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LIFE-CYCLE COST-BENEFIT (LCCB) ANALYSIS OF BRIDGES FROM A USER AND SOCIAL POINT OF VIEW [1]

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ABSTRACT

During the last two decades, important progress has been made in Life-Cycle Cost-Benefit (LCCB) analysis of structures, especially offshore platforms, bridges and nuclear installations. Due to the large uncertainties related to the deterioration, maintenance, and benefits of such structures, analysis based on stochastic modelling of all significant parameters seems to be the only relevant modelling. However, a great number of difficulties are involved, not only in the modelling, but also in the practical implementation of the models developed at present. The main purpose of this paper is to present and discuss some of these problems from a user and social point of view.

A brief presentation of a preliminary study of the importance of including benefits in life-cycle cost-benefit analysis in management systems for bridges is shown. Benefits may be positive as well as negative from user and point of view. In the paper negative benefits (user costs) are discussed in relation to maintenance of concrete bridges. A limited number of excerpts from published reports are related to the importance of estimating user costs when repairs of bridges are planned, and when optimized strategies are formulated, are shown. These excerpts clearly show that user costs in several cases completely dominate the total costs. In some cases the user costs are more than ten times higher than the repair costs. A simple example of how to relate and estimate user costs to the repair of a single bridge is shown. Finally, how the total maintenance costs (including user costs) may be estimated for a large bridge stock is discussed. This paper is primarily based on two previous International Association for Bridge Maintenance and Safety (IABMAS) conference papers by Thoft-Christensen [1], [2].

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[1] Ac cepted for publication in "Structure and Infrastructure Engineering" 2008.

1. INTRODUCTION

Life-cycle cost benefit (LCCB) 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 of LCCB are obvious. However, it is a fact that only a few real applications of LCCB in bridge engineering are reported in the literature. In the offshore area, the situation is somewhat different since maintenance in offshore engineering in general is very expensive since as for example, 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. There is therefore a great incentive to develop LCCB models in offshore engineering. In nuclear engineering the situation is more or less the same. It is therefore not surprising that the initial LCCB models were developed in these two areas.

To understand why LCCB is seldom used in bridge engineering, it is necessary to look at the modelling techniques used. There are several models available in the literature, but most of them are similar to that presented in this paper.

Highway agencies usually have very limited resources. Therefore, it is of great interest for the highway agencies to be able to estimate the total expected costs for a group of bridges and to try to minimize the total maintenance costs. The situation is quite different, and perhaps more complicated, if only a single bridge is considered. LCCB design of a new bridge, or the maintenance of an existing bridge, is considered in the paper. The most complete models seem to be models similar to the ones presented in section 3. A rather detailed presentation is given to show the comprehensive data needed. Designing a LCCB bridge management system is briefly presented in section 3 for a single bridge, and in chapter 4 for a bridge stock.

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

The problem is in some sense parallel to the problems 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 was more relevant than a deterministic approach. Even today, many structural engineers feel more confident with a traditional approach. Also, note that modern codes using partial safety coefficients are deterministic, although the calibration is often based on stochastic modelling of the relevant parameters.

It is a fact that user costs are usually not included when optimal maintenance strategies and decisions are made, although authors often mention that user costs ought to be included. The life-cycle costs are often minimized for the considered structure without considering the often significant costs for the users of the bridge and even without considering the long-term effects of the decision. Unfortunately, the maintenance decisions are often political decisions that are not easy to accept for the community. There is clearly a need to convince the decision-makers that user costs should be considered when major decisions are made.

Life-Cycle Cost (LCC) analysis is based only on the direct costs such as inspection and repair (preventive and essential). User costs are usually not included in an LCC analysis. Life-Cycle Cost-Benefit (LCCB) analysis is an extended LCC analysis where all kinds of indirect costs such as user costs are included. User costs are discussed in more detail later in this paper.

To illustrate the importance on including user costs in an LCCB bridge management system, a brief review of a few reports and other documents on user costs is presented in sections 5 and 6. Note that, in these (and most) documents user costs are modelled deterministically, although user costs are always very uncertain. Therefore, user costs must be modelled by stochastic variables or stochastic processes. However, a deterministic modelling based on statistic documentation is a good starting point for a stochastic modelling of user costs.

