{(1+\gamma)^{-1}\left[E[C_{Mi}(t)]P(M_{it}) + E[C_{Ui}(t)]P(U_{it}) + E[C_{Fi}(t)]\,P(F_{it}(t)\right]\} \end{aligned} \tag{3}$$

2. BRIDGE MAINTENANCE PROJECTS

Optimal bridge management strategies are based on a stochastic modelling like (3). However, such strategies are only being useful if they are also combined with expert knowledge. It is not possible to formulate all expert experience in mathematical terms. Therefore, it is believed that future management systems will be expert systems or at least knowledge-based systems; see Thoft-Christensen [2].

The first major research on combining stochastic modelling, expert systems and optimal strategies for maintenance of reinforced concrete structures was sponsored by EU from 1990 to 1993. The research project is entitled *"Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems"*. The results are presented in several reports and papers; see e.g. Thoft-Christensen [2] and Thoft-Christensen [3]. The methodology used in the project is analytic with traditional numerical analysis and rather advanced stochastic modelling.

In modelling reliability profiles for reinforced concrete bridges Monte Carlo simulation seems to be used for the first time in 1995 in the Highways Agency project *"Revision of the Bridge Assessment Rules based on Whole Life Performance: Concrete"* (1995-1996). The project is strongly inspired of the above-mentioned EU-project. The methodology used is presented in detail in the final project report; see Thoft-Christensen & Jensen [4].

In the Highways Agency project *"Optimum Maintenance Strategies for Different Bridge Types"* (1998-2000), the simulation approach was extended in, see Thoft-Christensen [5] and Thoft-Christensen [6] to include stochastic modelling of rehabilitation distributions and preventive and essential maintenance for reinforced concrete bridges. A similar approach is used in the project on steel/concrete composite bridges; see Frangopol [7].

In a recent project *"Preventive Maintenance Strategies for Bridge Groups* (2001-2003) the simulation technique is extended further to modelling of condition profiles, and the interaction between reliability profiles and condition profiles for reinforced concrete bridges, and the whole life costs. The simulation results are presented in detail by Frangopol [8] and Thoft-Christensen [9].

The simplified strategy for preventive maintenance presented in this paper is based on work performed in the last-mentioned project; see Thoft-Christensen [9].

3. PREVENTIVE MAINTENANCE ELEMENTS (PME)

In this paper the effects of doing preventive maintenance after corrosion initiation are modelled by 3 stochastic parameters:

- the change in reliability level $\Delta\beta$ at the time of maintenance action
- the change in corrosion rate $\Delta\alpha$ due to the maintenance action
- the corrosion delay $\Delta\tau$, i.e. the time to renewed corrosion initiation

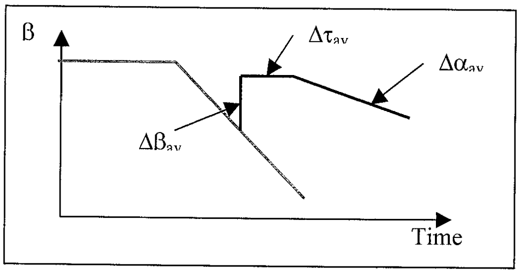

Figure 1. Definition of average preventive maintenance effects.

The above-mentioned effects are in this paper used on (large) groups of concrete bridges – not on individual bridges. Therefore, only average effects are needed, see figure 1. The average effect of the above mentioned actions may be obtained if the relative use of these actions is known (frequency) and if the mean effects for each of them are known.

Let the stochastic variable $\Delta\alpha_i$ with expected value $E(\Delta\alpha_i)$ and standard deviation $\sigma(\Delta\alpha_i)$ be the effect of the maintenance action *i* on the rate of deterioration and let n_i be the relative number of the maintenance action *i*. The number of potential maintenance actions is *N*. Then the expected value and the standard deviation of the average effect on the rate of deterioration is defined as

$$
\begin{aligned}
E(\Delta\alpha_{av}) &= \sum_{i=1}^{N} n_i \times E(\Delta\alpha_i) \\
\sigma(\Delta\alpha_{av}) &= \sqrt{\sum_{i=1}^{N} n_i^{\,2} \times (\sigma(\Delta\alpha_i))^2}
\end{aligned}
\tag{4}
$$

