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CHAPTER 138

MODELLING USER COSTS IN LIFE-CYCLE COST-BENEFIT (LCCB) ANALYSIS[1]

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ABSTRACT

The importance of including user's costs in Life-Cycle Cost-Benefit analysis of structures is discussed in this paper. This is especially for bridges of great importance. Repair or/and failure of a bridge will usually result in user costs greater than the repair or replacement costs of the bridge. For the society (and the user's) it is therefore of great importance that maintenance or replacement of a bridge is performed in such a way that all costs are minimized - not only the owners cost.

1. INTRODUCTION

In recent years, important progress has been made in Life-Cycle Cost-Benefit (LCCB) analysis of structures, especially for bridges. A Life-Cycle (LC) analysis of e.g. a bridge is a simple assessment of the condition of the bridge in the remaining life of the bridge, without taking into account the estimated costs of maintenance and the estimated costs of failure. A Life-Cycle Cost (LCC) analysis is an LC analysis with estimated maintenance and failure costs including. Finally, a Life-Cycle Cost-Benefit (LCCB) analysis is a, LCC analysis with user costs (benefits) included.

Due to the large uncertainties related to the deterioration, maintenance, and benefits of such structures, a stochastic modelling of all significant parameters seems to be the only relevant modelling. The main purpose of this paper is to present and discuss some of the problems related to model a LCCB management system with special emphasis on user costs.

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The importance of including user costs in life-cycle cost-benefit analysis in management systems for bridges is stressed. Numerous papers and reports related to the importance of estimating user costs when repairs of bridges are planned, and when optimized strategies are formulated, are shown. These references clearly show that user costs in most cases completely dominate the total costs.

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, and 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 a modelling based on simple, but relevant data.

This paper is primarily based on three papers by Thoft-Christensen (2004a), (2006), and (2008).

2. DEFINITIONS

It is important to remember that a LCCB is based on the assumption that benefits can be evaluated on basis of costs. There are benefits which are difficult to model by costs. This is for example the case for several environmental benefits. Therefore, environmental benefits are only briefly included in this paper. However, environmental benefits (usually negative) are in many cases of great importance when decisions regarding a new bridge or a new motorway are made. Therefore, the limitation to only briefly include environmental benefits is only made due to the fact that cost modelling of such benefits is difficult or even impossible.

The expected total Life-Cycle Cost Benefit (*LCCB*) of a structure will in general consist of the expected benefits for the society $B_{society}$, for the owners (agencies, private companies etc.) of the bridge B_{owner}, for the users B_{user}, and the expected benefits for the environment $B_{environment}$.

$$LCCB = B_{society} + B_{owner} + B_{user} + B_{environment} \qquad (2.1)$$

In the last 40 years, a lot of work is done in trying to define management systems for structures, e.g. bridge stocks, so that the total expected benefits of the structure in its intended lifetime is optimum, or alternatively the total expected costs is minimum. This is of course an extremely difficult task since several important factors are very uncertain. Most of the work in this area has concentrated on the owners costs. Some work has been done in recent years on estimating users' costs. Very little work has been done on the environmental issue and on the society issue.

It is often more convenient to work with the expected costs in the life time of the structure rather than the expected benefits. Eqn. 2.1 is then replaced with Eqn. 2.2. (*LCC* is the total expected costs; $C_{society}$ is the expected costs of the society, C_{owner} is the expected costs of the owner, C_{user} is the expected costs of the users of the structure, and $C_{environment}$ is the expected costs of the environment.

$$LCC = C_{society} + C_{owner} + C_{user} + C_{environment} \qquad (2.2)$$

The benefit terms as well as the cost terms in the two equations above are clearly uncertain and must be modeled by stochastic variables or processes. Therefore, in this paper expected values are used for all terms.