The first major research on combining stochastic modeling, expert systems and optimal strategies for maintenance of reinforced concrete structures in a LCCB bridge management system was sponsored by EU from 1990 to 1993; see Thoft-Christensen [3] and de Brito et al. [4]. The research project is entitled *"Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems"*. The methodology used in the project was analytic, using traditional numerical analysis and rather advanced stochastic modeling.

2. LIFE-CYCLE COST-BENEFIT LEVELS

Modelling of LCCB may be performed by a number of different approaches. In most cases, these approaches can be divided into three levels, e.g. levels analogous to the three levels of deterioration models introduced by Thoft-Christensen [5]:

- 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 LCCB 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 model, 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 LCCB. 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 models. A Level 1 model may be used on groups of bridges to obtain, for example, optimal maintenance strategies.

The simplified strategy for preventive maintenance of concrete bridges by Thoft-Christensen [6] 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.

The EU sponsored LCCB bridge management system presented by Thoft-Christensen [3] and de Brito et al. [4] is a typical level 2 model, but is based on some elements of a level 3 model. It is reasonable to believe that progress in this field will primarily be based on improved models for singular elements in the complete management system.

3. AN LCCB BRIDGE MANAGEMENT SYSTEM FOR SINGLE BRIDGES

LCCB bridge management systems have a broad spectrum of applications. A mentioned earlier, they are very useful for groups of bridges, but also for individual bridges. In this section, the EU-supported LCCB bridge management system mentioned in section 2 is presented to illustrate how user costs may be included in decision-making for single bridges. LCC and LCCB systems may be used in designing a new bridge, but are also very useful in connection with decision problems regarding, for example, repair of a bridge after an inspection has taken place. As will be shown in section 5 and section 6, the total cost related to maintenance or replacement of deteriorated bridges will often be strongly dominated by the user costs.

In this section, the modelling of user costs is discussed on the basis of a simple and straightforward implementation used in the above-mentioned research project entitled "*Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems*". In the model a number of issues related to user costs are included such as closing down one or more lanes during maintenance. All relevant parameters are modelled as stochastic variables. The detour costs for a given bridge are estimated by considering the loss in the marginal benefits by having the bridge compared to no bridge, but only nearby routes, for the traffic. This estimation is based on the average benefits for one vehicle passing the bridge by estimating the rental price of an average vehicle per km times the average detour length in km. Therefore, data on the traffic volume, including the increase in traffic volume per year are needed. The model shown here may easily be extended to include other kinds of user costs, such as different categories of vehicles, cost of accidents, and loss of time due to the detour.

After structural assessments of a bridge, say 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 the 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 & Hansen [7]:

$$\max_{T_R, T_N} W = B(T_R, N_R) - C_R(T_R, N_R) - C_F(T_R, N_R)$$

$$s.t. \quad \beta^U(T_L, T_R, N_R) \geq \beta^{min}$$

(1)

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. *T*he total expected benefit B in the remaining lifetime of the bridge minus the expected repair costs C_R, capitalized to the time T_0, and minus the expected failure costs C_F, capitalized to the time T_0, is W. The expected lifetime of the bridge is T_L. β^U is the updated reliability index and $\beta^{\min}$ is the minimum reliability index for the bridge.

The benefits, for example, be modelled by the sum of the benefits in each year in the remaining life of the bridge

$$B(T_R, N_R) = \sum_{i=[T_0]+1}^{[T_L]} B_i \frac{1}{(1+r)^{T_i - T_0}} \tag{2}$$

where $[T]$ signifies the integer part of T measured in years, and B_i are the benefits in year i. The time T_i is the time from the construction of the bridge and r is the discount rate (see section 10). The ith term in (2) represents the benefits from T_{i-1} to T_i capitalized back to time T_0. The benefits in year i may, for example, be modelled by

$$B_i = k_0 V(T_i) \tag{3}$$

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 per km times the average detour length. The reference year for k_0 is T_0. It is assumed that bridges are considered in isolation. More sophisticated models for B_i can easily be included, for example, by considering different categories of vehicles and adding other types of indirect benefits, see section 5 and section 6. 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

$$V(T) = V_0 + V_1(T - T_0) \tag{4}$$

where V_0 is the traffic volume per year at the time T_0, 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

$$C_R(T_R, N_R) = \sum_{i=1}^{N_R} (1 - P_F^U(T_{R_i})) C_{R_0}(T_{R_i}) \frac{1}{(1+r)^{T_{R_i} - T_0}} \tag{5}$$

