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ETSI PROJECT (Stage 1)

Bridge Life Cycle Optimisation

Editors: Jutila A. & Sundquist H.

TEKNILLINEN KORKEAKOULU
TEKNISKA HÖGSKOLAN
HELSINKI UNIVERSITY OF TECHNOLOGY

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Preface

On the 20th of November 2002 Mr *Juhani Vähäaho*, coordinator of bridge activities at the Finnish Road Administration (FinnRA) at that time, and *Aarne Jutila*, Professor of Bridge Engineering at Helsinki University of Technology (TKK), carried out a discussion on the future needs of Bridge Engineering in Finland. As a consequence, the latter one invented the acronym ETSI to describe the project to be carried out. ETSI originates from the Finnish words "***E****linkaareltaan* ***T****arkoituksenmukainen* ***SI****lta*", which in English could be translated as "*Lifelong Adapted Bridge*" or, more freely, "*Bridge Life Cycle Optimisation*". The original idea was to include in the project all issue related to a bridge "*from the cradle to the grave*".

In November 2004 FinnRA asked TKK to carry out and coordinate a pre-study, whose aim was to prepare a research programme for a larger Nordic project and to carry out a literature survey to evaluate the present state-of-the-art in the field of life cycle analysis (LCA) of bridges. This pre-study was successfully completed in spring 2005.

In the meanwhile, on the 10th of December 2004, a general agreement was signed between the five Nordic National Road Administrations for joint research and development work for the benefit of all parties. This agreement opened the way for the Nordic ETSI Project. After long discussions and many meetings a specified agreement of the ETSI Project was signed between the Finnish, Norwegian and Swedish National Road Administrations. So Stage I of the Project could be started in January 2006. This publication forms the outcome and report of Stage I and is limited only to bridge life cycle cost (LCC) issues.

Besides the three financing administrative units mentioned above the following Nordic research institutes or private enterprises were involved in the Project:

Helsinki University of Technology (TKK)

Norwegian University of Science and Technology (NTNU)

Ramboll Finland Ltd.

Royal Institute of Technology (KTH)

VTT Technical Research Centre of Finland (VTT)

The persons strongly involved in the Project and in the preparation work of this report are the following:

Seppo Aitta

Hans Bohman

Aarne Jutila

Raid Karoumi

Otto Kleppe

Per Larsen

Axel Liljencranz

Jan Nygård

Matti Piispanen

Heikki Rautakorpi

Lauri Salokangas

Håkan Sundquist

Marja-Kaarina Söderqvist

Timo Tirkkonen

Susanne Troive

Erkki Vesikari

Wenzhong Yuan

The Chair of the Project Steering Group (PSG) was *Matti Piispanen* from FinnRA. The Coordinator of the Project was *Aarne Jutila* from TKK.

The ETSI Project Stage I consists of four different sub-projects. The content of this report follows the same division. The material produced in the last sub-project, however, is not included here, because it can be found on the ETSI Home Page.

After a short introduction (Chapter I) Chapter 2 "State-of-the-art" presents a summary of a literature survey based on material presented in the latest conferences or on the Internet. It was prepared by *Heikki Rautakorpi* from Ramboll Finland Ltd. and coordinated by TKK.

Chapter 3 "Methodology" is a description of the theories used in bridge LCC analysis. This part was prepared by *Håkan Sundquist* and it is based in part on material presented by *Erkki Vesikari* and *Heikki Rautakorpi*.

Chapter 4 "Computer Programs" is a description and evaluation of three computer programs prepared for bridge LCC, two Nordic ones and one American one. It is mainly based on the diploma thesis of *Wenzhong Yuan* presented at TKK in December 2006. The guidance of *Marja-Kaarina Söderqvist*, *Raid Karoumi*, *Axel Liljencranz* and *Erkki Vesikari* is strongly appreciated here.

Finally, in Chapter 5 some suggestions are made for future research and development of LCC analysis tools needed in the Nordic countries.

The results of the last sub-project "ETSI Home Page" exist on the Internet under address http://www.tkk.fi/Yksikot/Silta/Etsiwww/. The pages were designed and prepared by *Lauri Salokangas* from TKK with input from the PSG and Project Working Group (PWG) members.

This report will be published in the Closing Seminar of the ETSI Project Stage I to be held on the 13th and 14th of February 2007. Consequently Stage I will be completed in the end of February 2007.

Finally, the editorial work of this publication was mainly carried out by *Håkan Sundquist*. His comprehensive editorial work is gratefully appreciated.

Otaniemi in February 2007 *Aarne Jutila*

Coordinator of the ETSI Project

Contents

1. Introduction

This report deals with the life cycle costs (LCC) of road bridges. The report is divided into three main themes:

- A state-of-the-art report compiling some of the vast number of reports and papers published in the field of LCC of bridges
- A discussion on different methodologies used for LCC
- A chapter describing three different computer programs used for LCC calculations.

Life cycle cost calculations are needed at least for the following purposes:

- Comparison of the different design alternatives before the construction of a new bridge
- Determination of the optimum balance between the investments and the required maintenance
- Decision on, when an old bridge should be replaced by a new one.

This stage 1 of the ETSI Project focuses on the situation, where different alternatives are compared prior to construction of a new bridge, but also other situations are shortly treated in this report.

This is the first introductory report in the ETSI Project and it is meant to be a starting point for a deeper study in this interesting subject. A field of special interest is the interchange of knowledge and systems between the three Nordic countries involved in the Project.

2. State-of-the-art

This chapter is focused on documenting of the state-of-the-art of life cycle cost (LCC) when comparing different design solutions of a new bridge. Additionally the purpose is to research documentary information used in the life cycle design of new bridges. At first the most important definitions and the general principles when applying the LCC calculations to bridges are introduced. Common economical tools and the road user costs are also defined. Next is presented the management or rehabilitation of bridges generally. The relevant material for concrete bridges, steel bridges, composite bridges and timber bridges is presented in the following sections, respectively. Finally, some excerpts about the relevant computer programs and the list of literature are presented.

2.1 Definitions

“Life Cycle Assessment LCA is a tool for identifying and evaluating the environmental aspects of products and services from the “cradle to the grave”: from the extraction of resource inputs to the eventual disposal of the product or its waste.” Bridge LCC, [8].

“Life Cycle Assessment LCA is for assessing the total environmental impact associated with a product's manufacture, use and disposal and with all actions in relation to the construction and use of a building or other constructed facilities. LCA does not address economic or societal aspects!” Tupamäki (2003b), [88].

“Life Cycle Costing LCC is a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs. In particular, it is an economic assessment considering all projected relevant cost flows over a period of analysis expressed in monetary value. Where the term uses initial capital letters it can be defined as the present value of the total cost of an asset over the period of analysis.” Tupamäki, (2003b), [88]

“LCC in H-BMS is defined as the sum of direct costs and the user costs for the next 100 years. Direct costs include actual regular maintenance and repair expenses. User costs are externalities like congestion and the increase of vehicle operation cost. Travel delay cost due to congestion is based on the amount of time lost in the slowdown section compared with driving by regular speed.” Nishibayashi et al. (2006), [52].

“Life-Cycle Cost Analysis is an economical set of actions and their timing during the life of a bridge to achieve the 50- to 100-year service life.” Hawk (2003), [26].

“Life-Cycle Cost analysis LCC 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.” Thoft-Christensen, (2006), [77].

“Life-Cycle Cost-Benefit LCCB analysis is an extended LCC analysis where all kinds of indirect costs such as user costs are included.” Thoft-Christensen (2006), [77].

The above excerpts show two slightly different definitions for LCC concerning the user costs of bridges.

2.2 Principles of the LCC calculations

Peng et al. (2006), [54], present the theoretical bases for the LCC calculations of bridges. For cost division they use the scheme shown in Figure 2.1. They suggest that stochastic parameters and risk evaluation should be systematically analyzed in the LCC calculations.

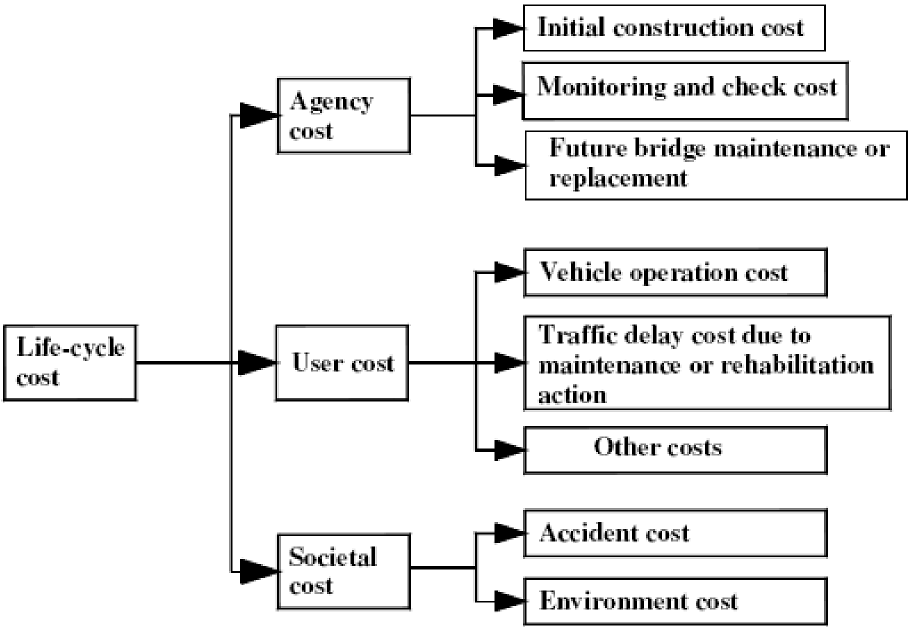

Figure 2.1 *Scheme for dividing the LCC cost into different subgroups according to Peng et al. (2006), [54].*

In the report by Ozbay et al. (2003), [53], the map of costs is presented in a slightly different form, as depicted in Figure 2.2.

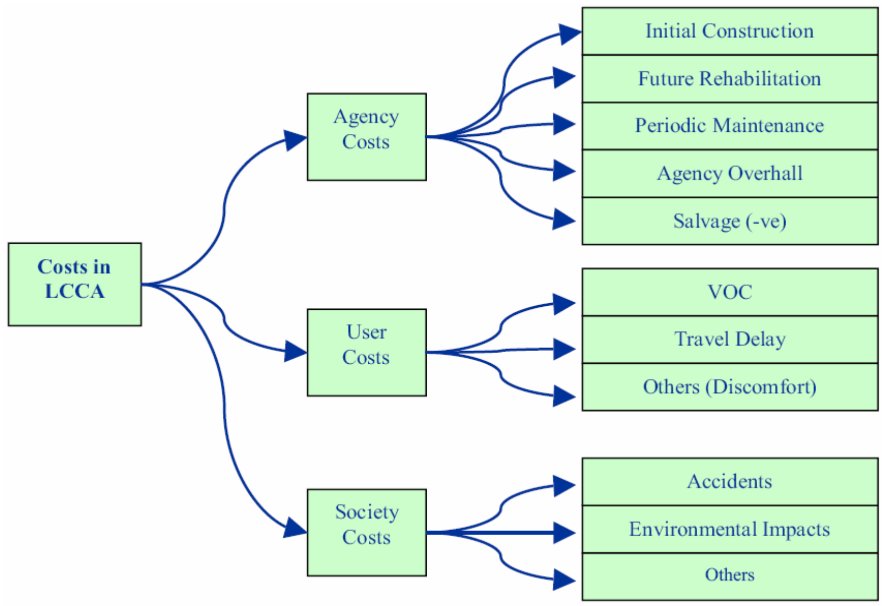

Figure 2.2 *Scheme for dividing the LCC cost into different subgroups according to Ozbay et al. (2003), [54].*

Common economic calculations can be applied when calculating the agency costs for bridges. The simplest form for the cash flow of agency costs is the diagram presented in the article for the Gravina access project, [38], as shown in Figure 2.3a below.

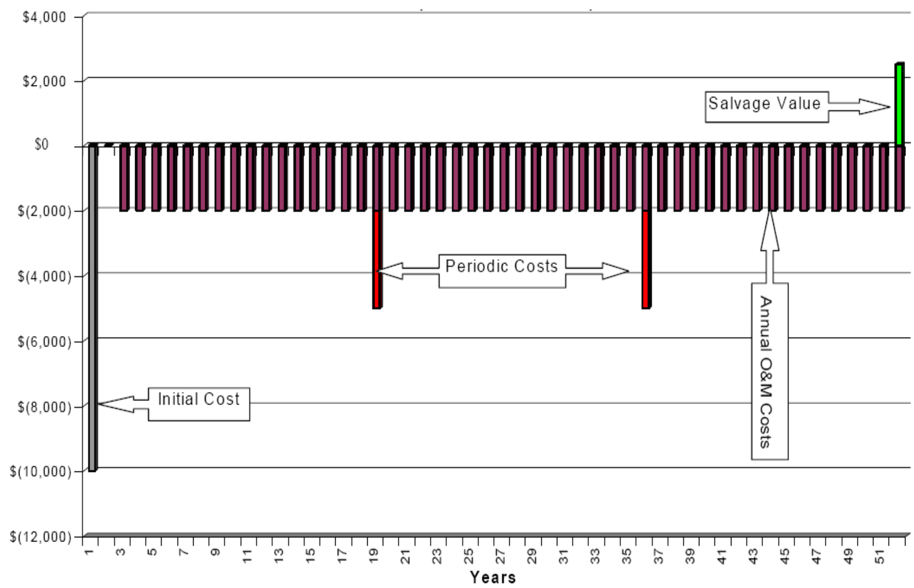

Figure 2.3a *Schematical picture showing the cost occurring during the lifetime of a bridge.*

The initial cost means the design and construction costs of a bridge. The annual costs contain maintenance and repair of small defects. Periodic costs are rehabilitations and large repairing works. The salvage value at the end of the life cycle can be positive or negative depending on the study period.

When comparing different bridge alternatives to each other, the most common LCC calculation method is the Net Present Value method. It means a method, where all costs during the lifetime of a bridge are discounted to the present-day cost by using a proper discount rate.

Therefore, the economical methods of calculation and especially the value of the discount rate are important aids in LCC calculations. They are studied separately in the following sections.

Troive (1998), [86], presents the agency costs and the user costs in one diagram, as shown in Figure 2.3b. She suggests a separation of the costs and the benefits.

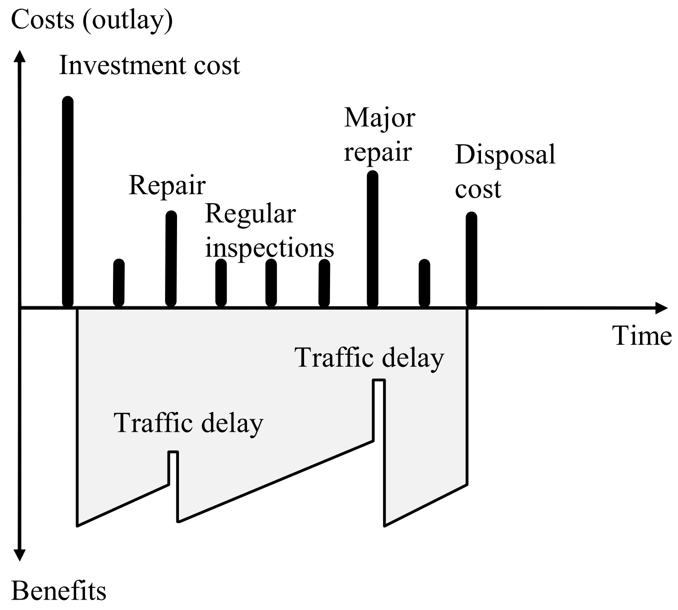

Figure 2.3b *Schematic figure showing separation of agency and user cost. Troive (1998), [86].*

A short theoretical presentation for the lifetime optimization of structures is given in the paper of Biondi & Marchiondelli (2006), [7]. In addition to the conventional mathematical optimization method, a new Evolutionary optimization method is presented. It is applied to an example of a cable stayed bridge.

Silva and Fernandes (2006), [71], outline LCC calculations that are based on probabilistic methods. They emphasize that the right timing of the repair actions is more important than the cost itself, because discounting to the net present value has a great influence on the final life cycle cost. Therefore, the deterioration models are more important than the costs.

Hawk gives in his report, Hawk (2003), [26], simple examples of probabilistic cost calculations. One example is shown below. It is assumed that the probabilities of the different cost levels of the present value (*PV*) are those shown in Table 2.1.

Table 2.1 *Example of a probabilistic cost calculation according to Hawk 2003, [26].*

Contract/final cost	10% below estimate	At estimate of $2,000,000	10% above estimate	20% above estimate
PV of cost	$1,556,654	$1,729,616	$1,902,577	$2,075,539
Probability	0.10	0.60	0.20	0.10

The expected value for the cost estimate (*EV*) can then be calculated as shown in Table 2.2.

Table 2.2 *Example of the expected cost estimate of a probabilistic cost calculation according to Hawk 2003, [26].*

$$EV_0 = \$1{,}556{,}654x0.10 + \$1{,}729{,}616x0.60 + \$1{,}802{,}577x0.20 + \$2{,}075{,}539x0.10$$
$$= \$1{,}781{,}504.$$

The report of Setunge et al. (2002), [68], is also based on probabilistic LCC calculations. Advisable ranges of variation are given there for some most important variables.

Today life cycle costs should be an essential part of the cost calculations when comparing different design alternatives. However, it is not so in practice. For instance, in the bridge conference held in Montreal in August 2006, only very few articles dealt with the life cycle costs. In the articles, where life cycle costs were estimated, the long-term costs were usually underestimated, as for instance in the article by Rao (2006), [59].

A simple example of LCC and LCA calculations applied to a footbridge in the Netherlands is given in the article of Tolman & Tolman (2003), [82]. Five different alternative designs were examined there. The results of the calculations are summarized in Table 2.3.

Table 2.3 *Example of LCC and LCA calculations applied to a footbridge, Tolman & Tolman (2003), [82].*

		dimension	painted steel	aluminised steel	G-FRP	aluminium	stainless steel
economy	construction	k€	40	55	70	76	100
	maintenance	k€	30	5.5	17	19	5.5
	total	k€					
environment	mass	Mg	3.0	3.0	1.7	1.6	2.8
	energy	GJ	270	270	120	269	300
	water	m^3	675	675	35	237	>675
	air	m^3	7	7	18	54	>7

One can see for example that stainless steel is much more expensive than the conventional painted steel but the maintenance costs of stainless steel are very low compared to those of the conventional steel.

The service life of a bridge is quite important especially when calculating annual costs. In a recent study carried out by Yunovich et al. (2001), [97], and funded by the Federal Highway Administration (FHWA), the estimated service lives of American bridges made of different construction materials are given (Table 2.4). Thus, the age of steel bridges is estimated to be slightly shorter than that of the concrete bridges.

Table 2.4 *Estimated service lives of American bridges according to Yunovich (2001), [97].*

MATERIAL OF CONSTRUCTION	AVERAGE ESTIMATE (Years)
Conventional Reinforced Concrete	72
Prestressed Concrete	73
Steel	58

In the same report, the annual direct costs of corrosion for highway bridges are estimated to be \$8.3 billion1. In this report Yunovich (2001), [97], estimates that the indirect costs due to traffic delays and lost of productivity are more than 10 times as big as the direct costs due to corrosion. Therefore, the user costs may be very important and they will be studied separately in Section 6 below.

2.3 Common economical tools

For determining the present value of the future one-time costs formula

$$PV = \frac{A_t}{(1+d)^t}$$

is used. Here

PV = present value,

A_t = amount of one-time cost at a time *t*,

d = real discount rate, and

t = time (expressed as number of years).

For determining the present value of future recurring costs formula

$$PV = A_0 \frac{(1+d)^t - 1}{d(1+d)^t}$$

is used. Here

PV = present value of future recurring costs,

A_0 = amount of recurring costs at a certain time,

d = real discount rate, and

t = time (expressed as number of years) [36].

For economical calculation of the life cycle costs, Tupamäki (2003), [88] gives equation

$$NPV = \sum_{t=0}^{N} \frac{C_t}{\left(1+d\right)^t}$$

where

NPV = the net present value

---

[1] Billion in American English is equal to 10^9.

C_t = cost over a specified period of time t,

d_{real} = real discount rate,

N = number of years, and

$$d_{\text{real}} = \frac{1+i}{1+a} - 1$$

where

i = interest rate and

a = general inflation.

Tolman & Tolman (2003), [81] present the same equations as

$$NPV = \sum_t Vp(0) = \sum_t V(t) \cdot (1+r)^{-t}$$

and

$$S = \sum_t (1+r)^{-t} = -\frac{(1+r)^{-T} - 1}{r}$$

By assuming that $V(t)$ is a constant (= A),

$$A = NPV \frac{r}{1-(1+r)^{-T}}$$

where

A = annuity,

NPV = net present value,

r = discount rate, and

T = number of years.

2.4 Discount rate

In the report of Ozbay et al. (2003), [53], the theoretical background of the discount rate is considered thoroughly. In addition to the theory, the report gives numerical values of the discount rate used in different countries. Quite different values have been used in different connections as shown below:

- The World Bank and The United Nations use the value from 12 to 15 percent in developing countries.
- Canada Transport Ministry is currently using a discount rate of 10 percent.
- According to the American Concrete Pavement Association (ACPA), the nominal discount rate used in LCCA should be equal to zero in the Departments of Transportation.

- In the Departments of Transportation of the United States, the real discount rate used has varied between 3 and 5 percent and the average has been 4 percent.

Tupamäki (2003), [88], suggests the following values for the discount rate in different applications:

Natural 0 % (= simple payback),

National 3 %,

State 6 %, and

Business 9 %.

The influence of the discount rate on the net present value of annual maintenance costs is shown in Figure 2.4.

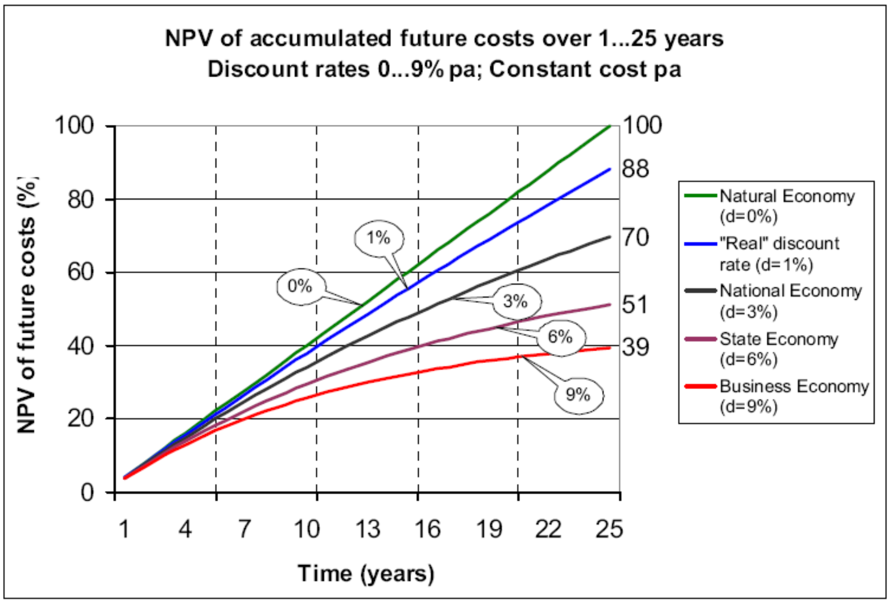

Figure 2.4 *Net present value for different discount rates, Tupamäki (2003), [88].*

In the report of Simbeya & Scalzo, 2006, [72], the following numerical values for the discount rates are reported:

2 %	in Switzerland,
3 %	in Germany,
10 %	in the United States, and
6 %	in Ontario, Canada.

In the report of Setunge et al. (2002), [68] the discount rates used in five countries are listed:

4 – 7 %	in Australia,
2 – 3 %	in US,
8 %	in UK,
4 %	in Sweden, and
6 %	in Finland.

According to Neff, [50], the American FHWA recommends to keep the real discount rate within the range of 3 to 5 percent (1998).

In one bridge project in Canada presented by Puccio et al. (2006), [57], three discount rates, 5 %, 6 % and 7 %, were used when comparing the replacement of an old bridge with the rehabilitation.

Bakker et al. (2006), [6] in the Netherlands as well as Godart & Vassie (2001), [22], and Troive, [84], in Sweden suggest the value of 4 % to be used for the discount rate.

According to Peng et al. (2006), [54], in some parts of China the discount rate varied between 3 % and 5 % in 2003.

According to Nishibayashi et al. (2006), [52], the fixed discount rate of 4 % per year is usually used for the cost-benefit analysis of infrastructure projects in Japan.

Meiarashi et al., [42], use the value of 2,9 % for the real discount rate, when they estimate the life cycle costs of Japanese suspension bridges.

In industrialised countries like the USA, the Netherlands, Japan and Sweden, the most comon discount rate value is 4 %, and in some other countries it is lower (in Switzerland 2 % and in Germany 3 %). In many developing countries, however, it is substantially higher (from 12 % to 15 %).

2.5 User costs

In Work Package 4 (1999), [94], the road user costs are presented for three different cases as follows:

- Reduced speed.
- Diversion.
- Signal regulation.

Complicated mathematical formulae are given for each case.

In the American computer program BridgeLCC, [18], the user costs are divided into three cases as follows:

- Driver delay costs.
- Vehicle operating costs.
- Accident costs.

The driver delay costs are calculated with the formula

$$Driver\ Delay\ Costs = \left(\frac{L}{S_\mathrm{a}} - \frac{L}{S_\mathrm{n}} \right) \cdot ADT \cdot N \cdot w$$

where

L is the length of affected roadway,

S_a is the traffic speed during bridge work activity,

S_n is the normal traffic speed,

ADT is the average daily traffic, measured in number of cars per day,

N is the number of days of road work, and

w is the dollar value of each hour of a driver's time.

Vehicle operating costs are calculated as

$$Vehicle\ Operating\ Costs = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \cdot ADT \cdot N \cdot r$$

where

r is a weighted average vehicle cost.

Accident costs are calculated as

$$Accident\ Costs = L \cdot ADT \cdot N \cdot \left(A_a - A_n\right) \cdot c_a$$

where

c_a is s the cost per accident, and

A_a and A_n are the accident rates per vehicle-kilometre during the construction and normally, respectively.

The presented equations (except the last one) were used for instance in the paper of Shin et al. (2006), [70], were the following driver's time values *w* were assumed:

$72,7 for bus,

$10,0 for truck, and

$9,7 for car.

Thoft-Christensen (2006), [77], cites the following mean values for the user delay costs (1996-1999):

$ 22,31 - 27,23 for trucks and

$ 11,38 - 11,58 for passenger cars.

He mentions that today (2006) these values are much higher due to inflation etc.

In the examples presented in the report of Hawk (2003), [26], the following user costs were assumed:

$25,00/hour for trucks and

$5,00/hour for other vehicles.

They were assumed to contain both the time costs and the vehicle-operating costs.

Yunovich (2001), [97], assumes the driver's time value to be 50 percent of the average wage, giving the value \$8,50 per hour (1998).

The Finnish Road Administration (2005), [78], uses the following average user costs (level 2005) based on the lost time of the driver and the passengers:

126,08 € for bus,

19,57 € for truck, and

16,03 € for car.

In addition to the above costs, fuel and maintenance cost of the vehicle and the environmental costs are taken into account.

According to Neff, [50], in the United States of America FHWA has recommended values for vehicle travel time ranging from \$10 to \$24 per hour. For vehicle crash costs, the recommended value ranges from \$151 000 per property damage crash to \$1,24 million per fatal crash (1998).

Thoft-Christensen (2006), [77], cites that values of typical accident costs are between \$1 091 000 and \$1 182 000 (1999).

The vehicle crash costs used in Finland (Finnish Road Administration, 2005), [78] vary between 2 700 and 2 205 000 € (2005).

The values given in Table 2.5 are presented by Yunovich et al. (2001), [97], for the user costs of a bridge during maintenance, repair, and replacement works of the deck slab. The bridge is assumed to have two lanes in each direction and the length is 37 m.

Table 2.5 *User cost of a bridge during repair of the deck slab according to Yunovich et al. (2001), [97].*

	"LOW" LEVEL OF USER COST	"MEDIUM" LEVEL OF USER COST	"HIGH" LEVEL OF USER COST
Average daily traffic	24,000	28,000	32,000
% of ADT in peaks	40%	40%	50%
Length of peak, minutes	140	120	140
Discharge rate, [cars/h]	1600	1700	2000
User cost per day, \$/day – no diversion	**\$28,784**	**\$68,609**	**\$124,025**
Maximum waiting time, minutes	30	30	30
User cost per day, \$/day – with diversion	**\$26,400**	**\$39,502**	**\$58,830**

Thus, the estimated user costs vary between \$1,2 and \$3,9 per vehicle depending on the traffic volume.

When calculating the user costs it is important to know, how long time the traffic limitations last. Lopez-Anido (2001), [39], has surveyed the time expenditures when replacing the deck slabs of American concrete bridges. The periods of time required for the removal of the old slab and the construction of a new slab are shown in Figures 2.5 and 2.6, respectively.

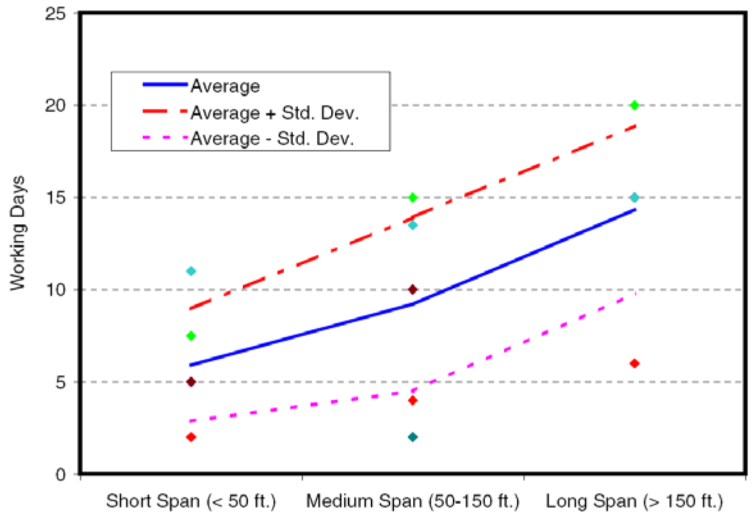

Figure 2.5 *The periods of time required for the removal of the old slab, Lopez-Anido (2001), [39].*

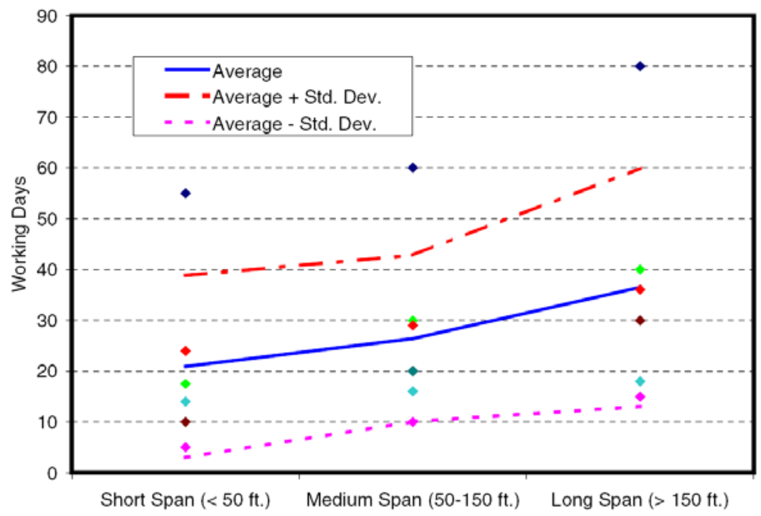

Figure 2.6 *The periods of time required for the construction of a new slab according to Lopez-Anido (2001), [39].*

This information is usable when estimating the user costs for a bridge rehabilitation project.

Rautakorpi (2004), [60], carried out a study concerning maintenance, rehabilitation and renovation works of small bridges (span about 6 m, costs on 2004 level). In this study he used the assumptions presented in Table 2.6.

Table 2.6 *Assumptions concerning maintenance, rehabilitation and renovation works of small bridges according to Rautakorpi (2004), [60].*

Bridge type	Mainte nance costs	Rehabi litation costs	Detour costs	Time for rehabi-litation	Time for renova tion	Rehabi-litation interval	Life time
	€/year	€	€	weeks	weeks	years	years
Concrete slab	450	45000		10		35	
Concrete frame	450	35000		10		40	
Corrugated steel arch	250		35000		3		50
Corrugated steel pipe	200		35000		3		50

2.6 Bridge management and rehabilitation

According to Mirza (2006), [46], the annual maintenance costs of bridges vary between 0,5 % and 1,5 % of the total construction cost. However, for older bridges the costs can be higher.

Nishibayashi at al. (2006), [52], use LCC calculations for determining maintenance and repair schedules of bridges. They present a schematic diagram, where the horizontal axis shows the interval of actions and the vertical axis the corresponding life cycle cost. In principle, there is an optimum repair interval to obtain the minimum life cycle cost. For shorter repair intervals the repair costs and the user costs increase rapidly.

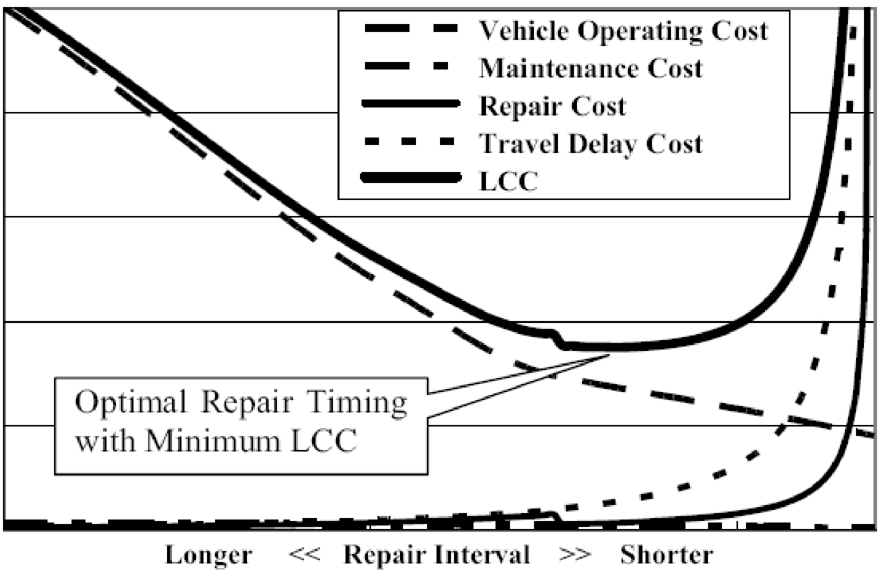

Figure 2.7 *Schematic diagram showing the correlation between the interval of repair intervals and the corresponding life cycle costs according to Nishibayashi at al. (2006), [52].*

In Figure 2.8 slightly different presentation originating from Neff, [50], is given. There the costs depend on the reliability desired.

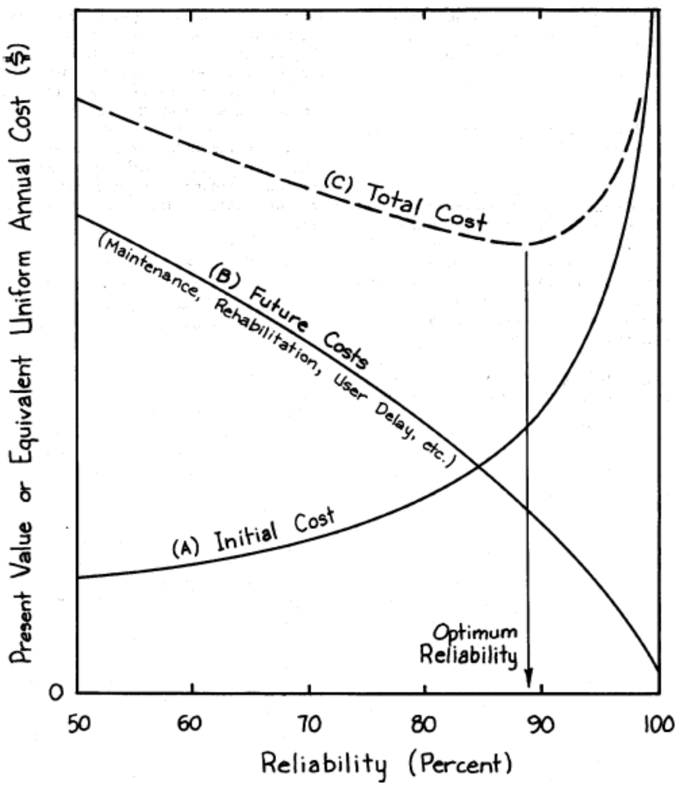

Figure 2.8 *Interaction and optimum of maintenance as a function of reliability according to Neff, [50].*

A methodology for a probabilistic life cycle cost approach to bridge management was applied to the concrete highway bridges in the Netherlands by Klatter & Noortwijk, [32].

According to Adey et al. (2006), [3], an expert evaluation was used to estimate the unit costs of the intervention works of different types of bridges. The unit intervention costs were estimated as percentage of the corresponding unit replacement costs. Experts were asked to estimate the repair costs of a bridge in proportion to the costs to restore the bridge to a “like new” condition. It was assumed that no de-icing material was used.

The intervention costs were assumed to include only the rehabilitation and replacement costs of the agency. The routine maintenance costs, such as clearing of drainage pipes and washing the bridges, were excluded. The user costs associated with the interventions were not included either. No discount to the present value was done.

The results are shown in Figure 2.9.

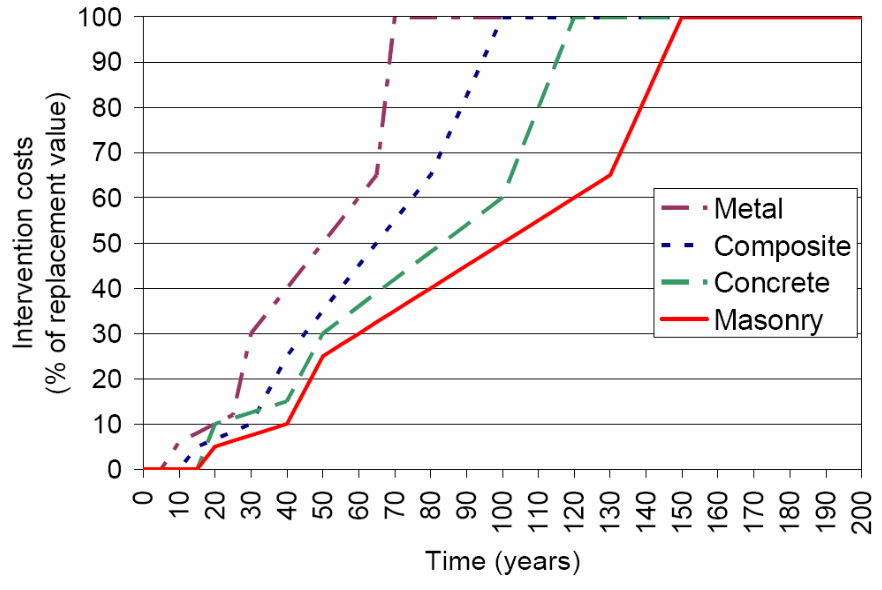

Figure 2.9 *Expert evaluation of the intervention costs as percentage of the replacement value as a function of the age of the bridge, Adey et al. (2006), [3].*

In the report of Yunovich et al. (2001), [97], the annual routine maintenance costs for a typical concrete bridge are estimated to be $1,000 per year. User costs are excluded from the annual maintenance activities. These costs include any maintenance required on the bridge, including miscellaneous repair patching as the deck ages, but excluding the scheduled maintenance due to significant deterioration of the concrete deck.

Lopez-Anido (2001), [39], made a survey of American concrete bridge decks considering various maintenance, repair and replacement measures. The most interesting results are presented in Figures 2.10, 2.11 and 2.12. The survey was carried out by sending a questionnaire to the engineers of the Department of Transportation (DOT) in five States.

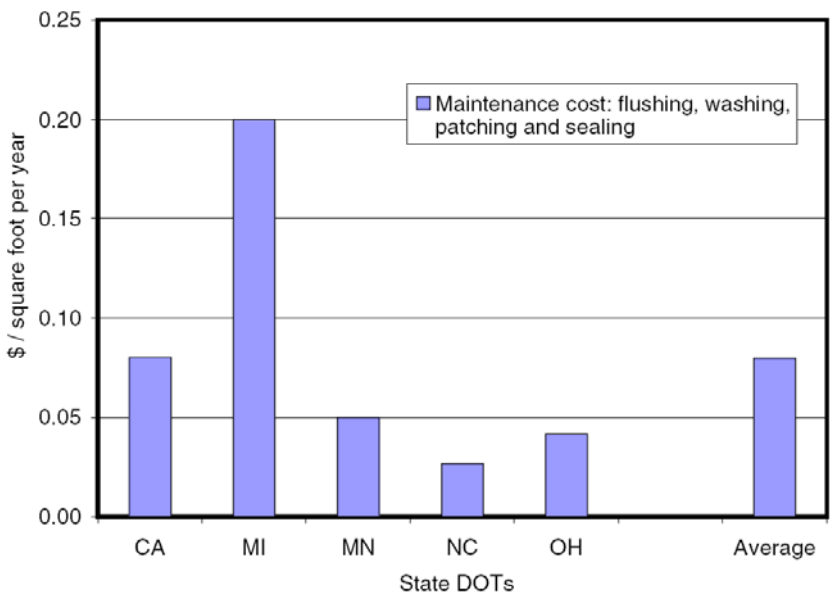

Figure 2.10 *Annual costs of concrete bridge decks considering various maintenance, repair and replacement measures in five American states according to Lopez-Anido (2001), [39].*

The construction costs of a new deck slab of bridges having different size are presented in Figure 2.11.

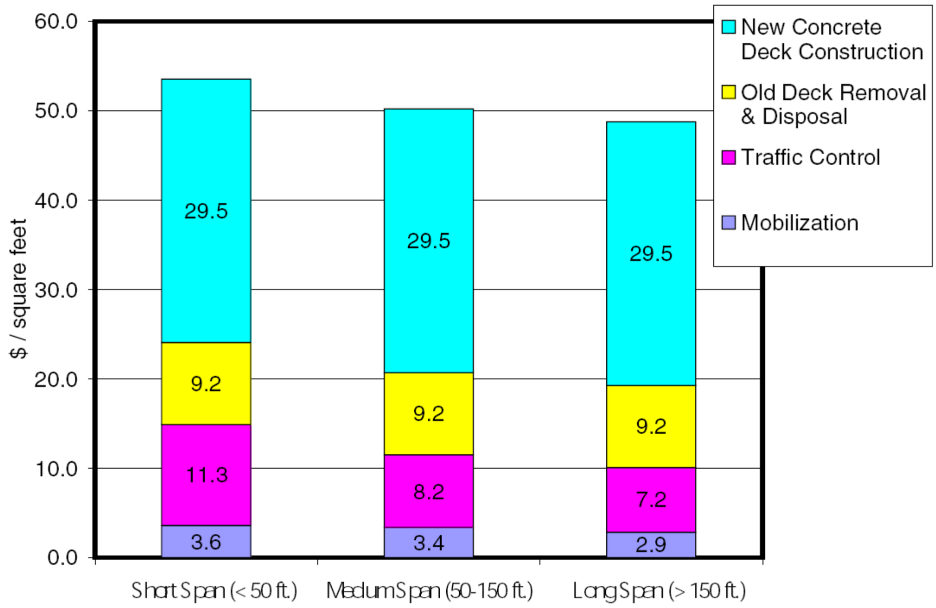

Figure 2.11 *Construction costs of a new deck slab of different size of bridges in five American states according to Lopez-Anido (2001), [39].*

The moments, when different actions are necessary to be carried out, are presented in Figure 2.12. Here ADT means the average daily traffic volume (vehicles per day).

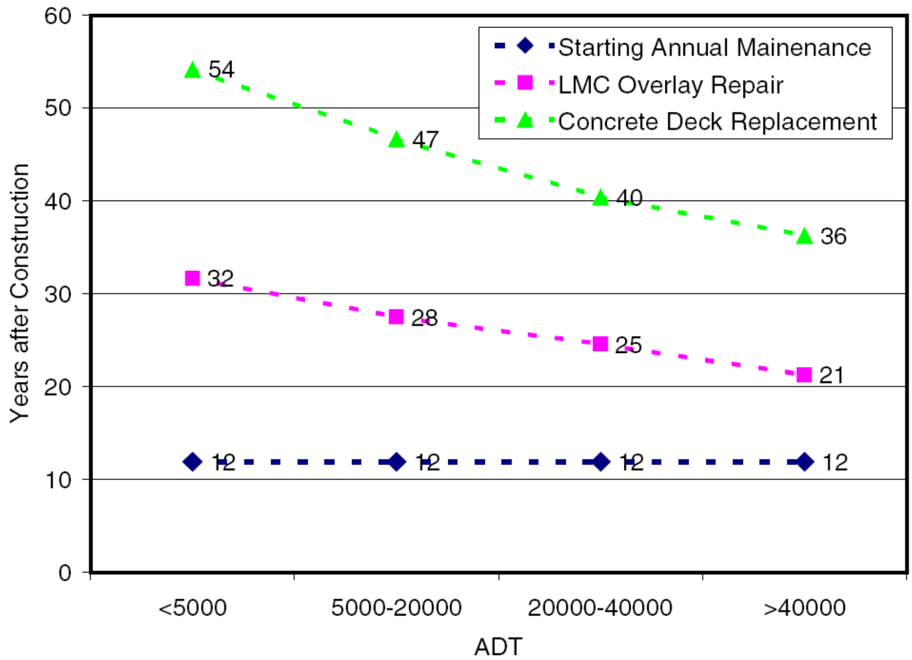

Figure 2.12 *Moments when different actions for concrete bridge decks are necessary in five American states according to Lopez-Anido (2001), [39].*

Lounis (2006), [40] applies a multi-objective optimization method to the bridge deck maintenance optimization problem using the following variables:

- Maximization of the bridge deck condition.
- Minimization of the maintenance costs.
- Minimization of the user costs.

Both the Euclidean and the Chebyshev metrics are used to determine the multi-objective optimality index and corresponding satisfactory solution.

To illustrate the method, Lounis presents an example of ten bridges (Table 2.7).

Table 2.7 *A multi-objective optimization method applied to the bridge deck maintenance optimization problem presented by Lounis (2006), [40].*

Bridge Deck Project	Damage Condition Rating	Maintenance Costs ($1,000)	User Costs ($1,000)	Euclidean Metric MOI_2	Chebyshev Metric MOI_∞
1	7	620	120	1.260	1.000
2	6	832	132	1.130	1.000
3	5	350	124	0.424	0.363
4	5	364	153	0.382	0.382
5	5	125	76	0.583	0.579
6	5	150	76	0.587	0.579
7	5	100	56	0.730	0.729
8	5	125	20	1.002	1.000
9	5	75	20	1.000	1.000
10	5	150	84	0.528	0.519
	Average= 5.3	Σ=$2891,000	Σ=$861,000	MIN=0.382	MIN=0.363

In this example bridges number 3 and 4 are the ones that need the most urgent rehabilitation.

Experiences based on construction contracts in Southern Ontario show that structural component costs represent only 50 % of the total costs. Other costs like those related to traffic control, environmental protection and construction administration cover the remaining 50 %, as shown by Pucchio et al. (2006), [57].

According to Fay (2006), [21], the costs of traffic management in a rehabilitation project of a big bridge in Canada were estimated to vary from 10 % to 15% of the total budget.

Mirza (2006), [46] suggests the use of a three R's thumb rule in environmentally sustainable constructions works. The R's are as follows:

- Reduce.
- Reuse.
- Recycle.

Reducing implies building only when needed and when the required function cannot be fulfilled by other means. Reusing means that any new "product" should be reusable. Recycling is basically similar to "reuse" but different in that sense that it can imply creating of something totally different compared to that what already exists.

2.7 Concrete bridges

LCC calculations of a typical viaduct were carried out by Bakker et al. (2006), [6] (Tables 2.8 and 2.9). The present values used were based on the discount rate of 4 %.

Table 2.8 *Example of a LCC calculation carried out by Bakker et al. (2006), [6], for a typical concrete viaduct.*

Maintenance measure		interval (yr)	unitprice (€)	unit	amount	cost
Concrete repair	parapeds	25	25	m2	121	€ 3.028
	bridgedeck	24	4,7	m2	853	€ 4.010
	main structure	30	2,2	m2	3.410	€ 7.502
	supports	30	1195	stk	4	€ 4.780
Guardrail	railing	20	54	m1	121	€ 6.541
	guardrail	21	163	m1	121	€ 19.745
Pavement	asphalt toplayer	8	19	m2	853	€ 16.210
	asphalt underlayer	24	42	m2	853	€ 35.833
Joints	maintenance	4	244	m1	32	€ 7.850
	replacement	12	1220	m1	32	€ 39.250
Bearings	replacement	40	145000	stk	20	€ 145.000
Regulair maintenance	maintenance	1	0,714285714	m2	974	€ 696
Inspection	inspection	10	1650	stk	1	€ 1.650
Structure	replacement	80	2100000	unit	1	€ 2.100.000

Table 2.9 *Example of a LCC calculation carried out by Bakker et al. (2006), [6], for a typical concrete viaduct. The present values (PV) in the second column are based on the discount rate of 4 %.*

Maintenance measure		PV	%PV	% PV excl. replacem.	Absolute	%Absolute	% absolute excl. replacem.
Concrete repair	parapeds	1722,0	0,5%	0,7%	9085,3	0,3%	0,7%
	bridgedeck	2412,7	0,7%	0,9%	12029,7	0,4%	0,9%
	main structure	3026,2	0,9%	1,2%	15004,3	0,5%	1,2%
	supports	1928,2	0,6%	0,8%	9560,0	0,3%	0,8%
Guardrail	railing	5253,5	1,5%	2,1%	26165,6	0,8%	2,1%
	guardrail	14136,0	4,1%	5,6%	59236,1	1,8%	5,6%
Pavement	asphalt toplayer	42073,3	12,2%	16,6%	162101,9	5,0%	16,6%
	asphalt underlayer	21560,4	6,2%	8,5%	107499,2	3,3%	8,5%
Joints	maintenance	44209,7	12,8%	17,4%	156999,1	4,8%	17,4%
	replacement	61426,6	17,8%	24,2%	235498,6	7,2%	24,2%
Bearings	replacement	36492,6	10,6%	14,4%	290000,0	8,9%	14,4%
Regulair maintenance	maintenance	16643,5	4,8%	6,5%	55674,6	1,7%	6,5%
Inspection	inspection	3286,7	1,0%	1,3%	13200,0	0,4%	1,3%
Structure	replacement	91107,1	26,4%		2100000,0	64,6%	
Total incl. replacement		345278,5	100,0%	100,0%	3252054,4	100,0%	100,0%
Total excl. replacement		254171,4					

According to Table 2.9, the construction costs are about 65 % of the total life cycle costs. The most expensive parts after construction period are the joints and the bearings which together cause about 21 % of the present value of the life cycle cost.

An example of LCC calculations of a conventional concrete bridge is presented by Hawk (2003), [26]. The basic assumptions for the calculations are:

- the length of the bridge is 100 m,
- the width of the bridge is 11 m,
- the real discount rate is 6 %, and
- the analysis period is 80 years.

The cost calculations are summarized in Table 2.10, where "Alternative B" means the concrete bridge alternative in question.

Table 2.10 *LCC cost calculation of a concrete bridge according to Hawk (2003), [26], Part 2 (NCHRP 12-43), p 82.*

Alt. B, Cost Item	Timing	Best-estimate cost ($)	Expected PV ($)
Plans and studies	year 0	100,000	100,000
Design & construction	years 1-2	2,200,000	1,969,168
Inspections	every 2nd year in service	1,000/inspection	6,522
Deck-overlay replacement	10-yr intervals	25,000/project	27,658
Total agency cost, Alt. B			**$2,103,348**

In this example, the future costs seem to be quite low, only about 1,7 % of the construction costs. The user costs are not included.