3. LIFE-CYCLE COST-BENEFIT LEVELS

Modelling of an LCCB analysis may be performed by a number of different approaches. In most cases, these approaches can be divided into three levels:

- 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 analysis is based on a sound and consistent scientific basis. Advanced information on the deterioration and maintenance of the bridge is used and detailed information on the environmental loading is taken into account. A level 3 model is typically used in the 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 existing 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 the semi-physical or average material deterioration parameters and the average effects of maintenance. They are also based on a number of engineering simplifications regarding the modeling 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 the design of new structures and for the 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. 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. those 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 (2004b) 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 modeled using 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 modeled as normally distributed stochastic variables.

The EU sponsored LCCB bridge management system presented by Thoft-Christensen (1995) and de Brito *et al*. (1997) 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.

4. MODELLING USER BENEFITS FOR A SINGLE BRIDGE AND A BRIDGE STOCK

A new bridge in an existing network will usually be of great importance for the users of the bridge primarily because it will reduce the travel time in the network. For the society there may also be some other benefits like reduced CO_2 emission and a reduce number of traffic accidents etc. In this section only the direct benefits for the users (including users cost) are discussed.

For a single bridge *i* the present value of the user benefits B^i_{user} in the expected lifetime *n* years may be modeled as

$$B^i_{user} = \sum_{t=1}^{n} B^i_{user,t} \frac{1}{(1+r(t))^t} \tag{4.1}$$

where $B^i_{user,t}$ is the user benefit in year *t* and $r(t)$ is the time-dependent annual discount rate. It is convenient to split the the benefits B^i_{user} in (positive) direct benefits related to the reduction in travel time and (negative) indirect benefits related to inspection, repair, and failure events

$$B^i_{user} = B^{i,direct}_{user} + B^{i,indirect}_{user} = \left[\sum_{t=1}^{n} B^{i,direct}_{user,t} + \sum_{t=1}^{n} B^{i,indirect}_{user,t}\right] \frac{1}{(1+r(t))^t} \tag{4.2}$$

Let the number bridges in a bridge stock be m, then the expected user benefit $B^{bridge\ stock}_{user}$ for the bridge stock is

$$B^{bridge\ stock}_{user} = \sum_{i=1}^{m}\sum_{t=1}^{n} B^i_{user,t} \frac{1}{(1+r(t))^t} \tag{4.3}$$

The expected user benefits for a bridge stock $B^{bridge\ stock}_{user}$ may also be split up in direct and indirect benefits for the bridge stock

$$\begin{aligned} B^{bridge\ stock}_{user} &= B^{bridg\ estock,direct}_{user} + B^{bridge\ stock,indirect}_{user} \\ &= \sum_{i=1}^{m}\left[\sum_{t=1}^{n} B^{i,direct}_{user,t} + \sum_{t=1}^{n} B^{i,indirect}_{user,t}\right]\frac{1}{(1+r(t))^t} \\ &= \sum_{i=1}^{m}\left[\sum_{t=1}^{n} B^{i,direct}_{user,t} \frac{1}{(1+r(t))^t}\right] + \sum_{i=1}^{m}\left[\sum_{t=1}^{n} B^{i,indirekt}_{user,t} \frac{1}{(1+r(t))^t}\right] \end{aligned} \tag{4.4}$$

5. EVALUATION OF USER COSTS

To illustrate the importance of including user costs in a LCCB analysis, a brief review of a few reports and other documents on user costs is presented in this section. Note that, in these (and most) documents, user costs are modeled deterministically, although user costs are always very uncertain. Therefore, user costs should be modeled by stochastic variables or stochastic processes. However, a deterministic model based on statistic documentation is a good starting point for the stochastic modeling of user costs.

In the technical report of a project entitled "*Corrosion Cost and Preventive Strategies in the United States*" written by Koch *et al*. (2001) 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*. (2001) 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.