The term $P_F^U(T_R)$ is the updated probability of failure in the time interval $]T_0, T_R]$. The factor $\left(1 - P_F^U(T_R)\right)$ models the probability that the bridge has not failed at the time of repair, and r is the discount rate. The term $C_{R_0}(T_{R_i})$ 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. 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 eight-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

$$C_F(T_R, N_R) = \sum_{i=1}^{N_R+1} C_F(T_{R_i})(P_F^U(T_{R_i}) - P_F^U(T_{i-1_i})) \frac{1}{(1+r)^{T_{R_i}}} \tag{6}$$

The ith term in (6) 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.

4. LCCB BRIDGE MANAGEMENT SYSTEMS FOR BRIDGE STOCKS

A bridge stock will usually consist 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 [3], [8]

$$\min E[C] = \min (E[C_M] + E[C_U] + E[C_F]) \tag{7}$$

where $E[C]$ is the expected total cost in the service life of the bridge stock, $E[C_M]$ is the expected maintenance cost in the service life of the bridge stock, $E[C_U]$ is the expected user cost, e.g. traffic disruption costs due to works or restrictions on the bridges in the bridge stock, and $E[C_F]$ is the expected cost due to failure of bridges in the bridge stock.

For a *single* structure i in the bridge stock, the expected cost $E[C_i]$ can be written

$$E[C_i] = E[C_{Mi}] + E[C_{Ui}] + E\left[C_{F_i}\right]$$
$$= \sum_{t=1}^{T} \{(1+r)^{-t}\left[E[C_{Mi}(t)]P(M_{it}) + E[C_{Ui}(t)]P(U_{it}) + E[C_{Fi}(t)]P(F_i(t))\right]\} \tag{8}$$

where r is the discount rate (factor), e.g. 6 %, $E[C_i]$ is the expected total cost for structure i, $E[C_{Mi}(t)]$ is the expected maintenance cost for structure i in year t, $E[C_{Ui}(t)]$ is the expected user costs for structure i in year t, $E[C_{Fi}(t)]$ is the expected failure costs for structure i in year t.

The probability $P(M_{it})$ is the probability of the event "maintenance is necessary" for structure i in year t, $P(M_{it})$ is the probability of the event "maintenance is necessary" for structure i in year t, $P(U_{it})$ is the probability of the event "user costs occur" for structure i in year t, T is the remaining service life or reference period (in years).

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

$$E[C] = \sum_{i=1}^{m} \{E(C_{Mi}) + E(C_{Ui}) + E(C_{Fi})\}$$
$$= \sum_{i=1}^{m} \sum_{t=1}^{T} \{(1+r)^{-t}\left[E[C_{Mi}(t)]P(M_{it}) + E[C_{Ui}(t)]P(U_{it}) + E[C_{Fi}(t)]P(F_i(t))\right]\} \tag{9}$$

The modeling shown here were used in the previously mentioned research project "*Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems*" sponsored by EU. Similar models are used in a number of research projects. Here only three projects sponsored by the Highways Agency, London will be mentioned.

Monte Carlo simulation has been used for decades to analyze complex engineering structures in many areas, e.g. in nuclear engineering. In modelling reliability profiles for reinforced concrete bridges, Monte Carlo simulation seems to be used for the first time in December 1995 in the Highways Agency project *"Revision of the Bridge Assessment Rules based on Whole Life Performance: Concrete"* (1995-1996, Contract: DPU 9/3/44). The project is strongly inspired of the EU-project mentioned above. The methodology used is presented in detail in the final project report in Thoft-Christensen & Jensen [9].

In the Highways Agency project *"Optimum Maintenance Strategies for Different Bridge Types"* (1998-2000, Contract: 3/179) the simulation approach was extended in Thoft-Christensen [10], [8] to include stochastic modelling of rehabilitation distributions and preventive and essential maintenance for reinforced concrete bridges. A similar approach was used in the project on steel/concrete composite bridges; see Frangopol [11].