The corresponding expected values of the average effects on the reliability index and the delay time are defined by

$$
\begin{aligned}
E(\Delta\beta_{av}) &= \sum_{i=1}^{N} n_i \times E(\Delta\beta_i) \\
\sigma(\Delta\beta_{av}) &= \sqrt{\sum_{i=1}^{N} n_i^{\,2} \times (\sigma(\Delta\beta_i))^2}
\end{aligned}
\tag{5}
$$

and

$$
\begin{aligned}
E(\Delta\tau_{av}) &= \sum_{i=1}^{N} n_i \times E(\Delta\tau_i) \\
\sigma(\Delta\tau_{av}) &= \sqrt{\sum_{i=1}^{N} n_i^{\,2} \times (\sigma(\Delta\tau_i))^2}
\end{aligned}
\tag{6}
$$

Using the central limit theorem, all 3 stochastic variables can be modeled as normally distributed variables.

4. PREVENTIVE MAINTENANCE ACTIVITIES

Maintenance actions for concrete structures may be divided into three types; see Maunsell [10]:

Routine Maintenance: Minor work carried out on a regular basis, such as cleaning drains and load-bearing shelves.

Preventive Maintenance: Maintenance work, which repairs defects, replaces components or otherwise slows the rate of deterioration, and may enhance the strength of the structure to some extent. Examples are steelwork repainting, expansion joint replacement, silane impregnation and cathodic protection.

Essential Maintenance: Rehabilitation work undertaken when a structure is (or is about to become) structurally inadequate. The work will strengthen the structure. Examples are major concrete repairs, replacement of structural elements and strengthening arising from the bridge assessment programme.

In Maunsell [10] 12 preventive maintenance actions for concrete structures are listed:

- *Deck Expansion Joints*
- *Re-surfacing & Waterproofing*
- *Positive Drainage*
- *Silane Treatment*
- *Anti-Carbonation Coating*
- *Concrete Repairs*
- *Cathodic Protection*
- *Desalination*

- *Realkalisation*
- *Corrosion Inhibitors*
- *Bearing Replacement*
- *Protective Enclosure System*

To implement the simplified preventive maintenance strategy, the above preventive maintenance element PME must be estimated for each of the 12 maintenance actions and their relative frequency must be based on experience.

5. DETERMINISTIC ESTIMATION

The modelling of the effect of a number of periodic preventive maintenance activities as defined in figure 1 is illustrated in figure 2. Three scenarios with time intervals ΔT equal to 5, 10, and 15 years. The considered period of time is 30 years.

For a given time interval $\Delta T = T / N$, Where N is a positive integer equal to the number of time intervals between preventive maintenance activities in the time period T, the reliability at the time T may be estimated by

$$\beta_T = \beta_0 + \frac{T}{\Delta T}\left[\Delta\beta_{av} - \Delta\alpha_{av}\left(\Delta T - \Delta\tau_{av}\right)\right] \tag{7}$$

where $\Delta\tau_{av} \leq \Delta T$ and where β_0 is the average reliability index at the time 0 for the bridge stock (time for the first preventive maintenance action) and where β_T is the reliability index at the time T (the remaining service time or strategy planning time).

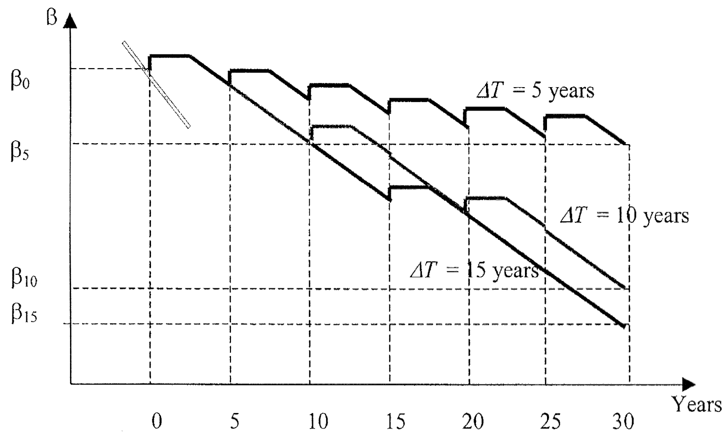

Figure 2. Modelling of preventive maintenance strategies.