The technical report of a project entitled '*Development of Road User Cost Methods*' is written by Daniels *et al*. (1999) and sponsored by the Texas 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 *RUC* can be expressed as:

$$RUC=VOC+AC+VOT \tag{5.1}$$

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 the USA was estimated as $11.38 for passenger cars and $27.23 for trucks. Today, these values are much higher due to inflation, etc.

The final technical report of a project entitled "*Development of User Cost Data for Florida's Bridge Management System*" is written by Thompson *et al*. (1999) and sponsored by the Florida Department of Transportation (FDOT). It 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 the

LCCB analysis. It also shows how the sensitivity of the user costs estimates may be evaluated.

The research report of a project entitled "*The Cost of Construction delays and Traffic Control for Life-Cycle Cost Analysis of Pavements*" is written by Rister & Graves (2002) and sponsored by the Kentucky Transportation Center and Kentucky Transportation Cabinet. The following excerpts are taken from the report:

> "Road User Costs (*RUC*) has 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 VOR rates for a passenger car with an initial speed of 96.5 km h^{-1} was \$6.31 per vehicle-hour in 1970 dollars and \$27.94 for a combination truck. The user delay costs (value of time) were on average \$11.58 and \$22.31 per vehicle-hour in 1996 dollars for passenger cars and combination trucks respectively. Typical fatality ranges between \$1.091 million and \$1.182 million.

The research report of a project entitled "*Strategic review of bridge maintenance costs*" is written by Maunsell (1999). The report was produced by Maunsell Ltd. in the 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's 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 the LCCB analysis. It also clearly shows the consequence for the society of delaying important maintenance of bridges.

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 (2002). Four of the bridge's approach spans collapsed and fourteen people were killed. The bridge is the states most important east to 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 at \$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 months. $12 million were spent on upgrading of the detour highways. The detours were used by approximately 17×10^3 vehicles every day the bridge was not open.

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 was estimated to cost approximately $2.43 million; see Schmidt (2005). The detour was approximately 28 km long. With fuel costs of $0.42 per liter and a traffic volume of 4500 cars per day, the fuel costs were about $2 million for a six to eight month period.

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*. (2003)). The total costs of the two alternatives were estimated at 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*. (2003), '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'.

6. DIRECT USER BENEFITS (USER COSTS)

A reduction of travel time obtained by using a bridge is an obvious benefit for users of the bridge. Therefore, an important factor in assessing the direct user benefits is based on the value of time. User travel time evaluation has been evaluated in details by Corotis (2007), Ben-Akiva & Gopinath (1995), and several others.

Corotis (2007) discuss methods of valuing user time. In the so-called “wage rate method” the value of time is based on a percentage of the user’s hourly wage rate “the thought being that time saved or delayed traveling is to some degree traded for productive working”, Corotis (2007). This method is the classical method, but it has some drawbacks, such as no rational way of determining the percentage of the user’s hourly wage rate exists.

In a different method, which could be called the “leisure time method”, it is proposed that the best way to assign benefits to time savings from transportation improvements is to recognizing that saving commuter travel time is, in effect, increasing their free or leisure time, Corotis (2007). The argument for this method is that people independent of their income levels value their leisure time equally.

Finally, a third method based on the life-quality index (LQI), see Rackwitz (2002), (2003), should be mentioned. This method seems to be the most acceptable, but is more complicated than the two before-mentioned methods. It is interesting to notice that the LQI may be used to evaluate rational discount rates.

7. INDIRECT USER BENEFITS (USER COSTS)

The indirect user benefits are usually negative. Therefore, it is more natural to consider the user costs C_{user} defined by

$$C_{user} = -B_{user}^{indirect} \tag{7.1}$$

For a *given bridge* a number of different inspection methods I_i, $i = 1,\ldots,a$, and a number of repair techniques R_j, $j = 1,\ldots,b$, are assumed to be relevant. For each inspection method I_i the user costs $C^I_{user,i}$ must be evaluated on basis of experience. Likewise, the user costs $C^R_{user,i}$ related to repair technique R_j must be evaluated. The total user costs related to inspections and repair may then for the bridge in question be formulated as a sum of user costs of all future expected inspections and repairs discounted back to present time.