Kawano, [30], has studied the life cycle costs of four prestressed concrete bridges located on coast lines in severe chloride environments. The service lives of the old bridges were only from 32 to 34 years except the one bridge still existing. The proportional initial costs, the maintenance costs and the removal costs of the bridges are given in Table 2.11, respectively. No discounting was taken into account.

Table 2.11 *Life cycle costs of four prestressed concrete bridges located on coast lines in severe chloride environments according to Kawano, [30]. I = investment, M = maintenance, R = repair.*

Name of bridge Service years	Length spans	I	M	R	I+M+R	Number of repair
Kuretsubo 32	144m 5spans	1.0	0.8	0.7	2.4	2 replaced
Iwakawa 34	35m 1span	1.0	0.5	? *	1.5	1 replaced
Ashikawa 34	117m 4spans	1.0	1.2	2.7	4.9	2 replaced
Koyataro 25	337m 9spans	1.0	1.2	(1.0)**	2.2	2

* not removed ** estimated

Methner et al. (2006), [45], compare the construction costs of integral concrete bridges with those of ordinary type bridges having bearings and expansion joints. Typical distribution of construction costs of these bridges is presented in Table 2.12:

Table 2.12 *LCC comparison between an ordinary bridge and an integral bridge. Methner et al. (2006), [45].*

Task	*Ordinary model in % of OM*	*Integral model in % of OM*
Earth Works	2.2	2.4
Drainage	2.4	2.4
Foundations	13.6	12.1
Concrete	26.1	25.2
Reinforcing Steel	13.4	13.8
Prestressing Steel	5.0	5.2
Formwork, Scaffolding	7.4	7.7
Components (Bearings, Joints, Drainage etc.)	11.3	5.5
Sealing, Roadway etc.	4.3	4.3
Site Facilities, Traffic Organization	14.3	14.3
Total	100.0	92.9

Another comparison between an integral bridge and a non-integral bridge is given by Mendoza (2006), [43]. LCC calculations for a flyover with the length of about 67 m and the effective width of 5,5 m were reported. The followings hypotheses were assumed:

- 50 years scenario.
- The construction costs are:

  154 745 € (integral bridge)

  170 573 € (non-integral bridge).
- The annual maintenance cost is 0.8 % of the initial investment.
- In the non-integral solution, the expansion joints will be replaced every 10 years and bearings every 20 years.
- Discount rates (*I*) of 4 %, 5 %, 6 %, 7 % and 8 % where admitted.
- No traffic delay or user costs where considered.

The results are shown in Table 2.13.

Table 2.13 *Comparison between net present value for an ordinary bridge and an integral bridge type. Mendoza (2006), [43].*

	Net Present Value (NPV)					
	I = 4 %	*I* = 5 %	*I* = 6 %	*I* = 7 %	*I* = 8 %	Construction Cost
Integral Solution	418 931	379 656	349 189	325 164	305 919	154 745
Non Integral Solution	479 657	433 218	397 198	368 800	346 061	170 573

According to Perez et al. (2006), [55], a rough estimate for additional costs caused by joints is that the structures with joints require maintenance costs that equal the construction costs about every 20 years.

Peng et al. (2006), [54], also give an example of cost comparison between a conventional bridge (A) and the corresponding integral bridge (B) (Table 2.14). The net present value of the LCC costs is also given. An analysis period of 50 years and discount rate of 4 % used.

Table 2.14 *Comparison between the net present values of a conventional bridge (A) and the corresponding integral bridge (B). The analysis period is assumed to be 50 years and the discount rate 4 %. Peng et al. (2006), [54].*

Table 3 Costs of strategy A and strategy B (Unit: RMB)

	Strategy A	Strategy B
Initial Cost	90,000	128,000
Maintenance cost	21,482.18	0
Replacement of expansion joint cost	169,980.8	0
User cost (traffic interrupted)	Closed	Smooth
Societal cost	Not included	None
Total cost	281,482.97	128,000(45.5%)

Note: Maintenance action for every year; and the time replacement of bearing and expansion joint is every ten years.

Troive, [85], made LCC calculations for thin deck slabs of concrete bridges. Deterioration models to predict the expected service life were used and the annuity cost of different concrete qualities and covering layers were calculated. The discount rate was 4 %. Some results are presented in Figure 2.13. The figures on the vertical axes express the dimensionless annuity.

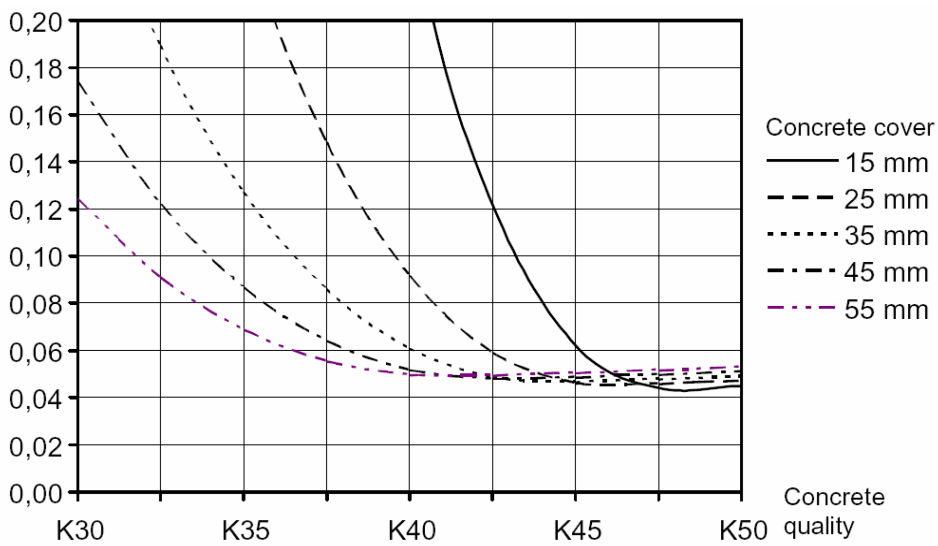

Figure 2.13 *Annuity cost of a concrete bridge slab depending on concrete quality and concrete cover. Troive, [85].*

Smith & Cornell (2006), [73], compared the life cycle costs of stainless steel reinforcing bars to those of conventional reinforcing bars. They point out that the total costs increase only by 1 % to 10 %, when stainless steel reinforcing bars are substituted for carbon steel reinforcing bars in the critical parts of highway bridges. In Figure 2.14 the life cycle cost comparison for the Öland Bridge in Sweden is presented.

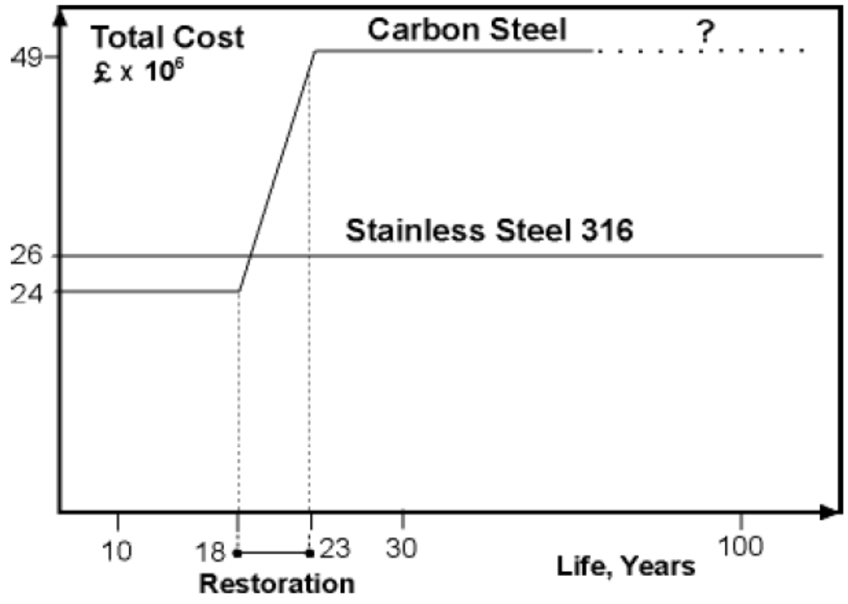

Figure 2.14 *Comparison of the life cycle costs of stainless steel reinforcing bars and those of conventional reinforcing bars for the Öland Bridge in Sweden. Smith & Cornell (2006), [73].*

Comparison of the life cycle costs of different types of reinforcing bars is presented in Table 2.15.

Table 2.15 *Life cycle costs of different types of reinforcing bars according to an American web site [17].*

	Uncoated Rebar-Bridge Deck	Epoxy-Coated Rebar-Top Mat	Epoxy-Coated Rebar-Both Mats
Added Cost of Protection System	N/A	$0.15 per lb.	$0.15 per lb.
Initial Investment[1] (construction & protection)	$35 per sf	$35.50 per sf	$36 per sf
Discount Rate	4%	4%	4%
Life Extension[2] from Protection System	N/A	15 years	25 years
Service Life	20 years	35 years	45 years
Repair/Rehab Cost[3]	$17.50 per sf	$17.50 per sf	$17.50 per sf
Annual Rate of Return On Investment	N/A	19%	15%
Net Present Cost (per sq. ft.)	**$52**	**$44**	**$41**

Yunovich et al. (2001), [97], presented a cost comparison between different types of reinforcing bars used in the deck slab of a conventional concrete bridge. The bridge deck had a surface area of 583 m^2, two lanes in each direction, a length of 36,9 m and a width of 15,8 m. Figure 2.15 shows the final annualized cost values for one maintenance scenario. No user costs are included.

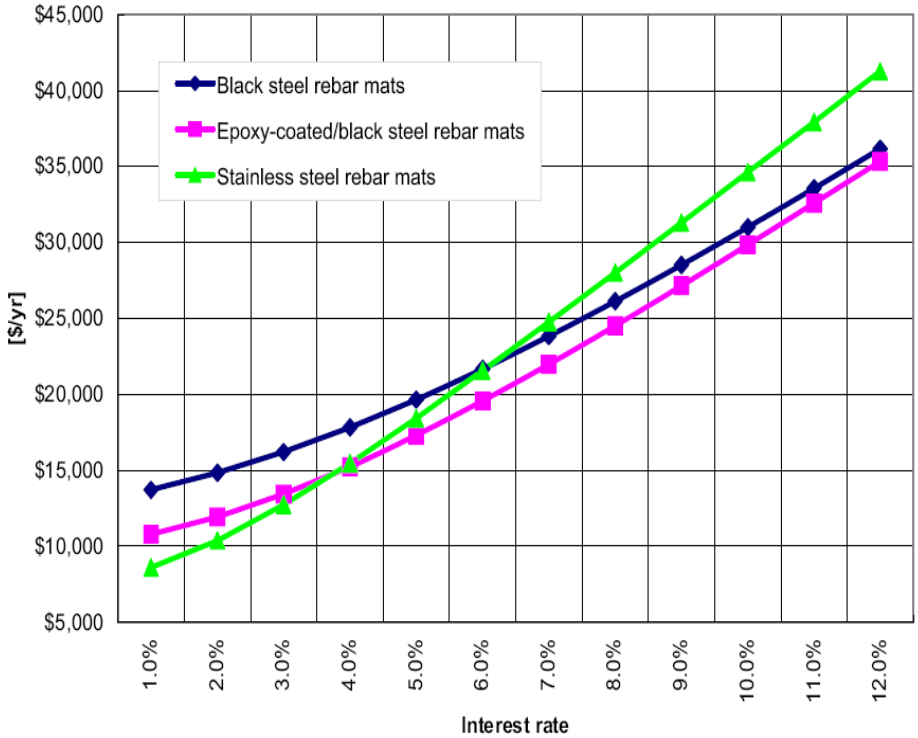

Figure 2.15 *Annualized cost values for one maintenance scenario for a bridge deck with a surface area of 583 m^2, with different types of reinforcing bars. Yunovich et al. (2001), [97].*

When the user costs for a daily traffic of 24 000 vehicles are included, the cost comparison takes the form presented in Figure 2.16.

Chusid et al., [14], used the computer program BridgeLCC (see section 4.3) to compare the life cycle costs of a painted bridge and an integrally coloured concrete bridge. They ended up to the result that a bridge made of coloured concrete is about 17 % cheaper than a painted bridge.

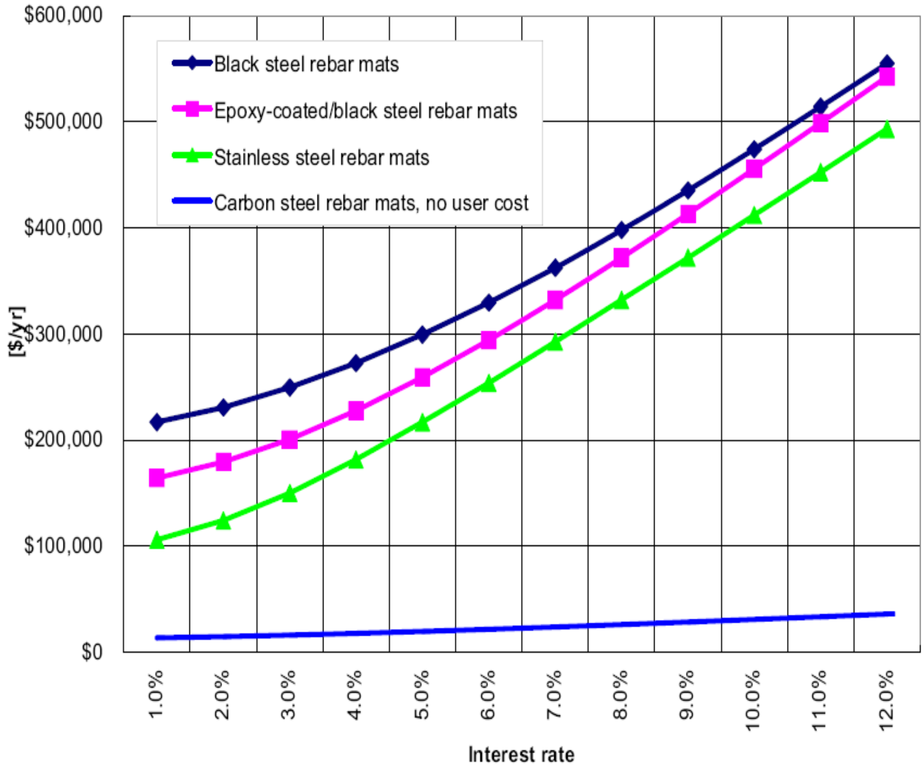

Figure 2.16 *Annualized cost values including user costs for one maintenance scenario for a bridge deck with a surface area of 583 m^2, with different types of reinforcing bars, Yunovich et al. (2001), [97].*

2.8 Steel bridges

The most important part affecting the life cycle costs of steel bridges is the painting. The overall surface costs are comprised of the costs of surface preparation, the painting material and the application activities. Yunovich et al. (2001), [97] present cost estimates for some coating systems of American steel bridges (1999), (Table 2.16). In the table DFT means "Dried-film thickness". The presented data concerns "moderate industrial environment in the southeast of the United States".

Table 2.16 *Cost estimates for some coating systems of American steel bridges (1999). Yunovich et al. (2001), [97].*

System	SSPC Surface preparation	DFT**** (mm)	Cleaning Cost ($/m^2)	Material Cost ($/m^2)	Application Cost ($/m^2)	Total Installed Cost ($/m^2)	System Life (5-10% breakdown) (years)	Cost/year ($/m^2)
Two-coat alkyd	2*	0.10	$5.92	$1.08	$5.38	$12.38	3	$4.09
	6**		$9.15			$15.61	6	$2.58
Two-coat epoxy	2	0.15	$5.92	$1.72	$6.46	$14.10	7.5	$1.83
	6		$9.15			$17.33	10.5	$1.61
	10***		$10.76			$18.94	12	$1.61
Two-coat epoxy/ urethane	6	0.15	$9.15	$2.26	$7.00	$18.41	9	$2.05
	10		$10.76			$20.02	10.5	$1.94

Another collection containing estimations for painting costs in the United States is given in Table 2.17. It has been composed from several different sources. Yunovich et al. (2001), [97]. Extra costs such as containment, waste disposal-related costs and workers health and safety costs are included. A typical cost distribution is shown graphically in Figure 2.17.

Table 2.17 *Cost estimates for different coating systems of American steel bridges including extra costs (1999). Yunovich et al. (2001), [97].*

CATEGORY	TYPE	ESTIMATED COST, ($/m^2)
Surface Preparation (labor + material)	SP-10 Near-White Metal Blast	$13.45
	SP-3 Power-Tool Cleaning	$ 6.46
Coating Application	Three-Coat Full Painting	$13.45
	Overcoating	$ 3.23
	Metallizing	$26.91
Coating Material	IOZ/Epoxy/Urethane	$ 5.27
	Epoxymastic/Urethane	$ 4.52
	Metallizing	$16.15
	Moisture-Cured Urethane	$ 2.69
	Three-Coat Alkyd	$ 2.05
Other Job Costs	Containment and Air Filtration Systems, SP-3 only	$ 5.38
	Containment and Air Filtration Systems, SP-10 only	$21.53
	Inspection, SP-3 only	$ 5.38
	Inspection, SP-10 only	$10.76
	Rigging	$ 5.38
	Mobilization	$ 5.38
	Hazardous Waste Storage and Disposal, SP-3 only	$10.76
	Hazardous Waste Storage and Disposal, SP-10 only	$26.91
	Worker Health and Safety, SP-3	$10.76
	Worker Health and Safety, SP-10	$21.53

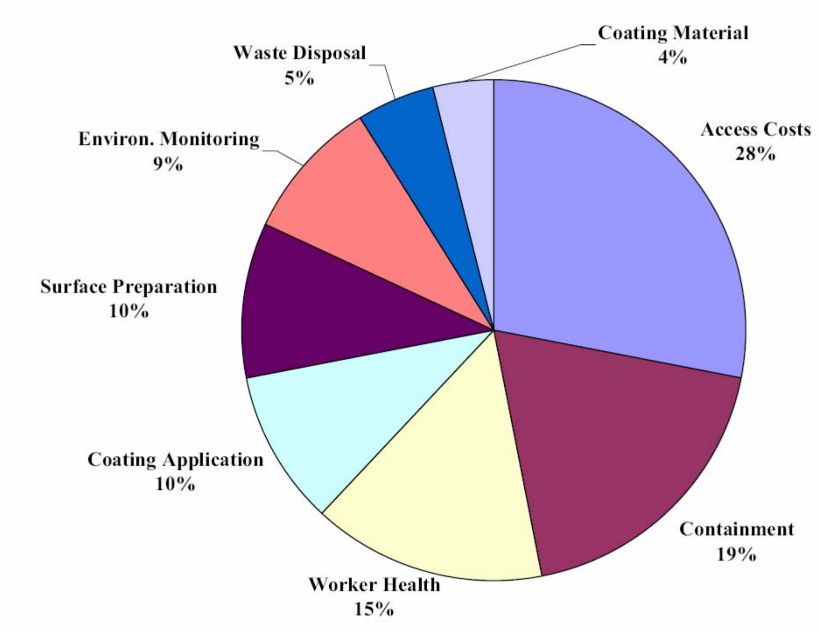

Figure 2.17 *A typical cost distribution for different coating systems of American steel bridges. Yunovich et al. (2001), [97].*

In the United States, the costs of total paint removal and repainting jobs can range from \$43.00 per m^2 to \$215.25 per m^2. Yunovich et al. (2001), [97], estimate that the cost of over coating ranges from \$11 to \$54 per m^2.

The estimated life time of several coating systems is presented in Table 2.18 (Yunovich et al. (2001), [97]). The life time is defined as the time when 10 percent of the surface area is deteriorated. The data proves that, depending on the surface preparation and the type of coating, the assumed service life can vary considerably in the range of 3 to 30 years.

Table 2.18 *The estimated life time for some coating systems according to Yunovich et al. (2001) [97]. The system lifetime is estimated to correspond to the time when 10 % of the surface area is deteriorated.*

COATING SYSTEMS	ESTIMATED COATING SYSTEM LIFE*
Ethyl Silicate Inorganic Zinc/Epoxy Polyamide/Aliphatic Urethane over SP-10 Near-White Metal Blast	15 years
Epoxymastic/Aliphatic Urethane over SP-10 Near-White Metal Blast	10 years
Epoxymastic/Aliphatic Urethane Overcoat over Existing Paint and SP-3	4 years**
85% Zinc/15% Aluminum Metallizing over SP-10 Near-White Metal Blast	30 years***
Low-VOC Alkyd Three-Coat System Overcoat over Existing Paint and SP-3	3 years**

Troive (1999), [84], has also estimated life cycle costs of painting in steel bridges. One example of the results (system S4.22) is given in Table 2.19.

Table 2.19 *Estimated life cycle costs of different painting systems of steel bridges according to Troive (1999), [84]. The table depicts an example.*

				fabrik	fält				
				nymåln 100%	bättr 10%	part 20%	bättr 10%	ren/blästr 100%	
Åtgärd/kostnad	fabrik	fält		0	20	40	60	80	år
Etablerings- och arbetsplatskostnader	-	300000	kr		600	600	600	600	kr/m2
Intäckning	-	150	kr/m2		150	150	150	150	kr/m2
Blästring (arb + uppsaml)	80	100	kr/m2	80	10	20	10	100	kr/m2
Målning (arbete)	30	35	kr/skikt/m2	120	14	28	14	0	kr/m2
Målning (material)	52	63	kr/m2	52	6	13	6	0	kr/m2
Deponeringskostnad, farligt avfall	-	30	kr/m2		3	6	3	30	kr/m2
Summa				252	783	817	783	880	kr/m2
Nuvärde				**252**	**357**	**170**	**74**	**38**	**kr/m2**
LCC (Summa nuvärde)	**892**	**kr/m2**							
Annuitetskostnad	**37,3**	**kr/år/m2**							

Based on Table 2.19, the shares of different items in the LCC are represented graphically in Figure 2.18.

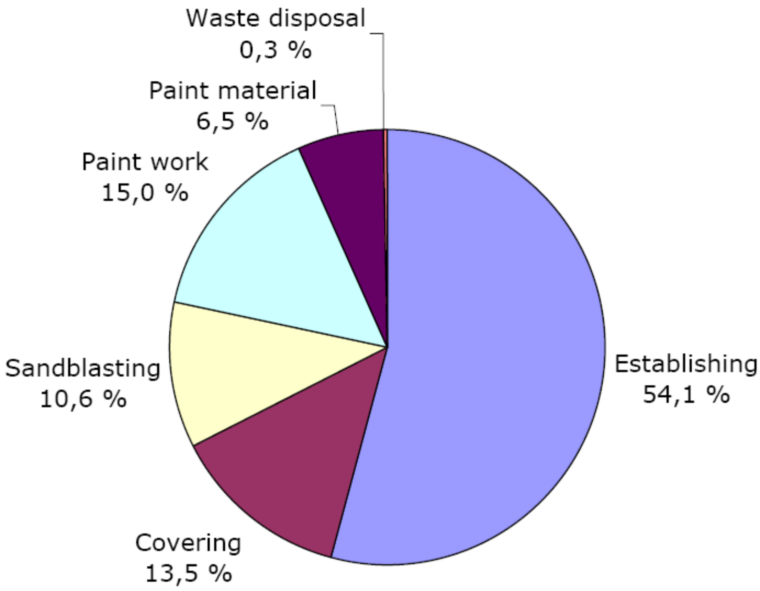

Figure 2.18 *The shares of different items of LCC in Table 2.19 presented graphically. Troive (1999), [84].*

The painting costs of steel truss bridges were studied by Carlin & Mailhot (2006), [10]. Unit painting costs are estimated depending on the accessibility of the construction. It has been found that the costs of the painting material itself represent only a few percentages of the total costs.

An old truss bridge was repaired in Canada during 2004. Based on the experiences of that project Mercier (2006), [44], collected unit replacement costs of various structural parts into one table (Table 2.20). The costs include site organization, removal and disposal of the replaced elements and replacement of rivets with bolts, except on the bottom chords.

Table 2.20 *Unit costs when replacing different parts of an old truss bridge, according to Mercier (2006), [44]. The cost items include site organization, removal and disposal of the replaced elements and replacement of rivets with bolts, except on the bottom chords.*

Parts replaced		Unit cost
Rivets		$70/unit
Bottom chords	Rivets	$60/unit
	Plates and angle	$19/kg
Bottom bracing		$22/kg
Angle irons of diagonal and vertical		$23/kg
Gussets of bottom bracing		$28/kg
Replacement of stringers		$12/kg

An example of LCC calculations of a conventional steel bridge is presented by Hawk (2003), [26]. The basic assumptions for the calculations are as follows:

- length of the bridge 100 m,
- width of the bridge 11 m,
- real discount rate 6 %,
- analysis period 80 years,
- traffic volume 3,500 vehicles per day, and
- 15 percent of the traffic is assumed to be trucks.

The cost calculations are summarized in Table 2.21, where "Alternative A" means the steel bridge alternative in question.

Table 2.21 *Example of a LCC calculation of a conventional steel bridge, Hawk (2003), [26].*

Alternate A Cost item	Timing	Best estimate cost ($)	Expected PV ($)
Plans and studies	year 0	100,000	100,000
Design & construction	years 1–2	2,000,000	1,781,504
Inspections	every 2nd year in service	1,000 per inspection	6,522
Painting	12 to 18 year intervals	153,000 per project	106,860
Deck overlay replacement	10 year intervals	25,000 per project	27,658
Total agency cost for Alternative A			**$2,022,544**

The net present value of the user costs in the example presented in Table 2.21 is $ 6452 without diversion.

Hadavi (2003), [27], studied the total life cycle costs of movable bridges. The ratios to the corresponding initial costs are presented in Figure 2.19. Presumably no discounting has been made, i.e. discount rate has been assumed to be zero.

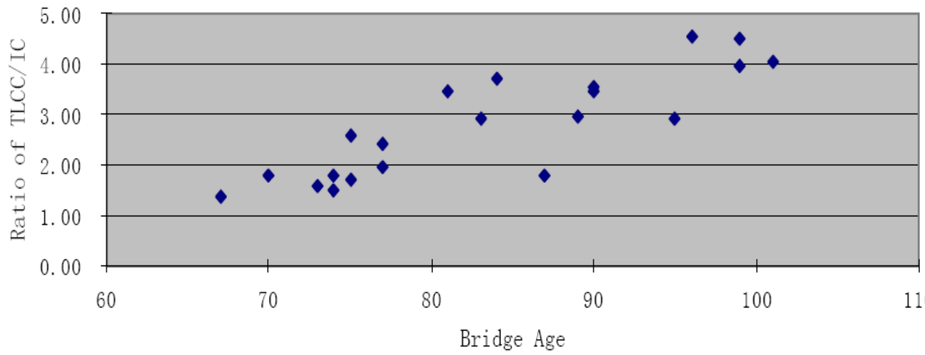

Figure 2.19 *Total life cycle costs of movable bridges according to Hadavi (2003), [27]. Presumably the discount rate has been assumed to be zero.*

Meiarashi et al., [42], compared the discounted life cycle costs of suspension bridges made of conventional steel or carbon fibre reinforced polymer (CFRP). The results are shown in Figure 2.20.

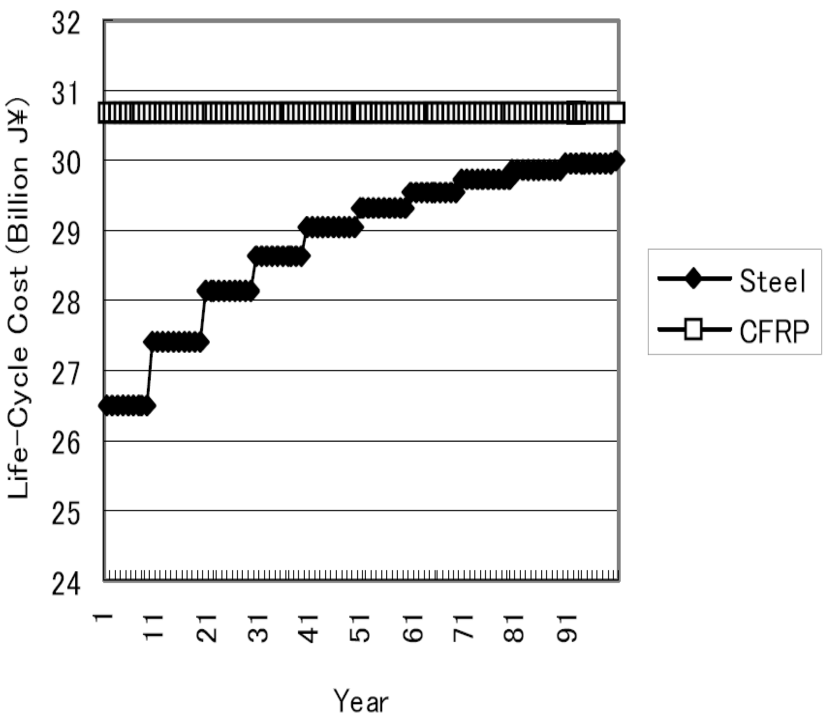

Figure 2.20 *Discounted life cycle costs of suspension bridges made of conventional steel or carbon fibre reinforced polymer (CFRP), Meiarashi et al., [42].*

2.9 Composite bridges

Shin et al., (2006), [70] present an example of an optimization based on life cycle costs. They surveyed a composite bridge with a concrete deck slab and three steel box girders. Total width of the bridge deck was 15.5 m. The load-carrying capacity of the bridge was based on the experience obtained from the deterioration, maintenance and repair measurements. The dimensions of the bridge deck were chosen so, that after a certain life time the reduced dimensions were big enough to fulfil the load-carrying requirements.

The total life cycle cost was calculated as a sum of the initial cost, the damage cost, the maintenance cost, the repair and rehabilitation cost, the user cost and the disposal cost. However, nothing is mentioned about the discount rate, *i.e.* it has been assumed to be zero.

The most important results are presented in the Figures 2.21 … 2.23. Instead of total life cycle costs, the annual costs are examined. The curves also represent the cost proportions of the different types of roads.

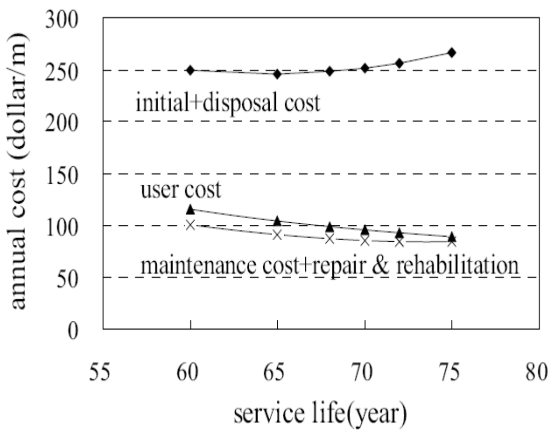

Figure 2.21 *Example of annual LCC costs of a composite bridge as function of the service life, according to Shin et al., (2006), [70].*

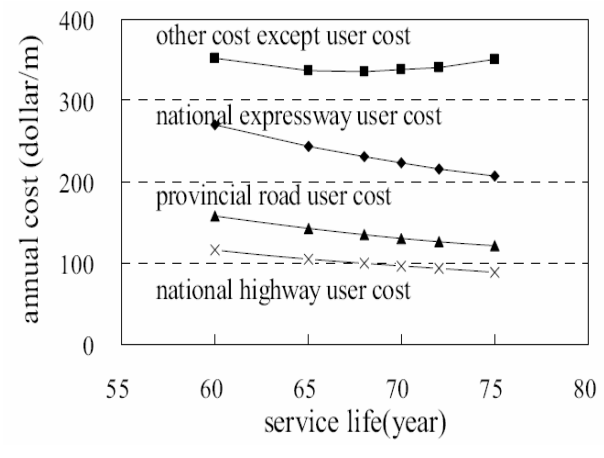

Figure 2.22 *Example of annual LCC costs of a composite bridge depending on the road type and service life, according to Shin et al., (2006), [70].*

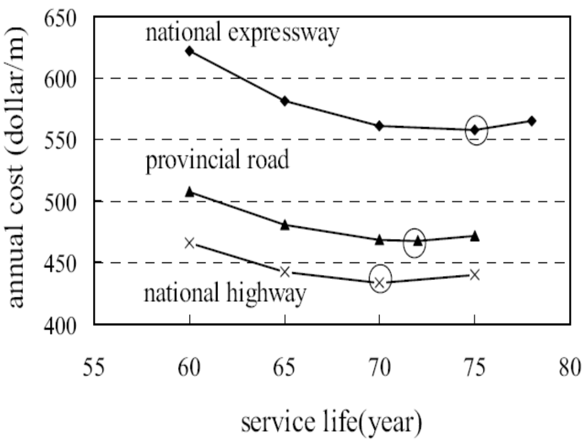

Figure 2.23 *The total annual cost and the optimum design service life of a composite bridge depending of the type of road, according to Shin et al., (2006), [70].*

2.10 Timber bridges

A survey of the construction costs of American timber bridges for truck traffic is described in articles [79] and [80]. The bridges in question were constructed between the years 1980 and 1992. The unit costs of the superstructures of the different types of bridges are summarized in Table 2.22.

Table 2.22 *Survey of the construction costs of American timber bridges for truck traffic, [79] and [80].*

Construction type	Observa-tions (no.)	Cost ($/ft^2)	
		Median	Mean
Slab	138	24.83	28.58
Stringer/multi-beam	56	31.12	31.59
Girder and floorbeam system	1	45.25	45.25
T-Beam	2	64.10	64.10
Box beam or girder			
Multiple	7	56.00	57.80
Single or spread	1	51.69	51.69
Frame	1	149.50	149.50
Truss, through	2	60.18	60.18
Arch, deck	1	39.09	39.09
Total	209		

The variation of the cost values is shown in Figure 2.24.

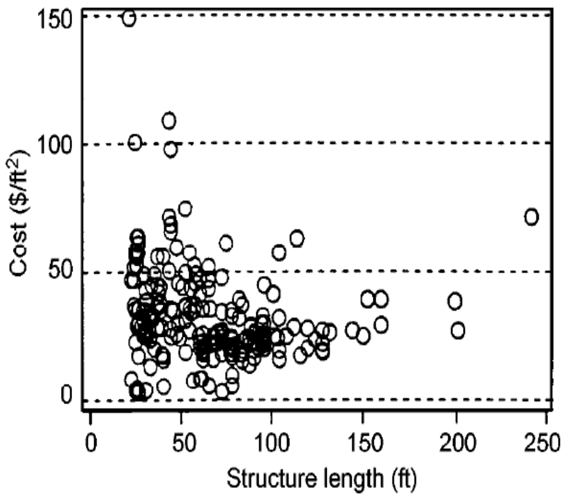

Figure 2.24 *Variation of the construction cost values of American timber bridges for truck traffic, [79] and [80].*

The conversion to the European (SI) units can be done according to Table 2.23.

Table 2.23 *Conversion from inch-pound units to SI units, [79] and [80].*

Inch–pound unit	Conversion factor	SI unit
inch (in.)	25.4	millimeters (mm)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.093	square meter (m^2)

A comparison of the corresponding bridges made of other materials is presented in Table 2.24, [79] and [80]. One can see that the median costs of timber bridges were less than those of the steel bridges and greater than those of the concrete and prestressed concrete bridges.

Table 2.24 *Comparison of cost per area for corresponding bridges made of different materials, [79] and [80].*

Data set	Observa tions (no.)	Cost ($/ft²) Median	Mean
Timber	222	26.40	31.84
Steel	27	27.50	31.40
Concrete	37	19.13	27.53
Prestressed concrete	115	21.67	25.45
Total	401		

Yttrup and Nolan, [95], investigated the life cycle of timber bridges in Tasmania, Australia, and give the following “rule of thumb” for the service lives of the planks, the deck, the beams and the piles. These are 5, 10, 20 and 40 years, respectively.

Dinkel (2005), [16], uses LCC to compare the costs of timber bridges and the bridges made of fibre material. He mentions that the service life of wooden deck planks varies between 6 and 8 years and that of the load-carrying parts between 15 and 30 years.

2.11 Computer programs

Bridge LCC is an American program for the life cycle cost analysis of bridges, Bridge LCC [8], Ehlen, [18]. It has the following features:

- risk assessments,
- sensitivity analysis,
- four probability distributions to quantity, unit cost and timing of individual costs, and
- driver delay costs, vehicle operating costs and accident costs.

An example of the cost calculation results is given in Figure 2.25. It represents graphically the annual costs and cumulative costs both in the current value and in a discounted value.

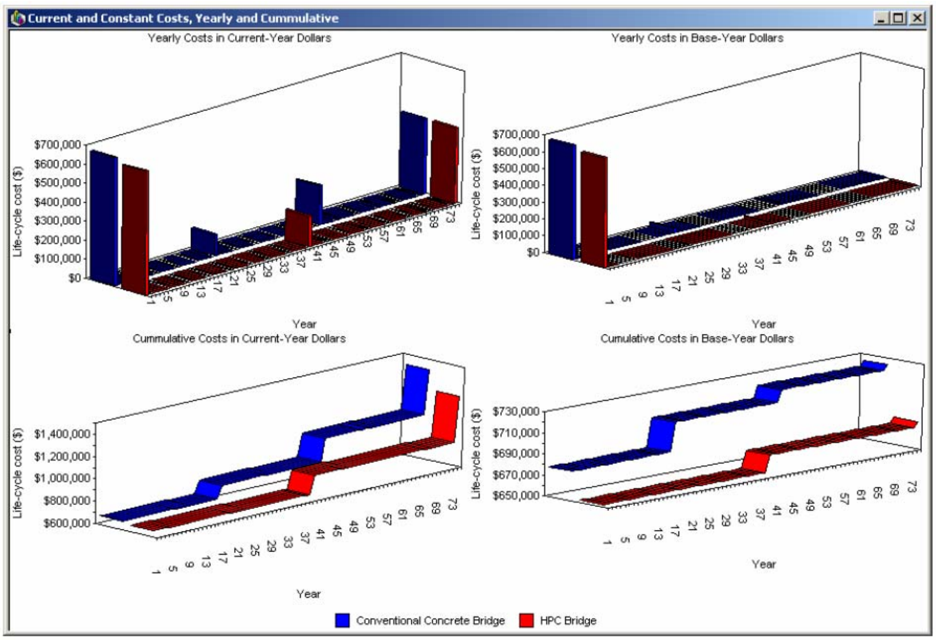

Figure 2.25 *An example of cost calculation results from Bridge LCC [8].*

Bridge LCC was used, for example, for the life cycle cost analysis of a bridge reported by Goulet (2006), [23]. *BridgeLCC* is presented in some detail in Chapter 4.

The computer program *Bridgelife* of Vesikari (2006), [92], enables the management and life cycle analysis of bridges. It was developed in Finland to serve the bridge owners. The program is based on the developed degradation models for concrete bridges. The future condition of the structural parts is predicted by using Markov Chain method that gives to the analysis a probabilistic nature.

An example of the results obtained by using *Bridgelife* is depicted in Figure 2.26.

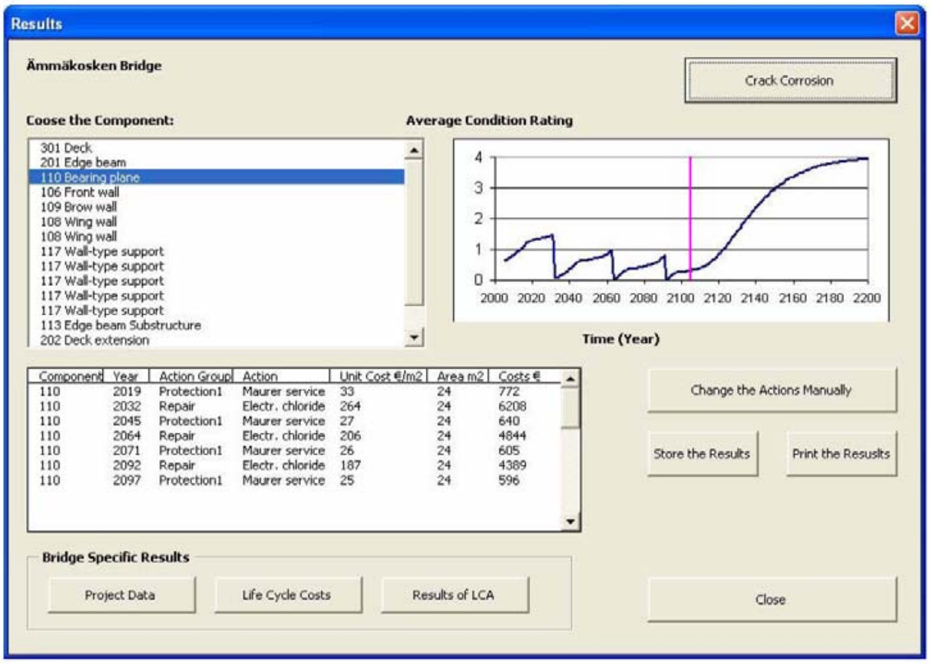

Figure 2.26 *An example of the results obtained by using Bridgelife, Vesikari (2006), [92].*

In Japan, professors Miyamoto and Nakamura have developed a bridge management system called *J-BMS*, Miyamoto & Nakamura (2003), [47]. It uses a LCC optimizing system to determine the maintenance works needed. The program uses a database based on the results of the visual inspection of the existing bridges.

Figure 2.27 and Figure 2.28 show an example of a maintenance plan based on the cost optimization proposed by Miyamoto and Nakamura (2003), [47].

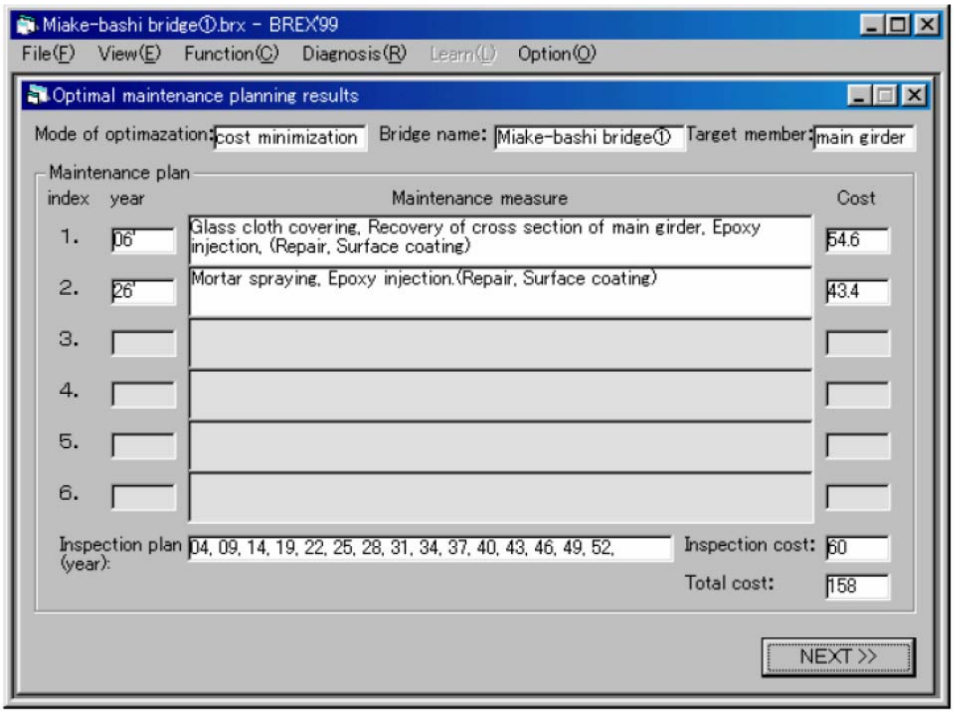

Figure 2.27 *An example of a maintenance plan based on the cost optimization proposed by Miyamoto & Nakamura (2003), [47].*

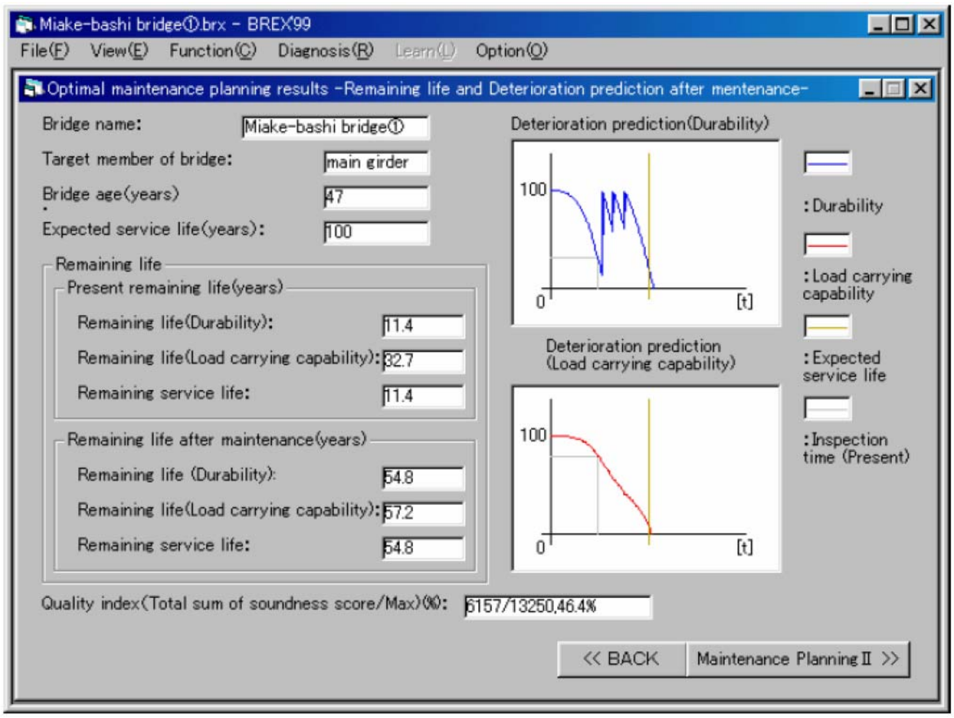

Figure 2.28 *An example of a maintenance plan based on the cost optimization proposed by Miyamoto & Nakamura (2003), [47].*

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3 Methodology

3.1 Introduction

The traffic infrastructure of a country is built to serve the society with roads, bridges, tunnels and other structures needed for an effective transportation sector. Taxes on vehicle fuel and likewise are used to pay for these services. The taxpayers want of course to get as much "value for money" as possible. The "value" is firstly a road system as effective as possible and with as few interruptions as possible for maintenance and repair. There are other values of importance concerning the environment, preserving energy and to use as little of not renewable material resources as possible. Very important values are also all kinds of traffic security issues. Other "values" could be esthetical or preserving old structures of historical interest.

The "money" in the "value for money" requirement could be investment cost, life cycle cost with or without user costs. There are many different views on how to calculate these kinds of costs. Some of these questions will shortly be discussed in this paper.

Life Cycle Costing LCC is a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs. In particular, it is an economic assessment considering all projected relevant cost flows over a period of analysis expressed in monetary value. Where the term uses initial capital letters it can be defined as the present value of the total cost of an asset over the period of analysis." [88] (Tupamäki, 2003b).

3.2 Notation

To be able to compare different methodologies it is practical to use the same kind of notation throughout this methodology chapter, since it is obvious from chapter 2 that different kinds of notations are used in different countries and by different researchers. In this chapter 3, has consequently translation of parameters used in the three countries Sweden, Finland and Norway been transformed to one set of notation.

Latin lower case

Symbol	Typical unit	Description
$a_1, a_2, \dots$		constants
p	-	Probability
r	%	General symbol used for rent, when no index is used the symbol stands for calculation rent or thing
t	year	Time
v	km/h	Speed

Latin upper case

Symbol	Typical unit	Description
ADT	number/day	Average daily traffic
A	Number/vehicle-km	Accident rate
C	$, €, SEK	General symbol for cost
CC	-	Condition class
L	m	Length
LCC		General symbol for life cycle cost. Different indices are used
LCV	% or ‰	Lack of capital value
N		General symbol for number i.e. number of days
OCC	-	Overall condition class
R	-	Probability for failure
T	year	Time interval i.e. life-time

Greek lower case

Symbol	Typical unit	Description

Greek upper case

Symbol	Typical unit	Description

3.3 Bridge management systems

A bridge owner who has many thousands of bridges to manage knows that it is a complex task to plan the management and therefore a bridge management system (BMS) is a must for the effective planning and procurement of new bridges and for the maintenance of the existing bridge stock. In the following short descriptions are given for the Swedish, Finnish and Norwegian BMS systems. Only the parts of interest for making LCC calculation will be presented in some detail.

3.4 What is a Bridge Management System?

A bridge management system (BMS) performs rational and systematic approach to the management functionalities related to bridges from the conceptual stage to the end of their useful life, through organising and implementing all the activities related to design, constructing, maintaining, repairing, rehabilitating and replacing structures. The overall activities include:

- Defining structure condition
- Monitoring and rating structures
- Finding and recommending optimum alternatives of maintenance, repair and rehabilitation (MR&R) measures for structures
- Identifying, predicting and prioritising structures for MR&R measures or even demolition
- Allocating funds for construction, replacement, rehabilitation and maintenance measures
- Maintaining an appropriate database of information.

In practice a bridge management system is usually divided into two parts:

- Network level system
- Programming / Project level system

The ultimate objective of the programming level system is to make the necessary decisions between the inspection of structures and the execution of MR&R projects. So, a project level system should be able to answer the strategic questions: Which bridges should be repaired? Which MR&R methods should be used? When to do the MR&R measures? How to combine the measures into projects? All these questions should be answered taking into account technical demands, functional performance, safety, economy and other necessary viewpoints. The MR&R projects are then executed according to the system assisted decisions.

A project level BMS addresses structures and structural parts on an individual basis. Planning is performed by going through all the levels of structural hierarchy starting from components, such as beams and columns, and ending up to programming level plans for projects. It offers tools, techniques and methodologies for analysing structures and structural parts for specifying MR&R measures, combining projects from individual MR&R measures and finally preparing the annual project and resources plans at the programming level.

The bridge management system often has a special network level system. This part of the system is meant mainly for high level decision making and economic research. It has two levels of analyses: a long-term (LT) analysis and a short-term (ST) analysis. It deals with categorised populations of structures and answers questions like: How much money is needed? What happens if? What is the optimum condition target for a bridge stock? The main idea is to find the cost-effective target level of bridge condition and to identify yearly the overall optimal solutions for MR&R activities and to calculate the required budget so that the structures and their performance can be kept in a cost-effective state year by year. It helps the administration level decision-makers to evaluate the level of funding on long term, to allocate it and to decide on the MR&R policy.

The MR&R policy is a target-oriented practice of the road administration for the maintenance of its bridge stock. It is a collection of targets and rules that should be considered in all the MR&R activities of the organisation. One purpose of a BMS is to control in practice that the strategic targets are taken into account at all the decision-making levels related to MR&R, also taking into account the funding constraints.

A traditional goal setting for a BMS is to keep a steady-state condition of the structures to preserve the asset value of the bridge stock. An optimum condition level for structures is obtained as a result of the network level analysis. This optimum condition level can be considered to be the long-term goal for the management. The short-term goal is to define the optimal yearly steps for approaching the optimum condition state at which the MR&R costs are assumed to be minimised. How rapidly the optimal condition level can be achieved depends on the available budget. The financing must be high enough to lift the condition from the "status quo" level, see Figure 3.1.

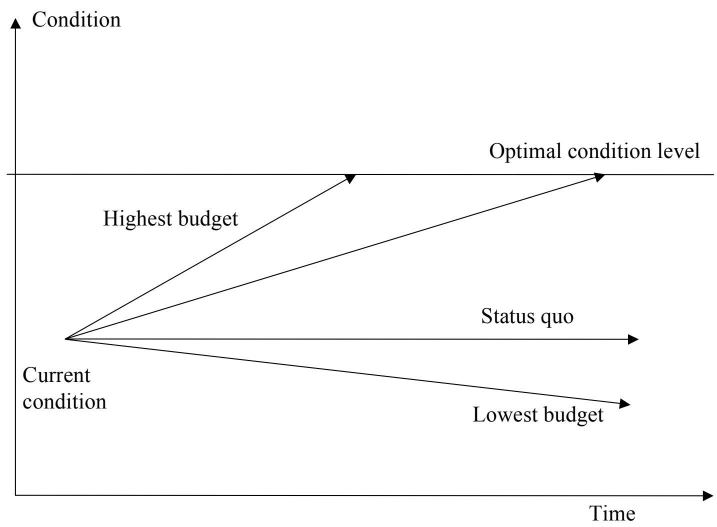


Figure 3.1 *The dependency of the future condition level on financing (ST analysis), Männistö & Feighan (1999).*

One of the main requirements of a BMS is the control of reliability of the structures over time. The safety is controlled by condition constraints, i.e. by defining the lowest allowable condition states for structures.