In a recent project *"Preventive Maintenance Strategies for Bridge Groups* (2001-2003, Contact 3/344 (A+B)) the simulation technique was extended further to modelling of condition profiles, the interaction between reliability profiles and condition profiles for reinforced concrete bridges, and the whole life costs. The simulation results are detailed presented in Frangopol [12], Thoft-Christensen [13], and Thoft-Christensen & Frier [14].

In these three projects, modelling of inspection and repair costs was discussed in detail. However, user costs were not included. User costs will be discussed in section 5 and section 6.

5. USER COST REPORTS

5.1 Corrosion cost and preventive strategies in the United States

This section is based on the technical report of a project entitled "*Corrosion Cost and Preventive Strategies in the United States*" written by Koch et al. [15] and sponsored by the Federal Highway Administration. The following excerpts are taken from the Highway Bridge section of the report:

> "There are 583,000 bridges in the United States (1998). Of this total, 200,000 bridges are steel, 235,000 are conventional reinforced concrete, 108,000 bridges are constructed using prestressed concrete, and the balance is made using other materials of construction. Approximately 15 percent of the bridges are structurally deficient, primarily due to corrosion of steel and steel reinforcement. The annual direct cost of corrosion for highway bridges is estimated to be $8.3 billion, consisting of $3.8 billion to replace structurally deficient bridges over the next ten years, $2.0 billion for maintenance and cost of capital for concrete bridge decks, $2.0 billion for maintenance and cost of capital for concrete substructures (minus decks), and $0.5 billion for maintenance painting of steel bridges. Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than ten times the direct cost of corrosion maintenance, repair, and rehabilitation."

> "Overall, approximately 15 percent of all bridges are structurally deficient, with the primary cause being deterioration due to corrosion. The mechanism is one of chloride induced corrosion of the steel members, with the chlorides coming from de-icing salts and marine exposure."

It is interesting to note that Koch et al. [15] estimated the user costs due to traffic delays and lost productivity to be more than ten times the direct cost of maintenance, repair, and rehabilitation. User costs are estimated as the product of additional travel time and the value of time.

5.2 Development of road user cost methods

This section is based on the technical report of a project entitled "*Development of Road User Cost Methods*" written by Daniels et al. [16] and sponsored by the theTexas Department of Transportation. In the project "road user costs (RUC) are defined as the estimated daily cost to the travelling public resulting from the construction work being performed" namely detours and rerouting that add to travel time, reduced road capacity, and delays in the opening of a new or improved facility. The total road user costs can be expressed as

$$RUC = VOC + AC + VOT \tag{10}$$

where VOC is the vehicle operating cost component and includes the costs of fuel, tires, engine oil, maintenance, and depreciation, AC is the accident costs (fatal accidents, non-fatal injury accidents, property damage accidents), and VOT is a function of the hourly wage rate. VOT is, in most cases, the most relevant component. In the report the mean value of VOT for a number of states in USA is estimated as $ 11.38 for passenger cars and $ 27.23 for trucks. Today these values are much higher due to inflation etc.

5.3 Development of user cost data for Florida's bridge management system

This section is based on the final technical report of a project entitled "*Development of User Cost Data for Florida's Bridge Management System*" written by Thompson et al. [17] and sponsored by the Florida Department of Transportation (DFOT), which applies the Pontis Bridge Management System to its user cost models. The following excerpts are taken from the report:

> "An analysis of the Pontis user cost model found that it was overly sensitive to extremes of roadway width, yielding unrealistic high benefit estimates. A new model was developed using Florida data on bridge characteristics and traffic accidents. The new model has superior behavior and statistical characteristics on a full inventory of state highway bridges".

> "The user cost model developed in this study is just one small part of FDOT's overall effort to implement the PONTIS bridge management system. PONTIS is intended to support improved bridge program decision-making by presenting objective information on the costs and benefits of policy and project decisions".

> "The user cost model developed in this study is an important part of the system's ability to measure the economic benefits of bridge investments".

This report is of great interest as it stresses the importance of including user costs in LCCB analysis. It also shows how the sensitivity of the user costs estimates may be evaluated.

5.4 The costs of construction delays and traffic control for life-cycle cost analysis of pavements

This section is based on the research report of a project entitled "*The Cost of*

Construction delays and Traffic Control for Life-Cycle Cost Analysis of Pavements" written by Rister & Graves [18] and sponsored by the Kentucky Transportation Center and Kentucky Transportation Cabinet. The following excerpts are taken from the report:

> "Road User Costs (RUC) have been defined by researchers at the Texas Transportation Institute as the estimated incremental daily costs to the traveling public resulting from the construction work being performed".