Let the probability, that inspection method I_i, $i = 1,\ldots,a$, is used in year t, $t = 1,\ldots,n$ be $P[I_{i,t}]$. Then the discounted user costs related to all inspections are

$$C_{user}^{inspection} = \sum_{t=1}^{n}\left[\sum_{i=1}^{a} P\left[I_{i,t}\right] C_{user,i}^{I} \frac{1}{(1+r(t))^{t}}\right] \tag{7.2}$$

Likewise, let the probability, that repair technique R_j, $j = 1,\ldots,b$, is used in year t, $t = 1,\ldots,n$ be $P[R_{j,t}]$. Then the discounted user costs related to all repairs are

$$C_{user}^{repair} = \sum_{t=1}^{n}\left[\sum_{j=1}^{b} P\left[R_{j,t}\right] C_{user,j}^{R} \frac{1}{(1+r(t))^{t}}\right] \tag{7.3}$$

In equations (7.2) and (7.3), the probabilities that a certain inspection method and a certain inspection technique are used in a certain year t must be based on experience or estimated using a LCCB bridge management system. The user costs associated with the inspection methods and the repair technique must be based on a detailed analysis of their consequences for the users.

For a *bridge stock* with m bridges the total user costs may be estimated simply by using equation (7.2) and (7.3) on each bridge in the bridge stock and sum over all bridges. Normally, a bridge stock will contain groups of similar bridges with similar inspection and repair costs. Then the calculation may be significantly reduced.

Inspection, and especially repair of a bridge, will often result in traffic regulation and/or traffic interruption. The resulting travel delays are one of the most important contributions to the indirect user costs $C_{user}^{inspection}$ and C_{user}^{repair}. Other contributions related to the vehicle are the increased fuel consumption, increased tire wear, etc. Further contributions could be due to an increased risk of traffic accidents.

8. LCCB BRIDGE MANAGEMENT SYSTEMS FOR SINGLE BRIDGES

It is a fact that user costs usually are not included when optimal maintenance strategies and decisions are made, although it is clear that user costs ought to be included. The life-cycle costs are often minimized for the considered structure without considering the significant costs for the users of the bridge and even without considering the long-term effects of the decision. Unfortunately, the maintenance decisions are in many cases 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 always be considered when major decisions are made.

As mentioned earlier, life-cycle cost-benefit (LCCB) analysis is an extended LCC analysis where all kinds of indirect costs such as user costs are included. The first major research on combining stochastic models, expert systems and optimal strategies for maintenance of reinforced concrete structures in a LCCB bridge management system was sponsored by the EU from 1990 to 1993; see Thoft-Christensen (1995) and de Brito *et al*. (1997). 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. This EU sponsored LCCB bridge management system is a typical level 2 model, but is based on some elements of a level 3 model.

LCCB bridge management systems have a broad spectrum of applications. They are very useful for groups of bridges, but also for individual bridges. In this section, the above-mentioned EU-supported LCCB bridge management system is used here to illustrate how user costs may be included in decision-making for single bridges. LCCB systems may be used in designing a new bridge, but then it is usually of great importance to include environmental considerations and costs. LCCB are also very useful in connection with decision problems regarding, for example, repair of a bridge after an inspection has taken place.

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 B minus the expected repair costs C_{repair} , minus the failure costs $C_{failure}$, and minus the user costs C_{user} in the remaining lifetime T of the bridge are maximized

$$\max LCCB = \max\left(B - C_{repair} - C_{failure} - C_{user}\right) \qquad (8.1)$$

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 t_R after a structural assessment that 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 (1993)

$$\max \sum_{t=0}^{n_L} (B(t_R, n_R) - C_{repair}(t_R, n_R) - C_{failure}(t_R, n_R) - C_{user}(t_R, n_R)) \qquad (8.2)$$

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. The total expected benefit B in the remaining lifetime of the bridge, minus the expected repair costs C_{repair}, capitalized to the time t=0 , and minus the expected failure costs $C_{failure}$ capitalized to the time t =0 is optimized.