In a BMS user costs are an important issue. For instance, a weak bridge may cause considerable extra expenses for some users as a result of a longer transport route. A narrow old bridge that causes a bottleneck for traffic results in extra expenses to all road users. Normally, the owner costs form a descending curve and the user costs an ascending curve as a function of increasing degradation of a structure. The minimum socio-economic costs, totalling the owner and user costs, would then lie between the extreme ends of high and low condition, as seen in Figure 3.2

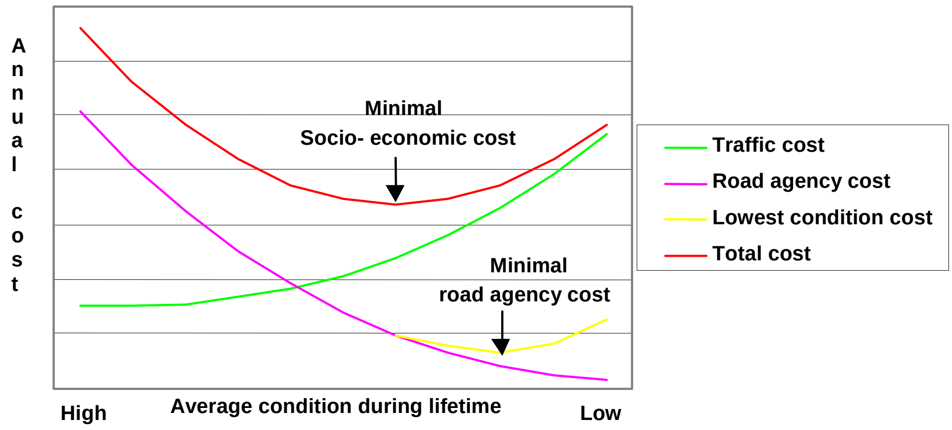


Figure 3.2 *Definition of the optimal condition level of structures from a socio-economic point of view (LT analysis), Männistö & Feighan (1999).*

A bridge management system is always based on a well-defined data inventory. The data structure of the inventory must be consistent with the system needs. It should allow the input of inspection and condition assessment data and repair data as well as structural data on all levels of structural hierarchy.

Typical needs and requirements for a bridge management system of the road administration are the following:

- Need for economic justification of decisions
- Objective basis for decisions, based on engineering, economic and ecological grounds
- Determination of medium and long-term targets and need for definition of appropriate maintenance strategies to achieve the targets
- Strategic guidelines for preservation of assets
- Optimising MR&R strategies based on engineering and economic grounds
- Need for selection of justifiable maintenance decisions within budget constraints
- Need for showing value for money in infrastructure provision and maintenance
- Need for allocation of funds
- Evaluation of whole life costing, including user costs
- Implication of lower standards of performance.

Especially, for the maintenance engineers and repair designers the needs are:

- Well organised condition assessment system and inventory for the structures
- Optimisation of MR&R measures for specific components, modules and objects
- Guaranteed safety
- Safeguarded investments

- Correct timing of MR&R measures
- Evaluation of MR&R costs
- Combination of optimised measures into MR&R projects
- Prioritisation of projects
- Production of annual repair and reconstruction programmes
- Budget control.

3.4.1 Short presentation of the Swedish Bridge management system

The Swedish Road Administration (SRA) has since the mid 1970s used computerized BMS. The latest update of SRA´s BMS is called Bridge and Tunnel Management system (BaTMan), which was introduced in 2004. BaTMan supports the management of a bridge structure during its whole lifecycle, from the design phase to the demolishing stage and even after. BaTMan is an Internet based system, which means that users all the time have updated information about the actual bridges online (https:/batman.vv.se).

Inspections

The main purpose of the inspections is to ensure that the safety and traffic ability of the bridges meet the requirements put on the Administration by the Government. More, the inspections reveal the physical and functional condition thus providing the basis for an efficient and economical bridge management. The bridge inspections in Sweden are since 1987 divided into three types, according to the nature of their aim, scope and frequency. They are:

- General inspection
- Major inspection
- Special inspection

The aim of the ***general inspection*** is to follow up the assessed damage during earlier inspections. Another important aim of this inspection type is to detect and assess new damage. Even this inspection type can detect if the contracted maintenance work has been properly performed.

Every structural part of the bridge together and their included elements have to be visually inspected. Structural parts under water are excluded. There is no demand on hand-close investigation unless new damage is detected.

General inspection is a simpler inspection compared to the major inspection. The scope of the general inspection is to check the recorded damage from previous major inspections and check if the assessed development of these was correct. If new damages are detected, they will be recorded and assessed according to current rules.

General inspection has to be performed on bridges with a theoretical span larger than 5,0 meters. Smaller bridges are normally exempted from this inspection type. The time interval between two general inspections is maximum three years. The personnel performing this inspection type have to posses the same competence as the inspectors performing major inspections.

Major inspection is the most important inspection type performed on the Swedish road bridges. The scope of this inspection type is to detect and asses damages and defects which can affect the designed function or the traffic safety, both in the short and the long run (within 10 years). Another aim is to detect even minor damage or defects that, if not attended to, can cause increased maintenance or repair costs within a 10-year period.

Every structural part and their in-going elements, which are within hand reach, have to be investigated. During this inspection, even the structural parts located under the water surface have to be closely inspected by qualified divers. Even adjoining parts of the bridge such as road embankments, slopes, abutment ends, fill revetment and fenders have to be inspected. If the inspected bridge contains mechanical or electrical equipment, such as movable bridges, these parts will also be subject to close inspection.

The inspection has to be done hand-close. Special inspection equipment, such as a bridge-lift, will allow a close look under the bridge deck, a structural part difficult to inspect otherwise.

This inspection type requires that a series of physical measurements have to be performed. Such measurements are made to determine for example the real bottom profile (erosion risk), chloride content and carbonization of concrete, measurements of the level of corrosion of the reinforcement bars and cracking.

The major inspection has to be carried out at least every sixth year. The demands on the bridge inspectors performing these are high.

Special inspection could complement information to be used in the LCC process, but is not presented here. For more information see Racutanu (2000) or the Swedish Bridge inspection Manual (SNRA 1996)

For making LCC calculations basic data can be transferred from the Swedish BMS system

- Condition class, *CC*, for the different members of a bridge.
- *LCV* values for the different members of a bridge and the whole bridge

These two systems will shortly be described in the following. The *LCV* and the *CC* values are gathered by inspection of the bridges.

Lack of Capital Value

Lack of Capital Value, *LCV* is expressed by the cost of the theoretical remedying measures that are necessary to undertake for restoring the bridge to its required economic condition.

The overall national maintenance policy of the SNRA is to manage *LCV* of the bridge stock to appropriate and consistent levels over time. *LCV* is used as a measure of overall bridge health, and socioeconomic characteristics of bridge management (costs and benefits) are derived as functions of *LCV*.

The bridge management methodology of the SNRA assumes that *LCV* consists of two components. The first component is related to the condition of the structural elements that have impact on the bearing capacity of a bridge. The monetary expression for this component is theoretical cost of those remedying actions only that improve the bearing capacity of the bridge and bring it to the expected level. The bearing capacity component of *LCV* is denoted as *LCV-b* or, in the formulas, LCV_b.

The second component of *LCV* is related to the durability of the bridge. Its monetary expression embraces the theoretical cost of the remedying actions that improve only the durability characteristics of the bridge without affecting its bearing capacity. The durability component of *LCV* is denoted as *LCV-d* or, in the formulas, LCV_d.

By definition, the overall LCV of a bridge is the sum of the two components:

$$LCV = LCV_b + LCV_d \tag{3.1}$$

The monetary expression for *LCV* and its components can be transformed into a relative form by dividing it by the theoretical bridge renewal cost. In its relative form, *LCV* is normally expressed in promille (1/1000) fractions of the bridge renewal cost (theoretical). For example, *LCV* of 20 means that the theoretical cost to bring the bridge to its required level of bearing capacity and durability makes 2 % (0,02) of the bridge's theoretical renewal cost.

The deterioration process is modeled by using the deterministic functions of *LCV*. The assumption is that within each quasi-uniform segment of the bridge population (stratum) it is possible to approximate the dynamics of *LCV* components with an analytical function.

As an approximation *LCV* can be approximated with the following exponential expression:

$$LCV = a_0 + a_1 e^{\alpha t} \tag{3.2}$$

Where t is the apparent age of the bridge in years, i.e. time since the bridge has been either constructed or rehabilitated to the zero-LCV condition.

Parameters a_0, a_1 and α will have to be estimated by using regression.

Deterioration models (i.e. sets of parameters a_0, a_1 and α) may vary by strata, and within each stratum, separate models will have to be developed for the bearing capacity and durability components of *LCV*.

According to the maintenance policy of the SNRA, decisions about undertaking remedying actions on a particular bridge are based on its condition, which is expressed in the form of *LCV-b* and *LCV-d*. These policies may vary across bridge strata, but generally, they are all proposed as combinations of the following generalized actions:

- No action
- Minor maintenance
- Maintenance - durability
- Maintenance – bearing capacity
- Replacement

Within each action type category (except "No action"), detailed actions can be specified.

Condition Class

The bridge inspector must record certain damage data during the inspection. The extent of the data depends on the type of performed inspection. The requirements are established in the bridge inspection manual of the SNRA. Two important requirements in the damage documentation process are the measurement and condition assessment of damages. This is done for damaged structural elements in the following two stages:

- Stating the physical condition in terms of measurements and measured values
- Assessment of the functional condition in terms of condition classes

The physical condition is determined with reference to the development of previous or new damages and certain known deteriorating processes. The different methods of measurement that are to be used for a particular type of damage are described in SNR (1996 d) publication 1996:038(E). The physical condition of a damaged structural element can then be described using the variable defined for each method of measurement.

The functional condition is described by the bridge inspector in terms of condition classes. The condition class describes to what extent a certain structural member satisfies the designed functional properties and requirements at the time of inspection.

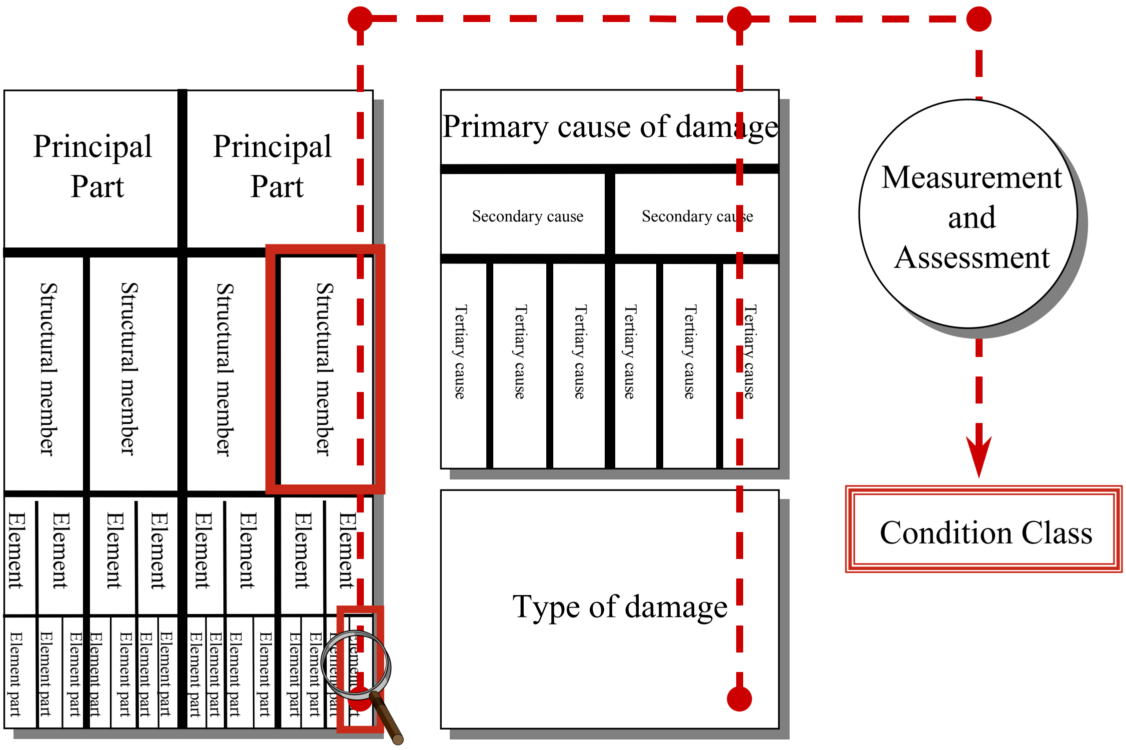


Figure 3.3 *Principle when reporting the assessed condition class for a structural member of a bridge at the time of inspection.*

It can be said that the assessment of condition classes is composed of previous and current measured values (the physical condition) and the inspectors competence in the propagation of different deterioration processes.

The condition class, *CC*, for a structural member can be registered on a scale of four. The scale implies that, at the time of inspection, the functional condition for the structural member was considered to be:

Table 3.1 Assessment of condition classes for bridge structural members

Condition class	Assessment
3	Defective function
2	Defective function within 3 years
1	Defective function within 10 years
0	Defective function beyond 10 years (No damage at time of inspection)

Another term that was used within the SNRA was the overall condition class. The overall condition class reflects the function of the entire structure with respect to the load carrying capacity, traffic safety and durability. The overall condition class, *OCC*, for bridges is determined by the assigned condition classes (*CC*) for the different structural members. The assessed condition classes are given different weights. Even if this measure is not used anymore it can be of value in a LCC calculation process.

Table 3.2. *Weighting factors for a structures different structural component for determining the overall condition class (OCC) for a bridge.*

Structural member	Weight
Foundations	4,0
Slopes and Embankment ends	3,0
Supports	4,0
Wing wall and retaining walls	3,0
Bearings	4,0
Primary load bearing elements	4,0
Other load bearing elements	4,0
Bridge deck	4,0
Edge beam	4,0
Waterproofing	1,0
Surfacing	1,0
Parapet	2,0
Expansion joints	1,0
Drainage system	1,0

If any of the structural members in Table 3.3 has been assigned condition class $CC = 3$, the entire bridge is then assigned $OCC = 3$. Even if assigned condition class $CC = 2$, the bridge will be assigned the overall condition class $OCC = 2$.

Table 3.3 *Decisive structural members for the overall Condition class (OCC) assigned to a bridge.*

Structural member
Foundations
Supports
Bearings
Primary load bearing elements
Other load bearing elements
Bridge deck
Edge beam

Reporting damage type

The Swedish system for inspection also incorporates a method for defining possible reasons for the damage to the different structural members. The system is not presented here but Figure 3.3 depicts an example how the system works for two examples

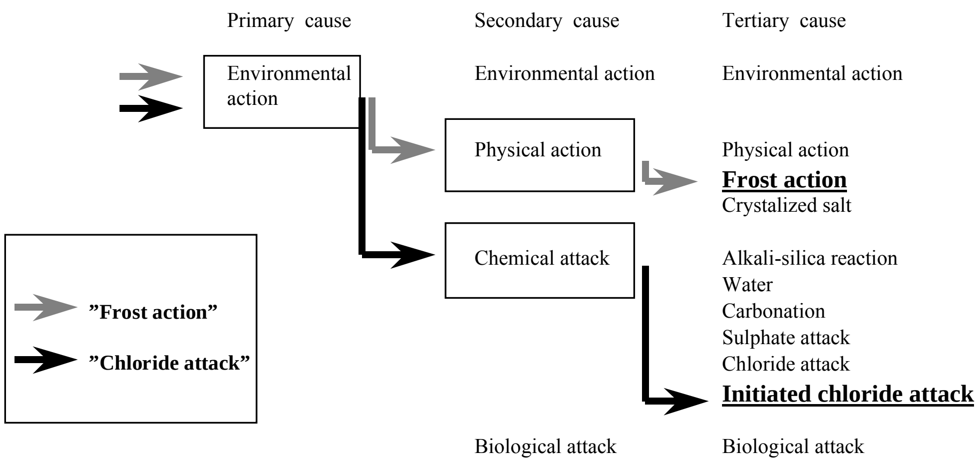


Figure 3.4 *Flow diagram. Subdivision of the main damage cause. Example shows how “Frost action” and “Initiated chloride attack” are reported.*

3.4.2 Short presentation of the Finnish Bridge management system

The overall principles and objectives of FinnRA's BMS system is outlined in the introction part of this chapter, section 3.4. The RinnRA system consists of the following three parts:

- Bridge Register and Inspections,
- Hanke-Siha and
- Network Level Bridge Management System.

Bridge register is a database that contains mainly only basic data of bridges. The condition of a bridge is classified according to a condition number given by inspectors using scale 0 to 4:

4 = very bad,

3 = bad,

2 = adequate,

1 = good and

0 = new.

The need of repair is judged by taking into account the condition, damage and urgency classes. A weighted damage value is determined for the main structural parts and the whole bridge.

All bridge inspectors have to participate in an education course ones a year.

The quality of inspectors is evaluated by FinnRA.

Hanke-Siha is a project level management system by which the development of the condition of a bridge can be followed.

Network Level Bridge Management System covers all bridges managed by FinnRA. The only language in the FinnRA BMS System is Finnish.

3.4.3 Short presentation of the Norwegian Bridge management system

Introduction

The BMS system managed by the Norwegian Road Administration is called BRUTUS which is an acronym for **BRU** and **TU**nnel **S**ystem.

The Norwegian Public Roads Administration is responsible for more than 17 000 bridges on national and county roads. The replacement value of these bridges is estimated at about NOK 45 milliards (USD 8,0 billion). In addition to the high level of safety that is required, many of the bridges are also exposed to extreme climatic and environmental conditions.

The computerised part of BRUTUS is a client/server application with a user inter face based on Microsoft Windows and utilises most of the latest advances in user friendly computer technology. BRUTUS comprises also handbooks for Bridge Inventory and Bridge Inspections as well as a Work Specification Handbook and user-manuals for the computer program. Appropriate training within each subject is a vital issue and will be given. It must also be emphasised that BRUTUS is functional without the computerised part, but this will of course be an inconvenience. The purpose of the system is to provide a basis for top and medium level management as well as guidance, support and assistance to bridge managers, to ensure cost effective inspections and maintenance operations and to document the results achieved.

The System Administration Module

The Administration Module handles the authorisation level of all users. The module handles also the safety routines of the System and the checking routines with National Road Data Bank. The modules deal with the logging of the use of the system as well. The content of this module is mainly information about the users with associated rights.

Bridge Inventory Module

The purpose of this module is to provide a complete and nationwide overview of all bridges in the Norwegian public road system. For management purposes BRUTUS provides technical, administrative and economic information. Together with the other modules, the bridge inventory module will provide a complete information system for all the bridges through their lifecycle, from design, via construction and operation to demolition.

The contents of this module is key data for all bridges, such as:

- Administrative data like; bridge no/name, status, etc.
- Road data like; location and traffic limitations etc.
- Load data like; axle loads and exceptional transport info etc.
- Element data containing details like; type, materials etc.
- Documentation data like; archive reference, photos, drawings etc.
- Remarks data like; information of incidents, experience etc.

Bridge Inspection Module

The purpose of this module is to be an effective tool for planning and a support for carrying through different types of inspections. The module contains information on the condition of bridges from various inspections in a structured mode as a basis for further processing and analysis. Also handling of results from material investigations is taken care of by this module.

The content of this module is information about condition and observations from all inspections, as well as action and cost estimates for the recorded damage. The different items in this module are

- Planning of inspections (type, interval, cost, etc.)
- Documentation of conditions with text and photos
- Evaluation of damage with degree, consequence, reason, extent and repair cost
- Tailor made inspection forms

Maintenance Module

The purpose of this module is to be an effective management tool for planning and assignment of priorities to carry out maintenance tasks in the most economical way possible.

The most important contents of this module is to incorporate all information on necessary maintenance tasks for the different elements, e.g.:

- Maintenance plan for each bridge
- Overview of the maintenance program on a yearly basis
- Management and print-out of job orders
- Overview of completed maintenance tasks

Cost Module

The purpose of this module is to be a support to the user concerning cost of the different maintenance activities. It produces the asset value as well.

The contents of this module are information on:

- Data for preparing a maintenance budget
- Asset value
- Cost Index

Some features of the BRUTUS system

Includes a lot of detailed technical information as in the Swedish and Finnish BMS systems. Each bridge is denoted by a bridge number which consists of a county number and the bridge number in the county.

The inspection module includes for instance an inspection plan, last inspection executed and the cost estimate of an expected maintenance work.

A figure (bridge condition index) indicates the urgency of the reparation work:

4 = has to be repaired within half a year,

3 = has to repaired within 1 to years,

2 = has to be repaired within 3 to 0 years and

1 = can to be repaired after 10 years or more.

There is information about the type, seriousness and consequence of a damage, i.e. load carrying capacity, environmental reason etc. Development of damages, for instance cracks, can be followed by pictures. Data is updated approximately by 50 bridge inspectors.

Only a Norwegian version exists at the moment.

Handbooks

The purpose of the handbooks is to guide and inform all bridge management staff involved in collecting and recording inventory data, inspection data as well as performance of maintenance activities. The handbooks and associated training courses should ensure a systematic and objective collection and evaluation of data. The following handbooks are included in BRUTUS:

- Guidelines
- Handbook for Bridge Inventory
- Handbook for Bridge Inspection
- Handbook for Work Specification

User interface and technical data

The environment is based on Microsoft Windows with context sensitive on-line help, editable code system and a wide range of pre-compiled or user defined reports.

The technical data of the system is a client/server architecture with

- Client: Windows NT, Windows 2000, Windows XP
- Server: Windows NT, Windows 2000 Server, Windows 2003 Server
- Oracle database

The system is operative on stand-alone PC and can be used with terminal server.

3.5 Methodology for LCC calculation

According to the definitions in section 2.1 a comprehensive definition of Life Cycle Costing LCC is that it is a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs. In particular, it is an economic assessment considering all projected relevant cost flows over a period of analysis expressed in monetary value. Where the term uses initial capital letters, *LCC*, it can be defined as the present value of the total cost of an asset over the period of analysis. (In principle according to Tupamäki, (2003b), [88].) LCC calculation can be performed at any stage during the life-time of the structure, thus resulting in i.e. remaining LCC costs for an existing structure.

For making a complete LCC calculation for a bridge at least the following parameters are needed:

1. Functional demands for the bridge. The most important of these demands are the planned life-time, accepted traffic interruptions
2. Physical description of the bridge. The structure is usually divided in parts, i.e. according to Table 3.2 and the different parts are given geometrical measures or weights.
3. Calculation methods for costs. This could be considered to be the LCC basic method including real interest rate calculations with known costs for operation, inspection, maintenance, repair, costs for accidents and demolition. Methods for this are discussed in section 3.4
4. Time for interventions and incidents during the life-time of the bridge.

Point 4. is the most complicated point in an LCC calculation, since it must be based on known future events and behaviour of the bridge. And real knowledge of the future is of course by definition not existing. Tools for this point are though discussed in this chapter in the following sections.

- Interventions based on experience by specialists, section 3.6.
- Interventions based on degradation models, section 3.7. Since the Markov Chain Method is such a valuable tool, this method will be described in a special section, section 3.8.
- Interventions based on economical following-up of degradation, the LCV-method, see section 3.7.

3.6 Basic calculation methods for LCC

The different contributions in a complete LCC analysis of a structure could be divided into parts, mainly because different bodies in the society will be responsible for the costs occurring as a consequence of constructing or using the structures. There are many reports in this field i.e. *Burley Rigden (1997), Hawk (1998), Siemens et al. (1985), Veshosky Bedleman (1992).* The following presentation follows *Troive (1998), Sundquist Troive (1998a* and *1998b)*

LCC = a general variable describing a cost, usually by using the net present value method calculated to the time of opening the bridge.

3.6.1 Owner costs

LCC_{owner} the part of the total LCC cost that encumber the owner of the project. This cost can in turn be divided into different parts according to eq. (3.3)

$$LCC = LCCA + LSC + LCCC \tag{3.3}$$

Where

LCCA = is the cost for acquisition of the project including all relevant costs for programming and design of the project, by the net present value calculated to a specified time usually the opening of the bridge

LSC = (Life Support Cost) is the cost for future operation, maintenance and repair of the bridge, by the net present value calculated to a specified time usually the opening of the bridge.

LCCC = (Life Cycle Cost Consequence), is the future costs for eventual negative consequences, by the net present value calculated to a specified time, usually the opening of the bridge. This kind of costs could eventual be a part of the societal cost.

The *LSC*, the Life Support Cost, can in turn be divided into two parts according to formula (3.4)

$$LSC = CI + CN \tag{3.4}$$

Where CI is the investment in the necessary equipment and other resources for the future operation and repair.

CN is the future cost for operation, maintenance and repair, by the net present value calculated to a specified time, usually the opening of the bridge

The investment part of the maintenance, CI, could be divided according to eq. (3.5)

$$CI = CI_{\mathrm{r}} + CI_{\mathrm{v}} + CI_{\mathrm{d}} + CI_{\mathrm{t}} \tag{3.5}$$

where

CI_{r} = spare parts and material

CI_{v} = instrument, tools, vehicles that is needed for inspection and maintenance

CI_{d} = documentation i.e. drawings and instruction manuals needed for inspection and maintenance

CI_{t} = education of personnel for operation and maintenance.

All of the costs mentioned above must be calculated to a given point in time, usually the time of inauguration of the bridge. The standard method for calculating life cycle costs is by discounting the different future costs to present values. The “present” time might differ, but usually the time used is the time of inauguration of the project. The life-cycle cost is then the sum

$$LCC_{\mathrm{owner}} = \sum_{t=0}^{T} \frac{C_{\mathrm{t}}}{(1+r)^t} \tag{3.6}$$

In eq. (3.6) is

C_{t} the sum of all costs incurred at time t,

p the real interest rate or a rate taking into account changes in the benefit of the structure and

T is the time period studied, typically for a structure for the infrastructure the expected life span.

The most important factor in eq. (3.6) is, except of course the costs, the interest rate p. The real interest rate is usually calculated as the difference between the actual discount rate for long loans (p_{L}) and the inflation (p_{i}) or more exact

$$p = \frac{p_{\mathrm{L}} - p_{\mathrm{i}}}{1 + p_{\mathrm{i}}} \tag{3.7}$$

The effect of the factor in the denominator is, taking the uncertainties into consideration, negligible.

If there is a change in the benefit of the structure, i.e. an increase in the traffic using the bridge, this could approximately be taken into consideration by using the formula

$$p = \frac{p_L - p_i - p_c}{1 + p_i} \tag{3.9}$$

where p_c is the increase in traffic volume using the structure. If there is a risk for the opposite, a decrease in the usefulness of the structure, this factor should be given a negative sign. This could i.e. be accomplished by building the structure at the wrong place or on a road with decreasing traffic. Taking all factors into account the p-value should be called "calculation interest rate" or likewise. Typical values for p are in the order from 3 % to 8 %, see section 2.4

Eq. (3.6) is usually used to calculate the owners cost for investment, operation, inspection, maintenance, repair and disposal.

The costs C_t at the time of inauguration are usually not too complicated to assume for the necessary above-mentioned steps in the management of a structure. There is a great uncertainty in choosing the p-value, but still more uncertain is the calculation of the time intervals between the different maintenance works and repairs. To be able to assume the time intervals used for calculation, the degradation rate of the different parts of the structure must be known. Every structural engineer knows that this is a very complicated task. According to our knowledge the best information for assuming the time intervals is historical data from actual bridge inspections and repairs. Theoretical degradation models such as using carbonation rates, Fick´s second law or similar approaches seem, at this stage not to feasible. Combination of historical data with Markov-chain methodology seems however to be feasible if enough data is available.

3.6.2 Costs for the society

Typical costs, not clearly visible for the owner are costs occurring due to damage to the environment, the usage of non-renewable materials and society costs for health-care and deaths due to traffic accidents.

Most construction materials consume energy for production and transportation. One way to take this into account is by multiplying all costs for materials for construction and repair with some factor due to energy consumption for manufacturing and transportation. The use of non-renewable materials might be taken into consideration by involving costs for reproducing or reusing materials when the structure is decommissioned.

Costs for health-care due to accidents and deaths is probably only actual when two different types of structures are compared and when the risks for accidents differs between the two concepts, or costs for accidents due to roadwork. The accident costs for roadwork could be calculated using the formula

$$LCC_{\text{society, accident}} = \sum_{t=0}^{T} \left(A_r - A_n\right) ADT_t \cdot N_t \cdot C_{\text{acc}} \frac{1}{(1+r)^t} \tag{3.10}$$

In eq. (4) A_n is the normal accident rate per vehicle-kilometres, A_r is the accident rate during roadwork and C_{acc} is the cost for each accident for the society, ADT_t is the average daily traffic, measured in numbers of cars per day at time t and N_t is the number of days of road work at time t. The costs should be calculated to present value and added up for all foreseen maintenance and repair works for the studied time interval T.

As an example the Swedish Road Administration uses a cost of about 1,5 million $ for deaths and a third of that sum for serious accidents.

3.6.3 User costs

User costs are typically costs for drivers, the cars and transported goods on or under the bridge due to delays due to roadwork. Driver delay cost is the cost to the drivers who are delayed by the roadwork. Vehicle operating cost is capital cost for the vehicles, which are delayed by roadwork. Cost for goods is all kinds of costs for delaying the time for delivering the goods in time. Other user costs might be cost of damage to the vehicles and humans due to roadwork not included in the cost for the society. Travel delay costs can be computed using eq. (3.11)

$$LCC_{\text{user,delay}} = \sum_{t=0}^{T} \left(\frac{L}{v_{\text{r}}} - \frac{L}{v_{\text{n}}} \right) ADT_t \cdot N_t \left(r_{\text{L}} w_{\text{L}} + (1 - r_{\text{L}}) w_{\text{D}} \right) \frac{1}{(1+r)^t} \tag{3.11}$$

In eq. (5) L is the length of affected roadway on which cars drive, v_{r} is the traffic speed during bridge work activity, v_{n} is the normal traffic speed, ADT_{t} is the average daily traffic, measured in numbers of cars per day at time t, N_t is the number of days of road work at time t, r_{L} is the amount of commercial traffic, w_{L} is the hourly time value for commercial traffic and w_{L} the hourly time value for drivers. The costs should be calculated to present value and added up for all foreseen maintenance and repair work for the studied time interval T.

Vehicle operating costs and costs fore transported goods can be calculated using eq. (3.12)

$$LCC_{\text{user,operating}} = \sum_{t=0}^{T} \left(\frac{L}{v_{\text{r}}} - \frac{L}{v_{\text{n}}} \right) ADT_t \cdot N_t \left(r_{\text{L}} (o_{\text{L}} + o_{\text{G}}) + (1 - r_{\text{L}}) o_{\text{D}} \right) \frac{1}{(1+r)^t} \tag{1.12}$$

In eq. (3.12) the same parameters are used as in eq. (3.11) except for o_{L} which are operating cost for the commercial traffic vehicles, o_{G} operating cost for transported goods and o_{D} operating cost for cars. The costs should be calculated to present value and added up for all foreseen maintenance and repair work for the studied time interval T.

There is usually an accident cost for roadwork for the user not included in the cost for the society. Eq. (3.6) could be used also for this by just adjusting the cost parameter for this case.

3.6.4 Failure costs

There is a small risk for the total failure of a structure. To get the cost for failure one has to calculate all costs ($K_{\text{H},j}$) for the failure, accidents, rebuilding, user delay costs and so on and then multiply these costs with the probability for failure and with the appropriate present value factor according to the formula

$$LCC_{\text{failure}} = \sum_{j=1}^{n} K_{\text{H},j} R_j \frac{1}{(1+r)^j} \tag{3.13}$$

In eq. (3.13), R_j is the probability for a specified failure coupled to $K_{\text{H},j}$. For normal bridges the probability of failure is so small that the failure costs could be omitted in the analysis. The cost for serviceability limit failure is discussed in *Radojičić (1999)*, but actually the methods presented in the present paper are a kind of statistically LCC-method given that the parameters for remedial actions are considered random.

3.7 Time between different MR&R actions

To be able to calculate costs incurring at different times and then be able to discounting these costs to present values, one has to assume the time intervals for different measures that has to be taken during the life span of a structure. Typically a bridge needs to be inspected, maintained and repaired many times during its life span.

Life span

One parameter of great importance is the planned service life span of the bridge. Standards often call for life spans from 80 to 140 years. In reality very few bridges survives such long lives. Due to the need for road rectifying, road widening, higher prescribed loads and changes in the society the actual service life of a bridge is shorter than the theoretical life span. In Sweden the mean time for decommissioning bridges is in the order of 60 to 70 years.

Time intervals for inspection and standard maintenance

All structures have to be inspected and maintained. The time intervals between these measures depends on the type of bridge, the experience in the different countries, the economical resources available, the *ADT* value, the usage of de-icing salt and so on.

In Sweden all bridges are cleaned every year after the winter season and lightly surveyed. More profound inspections are performed every third or six year. These kinds of measures will of course vary between different countries and different owners. These types of measures will build up a part of the whole life costing for the owner of the bridge. Table 3.0 shows a comparison of the time intervals for bridge inspections in different countries. Definitions of the different types of inspections are different from country to country, so it not possible to directly compare the denomination and the intervals.

Regular maintenance will of course always be needed. Typically railings, lampposts and other steel details need repainting regularly.

Railings are often demolished by cars. The time intervals and the probability for these kinds of incidents are very dependent of the bridge type and the *ADT*-value.

Table 3.0 *Inspection intervals in some countries.*

Country	Inspection intervals for		
	General inspection	**Major inspection**	**Special inspection**
Belgium	1 year	3 years	Depends on results from major inspection
Denmark		1-6 years depends on general inspection results	
France	1 year	5 years	
Italy	3 months	1 year	
Canada (Ontario)		Defines by the owner (2 years is recommended)	
Slovenia	2 years	6 years	when needed
Switzerland	15 months	5 years	when needed
Sweden	1 year	3 years	6 years
Germany	3 months	3 years	6 years
USA (national bridges)		2 years	

Degradation models

All the discussed equations in section 3.6 depend on information of lots of parameters, many of which are very uncertain. One very important factor is the time intervals between repair and maintenance work. These intervals for remedial actions are not fixed values as they are affected by the degradation and by considerations of which intervals that are most economical. It is here to mention that bridges usually are not degrading; it is their structural elements that degrade.

There are different methods to forecast the degradation of different structural elements of bridges:

- One method is to use mechanistic or chemical models like Fick´s second law for diffusion of chlorides, carbonation rates, number of frost cycles and combinations to try to forecast degradation. Such a method is used by Vesikari (2003) and Söderqvist & Vesikari (2003). This approach is used in combination with the Markov Chain Method as a tool for analysis and this system is presented and discussed in section 3.8 in this report.
- An other method is to use and evaluate results from field observations, *Racutanu (2000), Mattsson & Sundquist (2007).*
- The up to day most applied method is to use experience from specialists, usually people deeply involved with inspection of bridges.

A special problem when using more sophisticated methods is to find suitable tools for going from degradation models to time predictions for MR&R actions.

3.8 The Markov Chain Method (MCM)

The Markov chain is a convenient tool for estimating the service life of bridge components Jiang & Sinha (1989). The application of the Markov chain technique in estimating the service life of components in technical systems has been used in a number of different areas, such as the deterioration of sewer systems, Abraham & Wirahadikusumah (1999). The results in the form of numerically determined deterioration curves proved to give good approximations when compared to deterioration curves based on experience and expert opinions. A preliminary investigation of possible numerical implementations of the Markov chain method for estimating the service life of bridge components has been carried out by Ansell (2001).

The MCM method has in a very effective and interesting way being developed for making LCC analysis for concrete bridges has been developed by M-K. Söderqvist and E. Vesikari. The basis for the method is presented in Söderqvist & Vesikari (2003), Söderqvist & Vesikari (2006), Vesikari (2002) and Vesikari (2003). The computer program “Bridgelife” based on the method is presented in Chapter 4. of this report.

3.8.1 Matrix formulation of the Markov chain

A deterioration function based on a Markov chain is used here to couple an average condition rating at time *t,* estimated by a regression function $Y(t)$. The accuracy of this approximation depends on the step length taken during numerical calculation of matrices within the Markov chain so that:

$$E(t,\mathbf{P}) \cong Y(t) \tag{3.14}$$

The values of condition ratings $E(t,\mathbf{P})$, estimated by a Markov chain, is given Jiang & Sinha (1989) by the matrix and vector multiplications:

$$E(t,\mathbf{P}) = Q(t) \cdot \mathbf{R}^{\mathrm{T}} = Q_t \cdot \mathbf{R}^{\mathrm{T}} = Q_0 \cdot \mathbf{P}^t \cdot \mathbf{R}^{\mathrm{T}} \tag{3.15}$$

Where superscript $^{\mathrm{T}}$ denotes transformation. The number of objects at each state at a certain time is expressed by a state vector $Q(t)$, thus providing a damage index distribution. The condition rating at age t is calculated from the initial condition Q_0 at $t = 0$ by t times multiplication by a transition probability matrix $\mathbf{P}$, i.e. a chain multiplication. The deterioration is expressed in terms of discrete condition states.

In Sweden as explained in section 3.3.1 a four-graded scale is used, where index 0 to 3 defines the condition of the studied objects. Degradation index 0 represents the best condition, the initial condition state, while index 3 defines the limit state at which the service life is reached. Index 4 represents the post limit state. According to section 3.3.2 a 5 graded scale is used in Finland and in Norway a 4 graded scale is used. The exact definitions of the grading differ but we can assume that in the above matrix formulation, the vector **R** is a (5:1) vector of condition ratings which connects the states to the condition rating scale, here:

$$\mathbf{R} = \begin{pmatrix} 0 & 1 & 2 & 3 & 4 \end{pmatrix} \tag{3.16}$$

An initial state vector is thus:

$$\mathbf{Q}_0 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{3.17}$$

The relationship between state vectors as a function of age is:

$$\mathbf{Q}_{t_0+t} = \mathbf{Q}_{t_0} \cdot \mathbf{P}^t \tag{3.18}$$

An average transition probability matrix **P** is in the following denoted by $\mathbf{P}_{n\text{-}m}$, and is valid from year n to m. The number of years N over which the average of the transition elements within the matrix is taken is given by $m = n + N$. The chosen condition rating scale gives:

$$\mathbf{P} = \begin{bmatrix} p_0 & 1-p_0 & 0 & 0 & 0 \\ 0 & p_1 & 1-p_1 & 0 & 0 \\ 0 & 0 & p_2 & 1-p_2 & 0 \\ 0 & 0 & 0 & p_3 & 1-p_3 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.19}$$

The four diagonal transition elements p_0, p_1, p_2 and p_3 are the probabilities for the deterioration of a bridge component to remain in state 0, 1, 2 or 3 when the component ages one time period, which in this case is one year. The diagonal element 1 in the fifth row and column restricts the values of condition ratings to 4, i.e. the limit state. The elements $1 - p_0$, $1 - p_1$, $1 - p_2$ and $1 - p_3$ on the super diagonal are the probabilities for the deterioration to advance one state as the bridge component ages one year. As a component will either remain at the same state or proceed to the next state in the next time period, the row sum of **P** must always be 1.

The MCM can be used both for the degradation and the repair process. The denomination P is coupled to the degradation process and for this the following assumptions have to be made: The condition of the studied objects cannot be improved (repaired), and the condition state can either remain the same or shift to a higher within the next transition period.

In reality, structural members are repaired and they can shift in one step to the third or higher condition state. The first assumption makes the model accurate until major repairs are made, usually after approximately 30 years on bridges in Sweden. The repair process using the MCM is discussed in section 3.8.4. It also implies that the transition probabilities below the diagonal probabilities are zero. The second assumption can be considered reasonable if all accident related damages are exempted. As an example, an edge beam or a parapet on a bridge can be destroyed on the first day of their service life by a vehicle collision. If the assumption is taken, all the probabilities above the super diagonal in **P** are zero.

The matrix elements p_0, p_1, p_2 and p_3 could be determined from the known relation $Y(t)$ by solving the non-linear minimization problem or by other methods, see section 3.8.4:

$$\min \sum_{t=1}^{N} \left| Y(t) - E(t, \mathbf{P}) \right| \tag{3.20}$$

Where $0 \leq p_i \leq 1$ for $i = 1, 2, 3, 4, 5$ and N = 5. This is done using a simple algorithm, which combines the matrix elements while keeping count of the error given by Eq. (7). The combination of p_0, p_1, p_2 and p_3 that provides the least error is the solution. The method is time consuming for small steps, and it is recommended that a more sophisticated numerical method be used in practice.

3.8.2 Combination of Markov Chain Method with LCC

The basic idea of the method is to combine a Markov Chain based condition analysis with a life cycle cost analysis. Starting from the initial condition state distribution of a component a statistical condition analysis covering the whole design period is performed. The optimal MR&R (maintenance, repair and rehabilitation) actions are automatically specified by the help of decision trees. The timings of MR&R actions are automatically triggered by a condition guarding system which is built over the Markov Chain based condition analysis. Whenever the predefined maximum allowable probability of exceeding the limit condition state are attained the system triggers a MR&R action.

Markov Chain based Condition analysis

The Markov Chain method is a mathematical framework based on probability calculus and vector algebra. In the condition analysis of structural components it is used for predicting the future condition of structures over a certain time frame. The condition is presented in the form of condition vectors i.e. frequency distributions based on a predefined set of condition states. The annual changes in the condition state distributions are predicted by matrix multiplications using transition probability matrices.

The Markov Chain method as such does not contain any information on the rate of degradation of structures. However, if such data is available in any form it can usually be transferred into transition probabilities of the Markov Chain degradation matrices so that the results of the Markov Chain based condition analysis corresponds closely the original information. Markov Chain transition probabilities have also been proved to be suitable for modelling the action effects of various MR&R actions. The action effect models are necessary because the condition analysis must cover – not only the period up to the next repair of the structure – but over the whole design period which may comprise of many sequential MR&R actions of different types.

The following advantages can be gained by the Markov Chain based condition analysis:

- Fully probabilistic reproduction of the condition of a structure over the time frame.
- Capability of triggering actions based on the reliability theory.
- Capability of combining the condition related effects of both degradation and MR&R actions.

- Capability of straightforward combining sequential degradation processes such as the process of de-passivation by carbonation or chloride contamination and active corrosion of reinforcement.
- Capability of describing parallel time dependent processes and their interaction such as degradation of a coating on a structure which also is deteriorating.
- Easily attachable to a LCC analysis.
- Enables calculation of risk costs and costs that depend on the condition of the structure.

In the following a description on the basics of the Markov Chain method and its application to the condition analysis of structural components is given.

3.8.3 Basics of Markov Chain Modelling

The Markov Chain method evaluates the condition of structures as condition state distributions at each year *t*. A condition state distribution expresses the relative proportions (=fractions) of structures being at the defined condition states. A condition state distribution is exemplified in Table 3.4.

Table 3.4 *Condition state distribution (Example).*

State	0	1	2	3	4
Fraction	w_0	w_1	w_2	w_3	w_4
Example of fraction	0,25	0,35	0,25	0,10	0,05

When studying the condition of structures at the network level the fractions refer to the surface area (sometimes length or other functional unit) of all structures or structural parts belonging to a network of structures. At the object level the fractions refer to the surface area (or other functional unit) of one structure or a structural part. When predicting the condition of structures by the Markov Chain method the condition state vector is interpreted as expressing the probability of a structure or structural part to be at any of the condition states in the future. The sum of all fractions in a condition state vector must always be 1.

The number of condition states is not restricted. In the following examples of the Markov Chain calculus the number of states is assumed to be five consisting of states 0, 1, 2, 3 and 4. The condition state 0 represents the best and 4 the poorest condition. The condition state 3 defines usually the limit state of service life that is the state at which the structure should normally be repaired.

The changes in condition states as a result of both degradation and MR&R actions are evaluated by transition probability matrices. The condition state distribution of each year is obtained by multiplying the condition state vector of the previous year by the transition probability matrix. Mathematically the principle is presented in Equation 3.21. By repeated multiplication the condition state distributions can be predicted over time up to several years or even tens of years.

$$W(t) = W(t-1) \cdot P \tag{3.21}$$

where

$W(t)$ is condition state distribution of year t and

P is the transition probability matrix.

There are two kinds of transition probability matrices:

- Degradation matrices
- Action effect matrices.

Degradation matrices are applied in years when repair actions are not performed, i.e. the changes in the condition state distribution result only from degradation. The action effect matrices predict the condition state distribution, as it will be after the repair action. They are applied only in those years during which repair actions are performed. Accordingly, by the help of the Markov Chain it is possible to reproduce the condition of a structure during the whole time frame as a series of sequential annual condition state distributions. The treated time frame may include various maintenance and repair actions such as coatings, other predictive maintenance actions, repairs and renewals.

Degradation matrices

Usually the form of a degradation matrix is assumed to be as the one presented in Table 3.5. The elements of a transition probability matrix express the probability that a structure, which at the beginning of a year was at condition state i (vertical direction), will be at the end of the year at condition state j (horizontal direction).

It has been assumed in the table that within one year the structure either stays at the same condition state where it was at the beginning of that year or it drops to the next state, i.e. dropping more than 1 state in a year is not possible. Accordingly, most of the transition probabilities are 0. Only the diagonal probabilities, i.e. the probabilities that a structure stays at the same condition state and the probabilities next to the right of them expressing the probability that the structure will be transited to the next state during a year, are non-zero elements. The sum of transition probabilities in each row must be 1 ($p_{i;i} + p_{i;i+1} = 1$).

Table 3.5 *Transition probability matrix for degradation (5 state system).*

State	0	1	2	3	4
0	p_{00}	p_{01}	0	0	0
1	0	p_{11}	p_{12}	0	0
2	0	0	p_{22}	p_{23}	0
3	0	0	0	p_{33}	p_{34}
4	0	0	0	0	1

The transition probabilities of degradation matrices are determined automatically from previously developed degradation model functions by special conversion methods. So the information included in the material, structural and environmental parameters of the model functions are automatically transferred to the transition probabilities of degradation matrices.

The "drop-from-state" transition probabilities, $p_{i,i+1}$, can be deduced from the scaled degradation model functions by derivation of the model function and determination of the average value of the derivative within the interval of the states *i* and *i* + 1.

$$p_{i;i+1} = DoD'_{i;i+1} = \left(\frac{\partial (DoD(t))}{\partial t} \right)_{i;i+1} \tag{3.22}$$

where

$p_{i;i+1}$ is the transition probability from state *i* to state *i* + 1 and

$DoD(t)$ a scaled degradation function. *DoD* is "degree of damage" and is considered to be the same as condition state.

The average value of the derivative can be determined either by calculating the value of the derivative in several points within the range *i* to *i* + 1 or by determining the value of the derivative in a point that is proved to optimally represent the average.

The "Remain-in-state" transition probabilities, $p_{i;i}$, can be determined by subtracting the corresponding "drop-from-state" probability from 1.

$$p_{i;i} = 1 - p_{i,i+1} \tag{3.23}$$

At the lower right corner of the matrix the value of the probability element is always 1 as the structures in the highest possible condition state always stay at the same condition state.

The condition state vector after *n* years is predicted by multiplying the initial condition state vector, *W*(0), by the transition matrix *n* times in the row, as shown in the example of Figure 3.5. In this example the limit condition state of service life has been defined to be 3 (*DoD* = 3). The state 4 is assumed to be a "terminal state", i.e. an extra state where all structures finally end up. All structures in this case start off in perfect condition, so the initial damage index distribution is | 1, 0, 0, 0, 0 |.

Transition probability matrix

State	0	1	2	3	4
0	0.61	0.39	0	0	0
1	0	0.74	0.26	0	0
2	0	0	0.82	0.18	0
3	0	0	0	0.91	0.09
4	0	0	0	0	1

Year	State					
	0	1	2	3	4	Average DoD
0	1.000	0.000	0.000	0.000	0.000	0.00
1	0.610	0.390	0.000	0.000	0.000	0.39
2	0.372	0.527	0.101	0.000	0.000	0.73
3	0.227	0.535	0.220	0.018	0.000	1.03
4	0.138	0.484	0.319	0.056	0.002	1.30
5	0.084	0.412	0.388	0.109	0.007	1.54
6	0.052	0.338	0.425	0.169	0.016	1.76
7	0.031	0.270	0.437	0.230	0.032	1.96
8	0.019	0.212	0.428	0.288	0.052	2.14
9	0.012	0.165	0.406	0.339	0.078	2.31
10	0.007	0.126	0.376	0.382	0.109	2.46
11	0.004	0.096	0.341	0.415	0.143	2.60
12	0.003	0.073	0.305	0.439	0.181	2.72
13	0.002	0.055	0.269	0.454	0.220	2.84
14	0.001	0.041	0.235	0.462	0.261	2.94
15	0.001	0.031	0.203	0.463	0.303	3.04
16	0.000	0.023	0.175	0.458	0.344	3.12
17	0.000	0.017	0.149	0.448	0.385	3.20
18	0.000	0.013	0.127	0.434	0.426	3.27
19	0.000	0.010	0.107	0.418	0.465	3.34
20	0.000	0.007	0.091	0.400	0.502	3.40
21	0.000	0.005	0.076	0.380	0.538	3.45
22	0.000	0.004	0.064	0.360	0.573	3.50
23	0.000	0.003	0.053	0.339	0.605	3.55
24	0.000	0.002	0.044	0.318	0.635	3.59
25	0.000	0.002	0.037	0.297	0.664	3.62
26	0.000	0.001	0.031	0.277	0.691	3.66
27	0.000	0.001	0.026	0.258	0.716	3.69
28	0.000	0.001	0.021	0.239	0.739	3.72
29	0.000	0.000	0.018	0.221	0.760	3.74
30	0.000	0.000	0.015	0.205	0.780	3.77
31	0.000	0.000	0.012	0.189	0.799	3.79
32	0.000	0.000	0.010	0.174	0.816	3.81
33	0.000	0.000	0.008	0.160	0.832	3.82
34	0.000	0.000	0.007	0.147	0.846	3.84
35	0.000	0.000	0.006	0.135	0.859	3.85
36	0.000	0.000	0.005	0.124	0.871	3.87
37	0.000	0.000	0.004	0.114	0.883	3.88
38	0.000	0.000	0.003	0.104	0.893	3.89
39	0.000	0.000	0.003	0.095	0.902	3.90
40	0.000	0.000	0.002	0.087	0.911	3.91
41	0.000	0.000	0.002	0.080	0.919	3.92
42	0.000	0.000	0.001	0.073	0.926	3.92
43	0.000	0.000	0.001	0.067	0.932	3.93
44	0.000	0.000	0.001	0.061	0.938	3.94
45	0.000	0.000	0.001	0.055	0.944	3.94
46	0.000	0.000	0.001	0.051	0.949	3.95
47	0.000	0.000	0.001	0.046	0.953	3.95
48	0.000	0.000	0.000	0.042	0.957	3.96
49	0.000	0.000	0.000	0.038	0.961	3.96
50	0.000	0.000	0.000	0.035	0.965	3.96

Figure 3.5 *Calculation of sequential condition state distributions by the Markov Chain method.*

The expectation value of the degree of damage (= expected average *DoD*) is obtained by multiplying the scale vector $R = ¦\, 0, 1, 2, 3, 4\, ¦$ by the condition state distribution, as shown in Equation 3.24.

$$E(t) = W(t) \cdot R \tag{3.24}$$

where

$E(t)$ s the expectation value for the degree of damage (=average)

R is a scale vector comprising of the numerical values of condition states

The probability density functions and the cumulative probability functions for the states 0...4 are depicted in Figures 3.6 and 3.7.