> "…agree that RUC are an aggregation of three separate cost components for three different vehicle types. The three different cost components are; vehicle operating costs (VOC), user delay costs, and crash/accident costs. The three vehicle types are; passenger cars, single unit trucks, and combination trucks".

The VOC rates vary with the speed. As an example it can be mentioned that the VOC rates for a passenger car with an initial speed of 60 mi/h is 6.31 ($/Vehicle-Hr) in 1970 dollars and $ 27.94 for a combination truck. The user delay costs (value of time) are on average 11.58 and 22.31 ($/Vehicle-Hr) in 1996 dollars for passenger cars and combination trucks respectively. Typical fatality ranges between $ 1.091 million and $ 1.182 million.

5.5 Strategic review of bridge maintenance costs

This section is based on the research report of a project entitled "*Strategic review of bridge maintenance costs*"; see Maunsell [19]. The report is produced by Maunsell Ldt., UK for the Highways Agency, London, UK. The following excerpts are taken from the report:

> "A strategic review has been undertaken of annual maintenance costs of the Highways Agency's structures. …… The object of the exercise was to predict the annual expenditure on essential and preventive maintenance which will be required in each of the next forty years on the Highways Agency' bridge stock".

> "Road user delay costs due to maintenance were also estimated. These ranged from relatively small amounts to over ten times the direct maintenance costs, depending on the work being done and the type of road. However, the results are very sensitive to the assumptions used and only give a broad indication of likely delay costs".

> "If essential maintenance were under funded, bridges would, in time, need to be closed or restricted while awaiting repair. The main effect would be road user delay costs of the order of £4.6 million a year for each £1 million of essential maintenance not undertaken. The review showed that the cumulated effects of such under funding would soon become unacceptable due to the disruption".

The report demonstrates the importance of including the user costs in LCCB analysis. It also clearly shows the consequence for the society of delaying important maintenance of bridges.

6. MORE USER COST DATA

6.1 Bridge on Interstate 40 in Oklahoma, USA

On 26 May 2002 a barge slammed into the bridge on Interstate 40 over the Arkansas River near Webbers Falls, Oklahoma, USA (see Federal Highway Administration [20]). Four of the bridge's approach spans collapsed and fourteen people were killed. The bridge is the state's most important east-west transportation link, so the collapse had a major influence on the economy. The cost of repair of the bridge was about $ 15 million and the total user cost was estimated to $430 thousand per day for every day the bridge was closed. It was therefore essential to accelerate the repair, which was completed in about two month. $12 million were spent on upgrading of the detour highways. The detours were used by approximately 17,000 vehicles every day the bridge was not open.

6.2 Replacement of Structures on STH 27 in Wisconsin, USA

Replacement of the Holcombe Flowage structure and the Fisher River structure on STH 27 in the Town of Lake Holcombe, WI, USA with two new concrete bridges is estimated to cost approximately $2.43 million (Schmidt [21]). The detour was approximately 28 km long. With a fuel cost of $0,42 per litre and a traffic volume of 4,500 cars per day, the fuel cost were about $2 million for a six to eight month period.

6.3 Grassy Creek bridge in North Carolina, USA

Rehabilitation of the existing Grassy Creek Bridge (bridge no.123) in Ashe County, North Carolina, USA was considered "neither practical nor economical". Therefore, a replacement was decided. Two alternatives were considered (Koch et al. [22]).

The total costs of the two alternatives were estimated to approximately $ 450 thousand and $ 640 thousand. However, the winning bid for a redesign of the project was only $ 333 thousand. According to Koch et al. [22] "the average extra travel incurred by a motorist on the detour would be 2.6 miles, resulting in road user costs at $ 15,000 for the six month construction period".

7. CONCLUSIONS CONCERNING USER COSTS

The importance of including user costs in estimating the economic consequences of maintaining bridges has been studied in section 5 and section 6. It is argued that a cost-benefit analysis is needed when life-cycle analysis of maintenance (including inspection cost, repair cost, and user cost) of bridges is performed. This conclusion is based on an extensive study of documents on maintenance costs. From five of these documents a limited number of excerpts are shown. They are related to estimation of the importance of estimating user costs when repair of bridges are planned, and when optimized strategies are formulated. Further reference to three other documents is made. These excerpts clearly show that user costs in most cases completely dominate the total costs. In some cases, the user costs are even more than ten times higher than the repair costs.

