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CHAPTER 123

LIFE-CYCLE COST DESIGN – WHY IS IT NOT BEING USED? ¹

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ABSTRACT

During the last 20 years important progress has been made in Life-Cycle Cost (LCC) analysis of structures, especially offshore platforms, bridges and nuclear installations. Due to the large uncertainties related to the deterioration and maintenance of such structures, analysis based on stochastic modelling of significant parameters seems to be the only relevant modelling. However, a great number of difficulties are involved in this modelling, but also in the practical implementation of the models developed. The main purpose of this paper is to discuss these problems from a social point of view.

1. INTRODUCTION

LCC analysis may be used not only in the design of new bridges, but also in designing maintenance strategies for individual structures as well as groups of bridges. Therefore, several potential applications are obvious. However, it is a fact that only a few real applications of LCC in bridge engineering are reported in the literature. In the offshore area the situation is somewhat different. The reason is that maintenance is often very expensive since underwater repair is complicated. A major factor is also that closing down an offshore platform for repair will result in an expensive delay in the oil production.

To understand why LCC is seldom used in bridge engineering, it is necessary to look at the modelling techniques used. In planning maintenance budgets for e.g. highway agencies the total expected costs for a group of bridges must be estimated and minimized. There are several models available in the literature, but most of them are similar to the modelling presented in section 2.1. The situation is quite different and

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

more complicated if only a single bridge is considered whether LCC design of a new bridge or maintenance of an existing bridge is considered. The most complete modelling seems to be the modelling presented in section 2.2. A rather detailed presentation is given to show the comprehensive data needed.

Why is LCC not used in bridge engineering? There are many reasons, but the main reason seems to be that the bridge engineers do not at all understand the probabilistic concepts behind LCC. It is certainly not enough to have taken a course on probability theory or in structural reliability theory. What is needed is first of all a deep understanding of the advantages on using LCC.

The problem is in some sense parallel to the problems we met in the seventies and the eighties regarding structural reliability. It was very hard to convince an experienced structural engineer that a stochastic approach to safety is more relevant than a deterministic approach to modelling uncertainties. Even to-day many structural engineers feel more confident with a traditional approach. Also notice that modern codes using partial safety coefficients are deterministic although the calibration is often based on stochastic modelling of the relevant parameters.

2. MODELLING OF LCC

2.1 Groups of bridges

A large number of models for LCC of groups of structures have been proposed in recent years. These models are usually based on an estimate of the LCC where the expected initial costs IC, the expected failure costs FC, the expected inspection costs IC and the expected repair costs RC are simply added

$$\text{LCC} = \text{IC} + \text{FC} + \text{IC} + \text{RC} \quad (1)$$

The single terms in this equation have been discussed by numerous researchers, and more and more sophisticated models have been developed. The state of the art is now so advanced that one would believe that it is not straightforward to use these models. However, it seems fair to say that LCC design has been used in few cases only.

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. Let the number of bridges in the considered bridge stock be m . The expected total cost for the bridge stock can then be written; see Thoft-Christensen [1]

$$E[C] = \sum_{i=1}^m \sum_{t=1}^T \left\{ (1+\gamma)^{-1} \left[E[C_{Mi}(t)]P(M_{it}) + E[C_{Ui}(t)]P(U_{it}) + E[C_{Fi}(t)]P(F_{it}(t)) \right] \right\} \quad (2)$$

where

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

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

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

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

$E[C_{Fi}(t)]$ 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 cost happen” for bridge i in year t ,

$P(F_i)$ is the probability of the event “failure happen” for bridge i in year t ,
 T is the remaining service life or reference period (in years).

2.1 Individual bridges

For individual bridges LCC may be used in designing a new bridge, but is also very useful in connection with decision problems regarding e.g. repair after an inspection has taken place.

After a structural assessment at the time T_0 a difficult problem is to decide if the bridge should be repaired and if so, how and when should it be repaired. After each structural assessment the total expected benefits minus expected repair and failure costs in the remaining lifetime of the bridge are maximized. This model can be used in an adaptive way if the stochastic model is updated after each structural assessment or repair and a new optimal repair decision is taken. Therefore, it is mainly the time of the first repair after a structural assessment which is of importance.