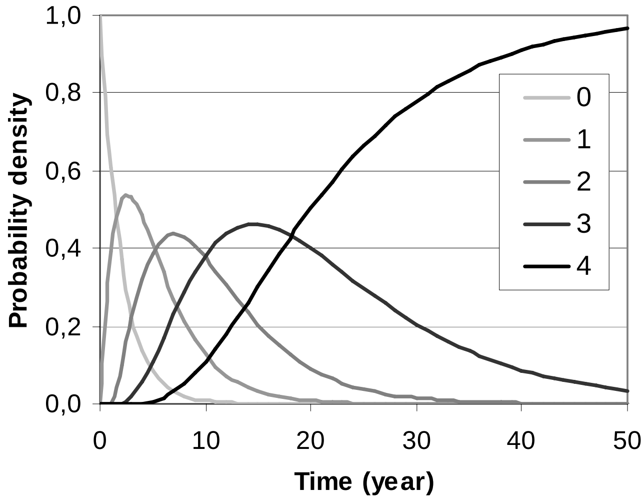


Figure 3.6 *Probability density functions for condition states (=degrees of damage) 0 - 4 calculated by the Markov Chain method.*

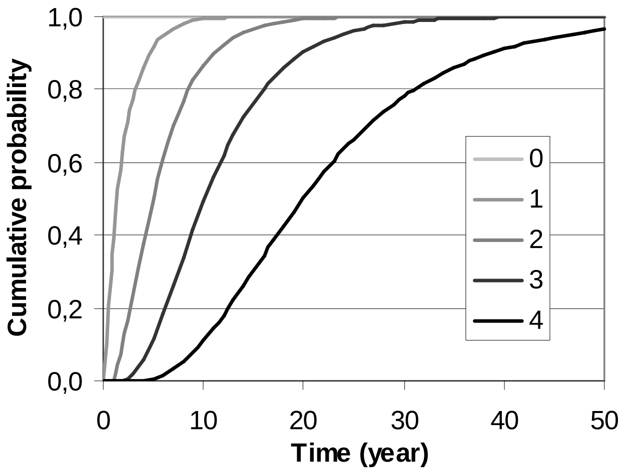


Figure 3.7 *Cumulative probability functions for degrees of damage 0 - 4 determined by the Markov Chain method.*

Action Effect Matrices

The action effect matrices are built individually for each repair action taking into account the probable changes in the condition of the structure as a result of the action and the risk of failure during repair. Thus the condition state distribution of the structure after a repair action is not necessarily the same as that for a new structure.

The general appearance of an action effect matrix is as shown in Table 3.6 As it is assumed that the condition state of a structure is always improved or at least remains the same as a result of a MR&R action, all the probability elements above the diagonal are 0. Other elements may have a value between 0...1. Again the sum of transition probabilities in each row must be 1. Usually heavy repair actions bring the structures close to the perfect condition so that the elements in the first column of the matrix are near 1 and the others near 0.

Table 3.6 *Transition probability matrix for MR&R action effects (5 state system).*

State	0	1	2	3	4
0	p_{00}	0	0	0	0
1	p_{10}	p_{11}	0	0	0
2	p_{20}	p_{21}	p_{22}	0	0
3	p_{30}	p_{31}	p_{32}	p_{33}	0
4	p_{40}	p_{41}	p_{42}	p_{43}	p_{44}

Much data is lacking in this area as very little research work has been done for studying the condition-related effects of various repair actions. So there is usually no conversion methods used for action effect matrices as were for degradation matrices. In practice the transition probabilities of action effect matrices are usually determined based on expert evaluation (Delphi study).

A typical action effect matrix can be seen on top of Figure 3.8. The purpose of Figure 3.8 is to visualise the action effects in a Markov Chain process. The calculation table is programmed so that a repair is done every time when signed by 1 in the column at the left side of the figure. The action effects can be readily seen in the condition state distributions and the average *DoD* curve presented in Figure 3.9.

Transition probability matrix of repair

State	0	1	2	3	4
0	1	0	0	0	0
1	0.95	0.05	0	0	0
2	0.92	0.05	0.03	0	0
3	0.9	0.05	0.03	0.02	0
4	0.88	0.05	0.03	0.02	0.02

Transition probability matrix of degradation

State	0	1	2	3	4
0	0.61	0.39	0	0	0
1	0	0.74	0.26	0	0
2	0	0	0.82	0.18	0
3	0	0	0	0.91	0.09
4	0	0	0	0	1

Repair	Year	State 0	1	2	3	4	Average DoD
	0	1.000	0.000	0.000	0.000	0.000	0.00
	1	0.610	0.390	0.000	0.000	0.000	0.39
	2	0.372	0.527	0.101	0.000	0.000	0.73
	3	0.227	0.535	0.220	0.018	0.000	1.03
	4	0.138	0.484	0.319	0.056	0.002	1.30
	5	0.084	0.412	0.388	0.109	0.007	1.54
	6	0.052	0.338	0.425	0.169	0.016	1.76
	7	0.031	0.270	0.437	0.230	0.032	1.96
	8	0.019	0.212	0.428	0.288	0.052	2.14
	9	0.012	0.165	0.406	0.339	0.078	2.31
	10	0.007	0.126	0.376	0.382	0.109	2.46
	11	0.004	0.096	0.341	0.415	0.143	2.60
	12	0.003	0.073	0.305	0.439	0.181	2.72
	13	0.002	0.055	0.269	0.454	0.220	2.84
	14	0.001	0.041	0.235	0.462	0.261	2.94
1	15	0.902	0.050	0.029	0.014	0.005	0.17
	16	0.550	0.389	0.037	0.018	0.007	0.54
	17	0.336	0.502	0.131	0.023	0.008	0.87
	18	0.205	0.502	0.238	0.045	0.010	1.15
	19	0.125	0.452	0.326	0.084	0.014	1.41
	20	0.076	0.383	0.385	0.135	0.022	1.64
	21	0.046	0.313	0.415	0.192	0.034	1.85
	22	0.028	0.250	0.422	0.249	0.051	2.05
	23	0.017	0.196	0.411	0.303	0.074	2.22
	24	0.011	0.152	0.388	0.349	0.101	2.38
	25	0.006	0.116	0.357	0.388	0.132	2.52
	26	0.004	0.089	0.323	0.417	0.167	2.65
	27	0.002	0.067	0.288	0.438	0.205	2.78
	28	0.001	0.051	0.254	0.450	0.244	2.88
1	29	0.903	0.050	0.028	0.014	0.005	0.17
	30	0.551	0.389	0.036	0.018	0.006	0.54
	31	0.336	0.503	0.131	0.023	0.008	0.86
	32	0.205	0.503	0.238	0.044	0.010	1.15
	33	0.125	0.452	0.326	0.083	0.014	1.41
	34	0.076	0.383	0.385	0.134	0.021	1.64
	35	0.047	0.313	0.415	0.191	0.033	1.85
	36	0.028	0.250	0.422	0.249	0.051	2.04
	37	0.017	0.196	0.411	0.303	0.073	2.22
	38	0.011	0.152	0.388	0.349	0.100	2.38
	39	0.006	0.117	0.358	0.388	0.132	2.52
	40	0.004	0.089	0.324	0.417	0.167	2.65
	41	0.002	0.067	0.288	0.438	0.204	2.77
	42	0.001	0.051	0.254	0.450	0.243	2.88
	43	0.001	0.038	0.221	0.456	0.284	2.98
	44	0.001	0.029	0.191	0.454	0.325	3.07
1	45	0.899	0.050	0.029	0.016	0.007	0.18
	46	0.548	0.388	0.037	0.019	0.008	0.55
	47	0.334	0.501	0.131	0.024	0.010	0.87
	48	0.204	0.501	0.238	0.046	0.012	1.16
	49	0.124	0.450	0.325	0.084	0.016	1.42
	50	0.076	0.382	0.384	0.135	0.024	1.65

Figure 3.8 *Action effects in a Markov Chain lifetime table.*

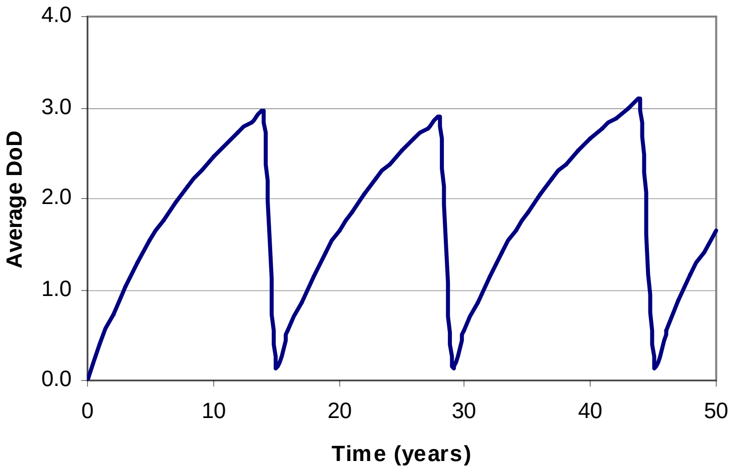


Figure 3.9 *The average DoD with time showing the effects of repair on the condition of a structure.*

A repair action may also have an impact on the rate of degradation after the repair. If the rate of degradation is expected to be changed after a MR&R action the degradation matrix is changed respectively.

Modeling of the Action Effects of Coatings

When applying coatings and other preventive maintenance measures the condition state of the structure is not considered to be changed at all but the rate of further degradation is reduced. So no action effect matrix is applied in connection of preventive maintenance actions but the degradation matrix is changed according to the expected rate of degradation. The effects of coatings on the condition of the structure depend on the condition of the coating, Vesikari (2002).

Coatings have both direct and indirect effects on the condition state of a structure. The direct effects are a result of the physical barrier which retards the penetration of aggressive agents, such as CO_2 and chlorides, into the concrete structure. The indirect effects result from the changed moisture content in the structure because of the coating as the moisture content has a remarkable effect on the degradation rate. The model of a degradation matrix which takes into account the <u>direct</u> effects of a coating to the degradation rate of a structure is presented in Table 3.7.

Table 3.7 *The assumed form a degradation matrix for a coated structure.*

State	0	1	2	3	4
0	$1 - p_c \cdot p_{01}$	$p_c \cdot p_{01}$	0	0	0
1	0	$1 - p_c \cdot p_{12}$	$p_c \cdot p_{12}$	0	0
2	0	0	$1 - p_c \cdot p_{23}$	$p_c \cdot p_{23}$	0
3	0	0	0	$1 - p_c \cdot p_{34}$	$p_c \cdot p_{34}$
	0	0	0	0	1

For more detailed information on the modeling of the condition-related effects of coatings using the Markov Chain method, see Reference Vesikari (2003). As the condition and the protection properties of coatings are time dependent the condition of the coating is first modeled by the Markov Chain and then the changes in the condition of the structure are determined taking into account the concurrent condition state of the coating. So the transition probabilities of the structure are not any more constant but are dependent on the condition of the coating. Figure 3.10 shows the result of calculation as an example.

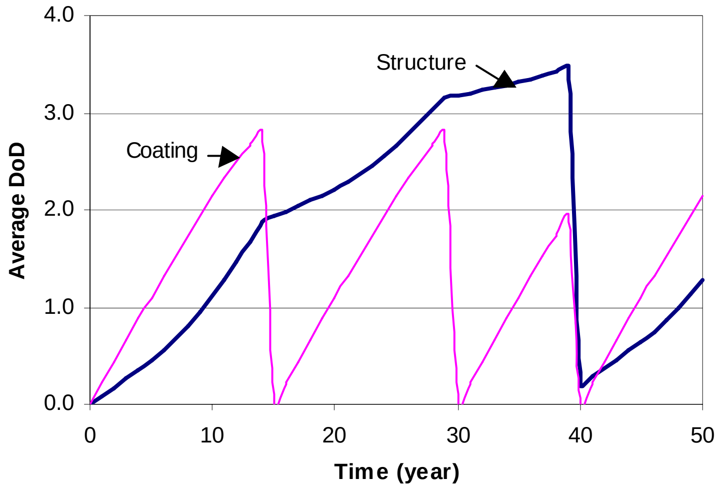


Figure 3.10 *Average DoD of the coating and the structure (example).*

3.8.4 Combined LCP-, LCC- and LCA-Analysis

Working on the "life cycle principle" means that the profitability of optional maintenance strategies is evaluated by the results of life cycle analyses. Not only MR&R costs but also the user costs and environmental costs, i.e. environmental impacts are determined by the life cycle principle and are considered in the decision making of maintenance strategies.

The principles of life cycle cost calculations with predefined MR&R action profiles are well known and described in international standards like ISO 15686-5 /5/ and ASTM E 917 /6/, see Vesikari & Söderqvist (2003). However, the traditional procedure of cost calculation with predefined action profiles could obviously not serve as the basis for a life cycle management system. Rather it is the task of the management system to specify the actions and to define the timings of actions using appropriate degradation models. So the calculation methods for the life cycle cost analyses in a life cycle management system must be more advanced and more automatic than those in a conventional life cycle cost analysis.

A Markov Chain based life cycle cost analysis is actually a combination of a life cycle performance (LCP), a life cycle cost (LCC) and a life cycle ecology (LCE) analysis. It integrates the Markov Chain based condition analysis to a conventional life cycle analysis framework. This first ETSI report will not cover LCA or LCE analysis. These kind of issues will be covered in consecutive ETSI reports.

General Principles

The life cycle cost analyses can be used both in object level and in network level studies. At the object level the LCC analysis is used for life cycle design of specific components and objects. Specific parameter values of structures (obtained from database) are used in these calculations. The purpose of such analyses is to find out the optimal MR&R action profiles for structural component and to find the optimal project profile for the object.

At the network level the purpose is to use the LCC analysis results for strategic planning of MR&R activities and to make short- and long term cost scenarios for the future. The structural parts are treated statistically as populations of structural parts. The calculations are conducted using average values of the material, structural and environmental parameters pertaining to the network or a sub-network of structures. The purpose is to find the optimal maintenance strategy for structures for varying environmental conditions and for varying material and structural properties. Typically answers for the following questions can be obtained: Is it cost effective to protect the structures by coatings or other protection methods? Which repair methods should be used? In which condition state should the structure be repaired and in which condition state should the coatings or other protections be renewed to minimise the *LCC.*

Specification of MR&R actions

For both the manual and the automatic analyses methods each MR&R action must be specified. The specification of actions is done by answering the following questions, se Table 3.8.

Table 3.8 *Definition of actions.*

1	Is the MR&R action group used during the design period?	Yes/no
2	Which MR&R system?	Code of the MR&R system within the MR&R action group
3	Limit condition state?	Limit state for the action, e.g. 3 or 4
4	Maximum allowable probability for exceeding the limit state?	Probability as %. Exceeding the given percentage will trigger the action.
5	Maximum number of repeated actions?	Number of allowable repetitions of an action before a heavier action.

The action groups mean MR&R action categories composed of similar MR&R systems. For concrete structures the MR&R actions groups may be the following:

- Coating
- Patching of coating
- Protection with concrete overlay
- Patching of concrete protection
- Patching of structure

- Repair of structure
- Renovation of structure.

Each MR&R action group contains several repair systems or methods. Accordingly, the group of coatings is comprised of several coating systems. The concrete protection group refers to methods in which a layer of shotcrete, conventional concrete or cement mortar is applied on the whole surface of the structure. Cathodic protection methods with a net anode embedded in a layer of concrete on the original structure is also included in this group of actions.

The group of structural repairs refers to major repair actions which improve the condition of the structural part. In concrete structures the structural repairs refer to actions by which the concrete around the reinforcement is renewed. This can be done by removing and replacing concrete around the steel bars by mechanical repair methods. Electrochemical methods such as re-alkalisation and chloride extraction are included in this group as the concrete environment around the reinforcement is renewed by re-alkalisation or removal of chlorides.

Patching means partial repair of the most attacked areas of the structure. Patching may refer also to partial repair of a coating or other protection. The methods of structural patching are comparable to the structural repair in that they also change the environment around the reinforcement. However, this is done only locally and the other parts of the structure remain unchanged. So patching is not considered to start a new service life but only to extend the ongoing service life.

Renovation refers to complete replacement of a component by a new one, so this group consists of methods for renovation. The component can be reconstructed at site or a new prefabricated element can be installed at the place of the old component.

The data related to specific MR&R action systems are presented in table of MR&R systems. The MR&R systems are arranged in the table according to action groups and they can be referred to by their <u>code numbers</u>. For example in the case of the coating group the code number refers to a specific coating system with defined materials and material thicknesses. In the case of concrete protection group it refers to specific concrete or cathodic protection systems with defined materials, thicknesses and techniques.

The <u>maximum allowable probability</u> sets the maximum limit for the probability of exceeding the limit state. In object level studies one can interpret it as expressing the maximum allowable fraction of the surface area of a component to be at the limit state or in still worse condition. In network level studies it means the maximum portion of structures which can be tolerated at the limit state or in still a worse condition. The MR&R actions for structures are automatically triggered when the maximum allowable probability for the defined limit state is exceeded.

<u>Maximum number of repeated actions</u> sets a limit to the number of the same MR&R action during the design phase. For instance the number of repairs or re-coatings can be limited. In the case of coatings the counter starts from zero every time when the component is repaired and in the case of repairs the repair counter starts from zero when the component is replaced by a new one.

The life of a component is considered to be composed of three phases for which the MR&R actions may be specified independently as follows.

Phase I Residual service life of the component. All actions of protection and patching are defined until the end of the on-going service life.

Phase II From the end of the residual service life to the end of the residual life cycle of the component. The repair methods are defined until the end of the life cycle of the component. The patching and protection methods for this period of time can be defined in another way than for the on-going service life. This is necessary as the need of protection may be changed after the repair.

Phase III From the end of the on-going life cycle to the end of the last life cycle. The methods of renovation are defined. For this period of time the repair methods can be newly defined as also the patching and protection methods.

The division of the life of a component is presented graphically in Figure 3.11. The life of a component can be described as a combination of nested arches which represent the lives of actions.

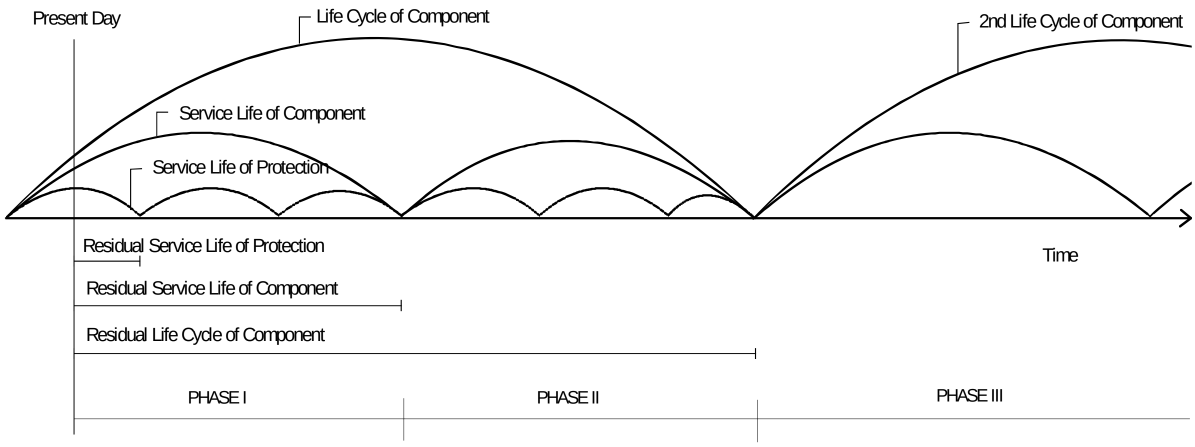


Figure 3.11 *Division of the life of a component into phases.*

Several action groups can be selected for the same design phase with appropriate limitations. So it is possible to apply for example coating together with structural repair or coating and concrete protection together with structural repair. However in the design phase I no repair is possible and in the design phase II no renovation is possible to select.

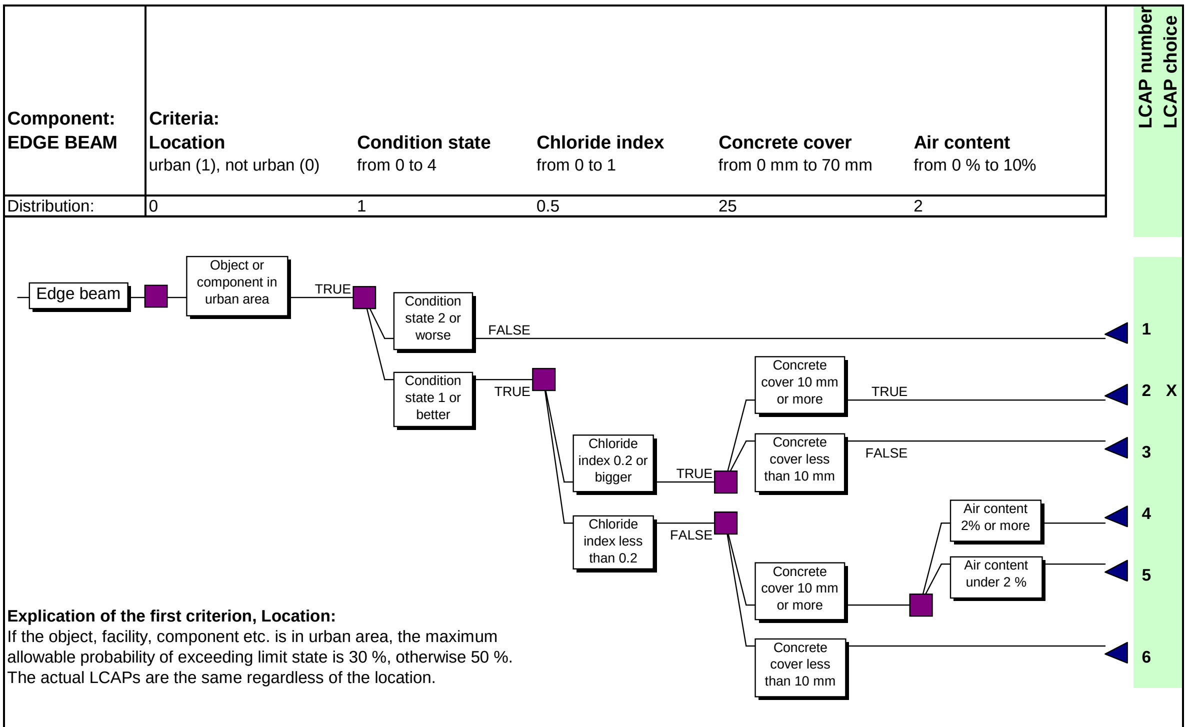
As a component can be repaired completely without replacing the whole component by a new one a new service life of the component is considered to start from the repair. Possibly many consecutive repairs can even be accepted before the component must be replaced. Thus the life cycle of a component is not considered to end until it is completely renovated or replaced by a new one. Accordingly a structural repair generates a new service life and a renovation or replacement generates a new life cycle for the component.

Specification of MR&R actions by a decision tree

The MR&R actions for a component can be specified automatically by a decision tree. The MR&R action profiles specified by a decision tree have been previously optimised by manually defined LCC analyses and risk analyses. The selection of a MR&R action profile for a particular component is done by the decision tree run during which several decision criteria related to the specific properties, environmental conditions and requirements of the component are evaluated. However, only the types of MR&R actions are defined by the decision tree. The timing of actions is determined by the Markov Chain life cycle table and the automatic triggering of actions.

A decision tree has a "root" which forks at "nodes" representing the relevant criteria related to properties of the component, severity of environment and special requirements of the object and makes with a growing number of nodes an ever-increasing amount of "branches". The final branches after the last node are called "leaves". The optimal sets of MR&R actions are the results of the tree and are inserted in the leaves of the tree.

An example of a decision tree and its solution is presented in Figure 3.12 The component specific data is given at the row "distribution". The tree is active to find the correct set of MR&R actions corresponding to the given data.



Recommended actions (= different possible Life Cycle Action Profiles) for edge beam

LCAP number	Immediate actions	Predicted preventive actions	Predictive repair actions	
1	Nothing	Nothing	Repair at DoD 4	
2	Impregnation	Reimpregnation at DoD 3	Repair at DoD 4	X
3	Thickening of concrete cover and impregnation	Reimpregnation at DoD 3	Repair at DoD 4	
4	Nothing	Nothing	Repair at DoD 4	
5	Impregnation	Reimpregnation at DoD 3	Repair at DoD 4	
6	Thickening of concrete cover	Nothing	Repair at DoD 4	

Figure 3.12 *Decision tree, illustrative presentation.*

In a LCC analysis program the decision tree is usually attached as a subprogram. In a program code of a decision tree the branches are implemented by IF...THEN statements, which can be nested multifold.

Normally the user has no access to the decision tree. However it is possible to make the computer program such that the user can do some changes in the MR&R specifications of the decision tree.

Principles of Condition Guarding and Triggering of Actions

In a condition controlled life cycle cost analysis the timing of actions is performed automatically. The principle of triggering actions in a Markov Chain life cycle table is presented in Figure 3.13. The sequential annual condition state distributions have been determined by Markov Chain on the left side of the figure. They show the probability of the component to be at any of the condition states at any time. In the middle of the figure the respective cumulative probabilities which express the probability of exceeding or being equal to any of the condition states are presented. In this example condition state 3 was selected for the limit condition state and 50 % as the maximum allowable probability for exceeding the limit condition state. If this criterion is exceeded during a year, a repair action will be performed immediately in the next year. The action effects on the condition state distribution of the structure are obtained by multiplying the condition state distribution of the year by the action effect matrix in the upper left corner. At the same time the repair costs are added in the cost counters in the right side of the figure. In other years only the increase of degradation is evaluated by the degradation matrix that is situated below the action effect matrix.

Transition probability matrix for repair action

State	0	1	2	3	4
0	1.00	0	0	0	0
1	0.95	0.05	0	0	0
2	0.92	0.05	0.03	0	0
3	0.90	0.05	0.03	0.02	0
4	0.88	0.05	0.03	0.02	0.02

LC COSTS PER UNIT AREA

Cumulative real costs	**600**	Euro/m^2
Cumulative PV costs	**221**	Euro/m^2
Average annual costs	**12.00**	Euro/m^2/year
Equalised annual costs	**9.90**	Euro/m^2/year

TOTAL LC COSTS

Cumulative real costs	**30000**	Euro
Cumulative PV costs	**11059**	Euro
Average annual costs	**600**	Euro/year
Equalised annual costs	**495**	Euro/year

Transition probability matrix for degradation

State	0	1	2	3	4
0	0.330	0.670	0	0	0
1	0	0.662	0.338	0	0
2	0	0	0.765	0.235	0
3	0	0	0	0.814	0.186
4	0	0	0	0	1

REPAIR CRITERIA

Limit state	3	(2 or 3)
Max Proba	0.5	(0.01-0.99)

Year	Condition state distributions State (DoD) 0	1	2	3	4	Average DoD	Cumulative distributions State (DoD) 0	1	2	3	4	Condition fulfilled	LC costs real	Discount factor	LC costs discounted
0	1.000	0.000	0.000	0.000	0.000	0.00	1.000	0.000	0.000	0.000	0.000		0	1.000	0
1	0.330	0.670	0.000	0.000	0.000	0.67	1.000	0.670	0.000	0.000	0.000		0	0.962	0
2	0.109	0.664	0.227	0.000	0.000	1.12	1.000	0.891	0.227	0.000	0.000		0	0.925	0
3	0.036	0.513	0.398	0.053	0.000	1.47	1.000	0.964	0.451	0.053	0.000		0	0.889	0
4	0.012	0.363	0.478	0.137	0.010	1.77	1.000	0.988	0.625	0.147	0.010		0	0.855	0
5	0.004	0.248	0.488	0.224	0.035	2.04	1.000	0.996	0.748	0.259	0.035		0	0.822	0
6	0.001	0.167	0.457	0.297	0.077	2.28	1.000	0.999	0.832	0.374	0.077		0	0.790	0
7	0.000	0.111	0.406	0.350	0.132	2.50	1.000	1.000	0.888	0.482	0.132		0	0.760	0
8	0.000	0.074	0.348	0.380	0.197	2.70	1.000	1.000	0.926	0.578	0.197	1	0	0.731	0
9	0.907	0.050	0.028	0.012	0.004	0.16	1.000	0.093	0.043	0.015	0.004		100	0.703	70
10	0.300	0.640	0.038	0.016	0.006	0.79	1.000	0.700	0.060	0.022	0.006		100	0.676	70
11	0.099	0.624	0.246	0.022	0.009	1.22	1.000	0.901	0.277	0.031	0.009		100	0.650	70
12	0.033	0.479	0.399	0.076	0.013	1.56	1.000	0.967	0.488	0.089	0.013		100	0.625	70
13	0.011	0.339	0.467	0.156	0.027	1.85	1.000	0.989	0.650	0.183	0.027		100	0.601	70
14	0.004	0.232	0.472	0.237	0.056	2.11	1.000	0.996	0.765	0.293	0.056		100	0.577	70
15	0.001	0.156	0.439	0.304	0.100	2.35	1.000	0.999	0.843	0.404	0.100		100	0.555	70
16	0.000	0.104	0.389	0.351	0.157	2.56	1.000	1.000	0.896	0.507	0.157	1	100	0.534	70
17	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		200	0.513	122
18	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		200	0.494	122
19	0.099	0.626	0.246	0.021	0.008	1.21	1.000	0.901	0.274	0.028	0.008		200	0.475	122
20	0.033	0.481	0.400	0.075	0.012	1.55	1.000	0.967	0.486	0.086	0.012		200	0.456	122
21	0.011	0.340	0.469	0.155	0.025	1.84	1.000	0.989	0.649	0.180	0.025		200	0.439	122
22	0.004	0.232	0.473	0.236	0.054	2.11	1.000	0.996	0.764	0.291	0.054		200	0.422	122
23	0.001	0.156	0.441	0.304	0.098	2.34	1.000	0.999	0.843	0.402	0.098		200	0.406	122
24	0.000	0.104	0.390	0.351	0.155	2.56	1.000	1.000	0.896	0.506	0.155	1	200	0.390	122
25	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		300	0.375	159
26	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		300	0.361	159
27	0.099	0.626	0.246	0.021	0.008	1.21	1.000	0.901	0.274	0.028	0.008		300	0.347	159
28	0.033	0.481	0.400	0.075	0.012	1.55	1.000	0.967	0.486	0.086	0.012		300	0.333	159
29	0.011	0.340	0.469	0.155	0.025	1.84	1.000	0.989	0.649	0.180	0.025		300	0.321	159
30	0.004	0.232	0.473	0.236	0.054	2.11	1.000	0.996	0.764	0.291	0.054		300	0.308	159
31	0.001	0.156	0.441	0.304	0.098	2.34	1.000	0.999	0.843	0.402	0.098		300	0.296	159
32	0.000	0.104	0.390	0.351	0.155	2.56	1.000	1.000	0.896	0.506	0.155	1	300	0.285	159
33	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		400	0.274	187
34	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		400	0.264	187
35	0.099	0.626	0.246	0.021	0.008	1.21	1.000	0.901	0.274	0.028	0.008		400	0.253	187
36	0.033	0.481	0.400	0.075	0.012	1.55	1.000	0.967	0.486	0.086	0.012		400	0.244	187
37	0.011	0.340	0.469	0.155	0.025	1.84	1.000	0.989	0.649	0.180	0.025		400	0.234	187
38	0.004	0.232	0.473	0.236	0.054	2.11	1.000	0.996	0.764	0.291	0.054		400	0.225	187
39	0.001	0.156	0.441	0.304	0.098	2.34	1.000	0.999	0.843	0.402	0.098		400	0.217	187
40	0.000	0.104	0.390	0.351	0.155	2.56	1.000	1.000	0.896	0.506	0.155	1	400	0.208	187
41	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		500	0.200	207
42	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		500	0.193	207
43	0.099	0.626	0.246	0.021	0.008	1.21	1.000	0.901	0.274	0.028	0.008		500	0.185	207
44	0.033	0.481	0.400	0.075	0.012	1.55	1.000	0.967	0.486	0.086	0.012		500	0.178	207
45	0.011	0.340	0.469	0.155	0.025	1.84	1.000	0.989	0.649	0.180	0.025		500	0.171	207
46	0.004	0.232	0.473	0.236	0.054	2.11	1.000	0.996	0.764	0.291	0.054		500	0.165	207
47	0.001	0.156	0.441	0.304	0.098	2.34	1.000	0.999	0.843	0.402	0.098		500	0.158	207
48	0.000	0.104	0.390	0.351	0.155	2.56	1.000	1.000	0.896	0.506	0.155	1	500	0.152	207
49	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		600	0.146	221
50	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		600	0.141	221

Figure 3.13 *Principles for the determination of condition state distributions, triggering of actions and calculation of life cycle costs [1,3].*

Many kinds of maintenance and repair actions can be included in a life cycle of a structure. So Figure 3.13 is inadequate to represent the whole life cycle cost analysis. For instance the degradation of a concrete structure can be retarded by applying an extra layer of concrete or a coating on the structure. However, both the extra layer of concrete and the coating deteriorate themselves. So before evaluation of their effect on the condition of the structure, the condition of the concrete layer and the coating must be first evaluated. In practice three lifetime tables of the form presented in Figure 3.14 are needed:

- Table of coatings
- Table of extra concrete layer
- Table of the structure.

These tables are connected to each other by rules and formulas, which take into account the mutual condition-related effects, as schematically presented in Figure 3.14.

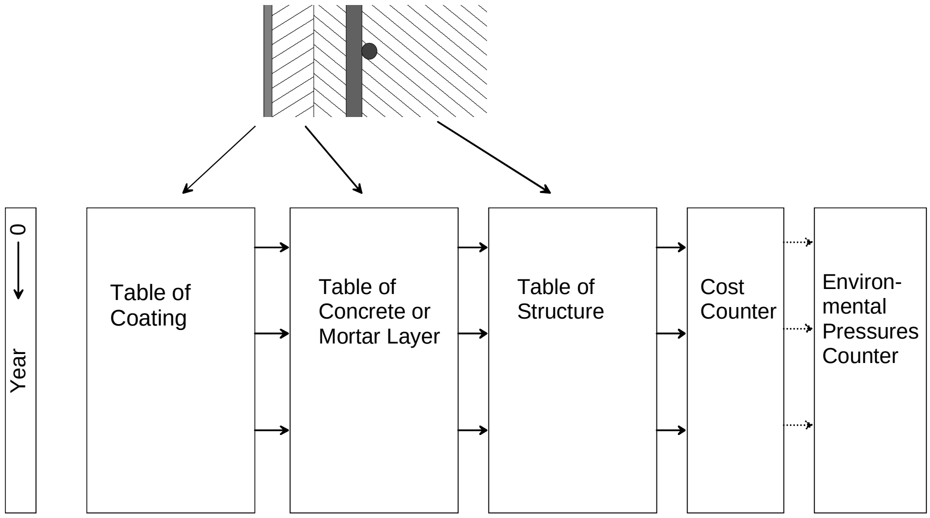


Figure 3.14 *Tables of coating, concrete or mortar layer and the structure connected to each other and counters for costs and environmental impacts.*

Methods of Counting Costs

The costs are counted according to the methods presented in section 3.4. The cost counters get their information from the Markov Chain life cycle table (types and timings of MR&R actions) and the table of the MR&R systems (unit costs for MR&R actions etc.). The task of the cost counters is to collect and summarise the costs from the total time frame. The costs are understood here to cover MR&R costs, user costs and environmental impacts.

The MR&R costs are comprised of real maintenance costs such as costs of coating, protection, patching, repair, rehabilitation, renovation etc.

The unit costs of MR&R actions are usually based on statistical data from earlier executed MR&R projects. In some cases the costs depend on the extent of the repair, i.e. the area of repair and the depth of concrete that is replaced from the structure. The unit costs may also depend on the general condition of the structure. Then a single value is not justified for unit costs but a model formula that determines the unit costs as a function of the relevant parameters is applied instead. An example of such a model formula is given in Equation (3.25):

$$UnitCost = UnitCost_0 \cdot C_{\mathrm{depth}} \cdot C_{\mathrm{area}} \cdot C_{\mathrm{cond}} \tag{3.25}$$

where:

Unit Cost	is unit costs of a MR&R action, Euro/m^2
$UnitCost_0$	unit cost of a MR&R action with respect to the minimum depth and the minimum area of repair, Euro/m^2
C_{depth}	coefficient depending on the depth of repair

C_{area}	coefficient depending on the area of repair
C_{cond}	coefficient depending on the condition of the structure at the moment of repair.

The presented equations in section 3.4 refer to the road user costs per hour. So the total road user costs depend on the total time of the repair work. The total costs per unit area (or other functional unit) can be determined as the product of the user costs per hour and the repair time. The repair time may be evaluated based on the production rate of the work [m^2/day] for each MR&R action system and the area of repair as follows:

$$t_r = \frac{A}{a_r} \tag{3.26}$$

where:

t_r is repair time, d

A area of repair, m^2

a_r production rate of the MR&R system applied, m^2/h.

This calculation method is not indisputable as in practice several works for several components can be performed at the same time. However, this offers one solution for the problem of addressing user costs for components.

Methods of Discounting

The life cycle costs are determined according to the principles presented in section 3.4 and in the state-of-the-art chapter 2.

3.8.5 Life Cycle Cost analysis process used in Bridgelife

The principles of three LCC programs are presented in Chapter 4. In this section some of the features and examples of the program *Bridgelife* will be presented.

The total life cycle cost analysis process is presented schematically in Figure 3.15. The phases of the analysis are the following:

1. Specification of the initial data
2. Analysis process
3. Presentation of results

Figure 3.15 shows also schematically the structure of the life cycle analysis program, *Bridgelife*. The program consists of several tables: (1) Tables of object and component specific data (2) Tables of MR&R systems (3) Tables for definition of actions (4) Markov Chain life cycle analysis tables (5) Tables for counting costs and (6) Tables of results. In the following the analysis process is described in more detail. The different steps in the analysis process in Bridgelife is as follows:

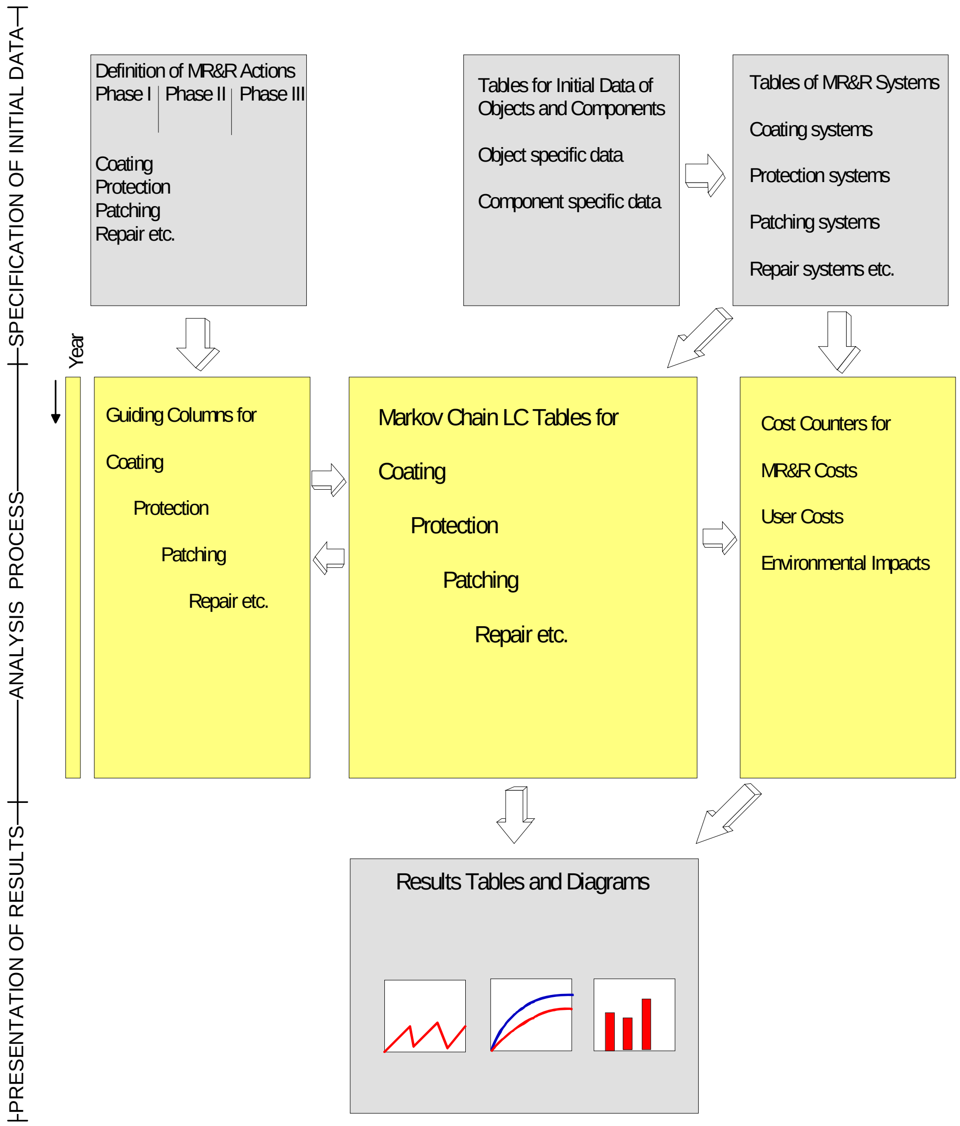


Figure 3.15 *General layout of a life cycle cost analysis process.*

Specification of the initial data

- time frame of the analysis
- discount rate
- object
- component
- MR&R actions (unless not specified automatically by the decision tree)

The object specific data contain:

- Identification data
- Measuring data
- Environmental burden data

- User cost data
- etc.

The component specific data contain:

- Identification data
- Measuring data
- Structural data
- Data on previous MR&R actions
- Inspection and condition assessment data
- etc.

Analysis Process

The following automatic routines are performed in Bridgelife:

- automatic application of object and component specific parameter data for degradation, action effect and cost models,
- automatic conversion of degradation models into Markov Chain transition probabilities,
- automatic definition of actions by the decision tree (unless manually defined),
- automatic arrangement of the guiding columns according to the specified MR&R action profile,
- automatic determination of the annual condition state distributions in the Markov Chain life cycle table,
- automatic timing of actions,
- automatic calculation of life cycle costs, user costs and environmental impacts, and
- automatic presentation of the analysis results in tables and diagrams.

Results of Life Cycle Cost Analysis

The main results of a life cycle cost analysis can be compacted into a small results table. Table 3.9 shows the life cycle costs calculated per unit area. The annual unit costs are calculated as average annual costs and equalised annual costs.

Table 3.9 *Results of life cycle cost analysis, unit costs (example).*

Unit Costs		**MR&R Costs**	**User Costs**	**Total Costs**	**ELU**
Cumulative Real Costs,	Euro/m^2	2 114	455	2 568	1,83
Cumulative PV Costs,	Euro/m^2	98	18	115	
Average Annual Costs,	Euro/m^2/a	8,46	1,82	10,27	0,01
Equalised Annual Costs,	Euro/m^2/a	3,91	0,70	4,61	

The true component costs are obtained by multiplying the unit cost by the surface area of the component. If, for example, the surface area of the component is 166 m^2 and the unit costs are those presented in Table 3.9, the true costs are presented in Table 3.10.

Table 3.10 *Results of life cycle cost analysis, true component costs (example).*

Unit Costs		MR&R Costs	User Costs	Total Costs	ELU
Cumulative Real Costs,	Euro	350 905	75 460	426 365	303
Cumulative PV Costs,	Euro	16 235	2 910	19 146	
Average Annual Costs,	Euro/year	1 404	302	1 705	1
Equalised Annual Costs,	Euro/year	649	116	766	

As can be seen from the results in Tables 3.9 and 3.10, the ELU costs calculated based on the EPS method are small as compared to both the MR&R costs and user costs.

The design period was in this case 250 years. The condition of the structure changes during this time is as depicted in Figures 3.16 and 3.17.

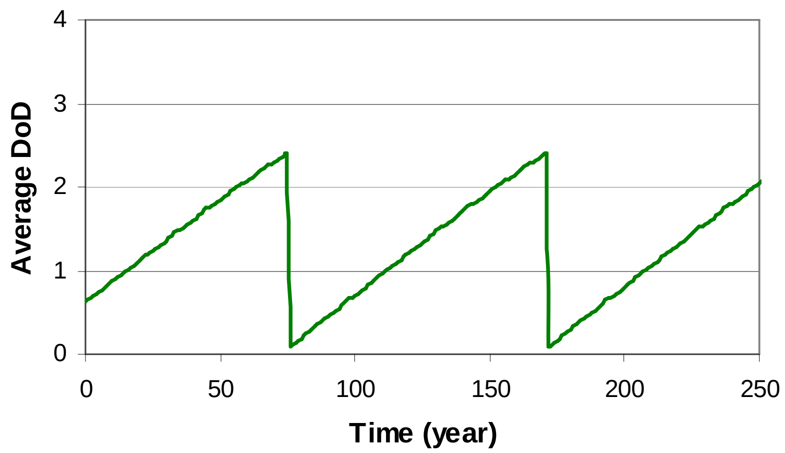


Figure 3.16 *Average Degree of Damage as a function of time.*

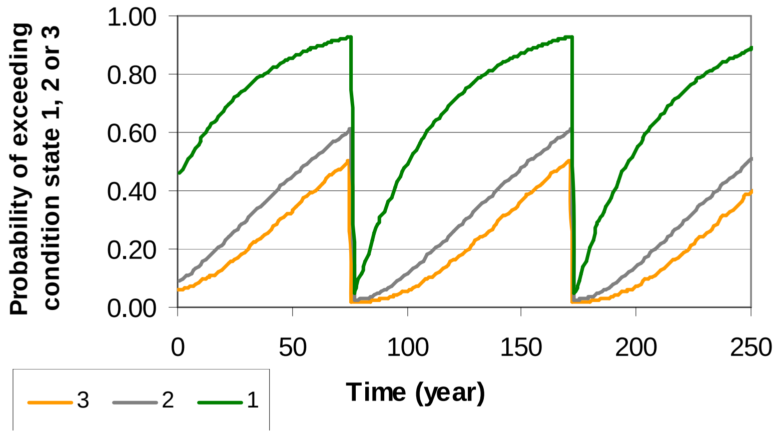


Figure 3.17 *Probability of exceeding the condition state 1, 2 and 3 as a function of time.*

In this example the maximum allowable probability of exceeding the condition state 3 (= limit state) was 50 %. From Figure 3.17 one can observe that the repair was triggered immediately every time when this limit was exceeded.

The costs can also be presented as a function time .Figure 3.18 shows the cumulative MR&R costs per unit area as real costs and present value costs. The MR&R costs in this case were composed of structural repair cost and coating costs.

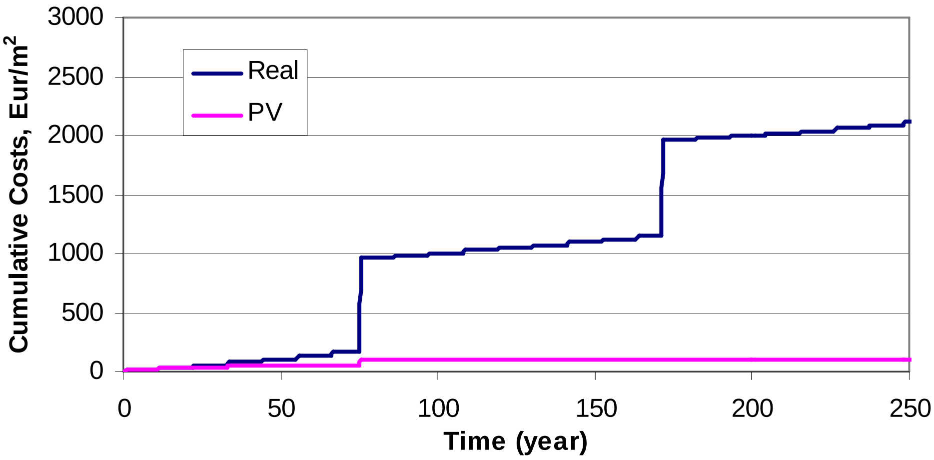


Figure 3.18 *MR&R costs per unit area presented cumulatively as a function of time.*

Figure 3.19 shows the cumulative MR&R costs and user costs per unit area.

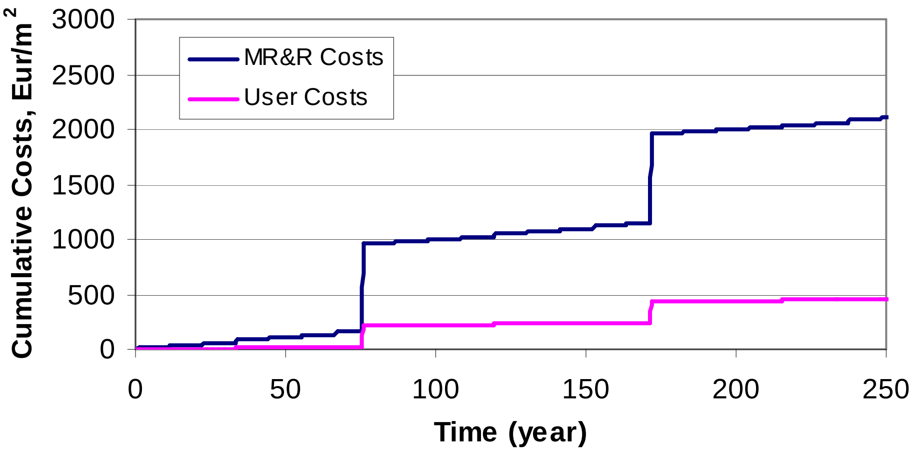


Figure 3.19 *MR&R and user costs per unit area as a function of time.*

3.9 Advanced LC analyses programs for object level and network level use

In different variations of the life cycle analysis programs additional features may be added in the program routine. Such extended analysis programs are those specially designed for the use of the Object level and the Network level management systems.

Life Cycle Planning Program for the Object Level Management

In a Life Cycle Planning Program for the object level use all components of an object are analysed one after another and the MR&R actions pertaining to different components of an object are reorganised into "projects". By projects we mean here groups of MR&R actions that are scheduled to the same year for the same object. Instead of project planning one could rather call it life cycle planning as not only the next coming project is planned but all the projects during the whole life frame are planned at the same time. The planning is done automatically but the program allows manually defined changes to the plans.

The reason for reorganising the MR&R actions into projects is that the optimal timings for various actions (for various components) will scatter too much. Project planning based only on the optimal timing of actions would result in too many small projects to be executed for the same object. That would be annoying for both maintainers and users. So the optimisation in the preliminary project planning is performed from a wider perspective than in the component level optimisation. As a result of proper object level planning in which the single MR&R actions are combined into reasonable groups, economic savings can be won by synergy profit.

From many possible ways of combining actions into projects only one is presented here. It is effective and probably also the fastest method, as it does not require a separate computer run. The combination of actions into projects can be performed already in connection with the first component level runs provided that a reasonable order in the analyses of components is used.