The “optimal” time interval ΔT_{opt} may then be calculated by setting

$$\beta_{\Delta T} = \beta_{crit} \tag{8}$$

where β_{crit} is the critical reliability index.

$$\Delta T_{opt} = T\,\frac{\Delta\beta_{av} + \Delta\alpha_{av} \times \Delta_{av}}{\beta_{crit} - \beta_0 + T \times \Delta\alpha_{av}} \tag{9}$$

6. EXAMPLE 1

Consider a situation where the conditions with regard to preventive maintenance activities are so that a preventive maintenance element PME is defined by

$$\Delta\beta_{av} = 0.1, \quad \Delta\tau_{av} = 2\,\text{years}, \quad \Delta\alpha = 0.15\,. \tag{10}$$

The average increase in the reliability index is 0.1 each time the defined PME is used. Likewise, the corrosion is delayed for averagely 2 years and the corrosion rate is 0.15 after the preventive maintenance activity.

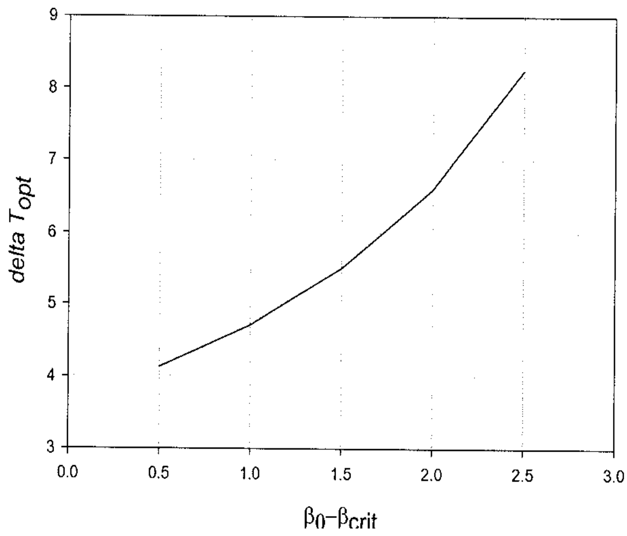

Figure 3. The optimal time between preventive maintenance activities ΔT_{opt} as a function of $\beta_0 - \beta_{crit}$, T = 30 years.

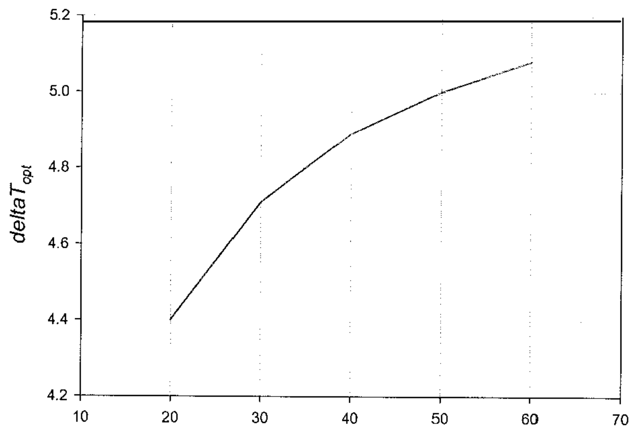

Figure 4. The optimal time between preventive maintenance activities ΔT_{opt} as a function of T, $\beta_0 - \beta_{crit}$ = 1.0.

The optimal time ΔT_{opt} (delta T_{opt}) as a function of $\beta_0 - \beta_{crit}$ and T = 30 years is then shown in figure 3. As expected, the optimal time between preventive actions ΔT_{opt} increases with $\beta_0 - \beta_{crit}$. Let, as an example, the average reliability index β_0 at the time of the inspection planning be equal to 6.0 and let the critical reliability index β_0 be equal to 3.8. Then figure 3 shows that the optimal time between preventive maintenance (at that point in time) is estimated to about 7 years.

The optimal time ΔT_{opt} (delta T_{opt}) as a function of T is shown in figure 4 for $\beta_0 - \beta_{crit}$ = 1. In this case depends only slightly of T. An increase of T from 30 years to 60 years only increases the optimal time between preventive maintenance actions from 4.7 years to 5.1 years.

From this example it may be concluded that the choice of T is not significant when a strategy for preventive maintenance is planned, but, as expected, the critical reliability index β_{crit} is significant.