The benefits are modeled by the sum of the benefits in each year t = 1,…,n in the remaining life of the bridge

$$B(t_R, n_R) = \sum_{t=1}^{n} B_t \frac{1}{(1+r)^t} \qquad (8.3)$$

where B_t is the benefits in year t, and r is the discount rate. The t^{h} term in equation (8.3) represents the benefits in the year [t-1;t] capitalized back to time t =0. The benefits in year t may, for example, be modeled by:

$$B_t = k_0 V(t) \qquad (8.4)$$

where k_0 is a factor modeling the average benefits for one vehicle passing the bridge. It is in this case simply 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_t can easily be included, for example, by considering different categories of vehicles and adding other types of indirect benefits. 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). $V(t)$ is the traffic volume per year estimated by:

$$V(t) = V(0) + k_1 t \qquad (8.5)$$

where V(0) is the traffic volume per year at the time t = 0, k_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 modeled by:

$$C_{repair}\left(t_R, n_R\right) = \sum_{i=1}^{n_R} \left[1 - P_F^U\left(t_{R_{i_i}}\right)\right] C_{repair}\left(t_{R_i}\right) \frac{1}{\left(1+r\right)^{t_{R_i}}} \tag{8.6}$$

The term $P_F^U\left(t_{R_i}\right)$ is the updated probability of failure in the time interval $\left[0, t_{R_i}\right]$. The factor $\left[1 - P_F^U\left(t_R\right)\right]$ models the probability that the bridge has not failed at the time of repair, and r is the discount rate. The term $C_{repair}\left(t_{R_{i_i}}\right)$ is the cost of repair, and consists of 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

$$C_{failure}\left(t_R, n_R\right) = \sum_{i=1}^{n_r+1} C_{failure}\left(t_{R_{i_i}}\right)\left[P_F^U\left(t_{R_{i_i}}\right) - P_F^U\left(t_{R_{i-1}}\right)\right] \frac{1}{\left(1+r\right)^{t_{R_i}}} \tag{8.7}$$

The i^{th} term in equation (8.7) represents the expected failure costs in the time interval $\left[t_{R_{i-1}}, t_{R_i}\right]$, and $C_F(t)$ is the cost of failure at the time *t years*.

The models 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 the 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 simulations have been used for decades to analyze complex engineering structures in many areas, e.g. in nuclear engineering. In modeling reliability profiles for reinforced concrete bridges, Monte Carlo simulations seem to have been 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 was strongly inspired by the EU project mentioned above. The methodology used was presented in detail in the final project report in Thoft-Christensen & Jensen (1996).

In the Highways Agency project '*Optimum Maintenance Strategies for Different Bridge Types*' (1998 - 2000, Contract: 3/179), the simulation approach was extended by Thoft-Christensen (1998), (2000) to include the stochastic modeling 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 (2000).

In a recent project '*Preventive Maintenance Strategies for Bridge Groups*' (2001 - 2003, Contact 3/344 (A + B)), the simulation technique was extended further to the modeling of condition profiles, the interaction between reliability profiles and condition profiles for reinforced concrete bridges, and the whole life costs. The simulation results were detailed in Frangopol (2003), Thoft-Christensen (2003c). In these projects, the modeling of inspection and repair costs was discussed in detail. However, user costs were not included.

9. CONCLUSIONS

The main conclusion of this paper 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 the literature. However, much more research is needed before an LCCB analysis in the bridge area can be made in a satisfactory way. However, this fact is not an excuse for not including user costs in life cycle cost estimations. Much of the work done until now is limited to narrow models without a wide area of application. The bridge owners must learn to listen to the public when decisions regarding repair or replacement of structures are taken.

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