This method of combination is based on definition of both the minimum and the maximum probability for exceeding the limit state. In an optimal timing of MR&R actions the timing is always triggered according to the maximum allowable probability. Now the action is triggered latest at the maximum probability but it can be triggered earlier if it seems reasonable from the view point of the project level planning. Accordingly the action is triggered if there is a previously defined action time (for any action in any component of the same object) and if the minimum allowable probability is exceeded. The minimum allowable probability is defined in the decision tree for this type project planning. (Figure 3.20)

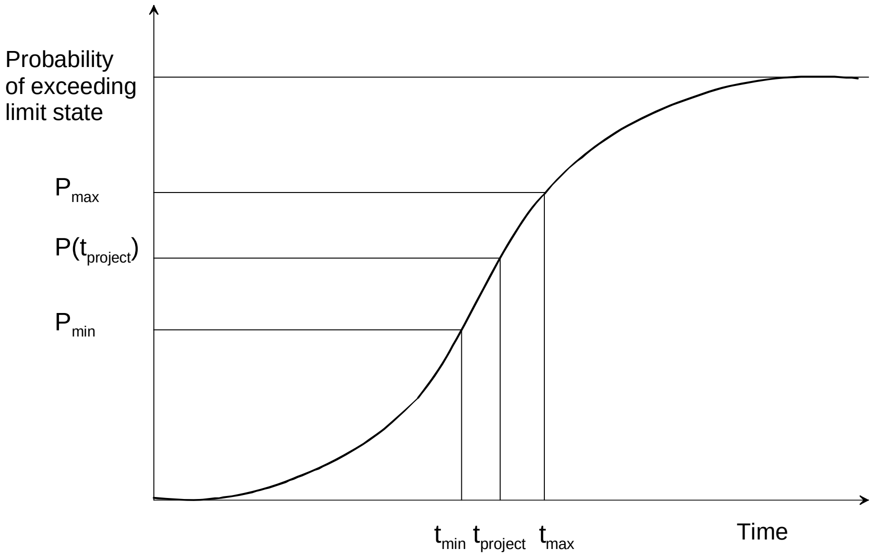


Figure 3.20 *Principle of triggering actions.*

The specification and timing of actions is performed for each component consecutively in the order of their relative importance. The timings of actions for the first component are defined at their optimal timings corresponding to the maximum probability. However, for the following components the timings of actions may be advanced from their optimal timings provided that any MR&R action (for any of the previously analysed components) was scheduled earlier than the optimal timing and the specified minimum probability is exceeded. The system still guarantees that the higher limit for exceeding the limit state is never overridden.

For the purpose of project planning a new row is added in the MR&R action definitions (Table 3.11).

Table 3.11 *Revised table for definition of actions*

1	Is the MR&R action group used during the design period?	Yes/no
2	Which MR&R system?	Code of the MR&R system within the MR&R action group
3	Limit condition state?	Limit state for the action, e.g. 3 or 4
4	*Minimum allowable probability for exceeding the limit state for accepting the timing of action?*	*Probability as % (exceeding the given percentage allows timing of the action to equal with a previously defined timing of any action for the same object)*
5	Maximum allowable probability for exceeding the limit state?	Probability as % (exceeding the given percentage will trigger the action *unless not triggered by the previous condition*)
6	Maximum number of repeated actions?	Number of allowable repetitions of an action before a heavier action.

Program for Cost Scenarios at Network Level

In an analysis program for cost scenarios at the network level the calculation procedures are essentially the same as those in the object level program. However the project design as presented above is not performed. The distribution of objects into components is preferably the same as that in the object level but the surface of components comprises the total surface area of all components in the treated network or sub-network. The total network is divided into sub-networks according to the decision tree definitions so that all components of the same type with the same definition of actions can be treated in the same analysis.

Another difference in the network level procedure as compared to the object level procedure is in the mathematical way how the triggering of actions is responded. In an object level analysis the response is that the action is performed and the condition state distribution is completely changed according to the action effect matrix. However, in the network level analysis only the fraction which overrides the maximum allowable probability is considered to be repaired, thus resulting in smaller but more frequent changes in the condition state distribution. The reason for this is that the network level changes in the condition distribution are statistical not individual as at the object level.

4 Desciption of three LCC programs

4.1 Bridgelife - program developed at VTT, Finland

Bridgelife is a life cycle design tool for project level bridge management developed by Tech Lic *Erkki Vesikari*, at VTT, Finland. This program is implemented in Excel. It is a result of EU project – LIFECON, and fulfils the LIFECON principles: predictive, integrated, life cycle based, optimising and probabilistic. It is capable for automatic design of single and groups of concrete bridges. There are two design aspects in this program: Life Cycle Design and Service Life Design. Life cycle design is used for the existing bridges, and service life design for new bridges and for repair of bridge structural parts. The main interface is shown in Figure 4.1.

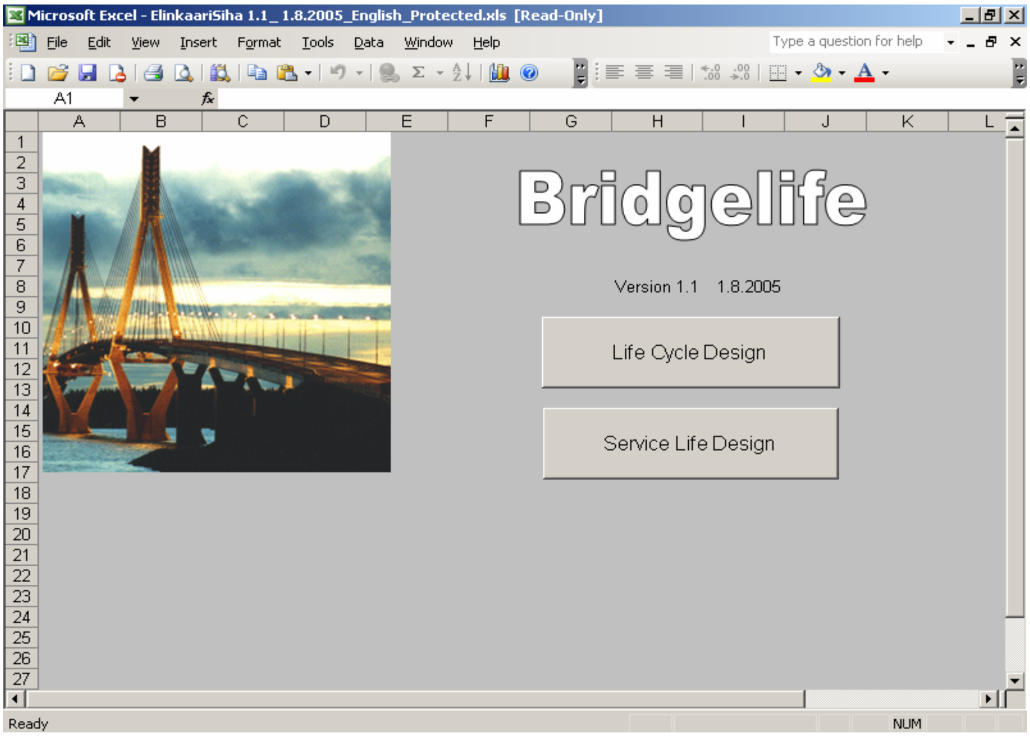


Figure 4.1 *The Bridgelife main interface.*

The program has the default values for all information and can therefore run independently. It is adopted by the Finnish Road Administration (Finnra) and is embedded in its bridge management system. Consequently it can freely obtain the latest data from the database when connected to that.

4.2 WebLCC - program developed at KTH, Sweden

WebLCC is a life cycle cost analysis program developed by Mr *Axel Liljencrantz* at KTH, Sweden. Originally it was academic-oriented and was used for education purposes in Sweden and was not officially adopted by the Swedish National Road Administration (SNRA). MATLAB was adopted as the calculation tool in this program. The first version of WebLCC is not web-based and still remains in an academic form. The new version was developed to a web-based program. The user needs to have an account and password to access the program. The main interface after logging in is shown in Figure 4.2.

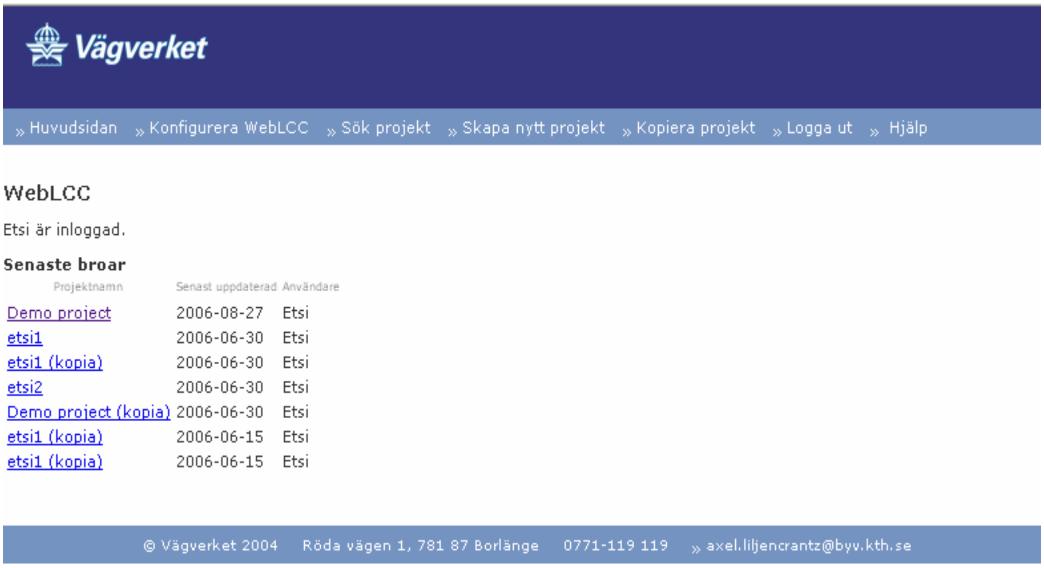


Figure 4.2 The WebLCC main interface page.

There are totally three tasks in this program: creating of projects, searching of projects and editing of projects. The main LCC operation lies in the task of editing of projects. This task consists of five parts: conditions, investments, maintenance, repairs and results. In addition, the sensitivity analysis is also included. The program is still under development. The LCC Expert System will be its future. It will include two languages: English and Swedish. The name *WebLCC* was later changed to *BroLCC*.

Database accessing is not involved in the *WebLCC*. All data needed is stored at KTH's server. For wider data resources it can be combined with the Swedish *BaTMan* (Bridge and Tunnel Management) system. In Sweden, *BaTMan* has been recently developed by SNRA as a bridge and tunnel management system. It is a computerized tool for organizing and storing data and carrying out activities within the management process. It is also web-based and allows anyone with the proper access rights and a standard web-browser to use the system. It is currently used by several regions and local authorities that own and manage structures in Sweden. Approximately 30,000 structures, mostly bridges, are currently managed using *BaTMan*. The system supports the management process on both network and project levels during the entire life cycle of a structure. The welcome page is shown in Figure 4.3.

Figure 4.3 *The BaTMan Welcome page.*

It is worth of noticing that in Sweden bridge condition is recorded according to three types of condition:

- the physical condition based on measurements related to development of previous or new damage, degradation processes, pollution processes, etc;
- the functional condition stated in terms of 4 classes: defective at the time of inspection, defective within 3 years, defective within 10 years, defective beyond 10 years; and
- the economic condition described in terms of quantity and cost of a remedial activity, the LCV method, the cost is calculated automatically.

4.3 BridgeLCC – program developed at NIST, USA

In USA, there are four systems developed for LCC: *PONTIS*[2], *BRIDGIT*[3], *BLCCA*[4] and *BridgeLCC*. *BridgeLCC* was developed by Dr. Mark A. Ehlen at the National Institute of Standards and Technology (NIST) to help bridge engineers to assess the cost effectiveness of new, alternative construction materials. The *BridgeLCC* 2.0 version was taken into this thesis as an alternative to the two Nordic programs mentioned above. The software uses a life cycle costing methodology based on both ASTM standard E 917 and a cost classification scheme developed at NIST. The ASTM E 917 practice insures that the cost calculations follow accepted practice; the scheme helps the user to account for all project costs, properly categorize them, and then compare breakdowns of the alternatives' LCCs.

[2] developed under an FHWA project and is available to agencies through the AASHTOware program.
[3] developed under the NCHRP and available from the developer, National Engineering Technology Corporation.
[4] developed under the NCHRP Project 12-43, National Engineering Technology Corporation.

The program runs in Windows 95, 98, 2000, NT, and XP. The software, along with related publications describing the underlying life cycle costing methodologies, can be freely downloaded from the following website: http://www.bfrl.nist.gov/bridgelcc/welcome.html. *BridgeLCC* 2.0 was improved from the former version *BridgeLCC* 1.0[5]. Improvements in version 2.0 include improved Monte Carlo capabilities, context-sensitive help, inclusion of an expanded concrete service life prediction tool, and a probabilistic events wizard that helps to add user-tailored events like earthquakes to the analysis. The *BridgeLCC* 2.0 program's main interface page is shown in Figure 4.4.

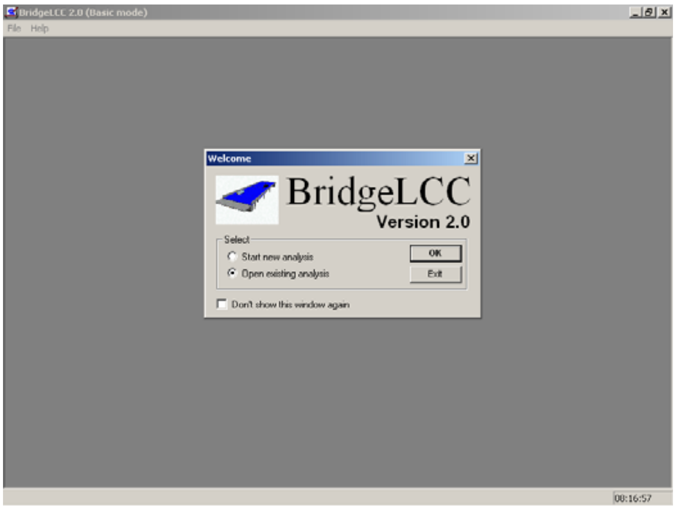


Figure 4.4 *The* BridgeLCC *main interface.*

4.4 Functionality exploration of the programs

The basic characteristics of the three programs are so different that it is impossible to have a LCC comparison for a common bridge. Therefore, each program is treated separately using its own local bridge example so that the individual characteristics can be pointed out.

4.4.1 Functionality of Bridgelife

Access to Bridgelife

There are two ways to use *Bridgelife* – either on a PC (Personal Computer without network connection) or online with access to Finnra's Database. The Finnish version of *Bridgelife* is used online in practice. The procedure of online accessing is introduced in Figures 4.5 to 4.11. They also give a general impression of the database operation. However, in this study, the English PC version is used.

[5] for which Dr. Mark A. Ehlen received BFRL's 1999 Communication Award.

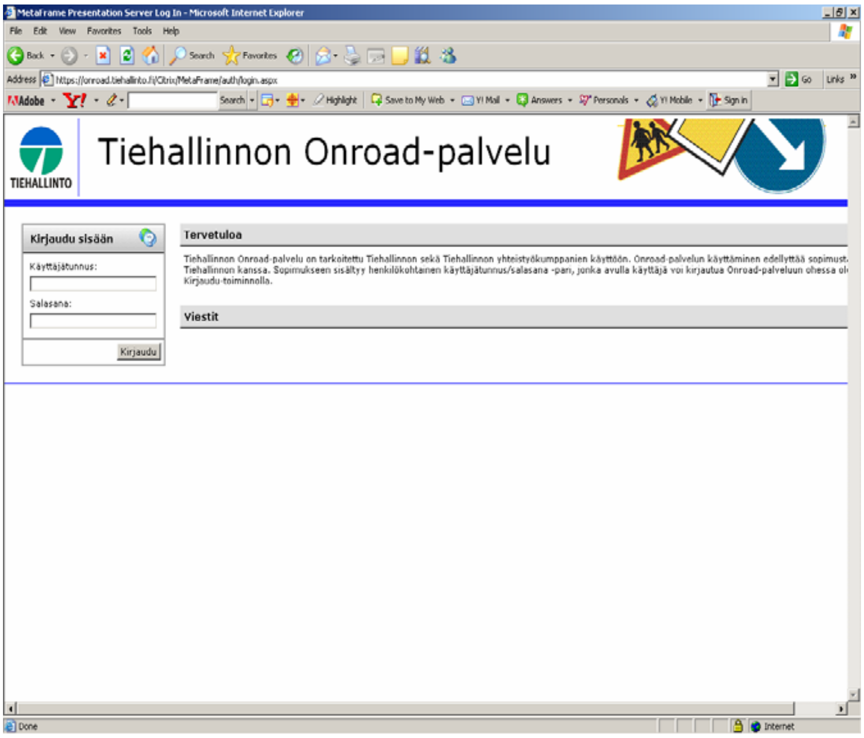


Figure 4.5 *Gateway of Finnra's LAN (Local Area Network.)*

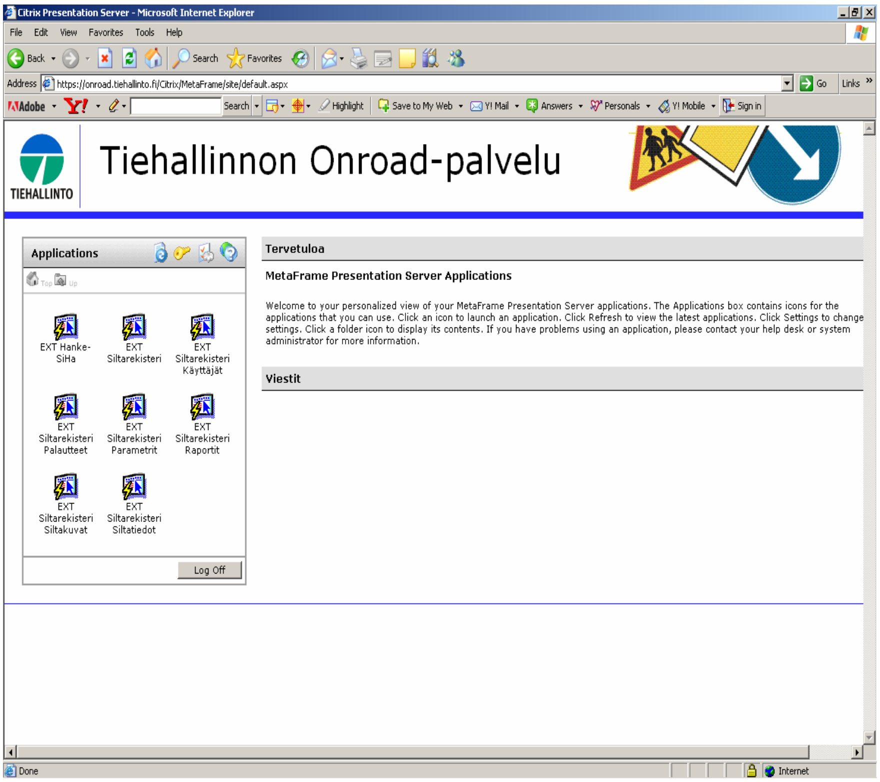


Figure 4.6 *The main window of the Finnra's on road service page*

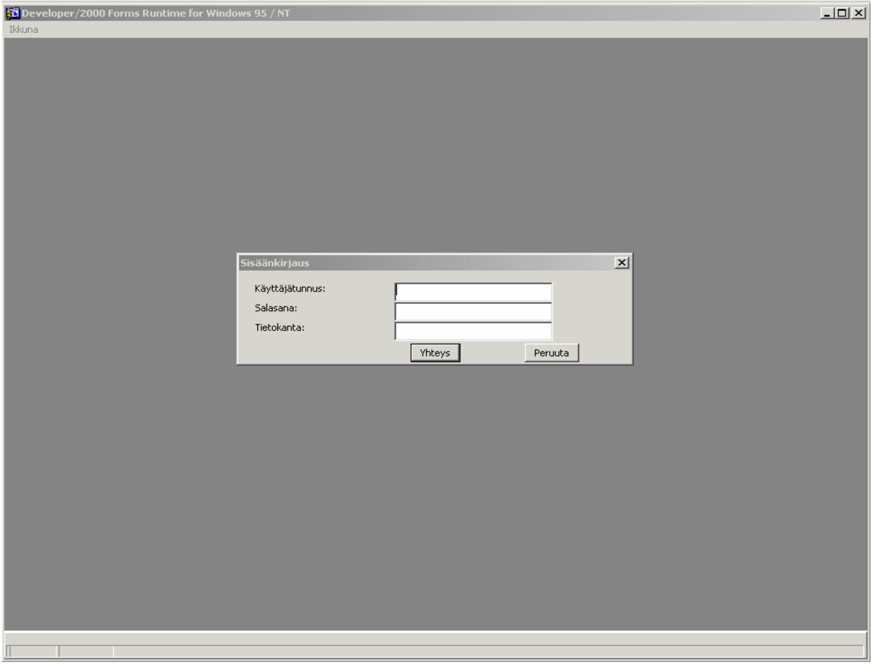


Figure 4.7 *Citrix Presentation Server gateway after clicking the "EXT Hanke-SiHa" symbol shown in Figure 4.6 (another user name and password are required).*

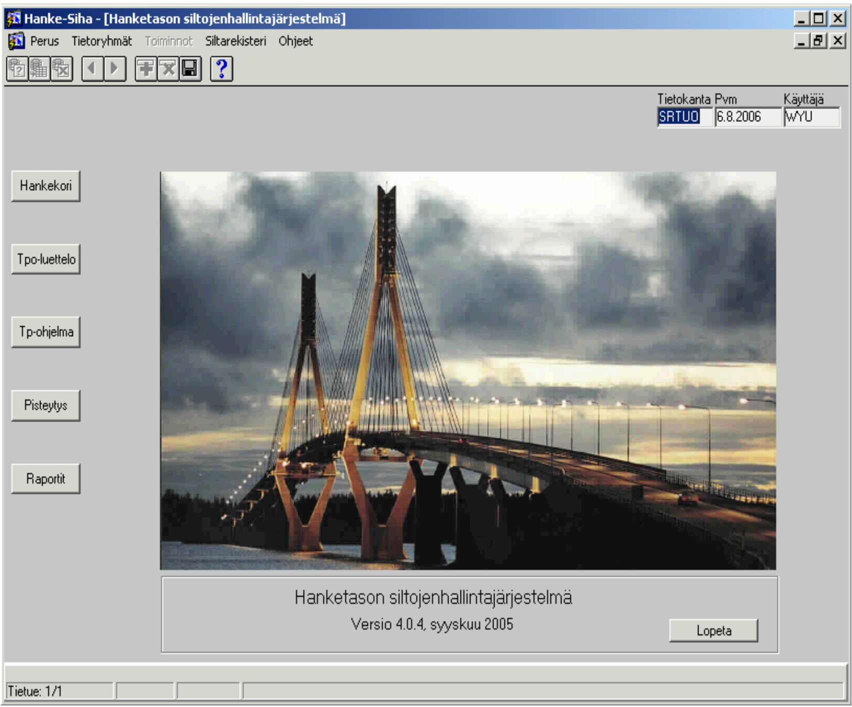


Figure 4.8 *The database interface after login in the Citrix Presentation Server shown in Figure 4.7.*

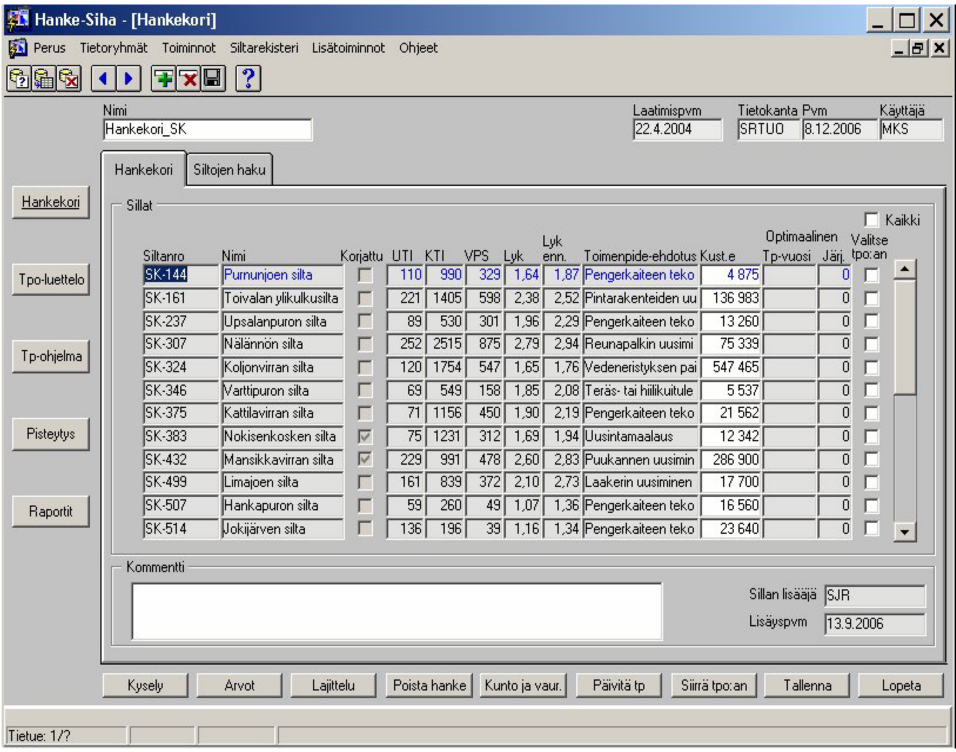


Figure 4.9 *Result window for clicking the "Hankekori" button shown in Figure 4.8.*

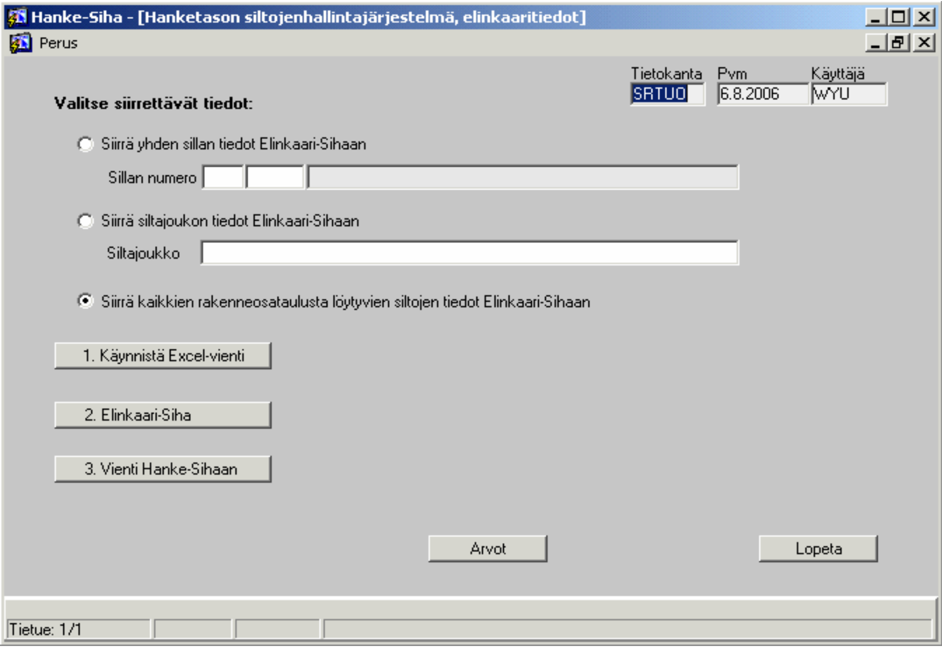


Figure 4.10 *Result window[6] from "Lisätoiminnot" to select "Tee elinkaarianalyysi" in Figure 4.9.*

[6] In this window, the button "Käynnistä Excel-vienti" is used for getting the initial data, the botton "Elinkaari-Siha" for running the *Bridgelife* program, and the button "Vienti Hanke-Sihaan" for bringing the results to the project level bridge management system.

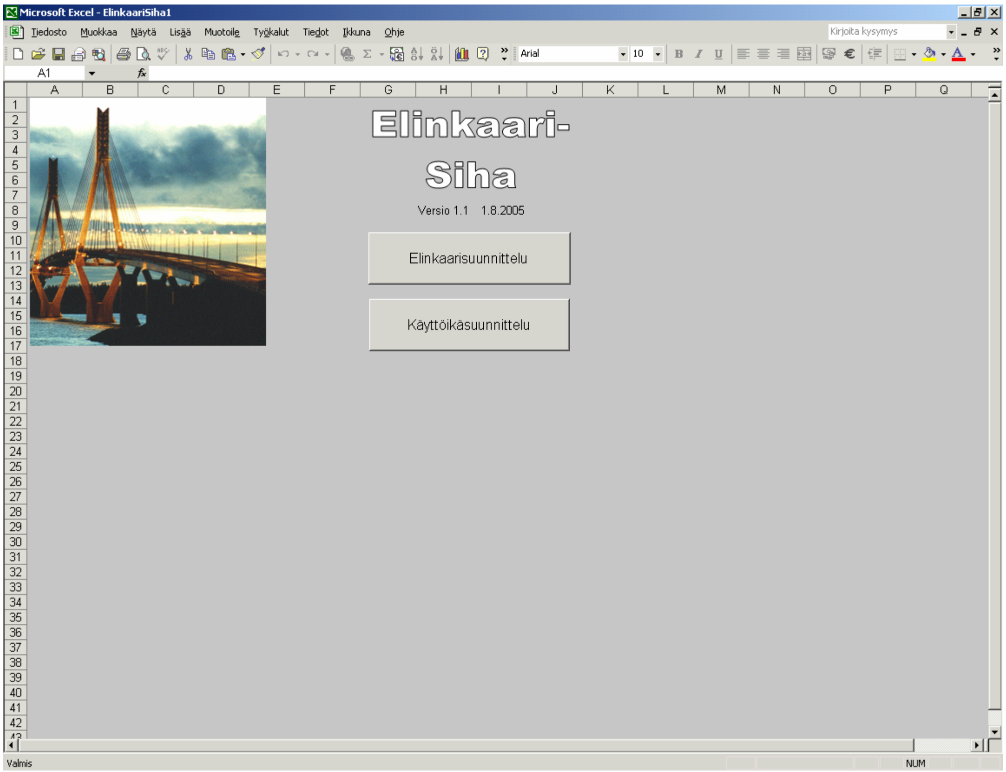


Figure 4.11 *The* Bridgelife *program (Finnish version, see the English version in Figure 4.1) after clicking the "Elinkaari-Siha" button shown in Figure 4.10.*

Life cycle design

After the button "Life Cycle Design" is pressed, the program first checks the initial data and then the user can get the "Initial Data" form for life cycle planning as shown in Figure 4.12. Then a list of the bridges in the initial data file can be seen. The program applies an initial data file produced by the bridge database, if it is running on the database. Otherwise it uses its own default values.

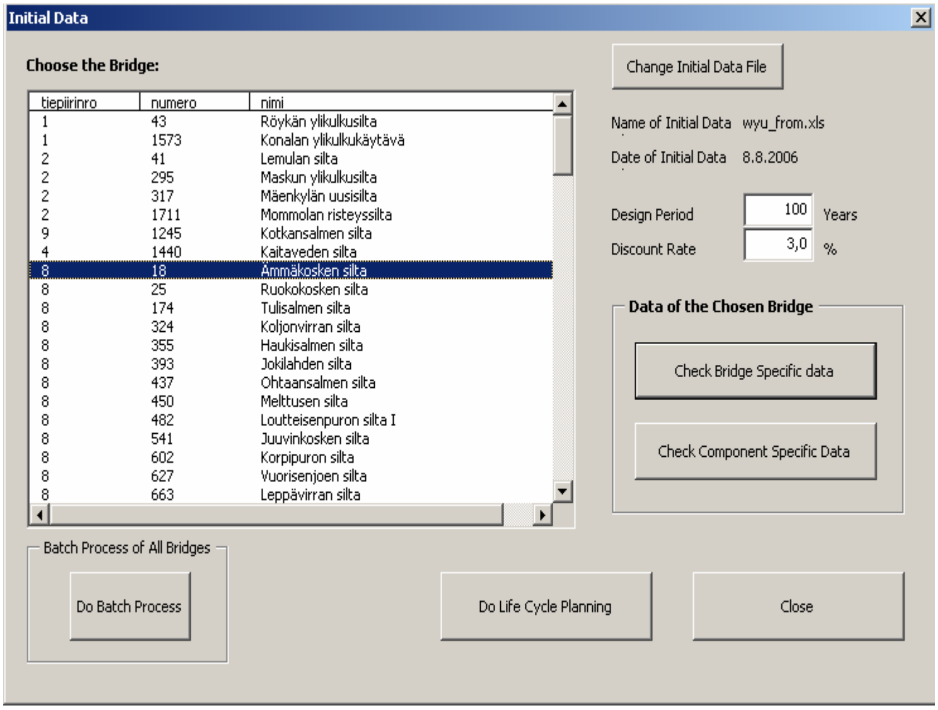


Figure 4.12 *Initial data window for life cycle planning*

Contributing functions

There are three contributing function buttons on the right hand side shown in Figure 4.12. The initial data file can be changed with the uppermost button "Change Initial Data File" on the "Initial Data" form. The length of the design period and the discount rate can be given by the user. Then the user selects the bridge from the list. For example, the Ämmäkoski Bridge is chosen here. The user can then check the initial data of the selected bridge by pressing the buttons in the frame marked "Data of the chosen bridge". This data comprises the structure, material, environment and condition assessment of the bridge. The further details are shown in Figures 4.13 and 4.14.

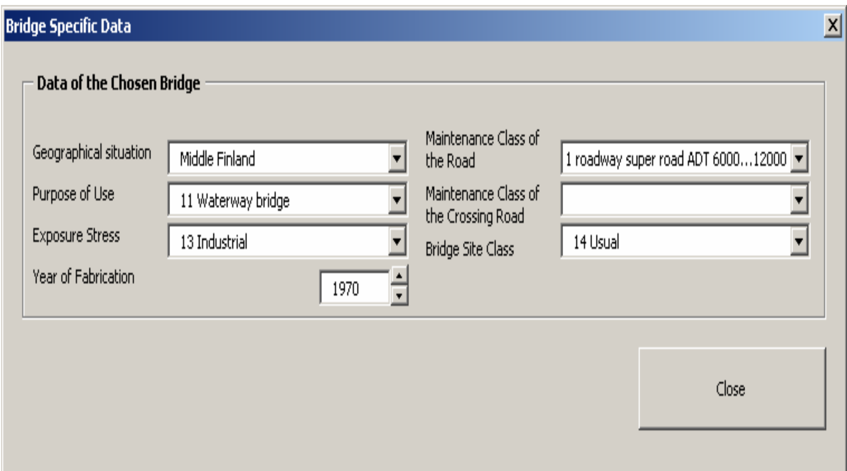


Figure 4.13 *Checking of the bridge specific data*

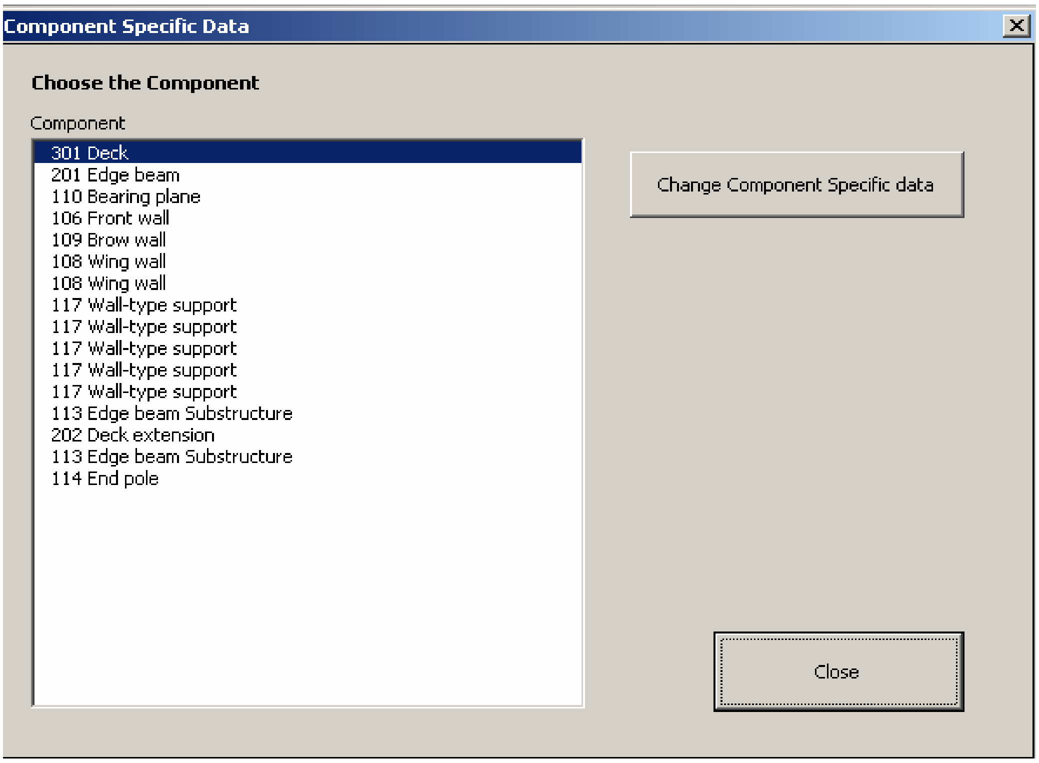


Figure 4.14 *Checking of the component specific data.*

Figure 4.14 shows how the user can select one component to change the specific data. After pressing the button "Change Component Specific data" the user will obtain the further details shown in Figure 4.15.

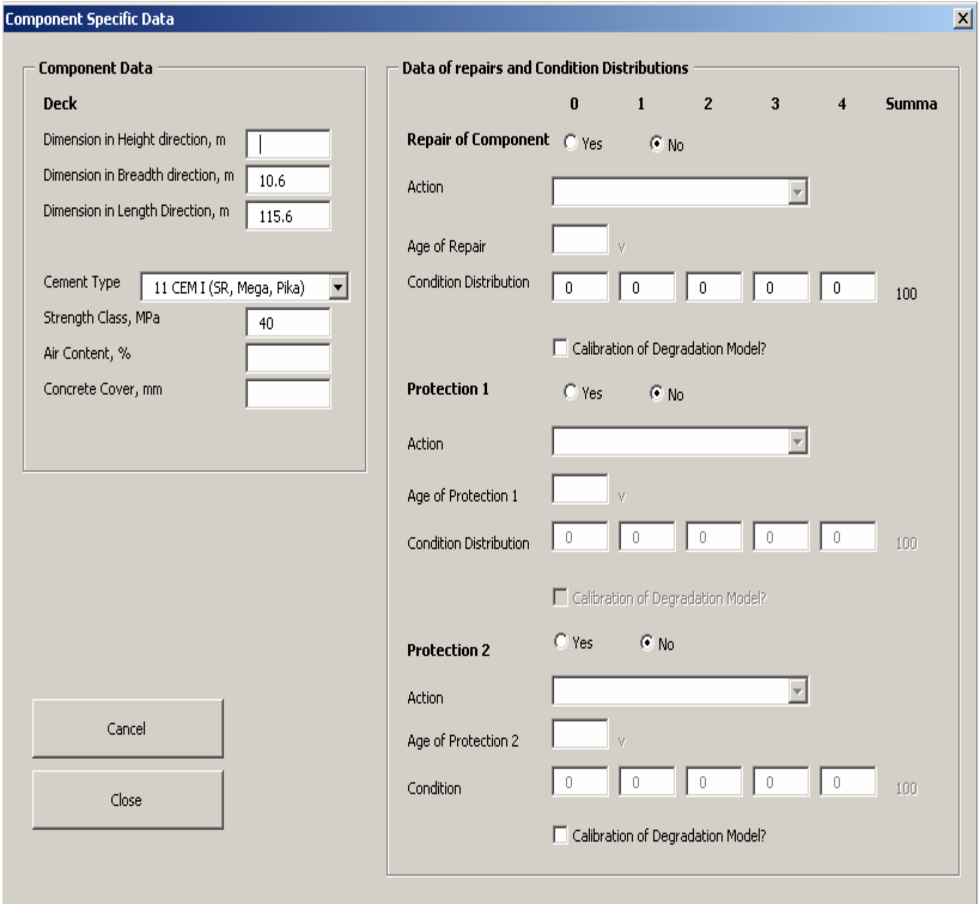


Figure 4.15 *Changing of the component specific data.*

Primary functions

There are two primary function buttons at the bottom of the window as shown in Figure 4.12, namely, the "Do Batch Process" button and the "Do Lifecycle Planning" button. The former button is needed to perform a life cycle planning for all the bridges in the initial data file. As a result of the batch process, a special output file should be created.

The latter button is needed to perform a preliminary life cycle plan of a selected bridge. The program then goes through all bridge components in a row and indicates the specific MR&R actions needed. In this process the decision tree, for an example see Figure 3.11, and the timing based on automatic triggering system are used. Actions that take place close to each other in the same year are automatically combined into bigger projects. As an example, the results obtained for the Ämmäkoski Bridge are shown in Figure 4.16.

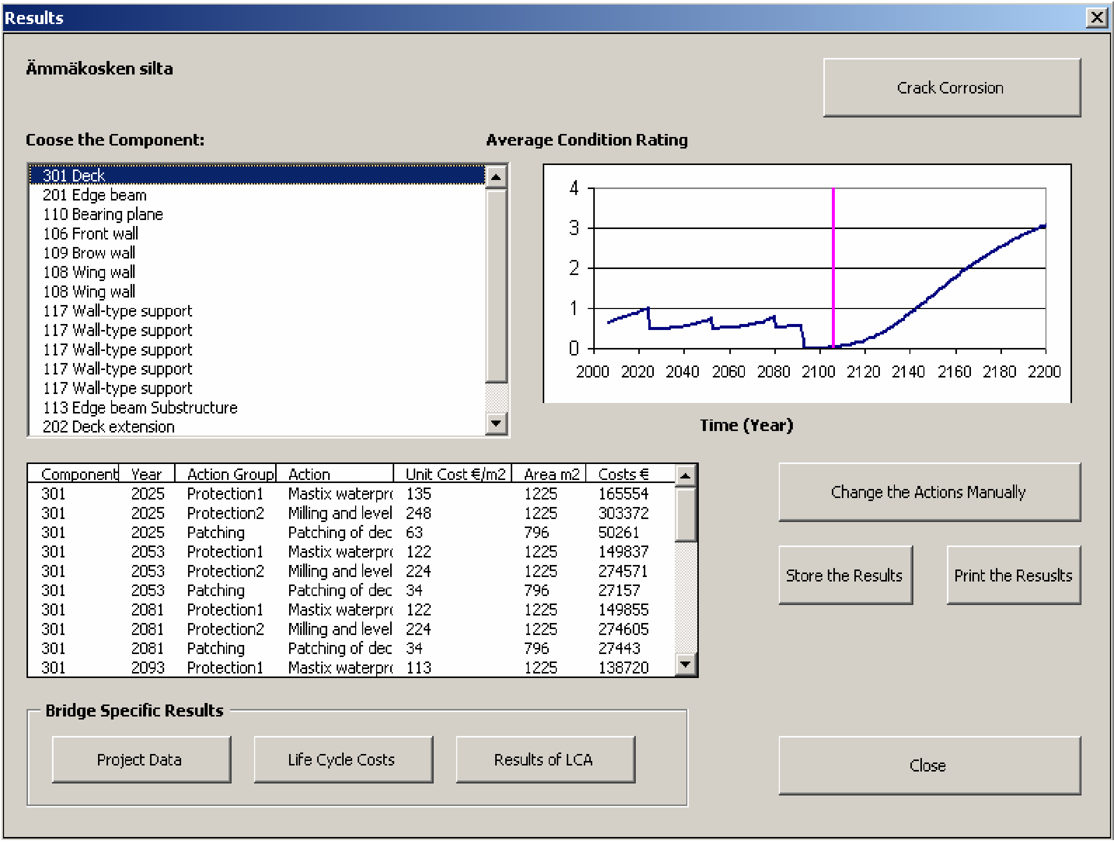


Figure 4.16 *Life cycle planning results window of the Ämmäkoski bridge.*

The components of the chosen bridge are listed in the "Results" window, as seen in Fig. 4.16 The user can choose whichever one he/she desires. The data, which show the life cycle action profile of the respective component, can then be seen in the list box below the component list. This list box contains all specifications of actions including timings and costs. The diagram which shows the average condition rating of the respective component during the design period is always automatically updated. The automatic design of the bridge includes optimal action profiles for each component. All the timings and costs of actions are calculated.

There are three primary function outputs in the frame "Bridge Specific Results" in Figure 4.16. "Project Data" gives detailed data on the first projects planned for the bridge, as shown in Figure 4.17. "Life Cycle Costs" window shows detailed LCC data as shown by Figure 4.18.

The window "Results of LCA" shows environmental impact data for the whole design period, as shown in Figure 4.19. The environmental impact, caused by the consumption of materials during the maintenance and repair actions, is calculated with the LCA analysis.

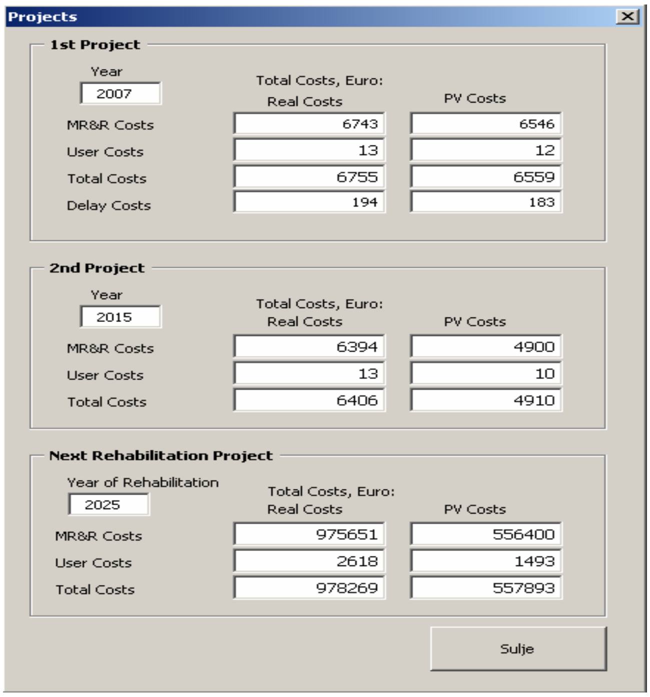


Figure 4.17 *Results window of "Project Data".*

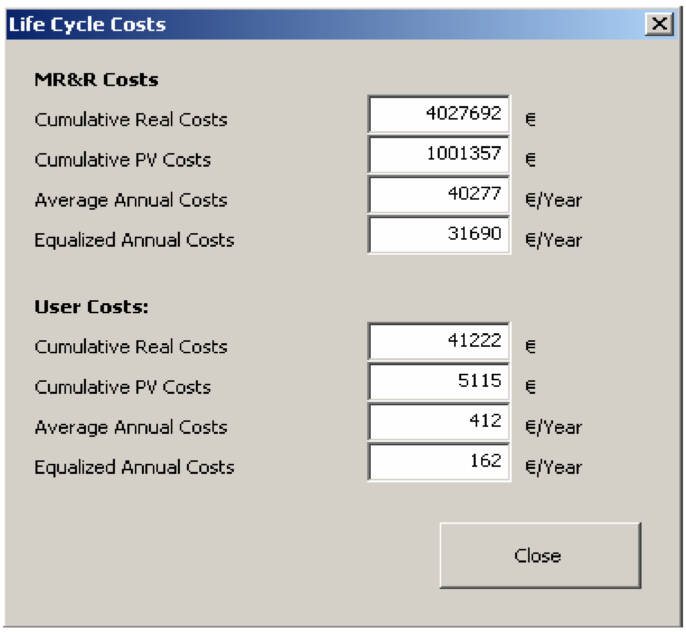


Figure 4.18 *Results window of "Life Cycle Costs".*

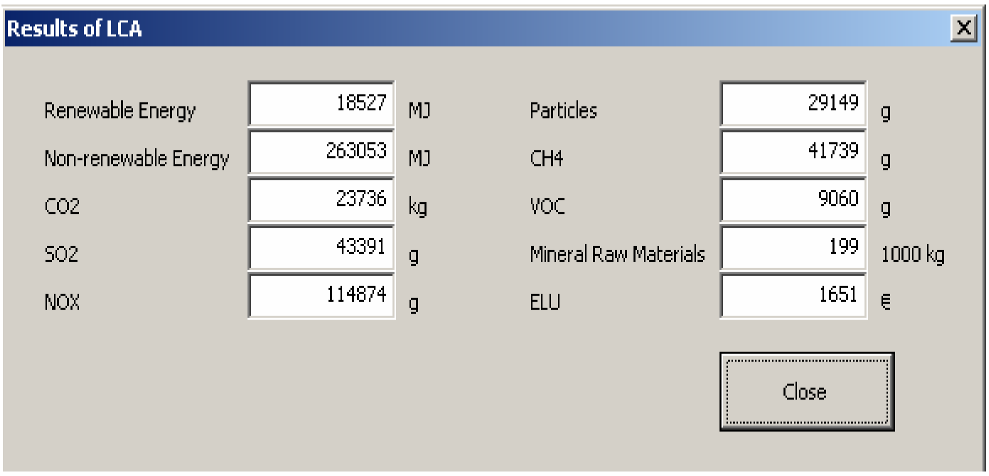


Figure 4.19 *Results window of "Results of LCA".*

There are also four additional contributing function buttons as shown by Figure 4.16, namely "Crack Corrosion", "Change the Actions Manually", "Store the Results" and "Print the Results". The results seen in Figure 4.20 can be obtained by pressing the "Crack Corrosion" button in the upper right corner.

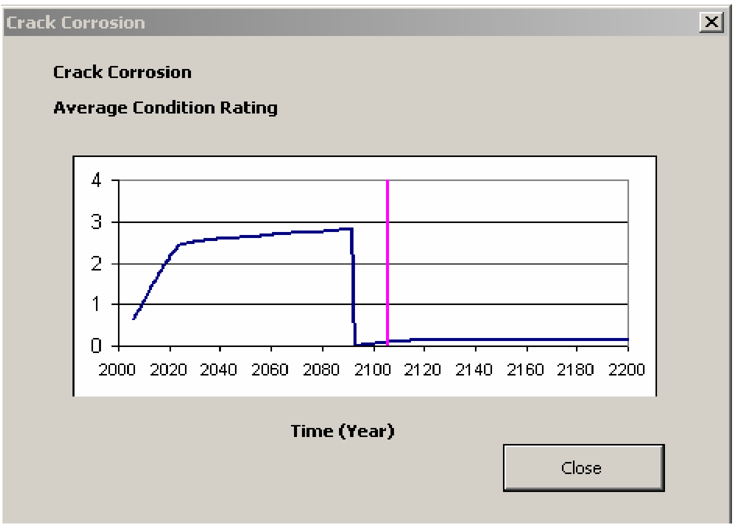


Figure 4.20 *Results window of "Crack Corrosion".*

Button "Change the Actions Manually" allows making manual corrections and changes to the plans prepared automatically by the program. This button produces a window shown in Figure 4.21. On this window the designer can change the definitions of the MR&R actions or their timings. The designer can also remove all previous definitions of actions and define his "own" MR&R action profile with fixed timing. The changes are inserted in the life cycle plan of the bridge by pressing the button "Transfer the changes into the plan".

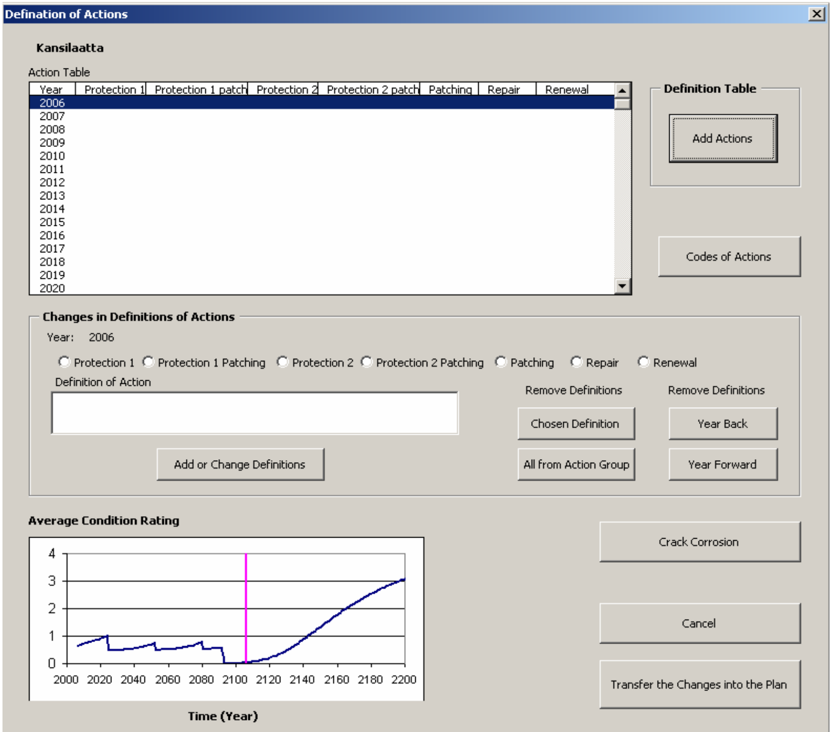


Figure 4.21 *Results window of "Change the Actions Manually".*

All buttons shown in Figure 4.21 are auxiliary contributing functions. The results window of "Add Actions" is shown in Figure 4.22 and the one of "Code of Actions" in Figure 4.23.