The main conclusion is that an LCC based bridge management system in most cases is insufficient. User costs will, in general, dominate the cost of inspection and repair. Therefore, an LCCB analysis is more reasonable to use.

There is an enormous amount of work on user costs in bridge engineering in the literature. However, much more research is needed before an LCCB analysis in the bridge area can be made in a satisfactory manner. Much of the work done until now is limited to narrow models without a wide area of application. A reliable life-cycle based

tool must include direct as well as indirect cost. The bridge owners must learn to listen to the public when decisions regarding repair or replacement of structures are taken.

8. 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 remaking service life of the bridge. Likewise, if politicians are informed that there is a failure probability of say 10^{-6} you will often be asked whether failure could take place tomorrow. Your answer will probably be yes, it is possible but, unlikely. The reply could then easily be that the suggested design is not wanted, but a 100% safe bridge is. The conclusion is that the general citizens, especially the decision-makers, need to be educated.

The public will is low, since designing a structure based on LCC analysis 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, as there are relevant factors for the LCC that 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. It is felt 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 society that LCCB design is the way forward – perhaps in a modified and simplified format. As experts, it is our responsibility to improve the public understanding.

9. DATA

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

The situation is perhaps a little easier for groups of bridges, since only average data is needed to obtain reasonable solutions to the optimization problems. Such data may, to some extent, be available in Highways Agencies' 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 analysis, but they are not usually included in the modelling. The reason is that modelling user costs is problematic and difficult, due to a lack of acceptable data. However, this is not a reasonable argument for not taking user costs into consideration.

10. THE DISCOUNT RATE

Some of the terms in the above-mentioned modelling of LCC analysis are strongly dependent on the discount rate r through the discount factor

$$f(r,t) = \frac{1}{(1+r)^t} \tag{11}$$

The factor $f(r,t)$ is shown for several values of r in figure 1. 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, e.g. 6%, rather than a more reasonable discount rate e.g. 2% to 3 %. With a high discount rate, using LCCB may be meaningless.
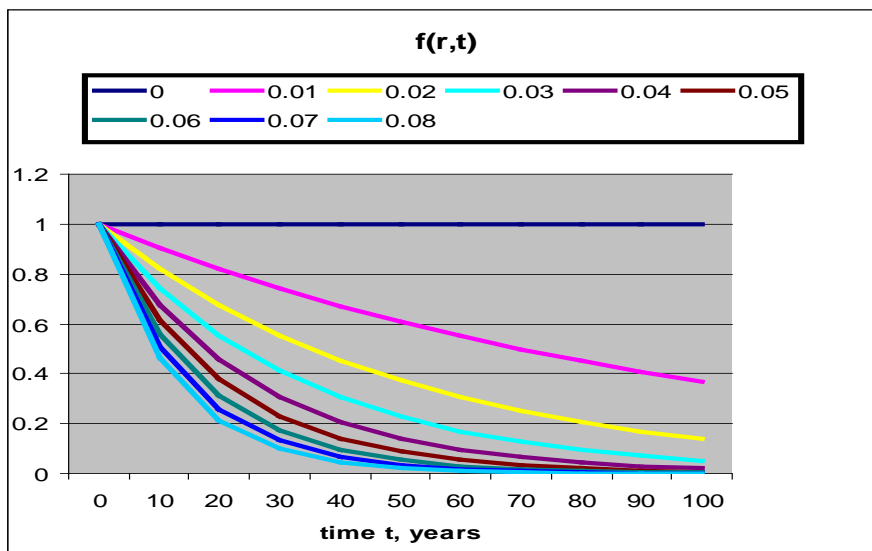

Figure 1. The discount factor $f(r,t)$.

11. CONCLUSIONS

LCCB 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 LCCB analysis. Insufficient data on bridge conditions, on deterioration of bridges, on user costs also contribute to the sparse application of the LCCB analysis. Finally, the use of high discount rates as laid down by politicians also reduces the importance of using LCCB analysis. 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.

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