In order to decide which type of repair is optimal after a structural assessment, the following optimization problem is considered for each repair technique; see Thoft-Christensen [2]

$$\begin{aligned} \max W &= B(T_R, N_R) - C_R(T_R, N_R) - C_F(T_R, N_R) \\ \text{s.t. } \beta^U(T_L, T_R, N_R) &\geq \beta^{\min} \end{aligned} \quad (3)$$

where the optimization variables are the expected number of repair N_R in the remaining lifetime and the time T_R of the first repair. W is the total expected benefit B minus the repair costs C_R capitalized to the time $t = 0$ and minus the expected failure costs C_F capitalized to the time $t = 0$ in the remaining lifetime of the bridge. T_L is the expected lifetime of the bridge. β^U is the updated reliability index. β^{\min} is the minimum reliability index for the bridge.

The benefits may be modelled by

$$B(T_R, N_R) = \sum_{i=[T_0]+1}^{[T_L]} B_i (1+r)^{T_0-T_{ref}} \frac{1}{(1+r)^{T_i-T_0}} \quad (4)$$

where $[T]$ signifies the integer part of T measured in years and B_i are the benefits in year i . T_i is the time from the construction of the bridge. The i th term in (4) represents the benefits from T_{i-1} to T_i . The benefits in year i may be modelled by

$$B_i = k_0 V(T_i) \quad (5)$$

where k_0 is a factor modeling the average benefits for one vehicle passing the bridge. It can be estimated as the price of rental of an average vehicle/km times the average detour length. The reference year for k_0 is T_{ref} . It is assumed that bridges are considered in isolation. Therefore, the benefits are considered as marginal benefits by having a bridge (with the alternative that there is no bridge, but other nearby routes for traffic). V is the traffic volume per year estimated by

$$V(T) = V_0 + V_1(T - T_{ref}) \quad (6)$$

where V is the traffic volume per year at the time of construction, V_1 is the increase in

traffic volume per year, and T is the actual time (in years).

The expected repair costs capitalized to time $t = 0$ are modelled by

$$C_R(T_R, N_R) = \sum_{i=1}^{N_R} (1 - P_F^U(T_{R_i})) C_{R_i}(T_{R_i}) \frac{1}{(1+r)^{T_{R_i} - T_0}} \quad (7)$$

$P_F^U(T_R)$ is the updated probability of failure in the time interval $]T_0, T_R]$. The factor $(1 - P_F^U(T_{R_i}))$ models the probability that the bridge has not failed at the time of repair. r is the discount rate. $C_{R_i}(T_{R_i})$ is the cost of repair and consists of the three terms, namely the functional repair costs, the fixed repair costs, and the unit dependent repair costs, respectively.

The functional repair costs depend on the duration of the repair in days, the number of lanes closed for the repair, and the total number of lanes.

The fixed costs depend on the distance to the headquarters, the roadblock costs, and the number of 8 hour periods needed to perform the repair of the bridge.

The unit costs depend on the defect and how easy it is to repair, the time needed to perform the repair, the extent of the repair using the relevant repair technique, the man hours needed for the repair technique considered, the man hour cost, and the material/equipment costs.

The capitalized expected costs due to failure are determined by

$$C_F(T_R, N_R) = \sum_{i=1}^{N_R+1} C_F(T_{R_i})(P_F^U(T_{R_i}) - P_F^U(T_{i-1})) \frac{1}{(1+r)^{T_{R_i}}} \quad (8)$$

The i th term in (8) represents the expected failure costs in the time interval $]T_{R_{i-1}}, T_{R_i}]$. $C_F(T)$ is the cost of failure at the time T .

3. LCC LEVELS

Modelling of LCC may be performed by a number of different approaches. In most cases they can be divided into 3 levels, e.g. levels analogous to the 3 levels of deterioration models introduced by Thoft-Christensen [1]

- Level 3 – Scientific Level
- Level 2 – Engineering Level
- Level 1 – Technical Level

Level 3 is the most advanced level. Models on this level are “exact models” in the sense that the modeling of LCC is based on a sound and consistent scientific basis. Advanced information on the deterioration of the bridge is used and detailed information on the environmental loading is taken into account. A level 3 modeling is typically used in design of a new large bridge such as a long suspension bridge. It is a very expensive modeling and it is not easy to formulate a level 3 method based on basis of information. An important application of level 3 models is to supply information to be used in a level 2 model.