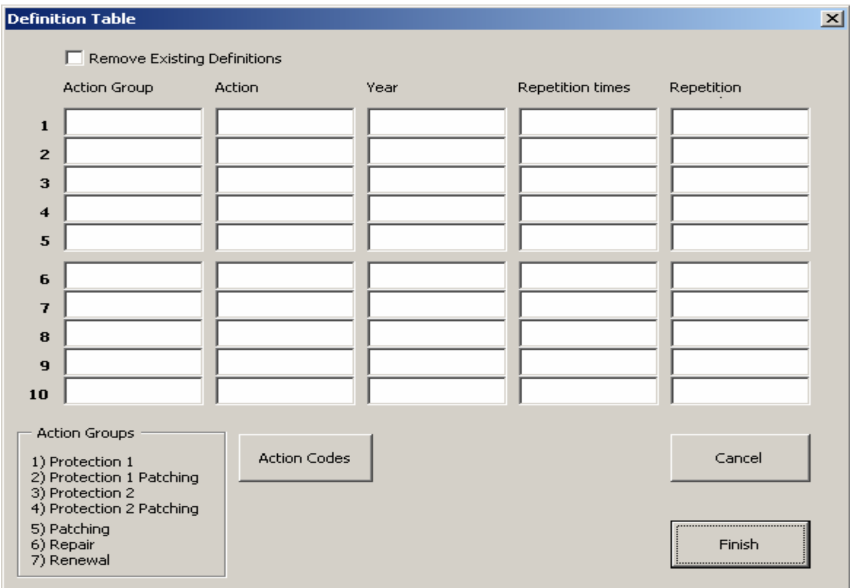


Figure 4.22 *Results window of "Add Actions".*

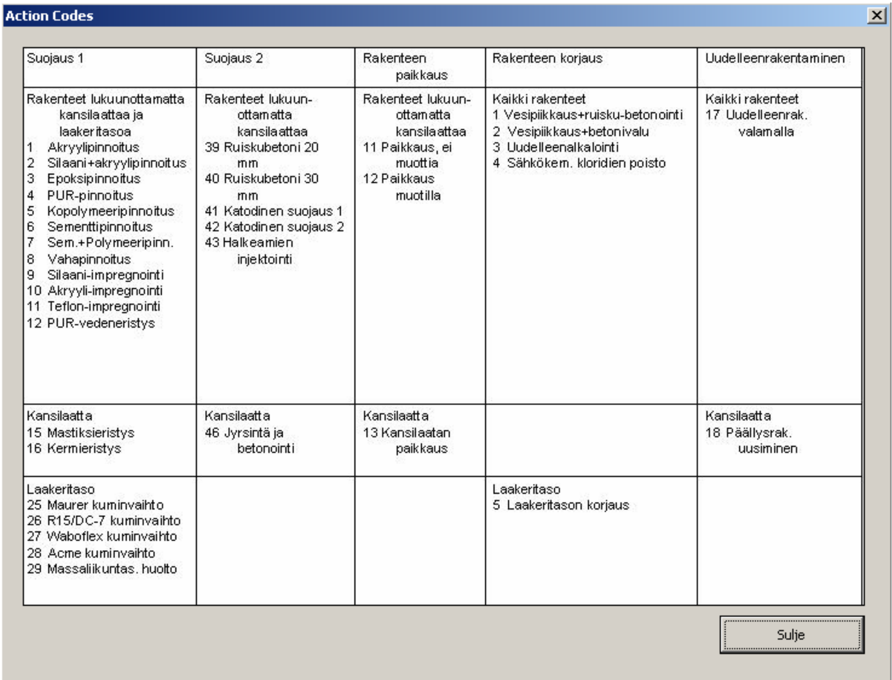


Figure 4.23 *Results window of "Codes of Actions" or "Action Codes".*

As shown in Figure 4.16, the two buttons "Store the Results" and "Print the Results" are used to produce the results file.

Service life design

Service life design as another primary function of the program completes the life cycle planning module of bridges. When the button "Service Life Design" is pressed, the results window shown in Figure 4.24 is presented. Some inputs can be given by the user with a desired value and the others have to be chosen among the available alternatives. The results windows can be obtained by pressing the corresponding buttons shown in Figure 4.24. The exposure data can be seen in Figure 4.25, the component data in Figure 4.26, the protection data in Figure 4.27 and the crack corrosion in Figure 4.28.

A new component of a bridge can be designed so that it fulfils the performance requirements set for it throughout its service life. The service life design is also based on the Markov Chain condition analysis, i.e., the deterioration models used in the service life design are the same as those used in the life cycle planning. The results shown in Figure 4.24 can be printed by pressing the button "Print the Results".

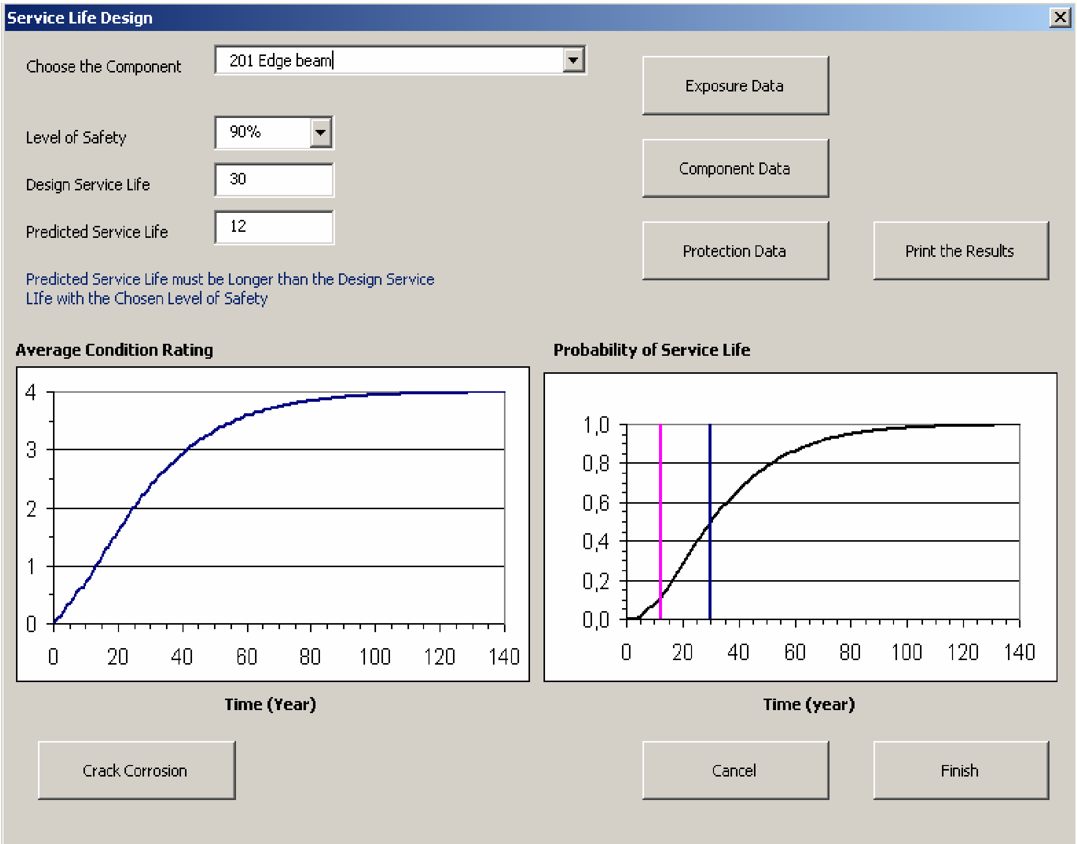


Figure 4.24 *Results window of "Service Life Design".*

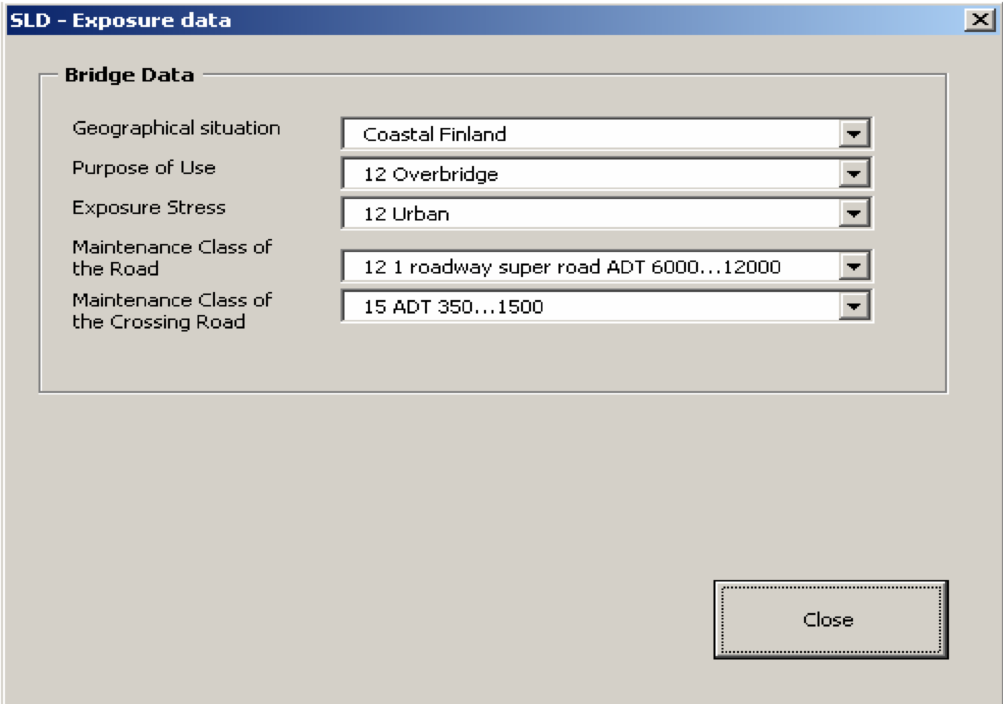


Figure 4.25 *Results window of "Exposure Data".*

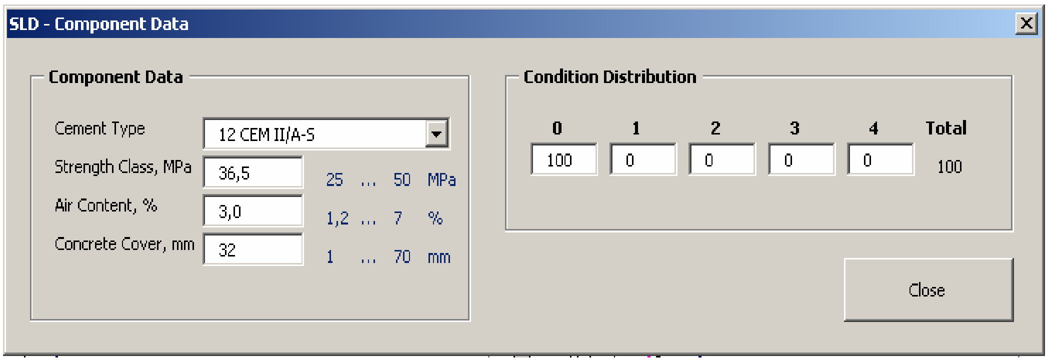


Figure 4.26 *Results window of "Component Data".*

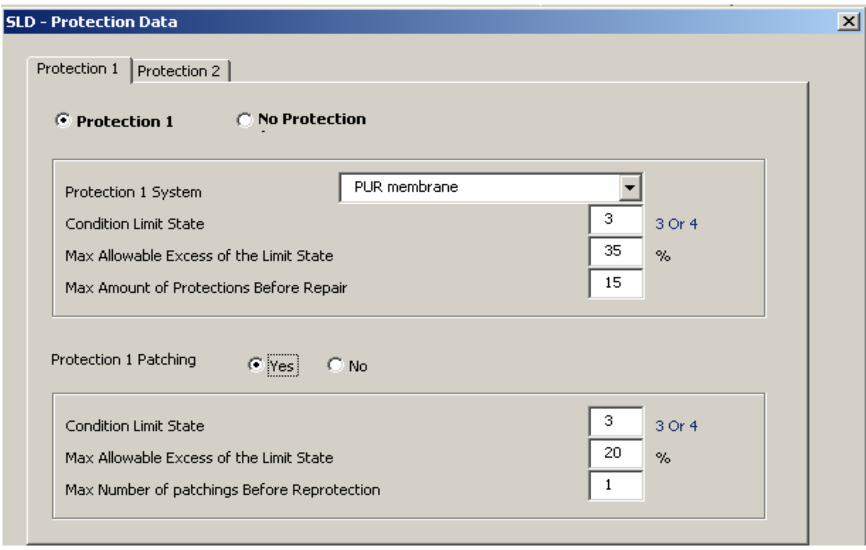


Figure 4.27 *Results window of "Protection Data".*

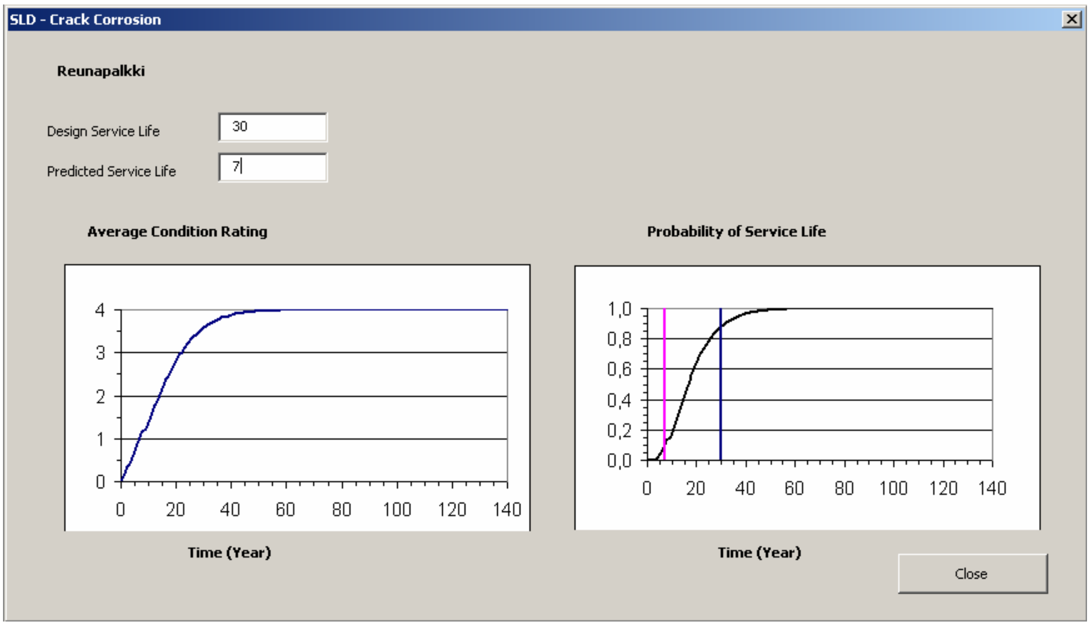


Figure 4.28 *Results window of "Crack Corrosion".*

4.4.2 Functionality of WebLCC

In the *WebLCC* main interface, Figure 4.2, there are seven items dealt in this program. "Huvudsidan" (home) is used to access the main interface anytime when using the program. "Logga ut" (logout) is used to exit from the program. There is no need to say more about these two items. The other five, however, will be discussed more thoroughly underneath.

Configuring WebLCC

When clicking "Konfigurera *WebLCC*" (configure *WebLCC*), the program will show the "Konfigurera konto" window, Figure 4.29, to allow the user to reset his account including the account name, password, figure width, figure height and the colour used.

Figure 4.29 *Results window of "Konfigurera WebLCC" in the WebLCC program.*

Tracking project

When clicking "Sök projekt" (tracking project), the program will show the window shown in Figure 4.30. This window allows the user to search for an existing project.

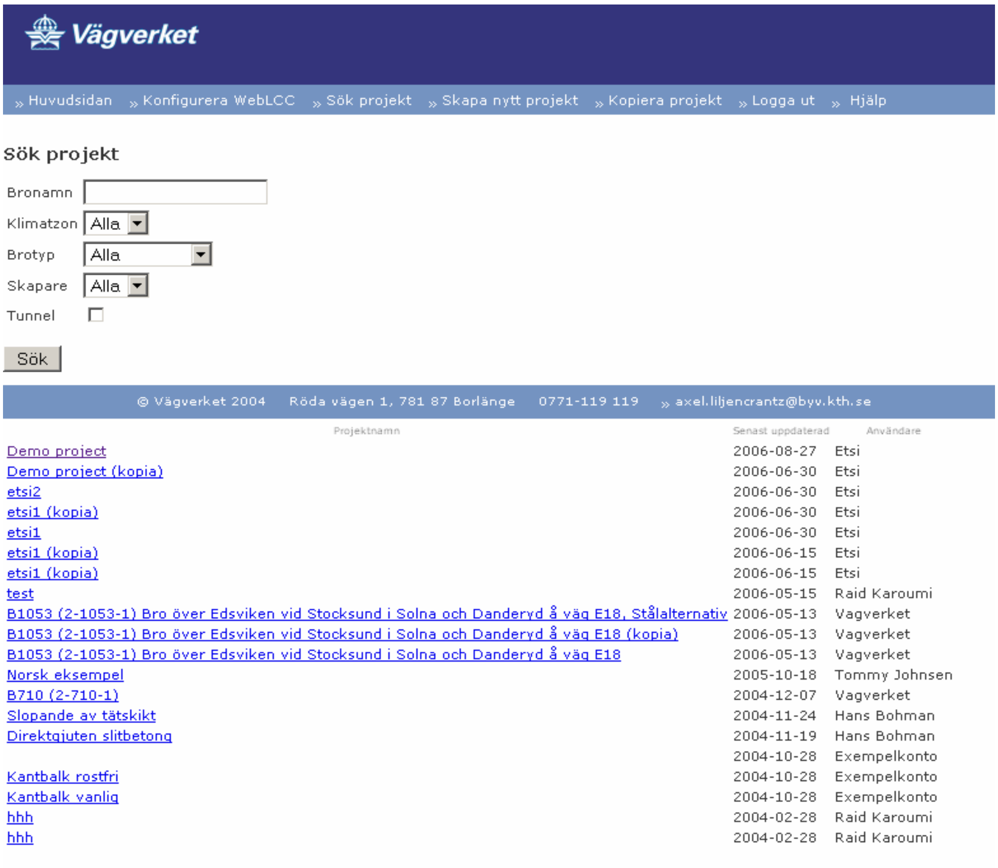


Figure 4.30 *Results window of "Sök projekt" in the WebLCC program.*

Creating a new project

When clicking "Skapa nytt projekt" (create a new project), the program will show the window shown in Figure 4.31. This window allows the user to create a new project. After giving a name and clicking "Skicka" (send) the program will show the most important user interface (Figure 4.32) with all required inputs in the window.

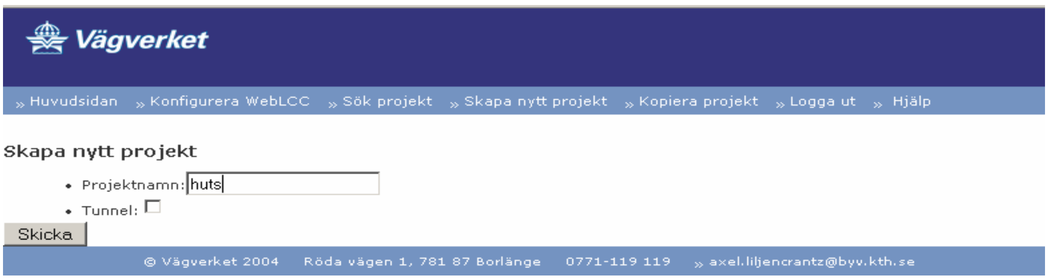


Figure 4.31 *Results window of "Skapa nytt projekt" in the* WebLCC *program.*

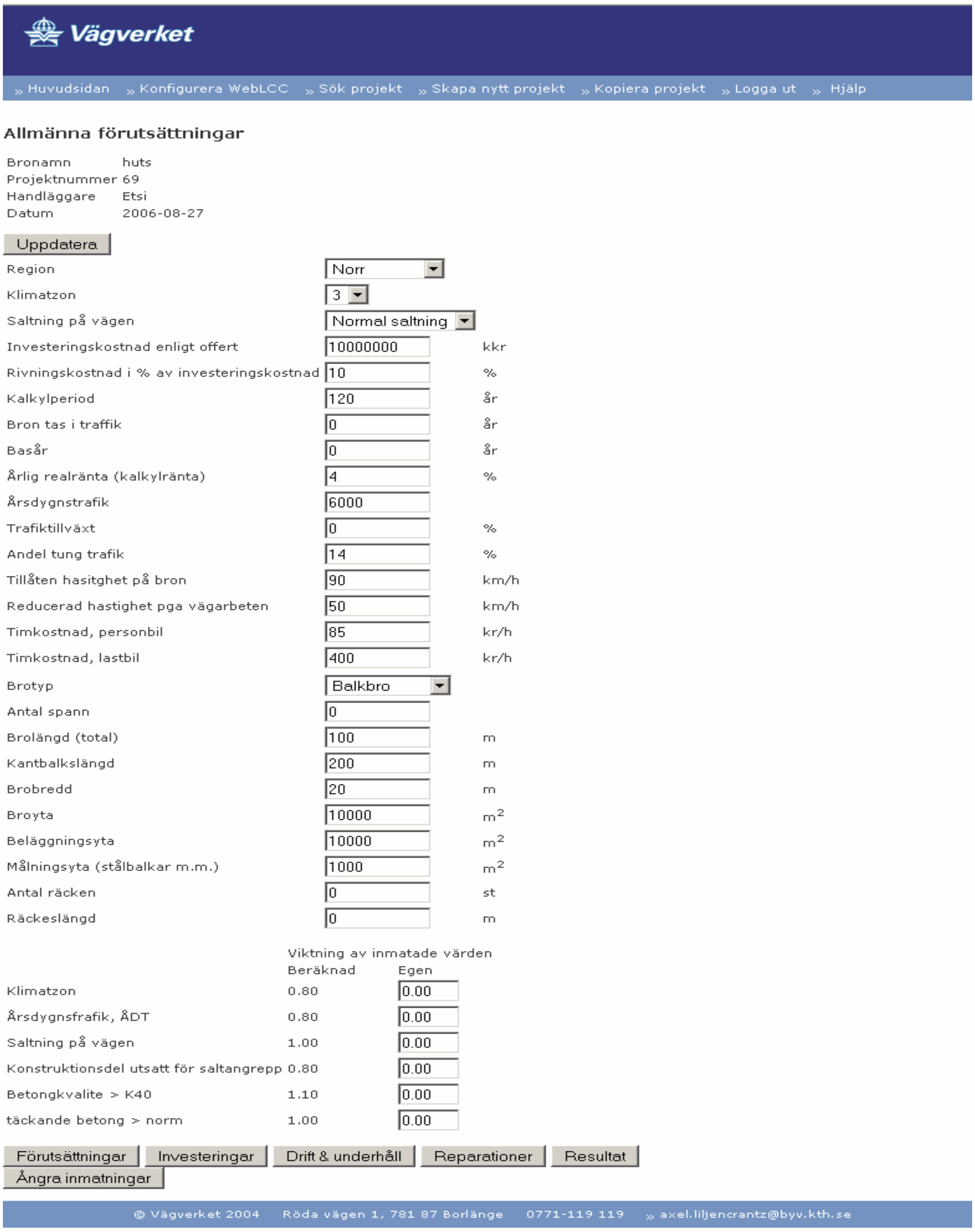


Figure 4.32 WebLCC *input window shown after creating a new project.*

There are five primary function buttons at the bottom of the screen as shown in Figure 4.32, namely, “Förutsättningar”, “Investeringar”, “Drift & underhåll”, “Reparationer” and “Resultat” (Assumptions, Investments, Usage & maintenance, Repairs and Result).

The button “Förutsättningar” is used for accessing to Figure 4.32 whenever needed. There are four drop-down list boxes in the input items shown in Figure 4.32. They show the corresponding prescribed alternatives for inputs, as shown in Figures 4.33 to 4.36.

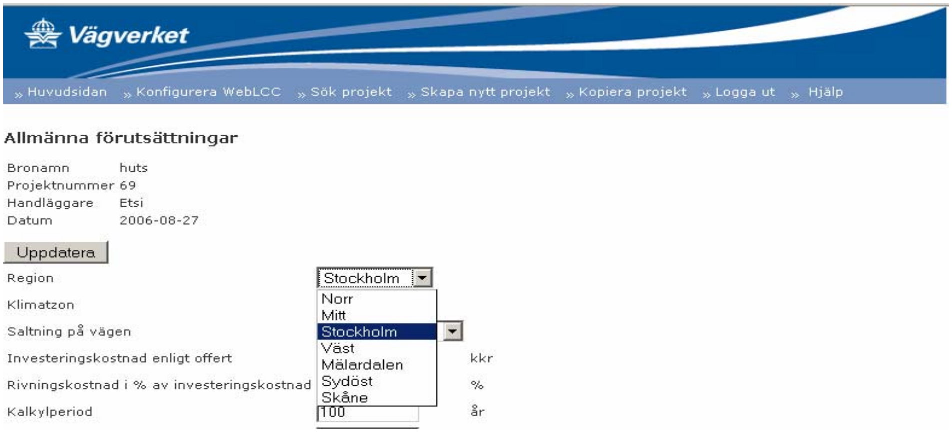


Figure 4.33 *Drop-down list box of "Region" in Figure 4.32*

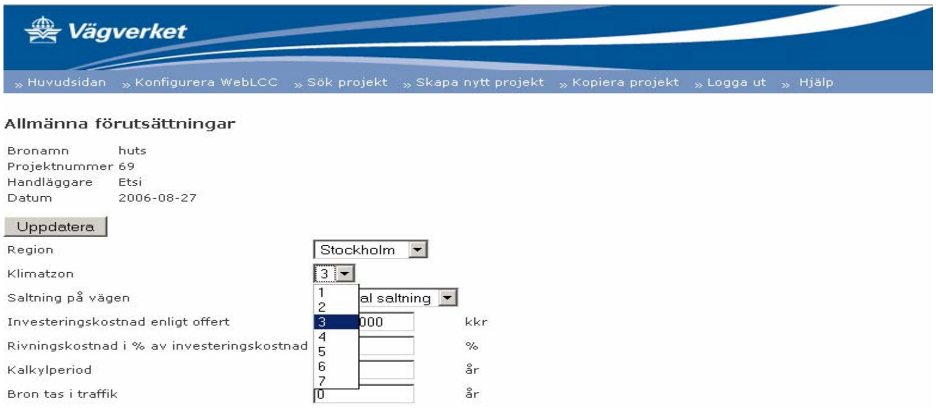


Figure 4.34 *Drop-down list box of "Klimatzon" in Figure 4.32*

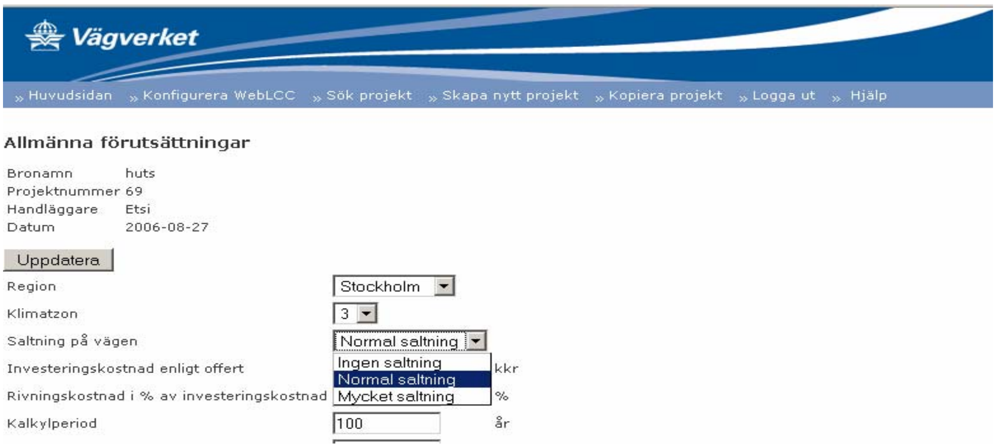


Figure 4.35 *Drop-down list box of "Saltning på vägen" in Figure 4.32.*

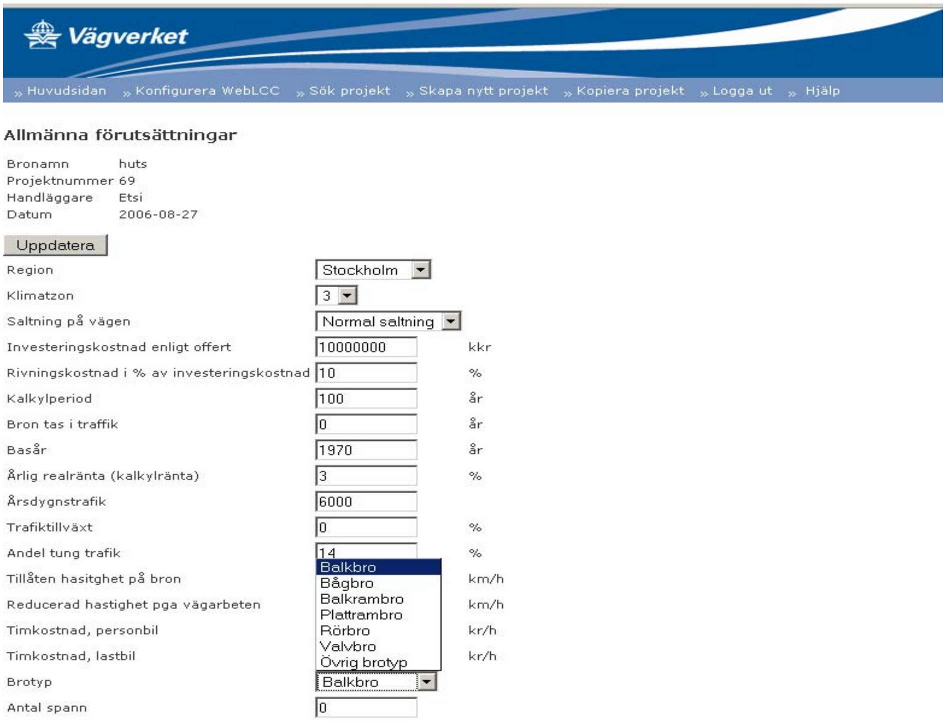


Figure 4.36 *Drop-down list box of "Brotyp" in Figure 4.32*

The results window, which appears after clicking button "Investeringar" in Figure 4.32, is shown in Figure 4.37. A drop-down list box in the input items shown in Figure 4.37 lists the prescribed possible inputs, as shown in Figure 4.38.

The results window, which appears after clicking button "Drift & underhåll" in Figure 4.32, is shown in Figure 4.39. There is also an un-editable drop-down list box in the input items shown in Figure 4.39. The corresponding prescribed inputs are shown in Figure 4.40.

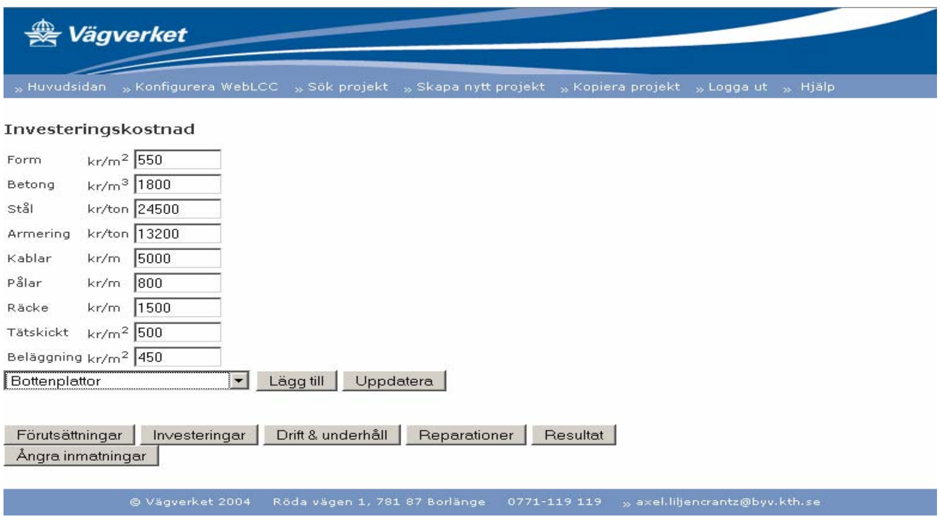


Figure 4.37 *Results window shown after clicking "Investeringar" button in Figure 4.32.*

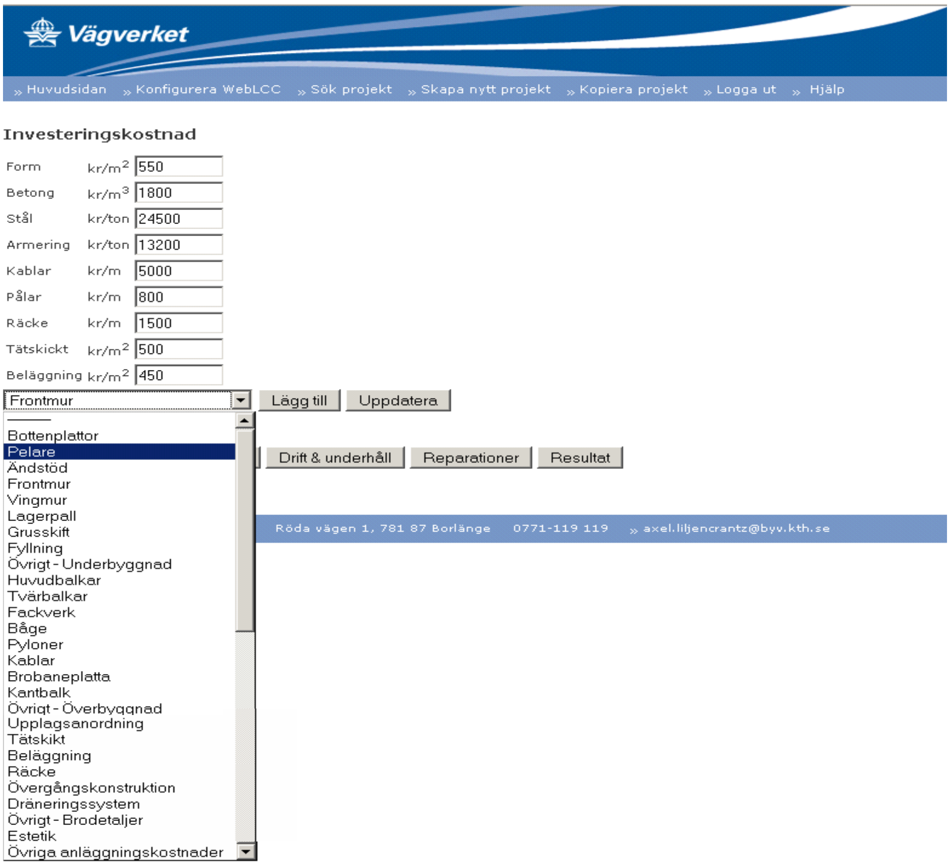


Figure 4.38 *Drop-down list box in Figure 4.37.*

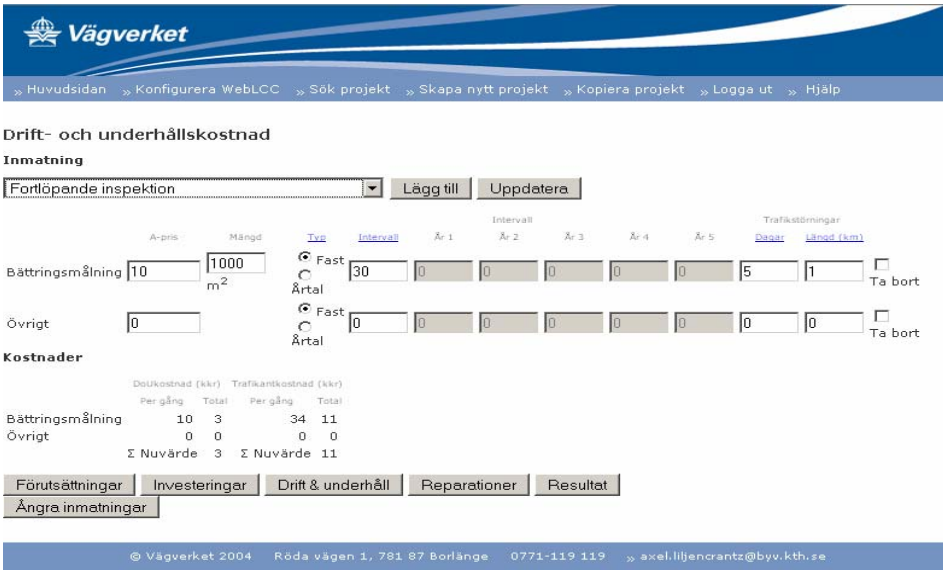


Figure 4.39 *Results window shown after clicking "Drift & underhåll" button in Figure 4.32.*

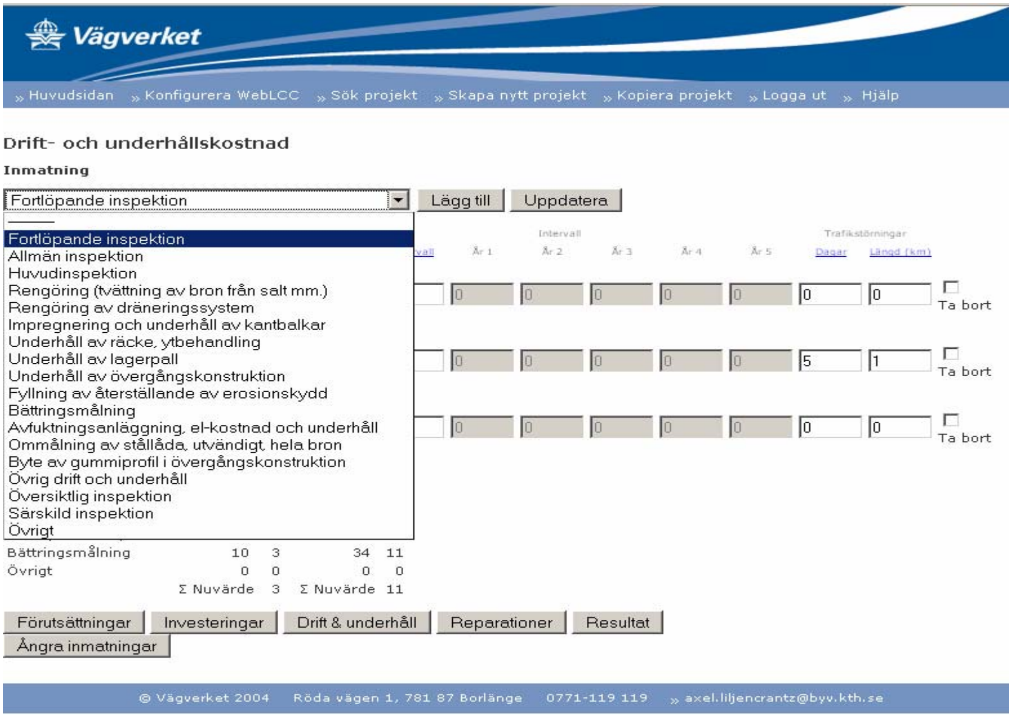


Figure 4.40 *Drop-down list box in Figure 4.39*

The results window, which appears after clicking button "Reparationer" in Figure 4.32, is shown in Figure 4.41. An un-editable drop-down list box concerning the corresponding inputs is shown in Figure 4.42.

Figure 4.41 *Results window shown after clicking "Reparationer" button in Figure 4.32.*

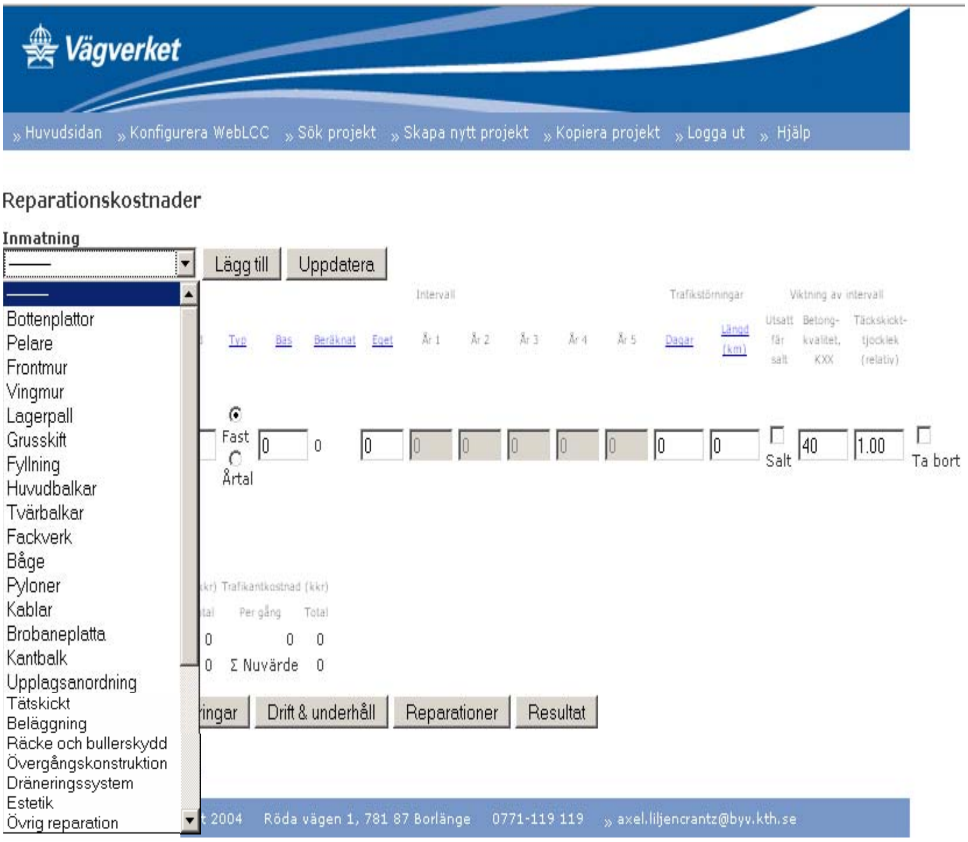


Figure 4.42 *Drop-down list box in Figure 4.41.*

There are two contributing function buttons in the window as shown in Figure 4.32, namely, “Uppdatera” and “Ångra inmatningar” (Update and Undo input). They can easily be understood in the words already. There is no need to explain them.

Copying a project

When clicking “Kopiera projekt” (copy a project), the program will make a copy of the project file in the server.

Online Help

When clicking “Hjälp” (help), the program will show the window shown in Figure 4.43. This window offers an online help whenever needed. Figures 4.44 to 4.48 show all the available online help functions.

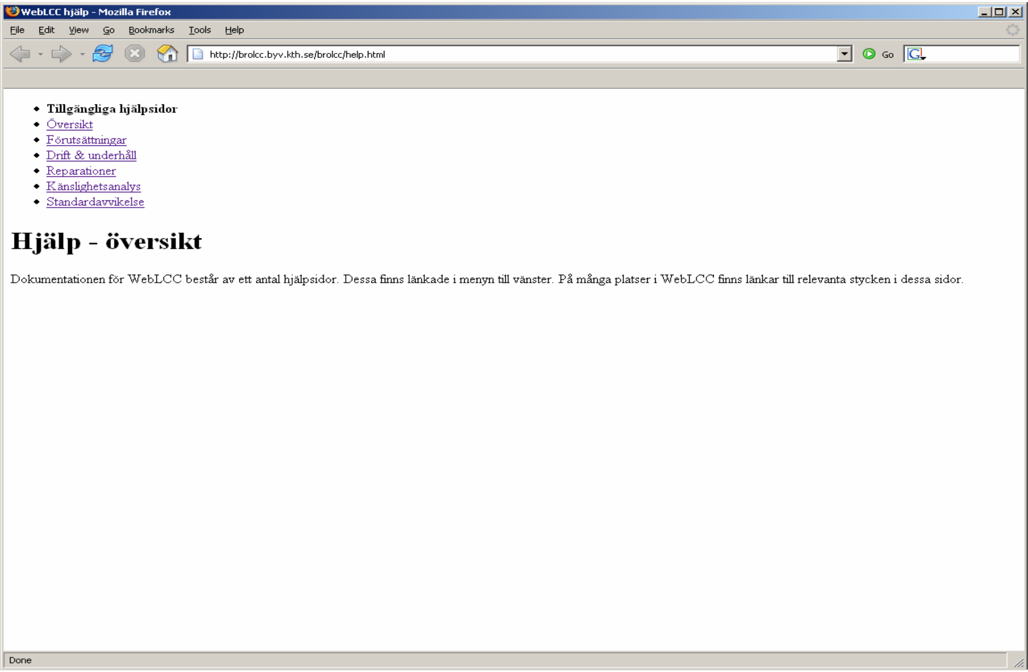


Figure 4.43 *WebLCC online help shown after clicking "Hjälp".*

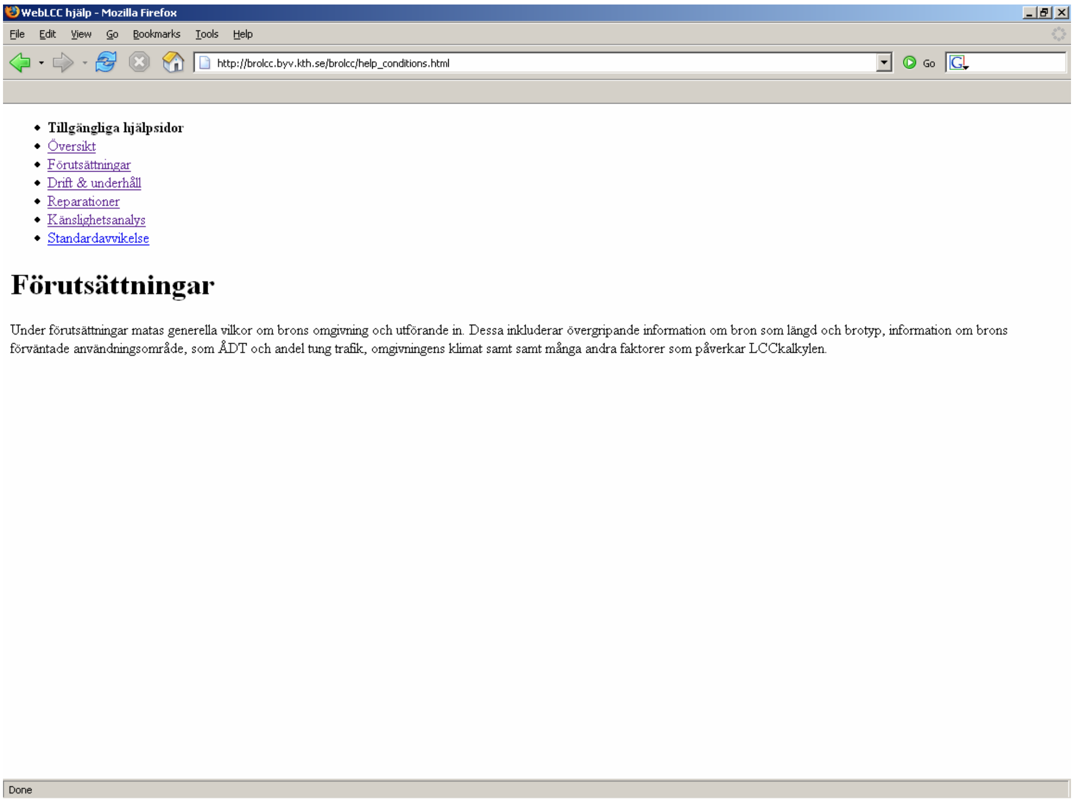


Figure 4.44 *Help window concerning the assumptions in WebLCC.*

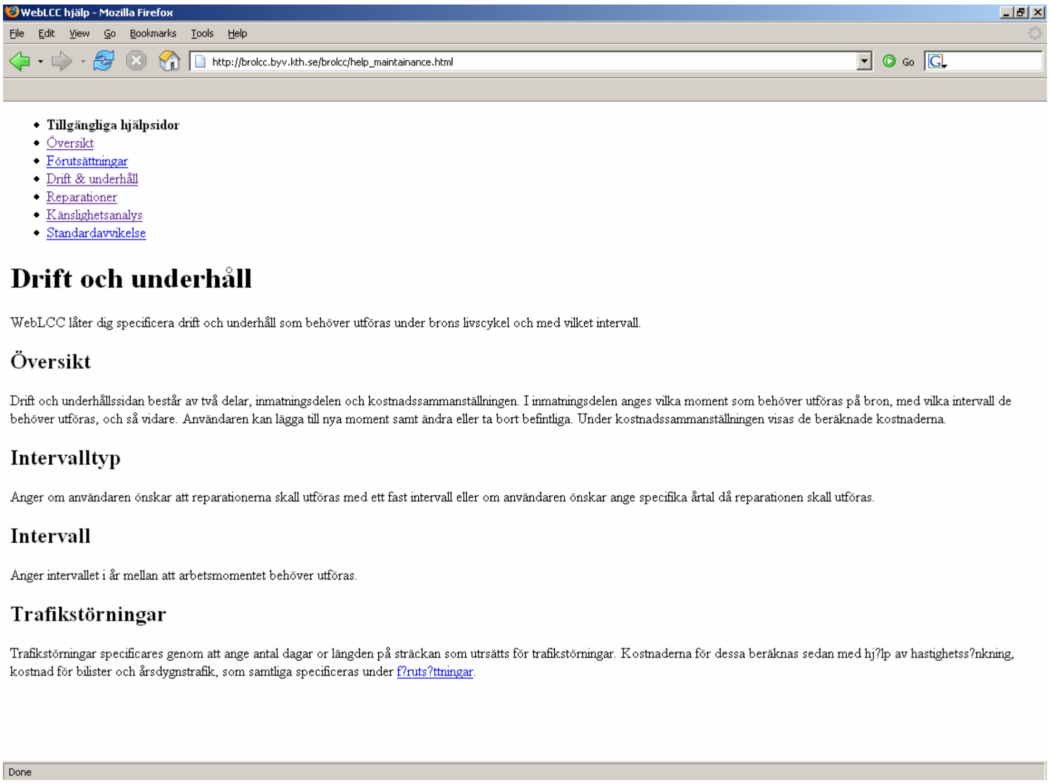


Figure 4.45 *Help window concerning the usage and maintenance in WebLCC.*

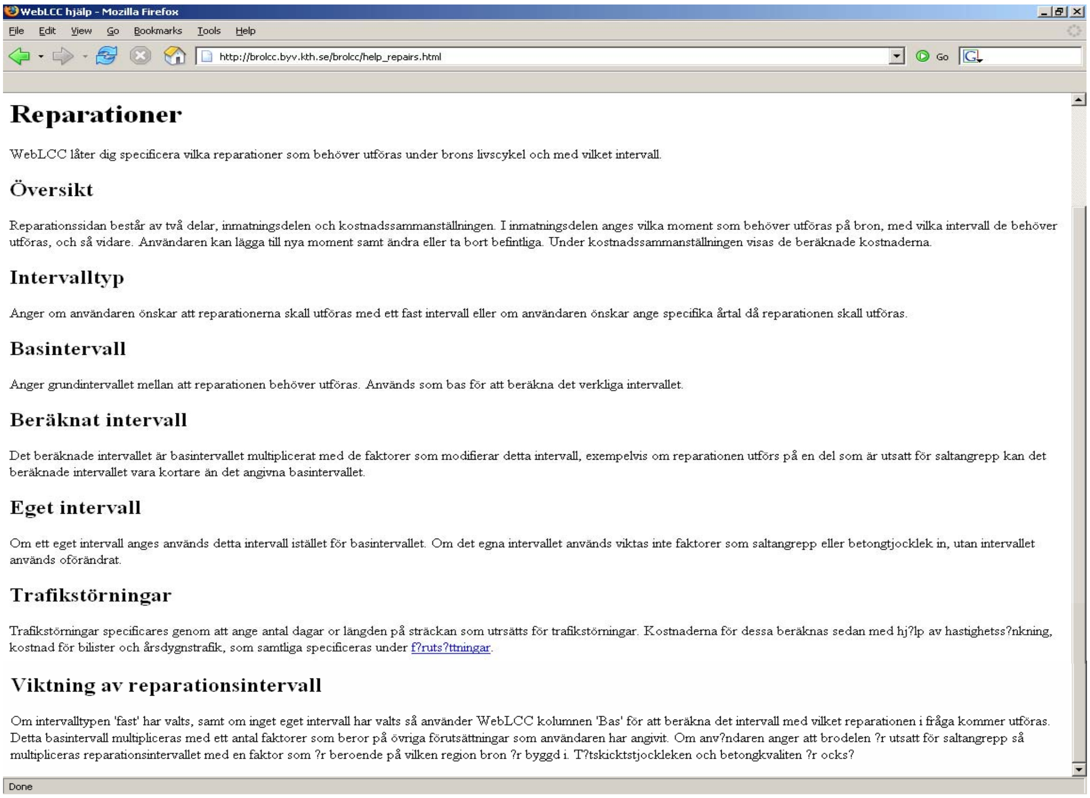


Figure 4.46 *Help windows concerning the repairs in WebLCC.*

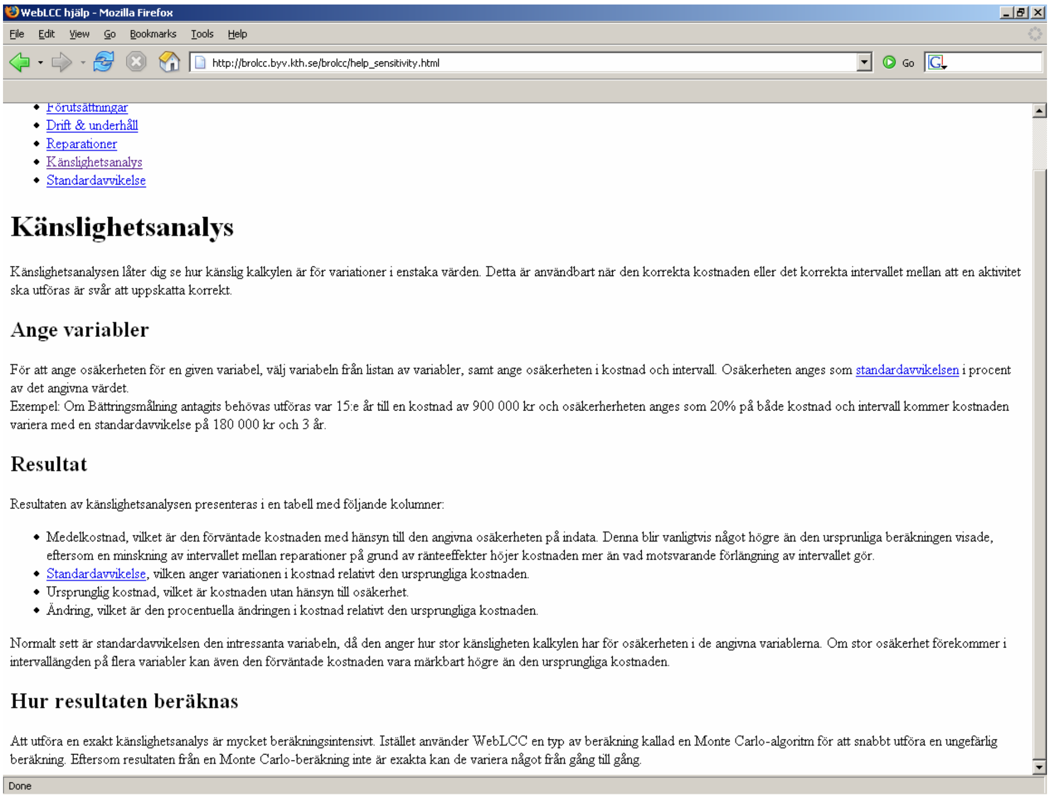


Figure 4.47 *Help window concerning the sensitivity analysis in WebLCC.*

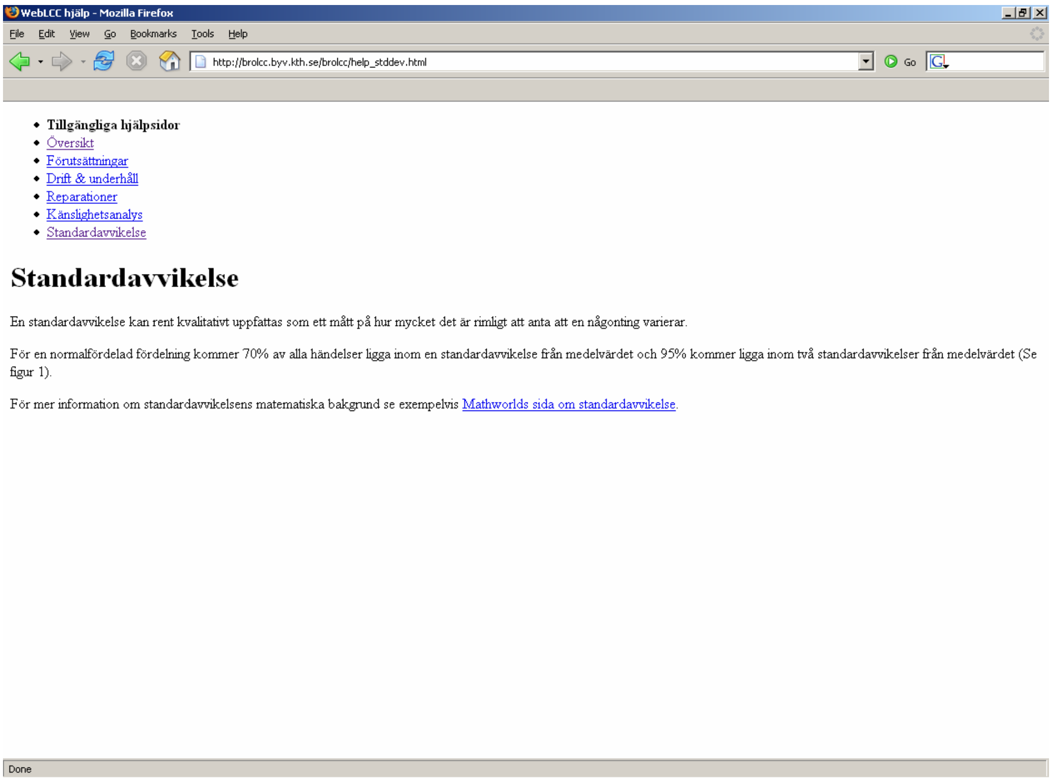


Figure 4.48 *Help window concerning the standard deviation in WebLCC.*

4.4.3 Functionality of *BridgeLCC*

BridgeLCC (version 2.0) is intended to be used by engineers, designers and analysts who need to assess the LCC effectiveness of their preliminary bridge designs. Important factors that can be analyzed include:

- alternative designs, construction materials, and construction processes;
- alternative traffic diversion strategies;
- alternative concrete mix designs that increase concrete strength or durability;
- alternative repair and replacement schemes; and
- other decisions that affect the cost of a structure over its lifetime.