7. PREVENTIVE MAINTENANCE COSTS

Consider again the preventive strategies illustrated in figure 2 for ΔT equal to 5 years, 10 years, and 15 years. Assume that the average cost of a preventive maintenance action is C_{av} and that the discount rate is r. Then the total discounted preventive cost $C(\Delta T, T)$ as a function of ΔT and T is

$$C(\Delta T, T) = C_{av} \sum_{i=0}^{T/\Delta T - 1} \frac{1}{(1+r)^{\Delta T \times i}} \tag{10}$$

8. EXAMPLE 2

Figure 5 illustrates the importance of the discount rate r on the costs of the strategies shown in figure 2 for ΔT equal to 5 years, 10 years, and 15 years. The considered remaining service life is T = 30 years. Figure 5 shows the total discounted preventive maintenance costs / average costs of a single preventive maintenance action $C(\Delta T, 30)/C_{av}$ (Total costs/single costs) as a function of the discount rate r.

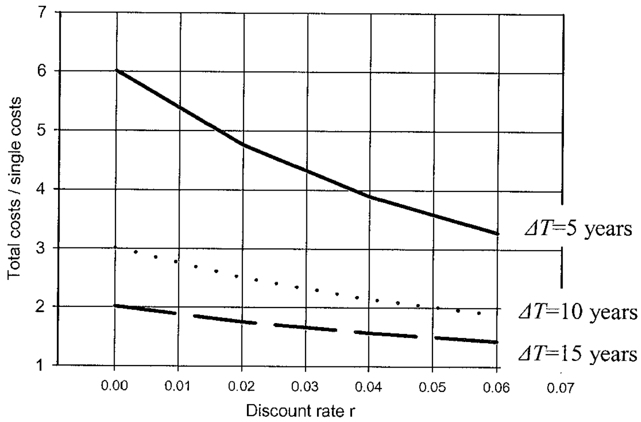

Figure 5. The total discounted preventive maintenance costs / average costs of a single preventive maintenance action $C(\Delta T, 30)/C_{av}$ (Total costs/single costs) as a function of the discount rate *r*.

It is interesting to observe that the discount rate plays a significant role in the total discounted preventive costs. Clearly a high discount rate reduces the total discounted preventive maintenance costs and

$$C(\Delta T, 30)/C_{av} \rightarrow 1 \quad \text{for} \quad r \rightarrow \infty \tag{11}$$

Life-cycle based management systems are of less importance if a relatively high discount rate is used. Unfortunately, in many countries an unrealistically high rate is ordered by the government e.g. 6%. If the much lower interest rates we are used to at present were used, it would be much easier to justify the use of life-cycle based bridge maintenance systems.

9. IMPLEMENTATION OF THE STRATEGY

Implementation of the simplified strategy outlined in this paper is quite simple and requires less data than most alternatives. The intention of this strategy is to obtain a preventive maintenance strategy for a not too small bridge stock. In the paper only the main features are sketched, but more details will be needed depending on special features in the individual applications. Therefore, the strategy will in most cases need some modifications. However, the general implementation methodology will be something like:

1. Specify the bridge stock e.g. reinforced concrete motorway bridges which will be given preventive maintenance in the next service life period, say 30 years.
2. Specify relevant preventive maintenance methods for the bridge stock.
3. Estimate, based on experience, how often the selected preventive maintenance methods are used.
4. Estimate the effect of each preventive maintenance methods on the three parameters in the preventive maintenance elements.
5. Calculate the average values of the three parameters in the preventive maintenance element, see figure 1.

6. Estimate the average reliability index for the bridge stock.
7. Specify the critical reliability index for bridges in the bridge stock.
8. Use equation (9) to estimate the optimal time between preventive maintenance activities.
9. Choose a discount rate and estimate the cost of preventive maintenance of the bridge stock in the service time period.

10. CONCLUSIONS

A new simple model for estimating the optimal time between preventive maintenance activities is presented. It is based on a number of simplified assumptions, but the model is believed to be able to model the most important factors related to the problem. The effect of a preventive maintenance activity is modelled by a simplified model based on three average parameters, namely the effect of a preventive maintenance action on the rate of deterioration, on the reliability, and on the time of delay of deterioration.

The model may easily be extended by modelling the above mentioned average quantities stochastically or by introducing time dependence. It is, however, questionable whether this will improve the model significantly, since reliable data are limited.

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