Level 2 is an average level from a sophistication point of view. Level 2 models are based on semi-physical or average material deterioration parameters and average effects of maintenance. They are also based on a number of engineering simplifications regarding the modelling of the average quantities used. A level 2 model will often limit the deterioration of the bridge to a few types of deterioration. Level 2 models may be used for design of new structures and for estimation of deterioration of existing

concrete structures. An important application of level 2 models is to supply information to be used in a level 1 model.

Level 1 is the most simplified level of modeling of the LCC. It is based on direct observations and expert experience regarding repair types, repair intervals and repair costs. A level 1 model is usually based on a limited number of parameters, e.g. obtained from level 2 modeling. A Level 1 model may be used on groups of bridges to obtain e.g. optimal maintenance strategies.

The simplified strategy for preventive maintenance of concrete bridges by Thoft-Christensen [3] is a typical level 1 model for groups of concrete bridges. The model may be used for estimating the optimal time between preventive maintenance (PM) activities. 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.

4. THE PUBLIC WILL

Designing a new bridge or a bridge maintenance strategy based on LCC will in general result in an apparently increased initial cost, so it is not attractive for Highways Agencies. This recognition in connection with the conservative tradition of only looking at the initial costs makes it unattractive to use LCC.

A modern LCC design is based on a probabilistic approach. Some of the terms in the cost equations are based on probabilistic distributions, expected values, etc. A bridge engineer not familiar with probability theory will be less prepared to accept designs based on a stochastic modelling. This is true not only for design of a bridge, but also for design of bridge maintenance strategies.

Bridge engineers often believe that the design of a new bridge or the repair of an existing bridge is 100% safe in the remaining service life of the bridge. Likewise, if you inform politicians that there is a failure probability of say 10^{-6} you will often be asked whether failure could take place to-morrow. Your answer will probably be yes, it is possible but, unlikely. His reply could then easily be that he does not want the suggested design, but a 100% safe bridge. The conclusion is that we need to educate the general citizen but especially the decision-makers.

The public will is low, since designing a structure based on LCC will result in an increased initial cost and could therefore give budget and re-election problems for the politicians.

Finally the mathematical modelling is not complete, since there are relevant factors for the LCC which may not be included in the model. Some minor repairs are often needed even if they are not directly important for the safety of the bridge. It may not always be possible to estimate the condition of the bridge in a rational way. Therefore, for some bridge engineers the concepts behind LCC is not always acceptable. They feel that the modelling is in some way too complicated and detailed, but at the same time not complete.

More research in this area is needed. However, it seems to be more important to illustrate for the society that LCC design is the way forward – perhaps in a modified and simplified format. As experts it is our responsibility to improve the public understanding.

5. DATA

It is obvious that using LCC in bridge engineering will require a lot of reliable data which in many cases are not available. This is especially true when a single bridge is considered, see section 2.2. In the case of a single bridge very good and comprehensive data regarding the condition of the bridge is needed. Using LCC in such a case requires a bridge engineer not only familiar with probabilistic thinking, but also with a lot of experience.

The situation is perhaps a little easier for groups of bridges, since only average data is needed. Such data may to some extent be available in Highways Agency databases. For groups of bridges LCC based strategies at level 1 may be the way ahead. However, the output of a level 1 modelling should not stand alone – it must be followed up by the knowledge of experienced bridge engineers.

In most countries user costs will be the dominating term in the modelling of LCC, but they are not usually included in the modelling. The reason is that modelling user costs are problematic and difficult. However, this is not a reasonable argument for not taking user costs into consideration.

6. THE DISCOUNT RATE

Some of the terms in the above-mentioned modelling of LCC are strongly dependent on the discount rate. A high discount rate will make LCC design less important than a low discount rate. There is a clear tendency in most countries to use an unrealistically high discount rate. If this is so then using LCC may be meaningless.

7. CONCLUSIONS

LCC analysis has only been used in bridge engineering in a few cases. The main reason is a missing understanding among bridge engineers, highway agency employers, and politicians of the advantages of using LCC. Insufficient data on bridge conditions, on deterioration of bridges, on user costs also contribute to the sparse application of LCC. Finally, the use of high discount rates as laid down by politicians also reduces the importance of using LCC. As experts it is our responsibility to convince the politicians that a realistic discount rate must be used. The way forward is to educate the relevant people and to use level 1 modelling based on simple but relevant data.

8. REFERENCES

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