Analyses are conducted on projects. After the specific requirements for building or repairing a structure are given, up to six alternatives are compared to determine, which of them satisfies the project requirements at the lowest LCC. The alternative with the lowest LCC is the cost-effective choice. As shown by Fig. 4.49 , there are two ways to use this program: "Start new analysis" or "Open existing analysis". The program provides online help for all of its windows. Key F1 provides help for the current window and key F6 allows access to the Table of Contents.

Start new analysis

As shown by Figures 4.49 to 4.52, there are four steps in the *BridgeLCC* program when starting a new analysis.

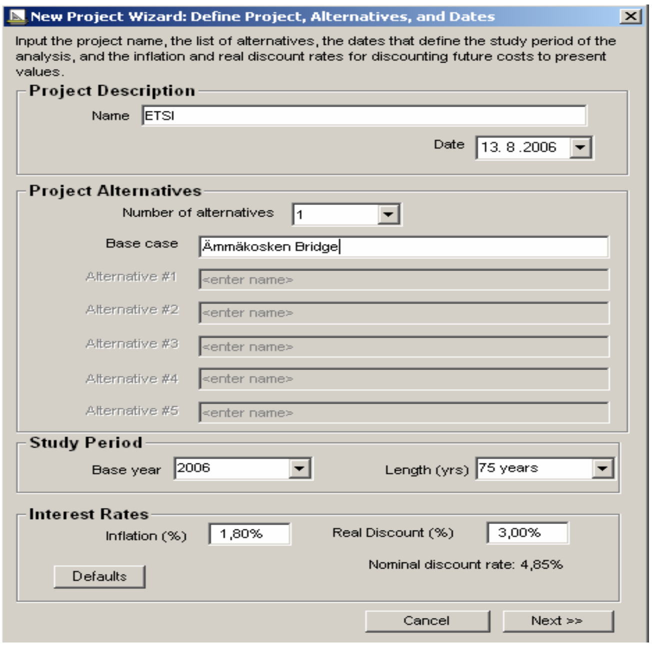


Figure 4.49 *Start new analysis in BridgeLCC - Step 1.*

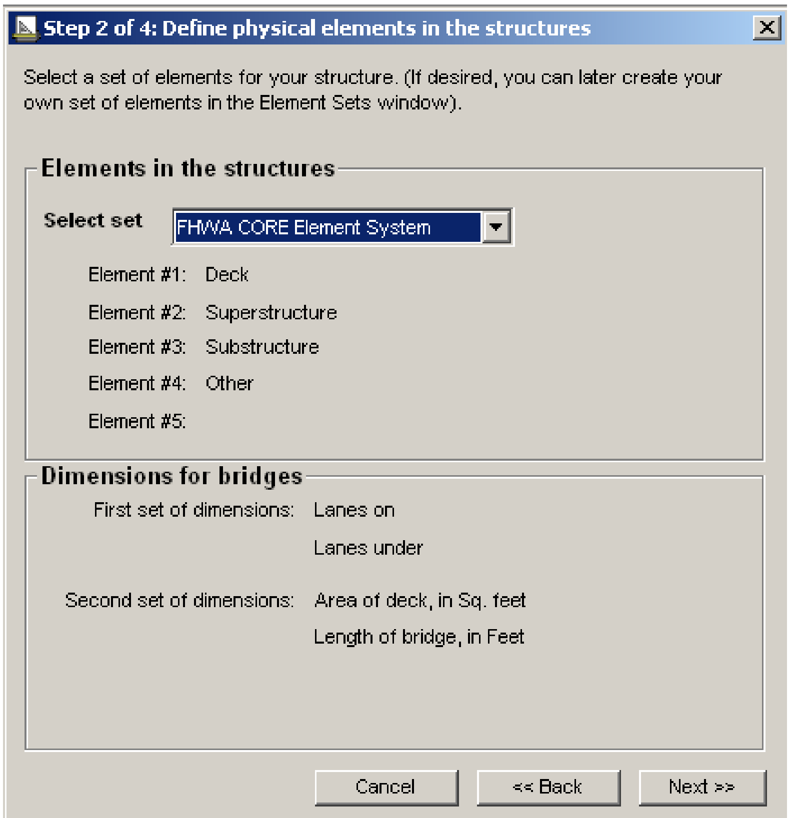


Figure 4.50 *Start new analysis in BridgeLCC - Step 2.*

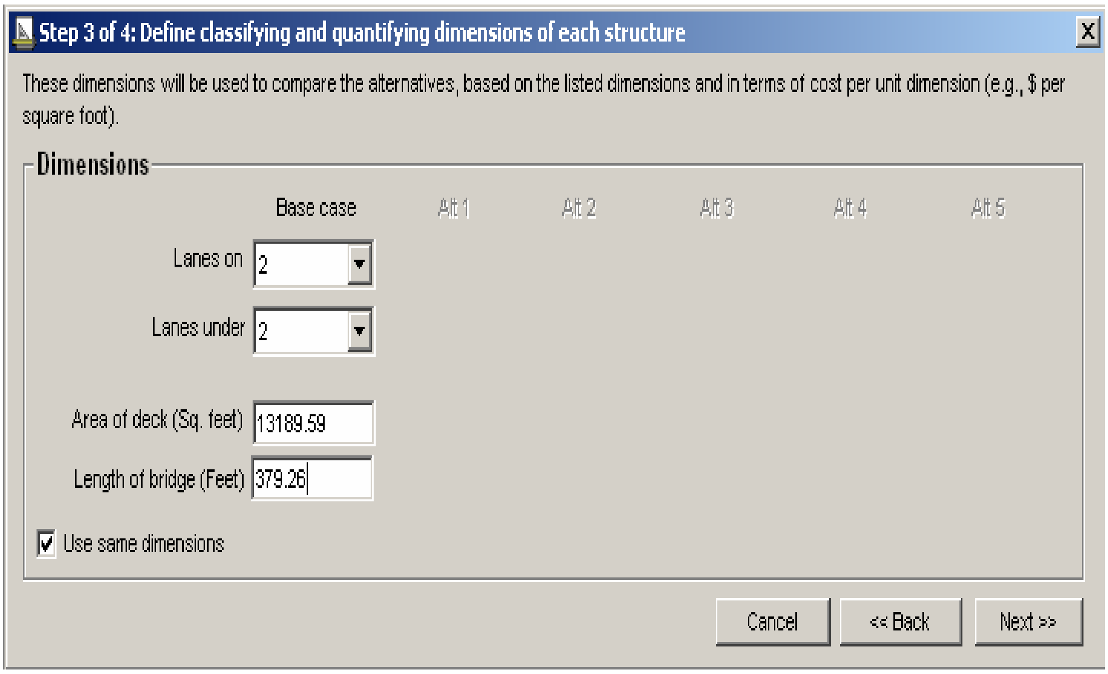


Figure 4.51 *Start new analysis in BridgeLCC - Step 3.*

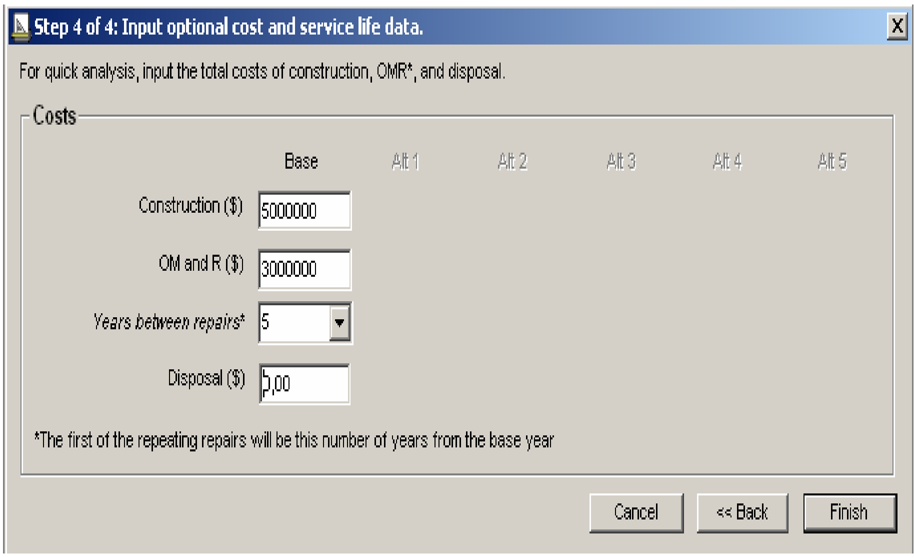


Figure 4.52 *Start new analysis in BridgeLCC - Step 4*

After completing the inputs of these steps, the main operational window – "Cost Summary" window shown in Figure 4.53 appears.

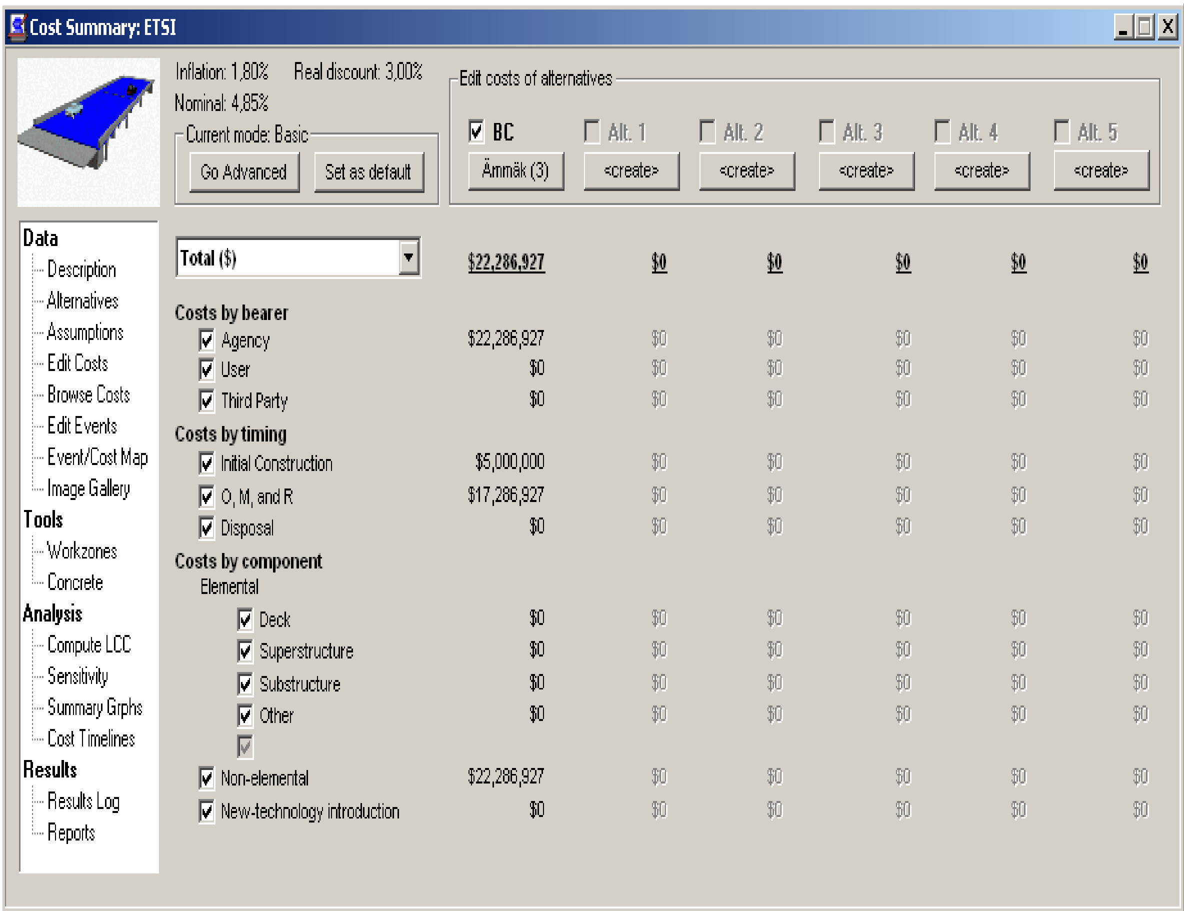


Figure 4.53 *Cost Summary window in BridgeLCC.*

The further operations are carried out in the next part of the program – Open existing analysis. However, there are two things worth mentioning. One is, that in Step 1, Figure 4.49, the inflation and discount rates shown in Table 4.1 are recommended to be used, and the other one is, that in Step 2, Figure 4.50, the so-called PONTIS 2.0 element structure is included. This procedure divides the bridge into four elements. The elements and the bridge components assigned to each element are listed in Table 4.2. The program assigns individual costs to the correct element.

Table 4.1 *Recommended inflation rate and real discount rate in* BridgeLCC *Ehlen.*

Inflation Rate					
	Length of Study Period				
Base year	**3-year**	**5-year**	**7-year**	**10-year**	**30-year**
2003 and beyond	1,5%	1,7%	1,7%	1,7%	1,8%
Real Discount Rate					
	Length of Study Period				
Base year	**3-year**	**5-year**	**7-year**	**10-year**	**30-year**
2003 and beyond	1,6%	1,9%	2,2%	2,5%	3,2%

Table 4.2 *FHWA CORE (Commonly Recognized) Bridge Elements in BridgeLCC, Ehlen.*

Element	**Includes**	
Deck	Concrete (Bare) Concrete Unprotected with AC Overlay Concrete Protected with AC Overlay Concrete Protected with Thin Overlay Concrete Protected with Rigid Overlay Concrete Protected with Coated Bars Concrete Protected with Cathodic System	Steel - Open Grid Steel - Concrete Filled Grid Steel - Corrugated/Orthotropic/Etc. Timber (Bare) Timber Protected with AC Overlay
Superstructure	Closed Web/Box Girder Open Girder/Beam Stringer (stringer-floor beam system) Thru Truss (Bottom Chord) Thru Truss (Excluding Bottom Chord) Deck Truss	Timber Truss/Arch Arch Cable (not embedded in concrete) Floor Beam Pin & Hanger Assembly
Substructure	Column or Pile Extension Pier Wall Abutment	Submerged Pile Cap/Footing Submerged Pile Cap Culvert
Other	Strip Seal Expansion Joint Pourable Joint Seal Compression Joint Seal Assembly Joint/Seal (Modular) Open Expansion Joint Approach Slab w/ or wo/AC Overlay Bridge Railing	Elastomeric Bearing Movable Bearing (roller, sliding, etc.) Enclosed/Concealed Bearing Fixed Bearing Pot Bearing Disk Bearing

Open existing analysis

There are a few examples in the program to show the model analysis. The list of them is shown in Figure 4.54.

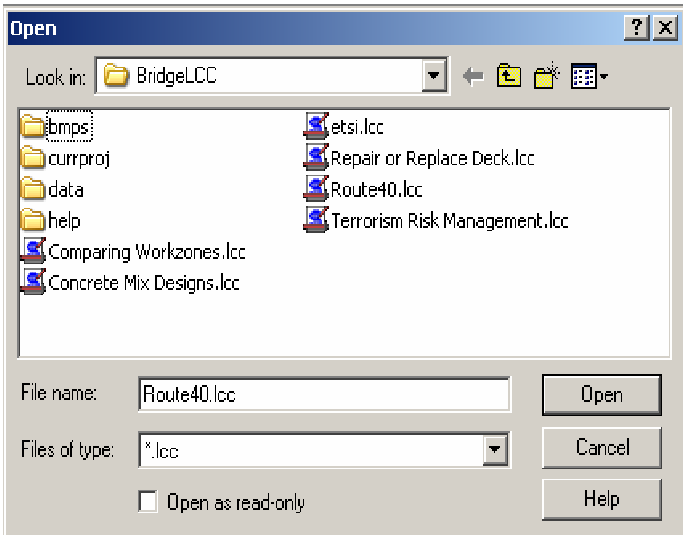


Figure 4.54 *Open existing analysis in BridgeLCC.*

As an example, one of them – Route40.lcc is used here. After the chosen file is opened, the "Cost Summary" window shown in Figure 4.55 appears. This is the same interface as already seen in Figure 4.53. The program is now in the "Basic" mode.

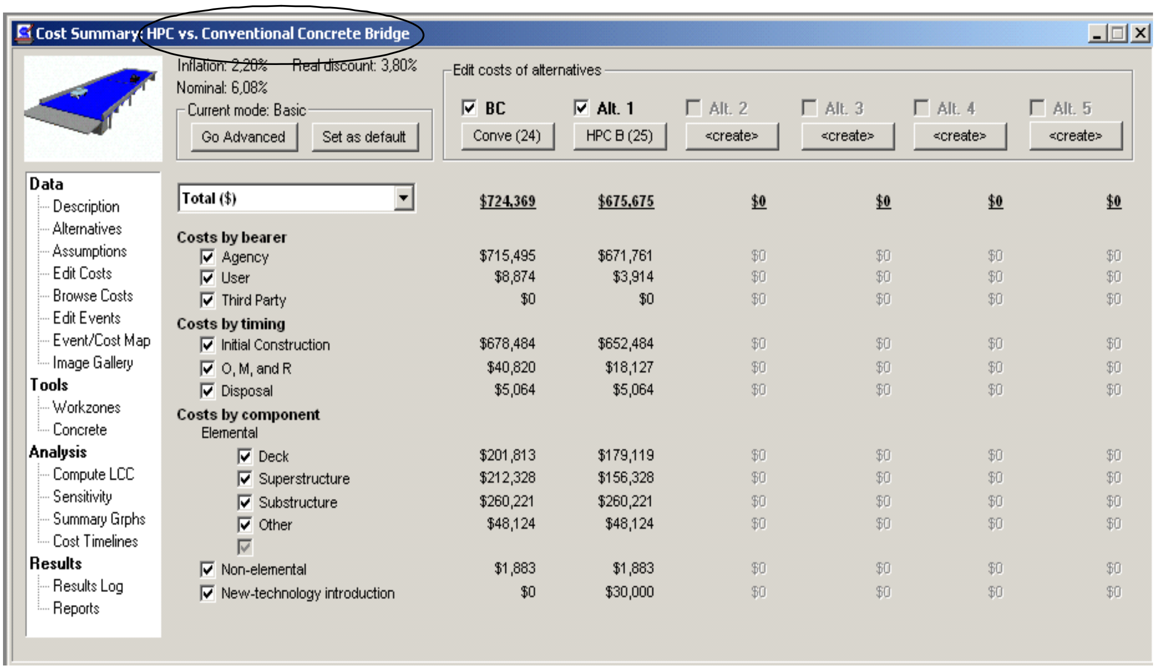


Figure 4.55 Cost Summary window – Basic mode in *BridgeLCC*

In this example the question is of a preliminary LCC design of a highway bridge, where two alternative types of concrete bridges are considered. The engineer has usually used conventional concrete. The alternative is to use a high performance concrete (HPC) that the engineer has not used before, but it should produce a stronger and more durable bridge. The engineer wants to determine, which of the two materials is LCC effective for this bridge. Let us first briefly have a look at the LCC calculation procedure presented in ASTM E 917 (1994). Here it is developed from the original five steps into nine steps as follows:

- Defining of the project objectives and the minimum performance requirements.
- Identifying the alternatives for achieving the objectives.
- Establishing of the basic assumptions for the analysis.
- Identifying, estimating and determining the costs.
- Computing the LCCs of each alternative.
- Performing the sensitivity analysis.
- Comparing of the alternatives' LCCs.
- Considering of the other project effects.
- Choosing of the most effective alternative from the LCC's viewpoint.

Now looking at the underlined total cost in Figure 4.55, the LCC of the conventional concrete bridge is 724 369 USD. Correspondingly, the cost for the HPC bridge is 675 675 USD. If the two concretes are equal in every other respect, then the HPC is the preferable choice.

The Cost Summary window, Figure 4.55, illustrates how this program follows the ASTM practice in categorizing costs. The Cost Summary window serves as a "home page," where the total LCCs are displayed, the alternatives' costs can be accessed, and a step-wise list can be used to access the most common tasks.

Besides the "Cost Summary" window, we can also read the LCC analysis results from the LCC summary and timelines graphs and the printed reports. However, both of them can be obtained from the "Cost Summary" window as well. To clarify this, let us now have a look at the function of the "Cost Summary" window to see some of the main output results of the program.

In the upper-left corner of the panel in Figure 4.55, the drop-down list box shows the prescribed types of choice for the calculated costs, as shown in Figure 4.56.

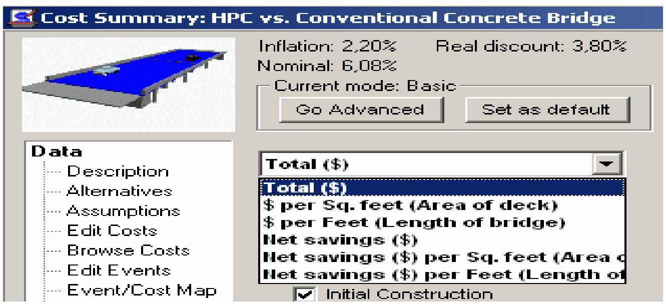


Figure 4.56 *Drop-down list box in the cost summary window shown in Figure 4.55.*

The desired results can be selected from the list. For instance, by selecting "Net Savings" from the list box it is possible to see where money can be saved by choosing the HPC. The "Cost Summary" window now shows the net savings of the HPC bridge, when it is compared with the conventional concrete bridge, see Figure 4.57.

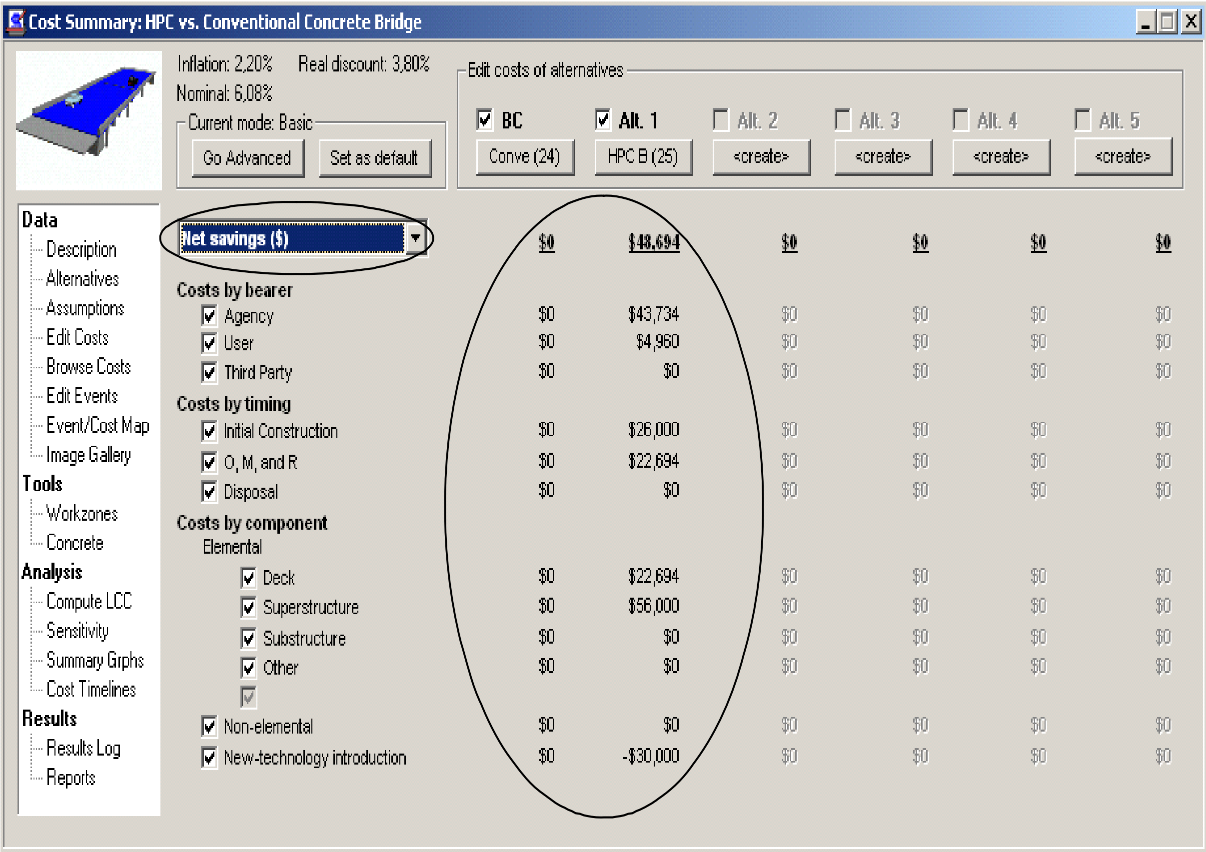


Figure 4.57 *"Cost Summary" window showing "Net savings" in BridgeLCC.*

The check boxes in the "Costs by bearer", "Costs by timing", and "Costs by component" categories allow the user to display results for a subset of costs. For instance, to show only the engineer's estimates of these two structures, the user checkmarks the "Agency" box in the "Costs by bearer" group, the "Initial Construction" box in the "Costs by timing" group, and all four boxes in the "Costs by component" group. The "Cost Summary" window shown in Figure 4.58 displays only the engineer's estimates for each alternative bridge, as a total on the "Total ($)" line and by cost types in the three major cost categories.

The upper left box contains "Go Advanced" and "Set as default" buttons. These allow the user to switch back and forth between the two fundamental modes, i.e. the "Basic" mode and the "Advanced" mode. The former one allows the user to conduct and complete analyses without any uncertainty in parameters and the latter one performs risk and uncertainty analysis.

In the upper-right section of the "Cost Summary" window, the "Edit costs of alternatives" box contains buttons for accessing two project alternatives and creating four additional alternatives.

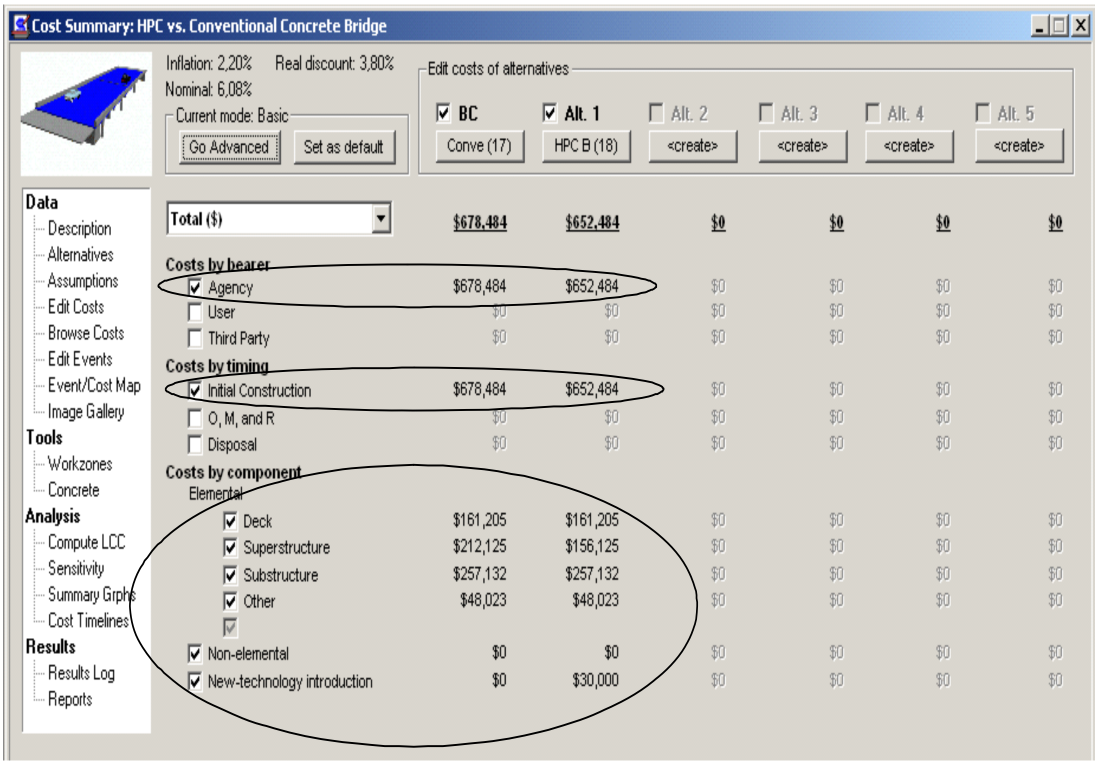


Figure 4.58 *Check box role in "Cost Summary" window in* BridgeLCC.

Most of the ASTM-consistent steps required to complete a LCC analysis can be accessed under "Data", "Tools", "Analysis", and "Results" in the "Cost Summary" window. There it is possible to

- describe the overall project and the alternatives under consideration,
- make project-wide assumptions,
- input and edit individual costs for each alternative bridge,
- test to see, if the results are sensitive to changes in particular parameters or costs, and
- print reports documenting the steps in the analysis and the results obtained.

Each step in the left-hand panel can be accessed by double-clicking the mouse on the step. Most of the steps are very straightforward. It is not necessary to check everything in detail. Some typical characteristics of the program can be shown with examples.

The "Project Assumptions" window, shown in Figures 4.59, 4.60, 4.61 and 4.62, can be opened by double clicking "DATA" → "Assumptions", "Tools" → "Workzones", or "Tools" → "Concrete". It is noteworthy that in Figure 4.62 the concrete panel requires the water-to-cement ratio and the silica-to-cement ratio as inputs. It also shows the amount of each ingredient per 1 cubic meter. The "Diffusion coefficient" field shows the chloride diffusion rates for these mixes in unit 10^{-12} /m^{2}s. The mix design of concrete is facilitated.

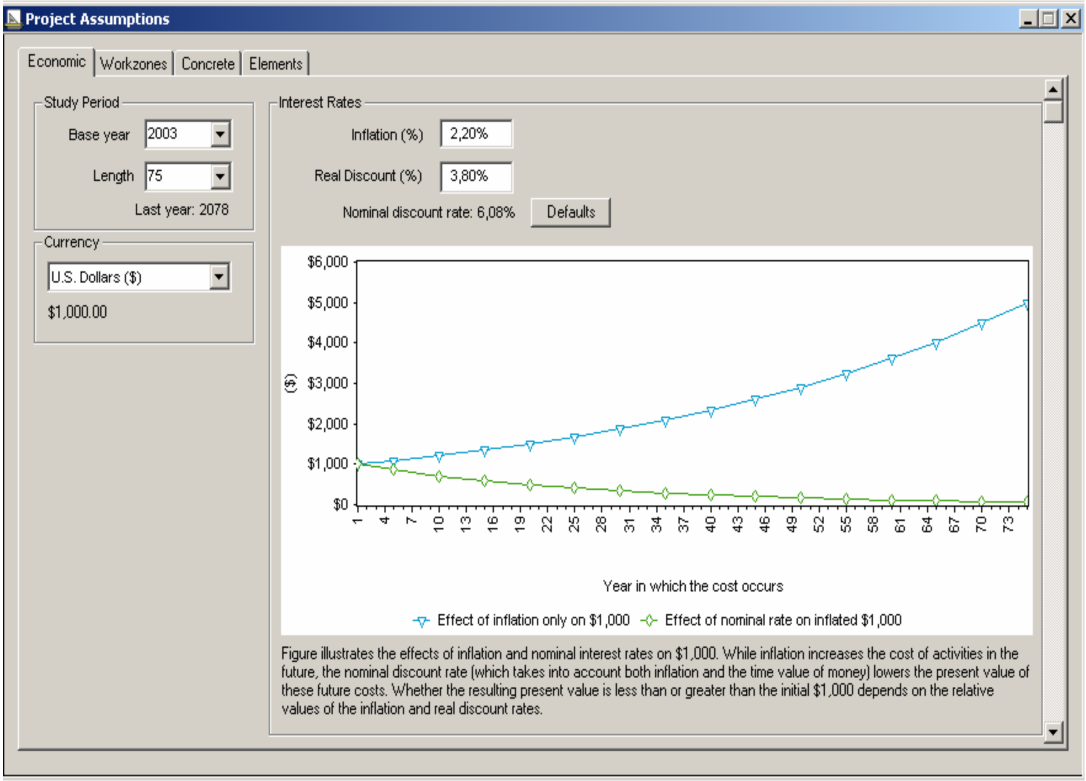


Figure 4.59 *Economic assumptions panel in BridgeLCC.*

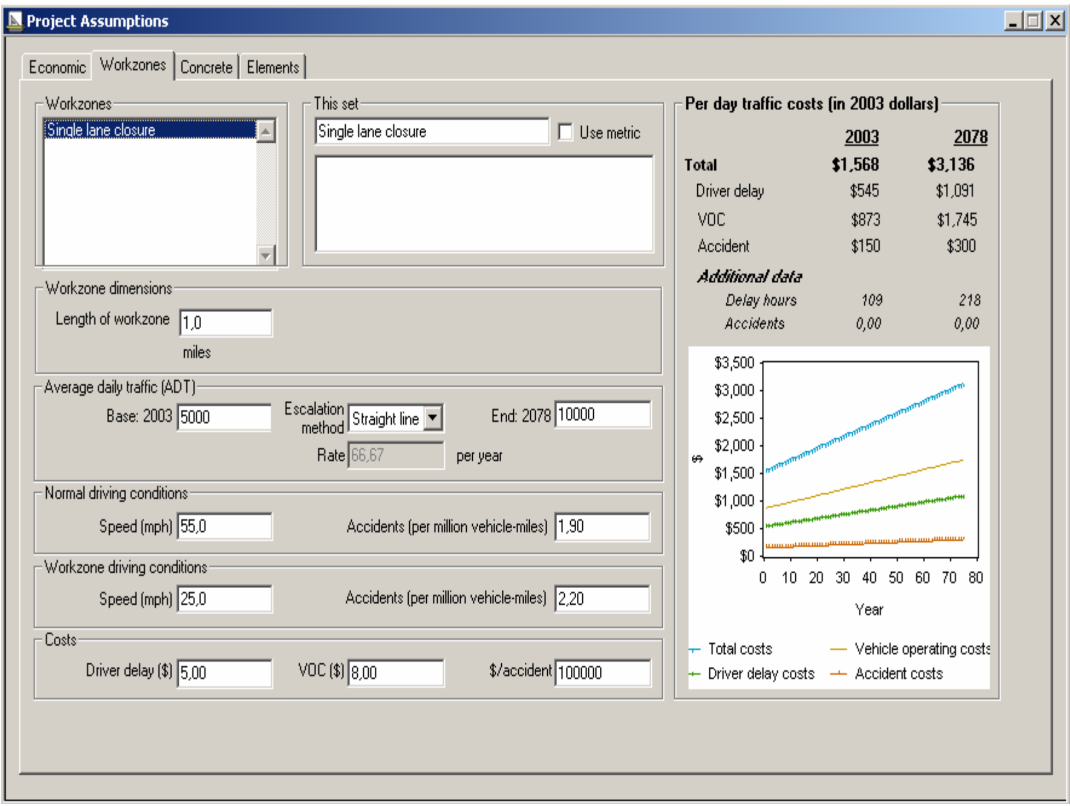


Figure 4.60 *Workzones assumptions panel in BridgeLCC.*

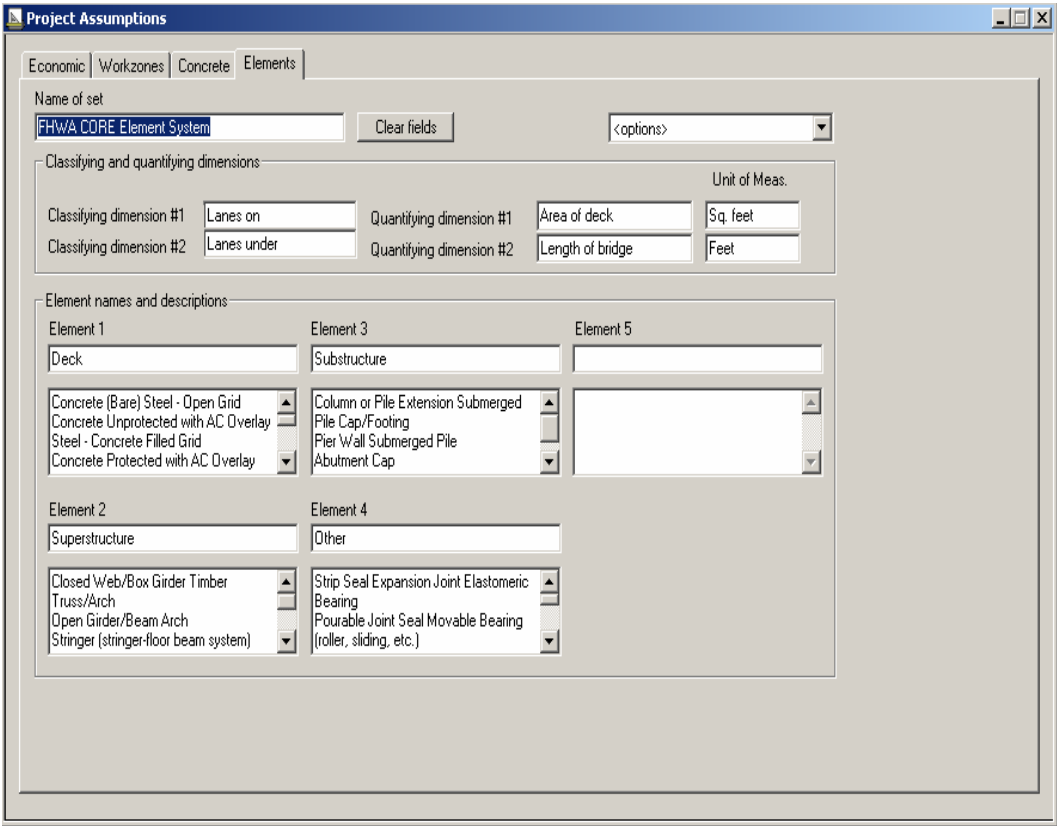


Figure 4.61 *Elements assumptions panel in BridgeLCC.*

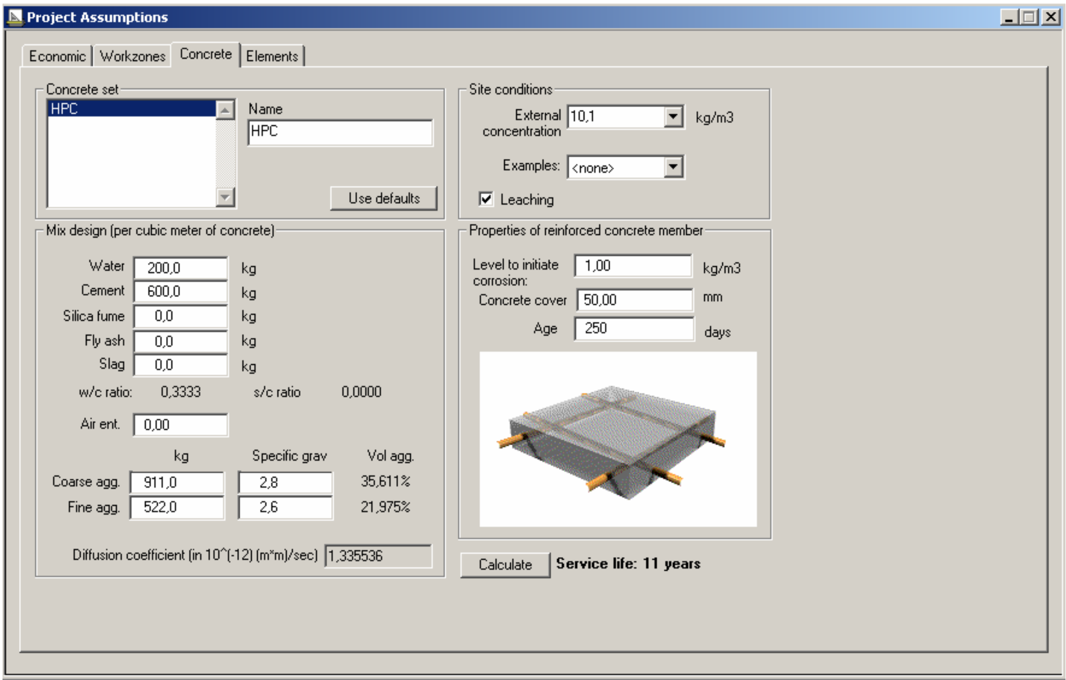


Figure 4.62 *Concrete assumptions panel in BridgeLCC.*

The LCC summary graphs shown in Figure 4.63 can be obtained by double clicking “Analysis” → “Summary Grphs”. The graphs are based on the data in the “Cost Summary” window. As indicated by the set of bars in front, the HPC bridge has lower agency costs, lower initial construction costs, and lower deck and superstructure costs. The largest project component costs are the substructure costs.

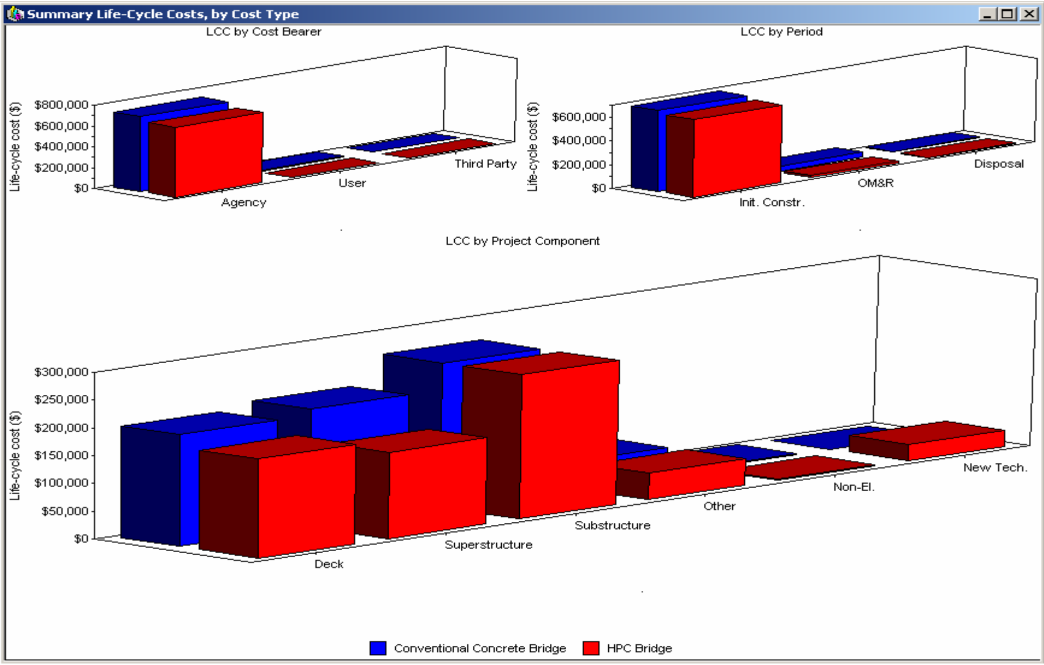


Figure 4.63 *The LCC summary graphs in BridgeLCC.*

The LCC timelines graphs shown in Figure 4.63 can be obtained by double clicking “Analysis” → “Cost Timelines”. These graphs illustrate the distribution of costs over time with two types of graphs – “Yearly Costs in Current-Year Dollars” and “Cumulative Costs in Current – Year Dollars”.

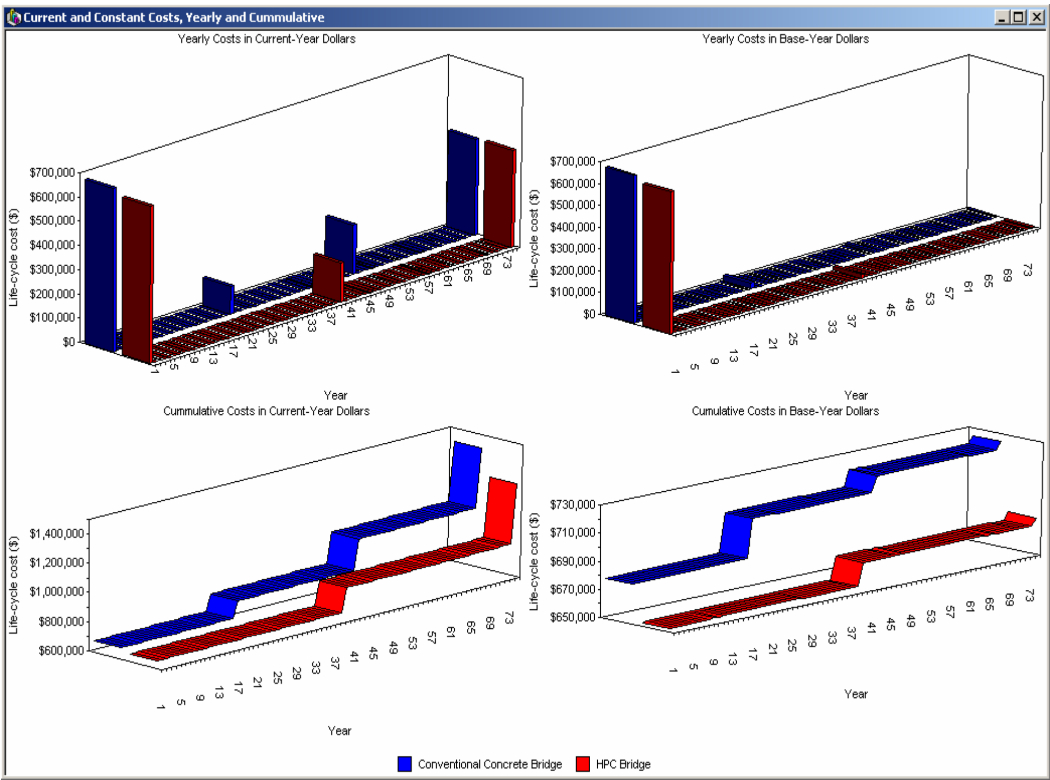


Figure 4.64 *The LCC timelines graphs in BridgeLCC.*

As regards the sensitivity analysis, for example, a graph, see Figure 4.65, of the effect of the real discount rate can be obtained by clicking “Analysis” → “Sensitivity” → “Input Values” → “Parameters” → “Interest rates” → “Discount Rate”. Here the “Variation” item in Figure 4.65 can have four different values provided in the drop-down list, i.e. +/-10%, +/-20 %, +/-50 %, and +/-100 %. Figure 4.66 shows in addition the “top 10” graphs that can be displayed after the relative weights of the analysed variables in the total LCC are calculated in the “Most Significant Factors” panel. There are two other alternative graphs, i.e. “top 25” and “all”, which are not shown here.

In order to carry out risk and uncertainty analysis, it is necessary to switch to the advanced mode shown in Figure 4.67. Now the “Uncertainty and Risk” window shown in Figure 4.68 appears, when the “Uncertainty” step is clicked.

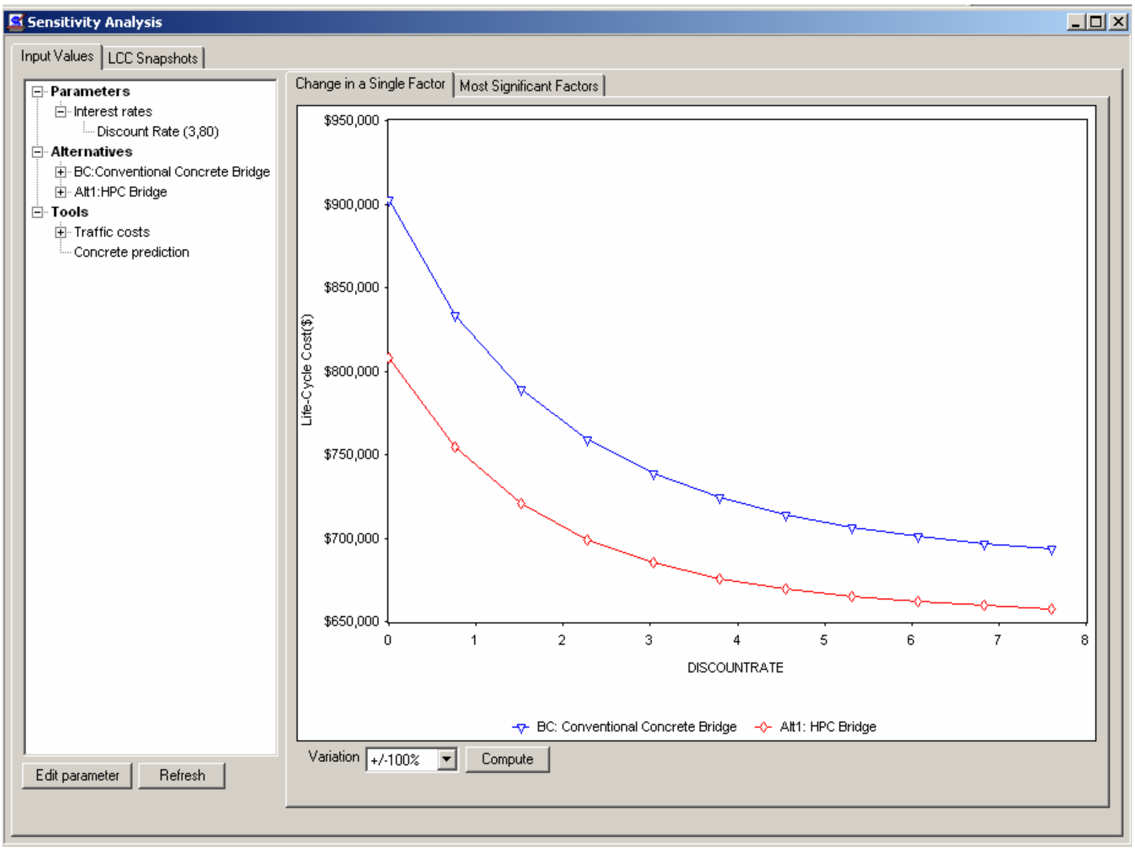


Figure 4.65 *Effect of Real Discount Rate on LCC in BridgeLCC.*

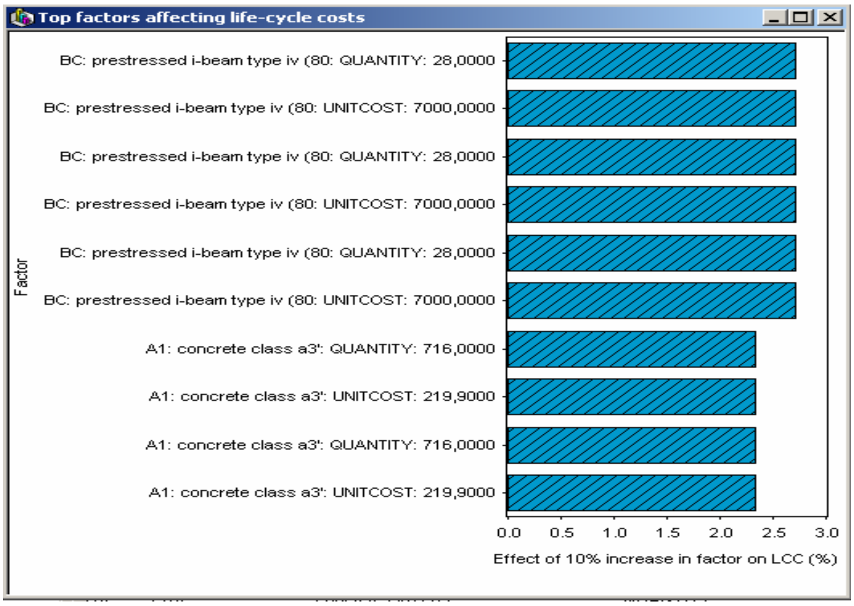


Figure 4.66 *Graph of Top 10 Factors affecting LCC in BridgeLCC.*

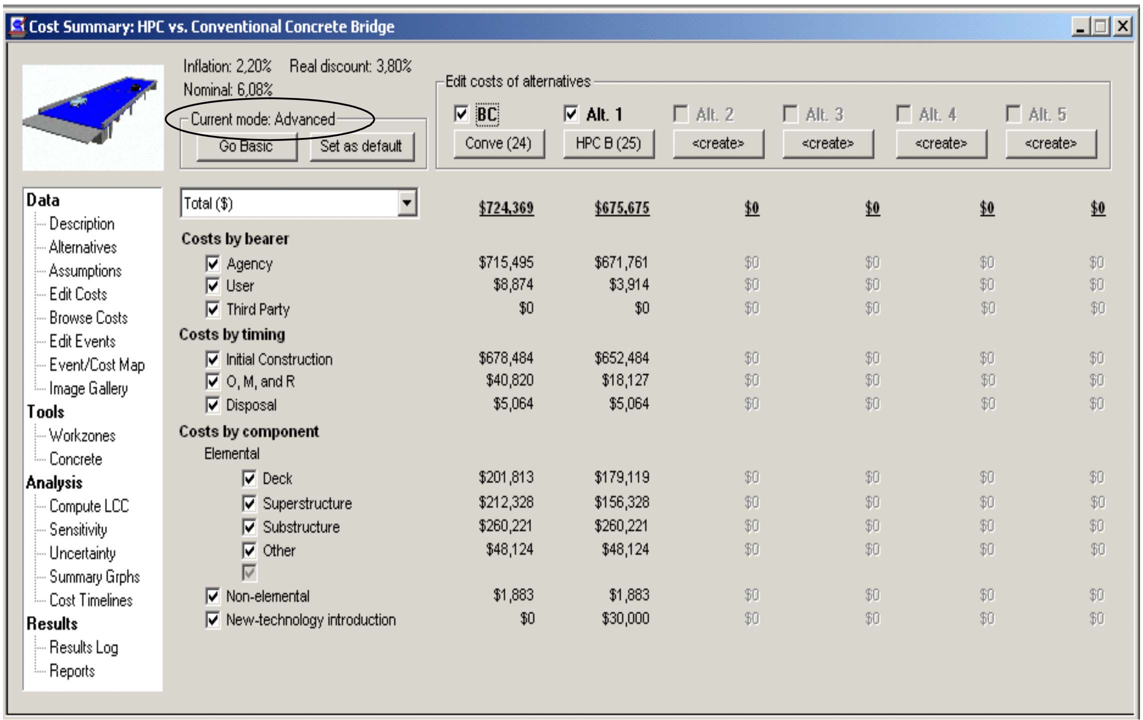


Figure 4.67 *Cost Summary window – Advanced mode in BridgeLCC.*

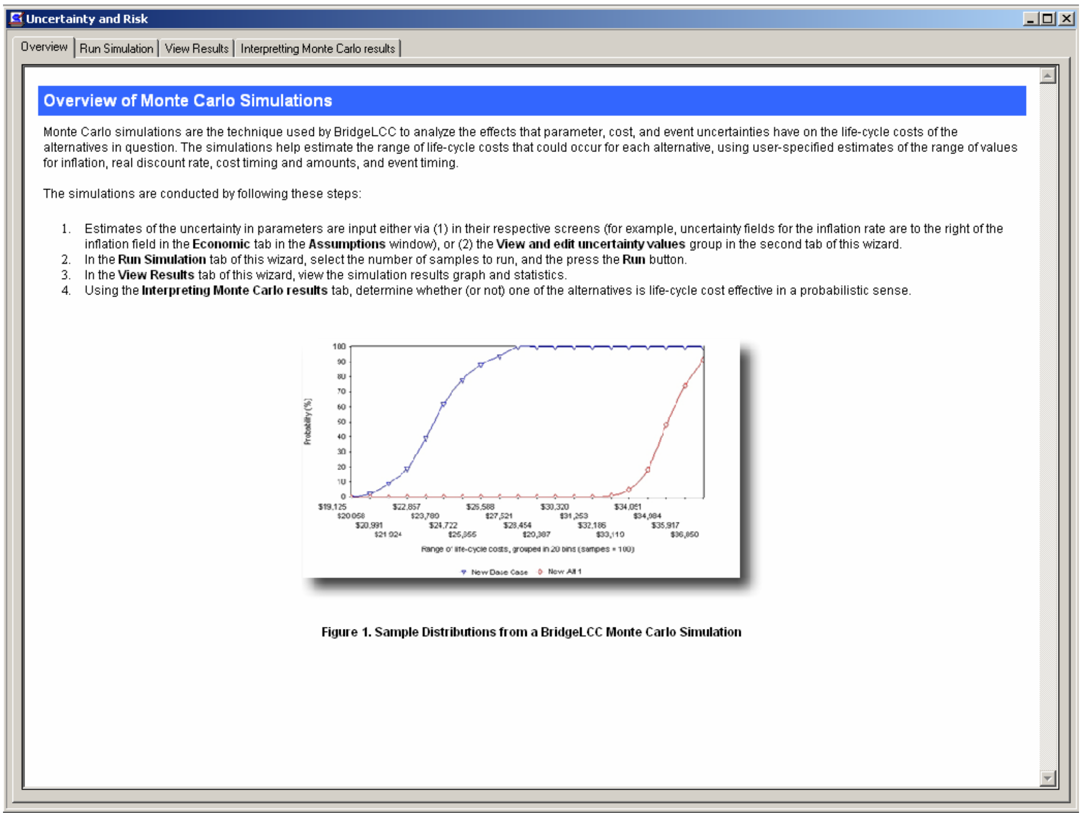


Figure 4.68 *Uncertainty and Risk window in BridgeLCC.*

The “Run Simulation” window is shown in Figure 4.69. When the number of samples has been chosen, the program is started by clicking the “Run” button. It will run for a while and calculate the Monte Carlo Simulation results shown in Figure 4.70. When the two options “Show as cumulative distribution” and “Show as line” are chosen, another form of Monte Carlo Simulation results shown in Figure 4.71 will be obtained.

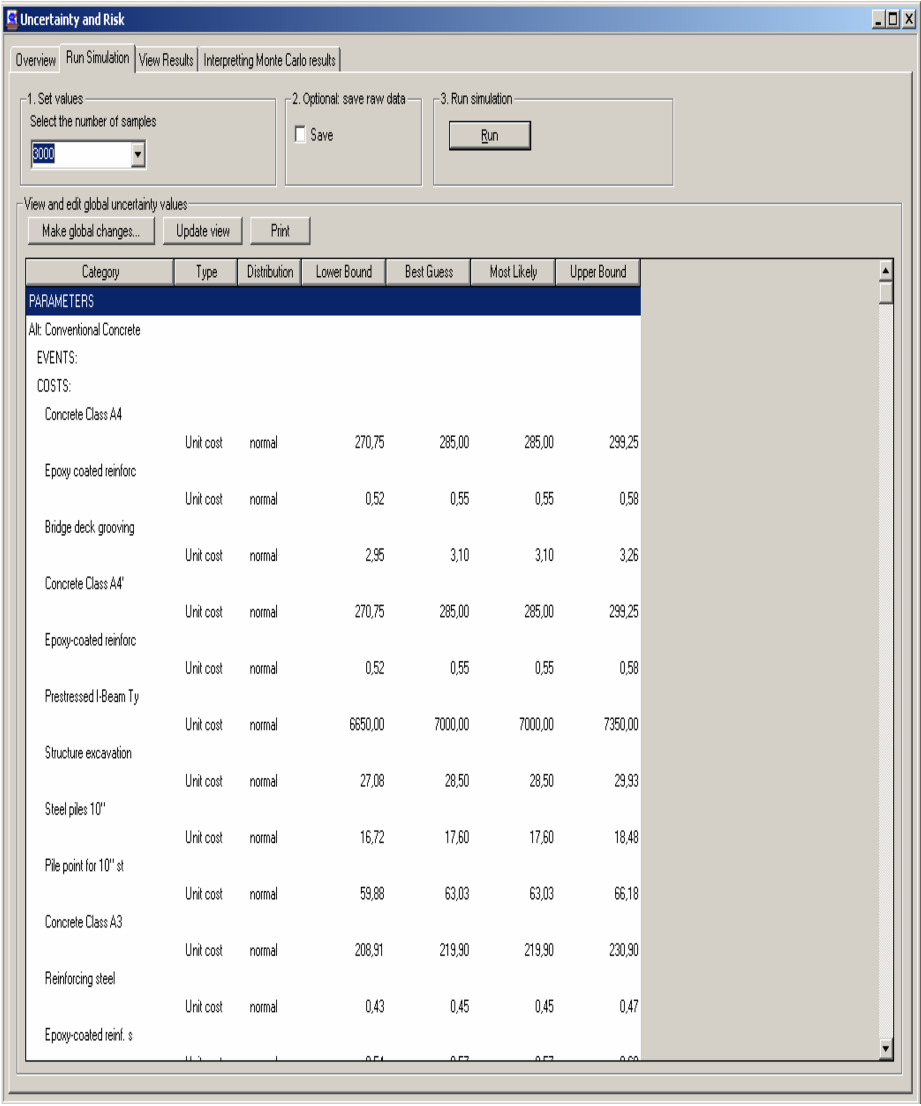


Figure 4.69 *Run Simulation window in BridgeLCC.*

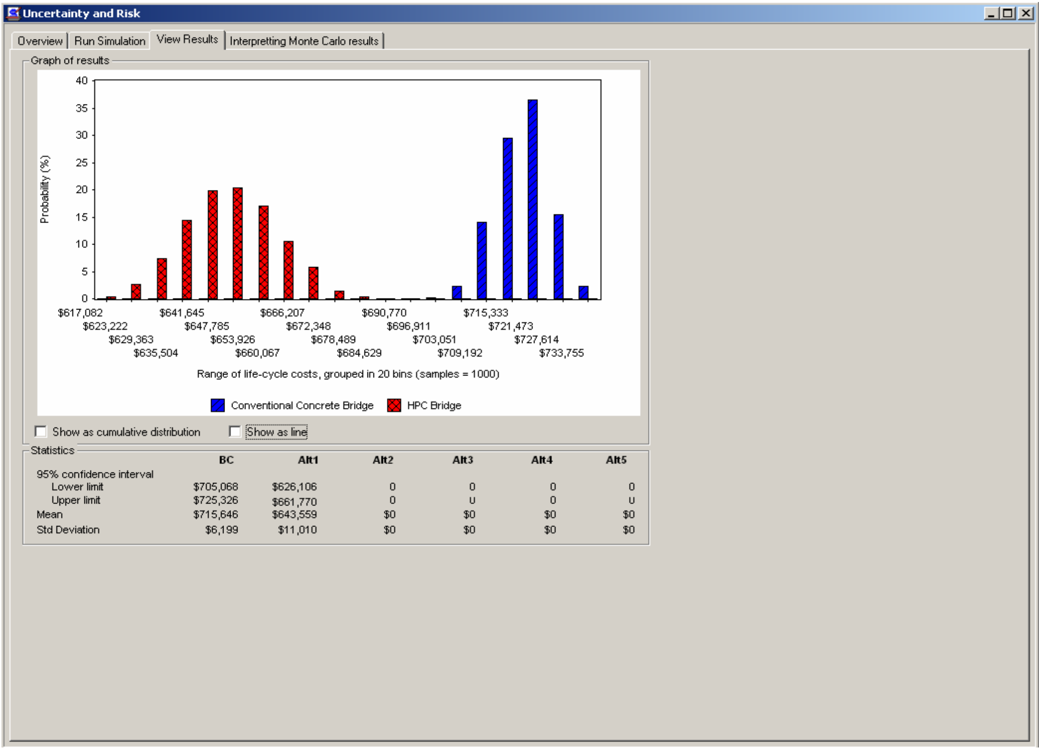


Figure 4.70 *Monte Carlo Simulation results in BridgeLCC.*

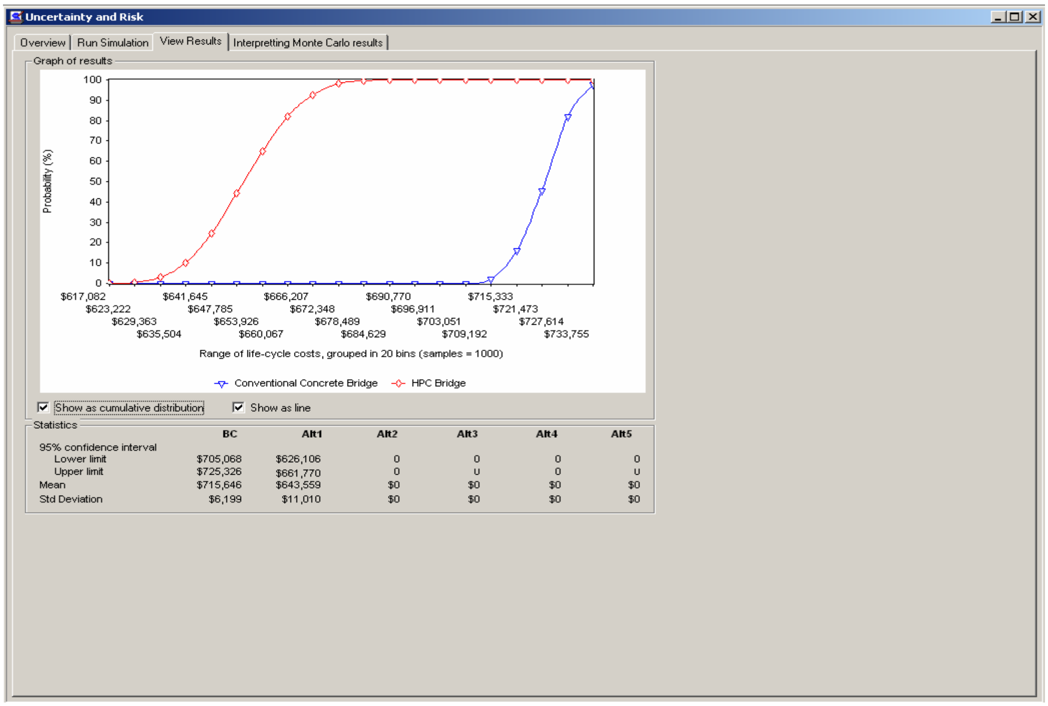


Figure 4.71 *Monte Carlo Simulation results in another form in BridgeLCC.*

The "Image Gallery" window in this program is used for organizing and printing images related to the analysis. It is an attractive feature in the program, but the details are not given here. The user can determine what is included in the report produced by the program. Clicking "Analysis" → "Reports" in the "Cost Summary" window (Either Basic or Advanced mode) opens the "Reports" window shown in Figure 4.72. The program produces a complete printed report for the whole LCC analysis. Typically, there are totally 34 pages in the report in this example, if all boxes in the reports window are check-marked. Check-marking just two boxes – “Introduction” and “Summary” produces a short report, typically 3 pages, showing the format of the reports.

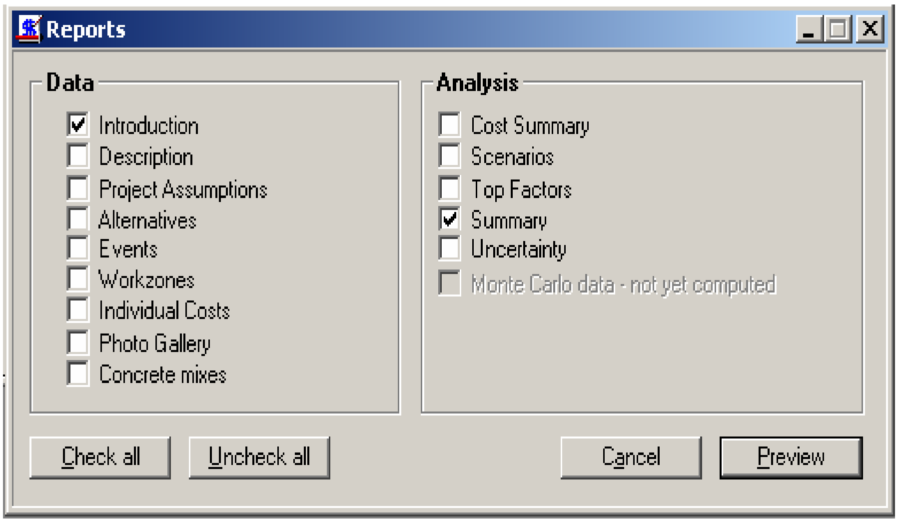


Figure 4.72 *Reports window in BridgeLCC.*

4.5 Comparison of the programs studied

The comparison of the programs studied will be done according to the exploration results and the individual software characteristics that are listed in Table 4.3.

Table 4.3 *The software characteristics of the three programs studied.*

Program	Programming language	Size [MB]	Application platform
Bridgelife	VBA	5,6	Citrix Systems' MetaFrame thin-client[7] or an independent PC
WebLCC	MATLAB	4	Web-based applications (also thin-client)
BridgeLCC	(Unknown)	18,7	Only on a PC not with remote, networked drives

4.5.1 Costs to be considered

The costs to be considered are different in the three programs. From “Project Data” shown in Figure 4.17 and “Life Cycle Costs” shown in Figure 4.18 it can be seen that three types of costs are calculated in the *Bridgelife* program: MR&R costs, user costs and delay costs. *WebLCC* takes into account the costs including investment costs, operation and upkeep costs, repair costs, traffic costs and demolishing costs. From the Cost Summary window shown in Figure 4.55, or Figure 4.5, it can be seen that *BridgeLCC* has an abundant cost category,

[7] A thin-client is a computer (client) in client-server architecture networks, which depends primarily on the central server for processing activities.

where the desired alternatives can be chosen freely by check-marking. There are three ways to divide the costs into categories: by bearer, by timing and by component. “Costs by bearer” have three categories: “Agency”, “User” and “Third Party”. “Costs by timing” also have three categories: “Initial Construction”, “O, M, and R” and “Disposal”. “Costs by component” have three categories: “Elemental”, “Non-elemental” and “New-technology introduction”. The Elemental costs have four subcategories: “Deck”, “Superstructure”, “Substructure” and “Other”. This is the so-called NIST cost classification. They help the user to account for all project costs, properly categorize them and then to compare the breakdowns of the alternatives’ LCCs.

Especially in *BridgeLCC*, the costs incurred on third parties, who are not direct users of the bridge but are impacted by the construction and repair works, are also included. It did not become clear to the author, how these costs are considered in the user and delay costs in *Bridgelife*. In *WebLCC*, the traffic costs are taken into account in broad sense. However, it is not quite clear, if the third party costs are fully included in the traffic costs calculated by *WebLCC*.

Initial construction costs and final demolishing costs are considered in *BridgeLCC* and *WebLCC*, but not in *Bridgelife*. Especially in *Bridgelife*, the LCC is not included in the results of the “Service Life Design” part. Therefore, the *Bridgelife* program does not seem to be particularly suitable to LCC analyses when seen from the bridge designer’s viewpoint.

There is one common shortcoming in all the three programs studied, i.e. the neglecting of extraordinary costs. Extraordinary costs, which are incurred when unusual events happen, typically include both agency costs and user costs. They should be part of LCC. Here unusual events involve hazards like flooding, seismic events or traffic occurrences that may or may not cause disruption or damage. These things must be considered by the agency responsible for bridge management. Although probability for unusual events is usually very small, the costs of such events may be considerable. Consideration of the extraordinary costs results in a more realistic estimate of the LCC especially in a network level bridge LCC analysis.

4.5.2 Techniques used

The present value method presented in section 3.6 forms the basis for all LCC calculations. To treat the uncertainty and risks, the *WebLCC* and *BridgeLCC* programs use the classic stochastic approach, in which the Monte Carlo simulation and sensitivity analysis techniques are applied. The *Bridgelife* program, however, adopts the Markov Chain method when treating the uncertainty in the costs data but not in the cost results.

Because of the need of the Markov Chain method, degradation model is used in the *Bridgelife* program. Decision trees technique is also used in it for planning of the MR&R actions. The applications of these techniques cannot directly be detected in this program, but LIFECON Deliverable D1.1 and D2.2 confirm, that these techniques are used. The two required coefficients c and n for a degradation curve used in the Markov Chain Method also prove the use of degradation model technique in this program. Because a degradation curve serves as a benchmark in the calculation of Markov Chain, it is clear that these two coefficients c and n are crucial in the calculations. The default values invisibly embedded in the program are actually the results of some research projects carried out by VTT. It is not an easy task for a program user to choose spontaneously the values of these two coefficients.

Deterioration is considered in the *BridgeLCC* program in a comprehensive way. Diffusion and corrosion of concrete, as shown by Figure 4.62, are evaluated in the calculations, but there is no degradation model in the program. *WebLCC* is similar to *BridgeLCC* in this respect. It does not include any degradation model.

4.5.3 Adopted standards

The principles of the *Bridgelife* program module follow the outlines described in the EU project LIFECON (GIRD-CT-2000-00378). According to LIFECON principles, the characteristics of a module are the following: predictive, integrated, optimizing, life cycle based and probabilistic. It is understood that the *WebLCC* program may follow some standard formulated by SNRA (Swedish National Road Administration).

The *BridgeLCC* program's costing methodology is based on the ASTM practice for measuring the LCCs of buildings and building systems (ASTM E 917) and a NIST cost classification scheme for comparing LCCs of different alternatives, respectively. The ASTM practice insures that the cost calculations follow the accepted practice; the scheme helps the user to account for all project costs, properly categorise them, and then compare breakdowns of the alternatives' LCCs. In addition, the *BridgeLCC* program uses FHWA CORE Bridge Elements to assign the individual costs to the correct element

4.5.4 Intended users and objectives

The *Bridgelife* program was developed for bridge owners, maintainers and designers who need to predict the condition of different bridge components, plan MR&R actions and calculate maintenance costs, user costs and environmental impacts during the design period of a bridge. The life cycle design part of the program is the most essential part and it is more frequently used than the service life design part. It is understood that this program is mainly used by the administration sector of Finnra.

The *WebLCC* program is an academic-oriented program that is intended to illustrate the theory of LCC calculations. It is understood that it is used by the users interested in the LCC calculation theory.

The *BridgeLCC* program is specifically designed to help bridge engineers, material specialists and budget analysts to determine the LCC effectiveness of bridge designs and processes. The user defines the project (a bridge), defines the alternatives (such as use of steel instead of concrete), compiles the costs of construction and maintenance and finally compares the alternatives presented.

4.5.5 User interface and inputs

The *Bridgelife* and *BridgeLCC* programs use normal window interface. The web-based *WebLCC* program uses vertical scrolling window interface with a scroll bar. From the usability viewpoint, normal window interface looks more user-friendly than a scrolling window interface. As far as the window interface is concerned, it looks like the *Bridgelife* program would need more improvement than the *BridgeLCC* one. As shown in Figures 4.12 to 4.28, all windows of the *Bridgelife* program have only one symbolic "Close" button on the top right corner of the window, while the most of the *BridgeLCC* program windows have three buttons, one for minimizing, one for maximizing and one for closing the window. The latter system tends to be more user-friendly.

The *BridgeLCC* program is the only program that considers the inflation rate, as shown by Figures 4.49 and 5.59. It uses the selected input values for inflation and real discount. It is obvious that the other two programs fully ignore the effect of the inflation rate.

4.5.6 Documentation

The *Bridgelife* program provides a life cycle design results file and a service life design file, respectively. The *WebLCC* program provides a similar file. The *BridgeLCC* program, however, provides a full documentation printout, Figure 4.72, where the content related to the LCC analysis is included. At least in this regard, the *BridgeLCC* program tends to be much closer to a commercial product program than the two other ones, although it is freely available online. One disturbing detail from the program user's viewpoint may be, however, that the title NIST is reported at the bottom of every single page.

4.5.7 User guide

The *Bridgelife* program has a user manual available both in English and in Finnish, but without any help functions in the program. The *WebLCC* program provides online help, but it is rather simple. The *BridgeLCC* program provides context-sensitive help functions for all of its windows as well as a detailed user manual following a standard window nomenclature. Therefore, in this regard the *BridgeLCC* program is more user-friendly than the two other ones.

4.5.8 Programming language

There are many computer programming languages available. All languages have their own specialities. It is important to choose the right language for a particular job. There are also many factors involved, but the most important one is the suitability. Some languages are very easy for the computer to understand and so very efficient. Other languages may be less efficient but practical.

Excel

Excel is an electronic spreadsheet program that resembles a paper ledger sheet. In that environment, number manipulation is easy. The VBA (Visual Basic for Applications) functions were included into Excel, when Microsoft Visual Basic was integrated into Microsoft Office applications. VBA as a Basic-based programming language allows the automation of certain operations. VBA is adopted by the *Bridgelife* program. The main advantages of a VBA program are as follows:

- Vast functionality available;
- No need to design or create a user interface.

Consequently, the drawbacks are as follows:

- Low calculation efficiency and sensitivity to calculation errors due to the characteristics of a Basic-based program;
- An Excel platform, Figure 4.73, is needed to run the program which means, that a stand-alone program possibility is excluded;
- The program does not function on the web.

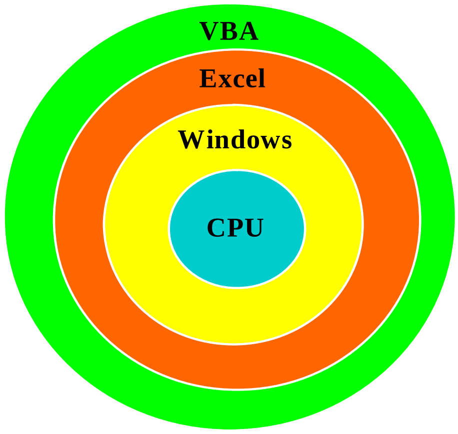


Figure 4.73 *The Software Platform for VBA.*

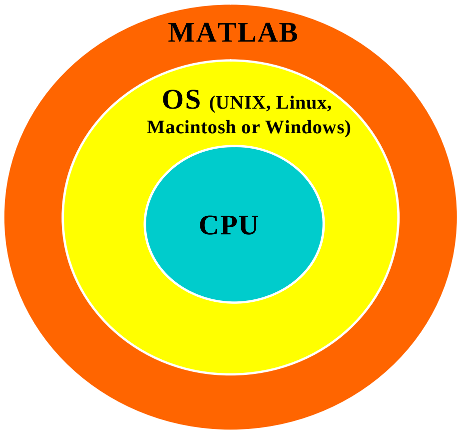


Figure 4.74 *The Software Platform for MATLAB.*

MATLAB

MATLAB (abbreviation for MATrix LABoratory) is an interactive, high-level, high-performance matrix-based system for doing scientific and technical computation and visualization. The advantages of a MATLAB program are as follows:

- It suits very well to numerical computations, because it is a C-based program (it is optimized to be even quicker than a C program when performing matrix operations);
- it can be used on various platforms - compatible with UNIX, Linux, Macintosh and Windows operating systems, Figure 4.74;
- its graphics capabilities are very powerful;

- it functions on the web.

Consequently, the drawbacks are as follows:

- in general it is not more user-friendly than Excel VBA;
- it is not suitable for things like parsing text, because it is mainly designed for scientific computation.

4.5.9 Program size

A program size depends on the total number of lines of the code. To implement one function point, different lines of code are needed when using different programming languages. The LOC/FP (lines of code/function point) estimates are valid for different programming languages. According to that Excel VBA has 6 LOC/FP and MATLAB has 12 LOC/FP which means that MATLAB, compared to Excel VBA, needs twice as many lines of code to implement the same amount of function points. As seen in Table 4.3, the size of the *Bridgelife* program is 5,6 MB and that of *WebLCC* 4 MB. Therefore, a preliminary conclusion is that *Bridgelife* has more function points than *WebLCC*. To a certain extent, the more function points, the better functionality.

4.5.10 Application platform

Bridgelife and *WebLCC* are both available in a web-based form. However, they adopt different web-based applications. *Bridgelife* is used on the web by means of the Citrix Systems' MetaFrame thin-client solution (Excel VBA itself does not function on the web). *WebLCC* adopts a classic web-based thin-client application. This is possible due to the fact that MATLAB functions on the web. These two programs use different intranet[8] technology, as shown in Figure 4.75.

In Figure 4.75, Citrix Presentation Server functions with any application, with any device and over any connection, with ultimate flexibility. That is why *Bridgelife* can also be applied in web form with the Citrix Presentation Server - the special type of intranet technology. However, the Citrix solution is hardware intensive. The Citrix Secure Gateway, Figure 4.76 of the Citrix solution encompasses three modules installed on three servers (Secure Gateway, Web Interface and the Secure Ticketing Authority). Adding redundancy into this architecture increases the complexity even further. The Citrix solution needs considerable hardware, deployment, support and maintenance costs. Therefore, a Citrix solution is an expensive solution for the *Bridgelife* program when used on the web.

[8] An intranet is a service that uses the technologies of the World Wide Web (usually HTML over HTTP) to distribute information within a single organisation over its internal network. Note that the intranet is no longer the network itself, but a service run over it.

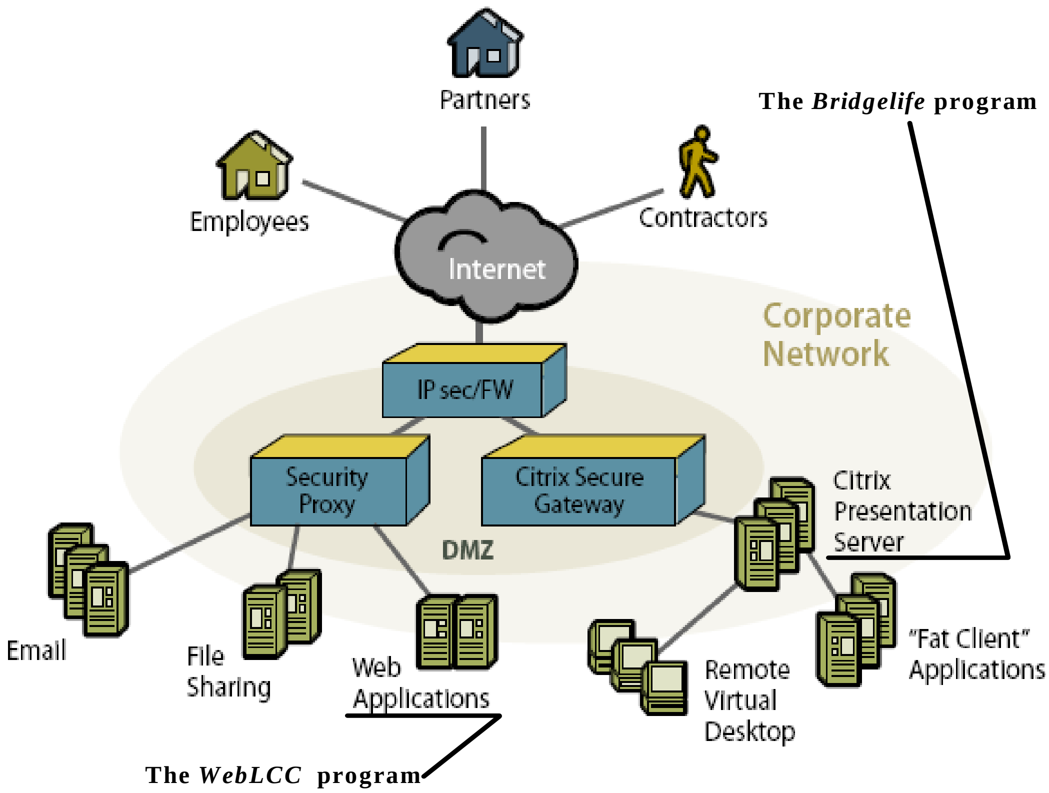


Figure 4.75 *The different network routes for Bridgelife and WebLCC*

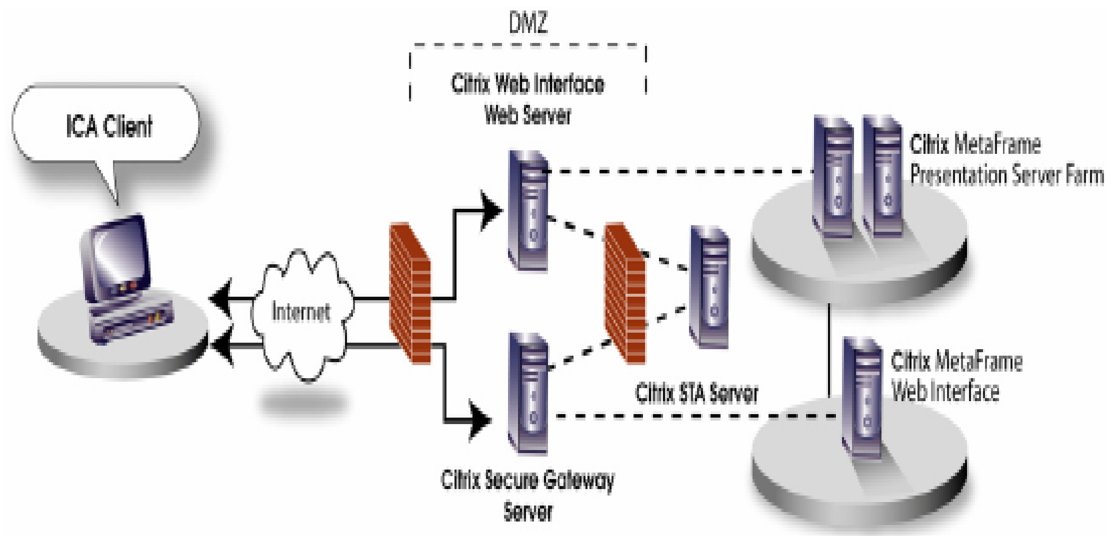


Figure 4.76 *Citrix Secure Gateway Complexity.*

As seen in Figure 4.75, the *WebLCC* program needs only one server to be web-based. Its web-application model is shown in Figure 4.77. This is the way *WebLCC* usually is used on the web. Using of the *WebLCC* program on the web is easier and less expensive than using of the *Bridgelife* program.

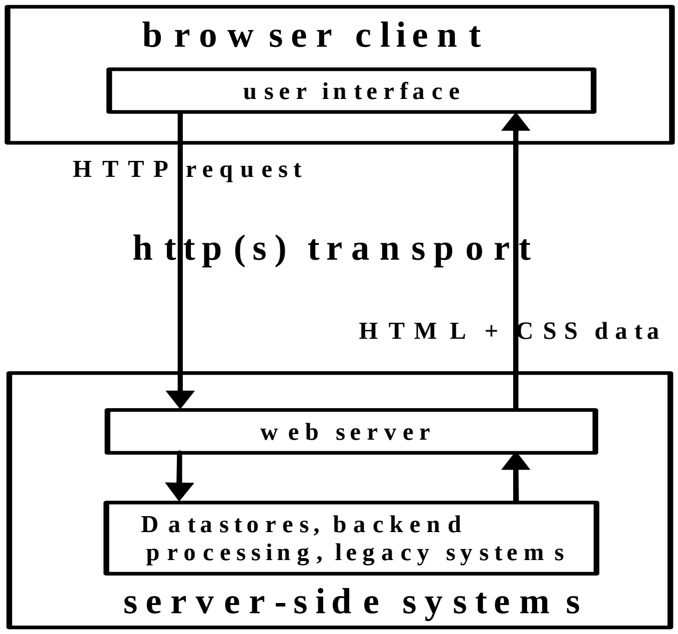


Figure 4.77 *A classic web-application model.*

The *BridgeLCC* program only runs on a personal computer with a local hard drive. It does not work with remote, networked drives.

4.5.11 Summary of the comparison

The summary of the comparison is shown in Table 4.4.

Table 4.4 *The characteristics of the three programs studied.*

Comparison	*Bridgelife*	*WebLCC*	*BridgeLCC*
Costs considered	MR&R, user and delay	Investment, operation & upkeep, repair, traffic and demolishing	By bearer: agency, user and third party. By timing: initial construction, “O, M, and R” and disposal. By component: elemental (includes deck, superstructure, substructure and other), non-elemental and new-technology introduction
Mathematical solutions	Markov Chain stochastic	Classic stochastic	Classic stochastic
Standard adopted	LIFECON (GIRD-CT-2000-00378)	SNRA	ASTM E 917 and NIST cost classification scheme
Intended user	Bridge owners, maintainers and designers	Those who are interested in the LCC calculation theory	Bridge engineers, material specialists and budget analysts
Objectives	Predicting the condition of different bridge components, planning MR&R actions and calculating LCC during the design period of a bridge	Illustrating the theory of LCC calculations	Determining the LCC effectiveness of bridge designs and processes
User interface	Normal window interface.	Vertical scrolling window interface	Normal window interface
Inputs	Fully ignoring the effect of the inflation rate	Fully ignoring the effect of the inflation rate	Including inflation rate
Documentation	Providing a life cycle design results file and a service life design file	Providing a results file	Providing a full documentation printout
User guide	User manual in English and in Finnish, but no help functions in the program	Simple online help	User manual and context-sensitive help functions for all of its windows
Programming language	VBA	MATLAB	(Unknown)
Program size [MB]	5,6	4	18,7
Application platform	Citrix Systems' MetaFrame (thin-client); An independent PC	Web-based applications (also thin-client)	Only on a PC; Not with remote, networked drives

4.6 Conclusions and recommendations

This study was designed firstly to expound the principles of LCC and secondly to focuse on the comparison of three bridge LCC analysis programs. The final goal is to conclude, what a commonly accepted bridge LCC analysis program should be like. This section presents key lessons and recommendations based on the results of this study.

4.6.1 Conclusion

Within the context of this study, the following conclusions are made.

1. The basic deterministic method is the basis of LCC analysis

Although each program has different cost breakdowns to calculate the LCC, the idea shown in section 3.6 about, how to accumulate the LCC, does not change. The deterministic method of LCC calculations is the foundation of all LCC calculations.

2. The *Bridgelife* program, applying Markov Chain method in project level LCC, shows its originality in bridge LCC analysis

The Markov Chain method, as a mathematical framework, has not been used in project level LCC before, although it has been the most commonly used mathematics in the existing predictive facility management systems in the world. The *Bridgelife* program creates an excellent prototype for its application in this domain. Degradation models are important in this program and the reliability of the calculation relies very much on them.

By and large, The *Bridgelife* program has three defects due to the programming language VBA used in it. Firstly, relatively long time is needed to solve problems, which leads to low calculation efficiency. Secondly, the program has poor portability due to the fact, that it cannot be a stand-alone program – Excel is a must. Thirdly, the program cannot be web-based without costly IT infrastructure, i.e. the Citrix Presentation Server.

3. The *WebLCC* program has computational and web-based advantages compared to the *Bridgelife* program

MATLAB is undoubtedly superior to Excel in matrix manipulation, especially when complex algorithms are concerned. With MATLAB it is not necessary to deal with raw numbers, but the Excel users have to handle the raw numerical data in detail. It is also easy for a MATLAB program to be web-based.

The programs explorations show that the user interface of the *WebLCC* program is not as user-friendly as that of the *Bridgelife* program. This is a minor drawback of MATLAB. However, there is a new tool – Excel Link, which makes it possible to write MATLAB programs that can transfer data between MATLAB and Excel.

4. *BridgeLCC* program explicitly embodies the usefulness of a LCC analysis

This program is used to get an optimum bridge LCC design by comparing the different design alternatives' cost results rather than counting on the cost results. The other two programs calculate the LCC results, but they deal with one alternative at the time only.

4.6.2 Recommendations

The investigated programs mainly tackle the number of maintenance actions - the most difficult and uncertain factor in a LCC calculation. A LCC calculation tends to be perfect, when the other two factors, that is the cost of maintenance action and the interest rate, are taken into account as well. The following recommendations are given under the premise, that a new program would be developed for the Nordic road authorities.

1. Unifying cost breakdown

It is understood that a unified cost breakdown is needed, if a new common program will be used in the Nordic countries. The unit costs are not same in the different countries and that is why the choice of unit costs should be left to the users. An alternative method would be to let the user choose the country and the program would then provide the cost information. This alternative may cause problems in maintainability, if the new program needs to be adopted by other countries afterwards.

2. Standardising a yield curve[9] for the discount rate

In Ehlen, *BridgeLCC* shows the information needed for the yield curve describing the recommended inflation and discount rate in the USA. It is often difficult for the program user to take into account the effects of the inflation and discount rate. So, it is necessary to have standard yield curves for the inflation and discount rate especially, when they have significant effect on the calculation result. Then the program user can easily and precisely decide what inflation or discount rate should be used in the LCC analysis. The inflation rate is not considered in *Bridgelife* and *WebLCC*, so the yield curves for discount rates at least should be standardised.

3. The use of Markov Chain -based LCC analysis in future applications

In the *Bridgelife* program, the Markov Chain method is combined with a traditional LCC analysis. As a consequence, the timing of MR&R actions can be defined on the basis of an automatic condition guarding system. On the other hand, combined with the decision trees for optimal MR&R action profiles, the Markov Chain method enables automatic life cycle design of bridges. From this it follows, that the *Bridgelife* program is the most suitable one for the bridge administration sector. The unique feature of the *Bridgelife* program is the original use of the Markov Chain method and that is why this method should be used in the future applications as well. In other words, if a new program was developed, then the functionality of the *Bridgelife* program should be adopted because of its superiority compared to the two other programs.

4. MATLAB as the programming language

As described in section 4.5.8 there are many advantages for the favour of MATLAB as a programming language of a new *WebLCC* program. The only minor drawback is the user interface. As known, Excel provides good interface and allows flexible examination of the data. If the user interface needs to be improved, then an Excel Link can be a good solution. An Excel

[9] In finanal studies, the yield curve means the relation between the interest rate (or cost of borrowing) and the time to maturity of the debt for a given borrower in a given currency.

Link allows to use Microsoft Excel spreadsheets, while MATLAB calculates and creates graphics on the background. The functionality of an Excel Link is shown in Figure 4.78.

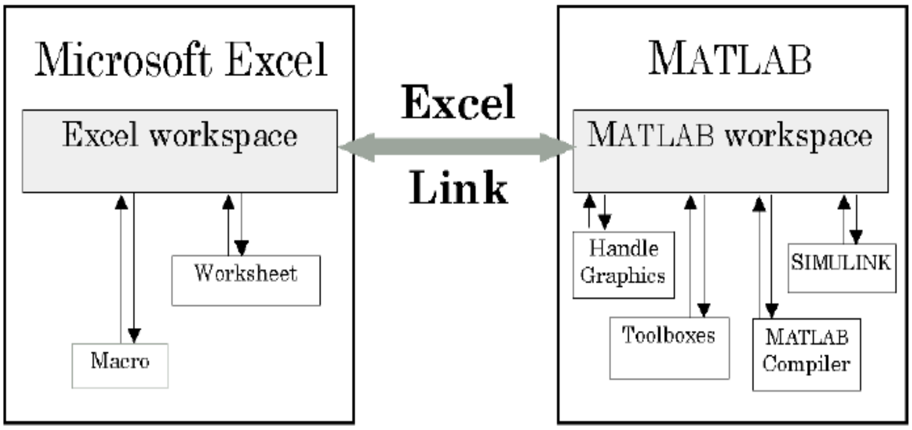


Figure 4.78 *Functionality of an Excel Link.*

5 Suggestions for future research and development

The final task of the ETSI project is to develop a Nordic unified methodology for LCC and LCA calculations. This final goal is maybe not possible to reach, but some steps are absolutely reachable, which is clearly visible when studying this report. Both the State-of-the-art chapter, the methodology and comparison of the existing programs indicate the path that should be followed to at least reach some steps on the road to a unified LCC and LCA methodology and computer program.

A LCC methodology a consists of two main parts

1. An economic methodology
2. A system to decide the MR&R interventions in time.

This reports show that the knowledge of the first question is enough, except the choice of the real interest rate. This choice is considered not to be a part of the work of this project and should be more of a political issue.

The second question is much more complicated. It consists of different parts

1. Degradation models for all kinds of bridges and their structural elements.
2. Tools for transforming degradation models into timings for MR&R actions.
3. Methodologies for describing bridges both regarding their measures, structural parts and their conditions.
4. Computer tools for making LCC and LCA analysis.

1. Degradation models

Degradation models are the most important and most complicated part of a LCC analysis. For at least some structural elements of concrete bridges, the methodology presented in section 3.8, based on the work done by Vesikari et al. and presented in the *Lifecon* project seems to be in the forefront of knowledge for these kinds of structures. For other materials and other structural elements more research is needed.

2. Tools for transforming degradation models into timings for MR&R actions.

The Markov Chain method is judged to be a fruitful tool for combining degradation with condition classes that could be used in a LCC analysis. As a consequence, the timing of MR&R actions can be defined on the basis of an automatic condition guarding system.

Since it is estimated that the input needed for a Markov chain assessment, other methods should be tested in the future ETSI work.

3. Methodologies for describing bridges both regarding their measures, structural parts and their conditions.

It is understood that a unified cost breakdown is needed, if a new common system will be used in the Nordic countries. A unified system for condition rating and breaking down the different structural parts of a bridge for calculating degradation of these and the associated costs is probably needed. Of course the unit costs are not same in the different countries and that is why the choice of unit costs should be left to the users.

Comparing the methodologies used in the three countries it is clear that the Swedish system has to few classes to be used in the future system. It is suggested that changing this should be a part of the future work.

4. Programming language

The most effective system for making a web based computer subsystem is using a MATLAB based system. It is suggested that the next step in the ETSI program should be to merge the *Bridgelife* and *WebLCC* system into one new Web-based program system, with more functionalities than the envelope of the two systems of to-day.

6 Literature and references

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