

## Life Cycle Cost Methodology and LCC Tools

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# Acronyms and notations

## Acronyms<sup>1</sup>

BaTMan	The Swedish bridge and tunnel management system
BLCCA	Bridge life-cycle cost analysis
BMS	Bridge management system
CC	Condition class
CUR	A general notation for currency, can be DKK, SEK, NOK, £, €, \$,...
ETSI	Bridge Life Optimisation
EXCEL	
LCC	Life cycle costing
LCP	Life cycle plan
MathCad	A program system for engineering calculations
MR&R	Maintenance, Repair & Rehabilitation
NVDB	The Swedish national road database
O&M	Operation and maintenance
TG1, TG2, TG3,...	The ETSI project is performed within different sub-projects, and different task-groups are responsible. TG3 is responsible for the LCC subproject and TG4 for the LCA project.
TrV	Trafikverket, the Swedish Transport Administration
WebHybris	Software navigation tool that can access BaTMan database
WLC	Whole-life costing

## Upper case roman letters<sup>1</sup> (quantities)

$A_{L,r}$	Annuity factor
$ADT$	Average daily traffic/(vehicle/day)
$ADT_t$	is the average daily traffic, measured in numbers of cars per day at time $t$ ,
$C_0$	Future cash flow expected to fall due every year during the service life-span $L$
$C_{ACC}$	Accident cost/CUR
$C_{EAC}$	Equivalent annual cost/CUR
$C_{FA}$	Average cost per fatal accident (CUR/accident)
$C_i$	Sum of all cash flows in year $i$ /CUR
$C_{IA}$	Average cost per serious injury accident (CUR/accident)
$C_{INS}$	Inspection cost/CUR
$C_{INV}$	Investment Cost/CUR
$C_{TDC}$	Traffic delay cost/CUR
$C_{VOC}$	Vehicle operating cost/CUR
$EAC$	Equivalent annual cost/CUR
$L$	Service life-span/a
$LCC$	Life-cycle cost/CUR
$LCI$	Life-cycle income/CUR

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<sup>1</sup> Acronyms should according to ISO be written in Romans style (upright). Quantities, always including a unit, should be written in italic (sloping style). The unit a (Latin annum) refers to "year". Year is not an allowed unit.

$N_t$	Number of days of road work at time $t$ ,
$P_F$	Average number of killed persons in bridge related accidents (Persons/Accident)
$P_I$	Average number of injured persons in bridge related accidents (Persons/Accident)
$S$	is the length of affected roadway on which cars drive due to MR&R actions
$S_{\text{Detour}}$	Detour length/m
$T$	Time studied/a. Usually the life-span ( $L$ ) of the bridge
$WLC$	Whole life cost/CUR

### Lower case roman letters<sup>1</sup> (quantities)

$o_D$	Average hourly operating cost for one passenger car/(CUR/h)
$o_L$	Average hourly operating cost for one commercial truck/(CUR/h)
$p_L$	Percentage of commercial traffic/%
$r$	Discount rate/%
$r_i$	Inflation rate (%).
$r_L$	Discount rate (%) for loans with long duration
$r_{TG}$	Traffic growth rate/%
$t$	time/a
$v_n$	Normal traffic speed,
$v_r$	Traffic speed during bridge work activity/(km/h)
$w_D$	Hourly time value for one passenger car/(CUR/h)
$w_L$	Hourly time value for one truck/(CUR/h)

### Indices

All type cost items could be given an explanatory index. Some of the important indices are given above, but more are given in the text.

# **1. What is Bridge Life Cycle Costing**

## **1.1 General**

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 report.

This report on LCC is a part of the ETSI project. ETSI is interpreted as bridge life optimisation. This term is of course very general, but within the project it has been decided that only the situation when a new bridge is to be built, is studied. The tools developed are thus only suitable at this stage, where costs, environmental, aesthetical and cultural values are compared and the “best” bridge is to be sorted out and the early design stage.

## **1.2 Life Cycle Cost and BMS**

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.

Usually LCC is one important tool in a bridge management system (BMS). There are many other tools needed in a BMS, like LCA, but these will be described in other reports.

A bridge management system is usually divided into three levels:

- Country or county level
- Road or railway network level
- Project level, which usually is interpreted as a BMS for individual bridges.

There is however a close interaction between bridge LCC and BMS, because much of the information needed is the same. This means that, at least for individual bridges, the LCC can both be seen as a tool within the BMS or the LCC completed with some systems can be used as a steering system for the BMS.

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 the bridge.

For both a BMS and for LCC the following information is needed:

- Definition of the bridge, its parts, elements, details and equipment with measures and quantities, also including relevant information about the relevant surrounding conditions. This information should be organised in a well-defined data inventory organised in a logical structural hierarchy. The data structure of the inventory must be consistent with the system needs.
- Planned management systems including maintaining an appropriate database of information
- Planned operation systems.
- Planned monitoring and rating systems.
- Planned alternatives for maintenance, repair and rehabilitation (MR&R) measures for the bridge parts and elements.
- Planned information on the use of the bridge like the amount and type of traffic flow.
- Planned demolition scheme.

Definition of these measures could be collected in a “Life cycle plan (LCP)”. If this plan is supplemented with economical information, like interest rates, and economical planning tools like the net present value method this can be called a LCC plan. It is an inherent condition that the LCC should be designed so that variation of the input values should be able to find an optimal solution for the LCP, because there are always economical constraints on the available resources for Maintenance, Repair and Rehabilitation (MR&R).

In a more general sense the LCC defining costs for the owner and the users, should be compared with a socio-economic income for the society. The bridge shall of course not be built unless it contributes to the social and economic development of the society.

### **1.3 LCC tools**

For simple cases it is rather easy to make simple LCC calculations i.e. using EXCEL or MathCad. In the ETSI project and at the department of Structural Engineering and Bridges at the Royal Institute of Technology (KTH), several LCC programs have been developed. A Stand-alone program based on EXCEL will be more in detail described in this report, but the principle of a web-based program will also shortly be discussed. A further development with more functionality will also shortly be discussed.

### **1.4 How to use the LCC tools**

The LCC tools are intended to be a part of the design process of bridges. The definitions, notations, see Chapter 3 are “ETSI-definitions” and are designed to be the “lowest common denominator” of the systems used in the Nordic countries. The idea is that the tools should be adapted to the methods used in each country.

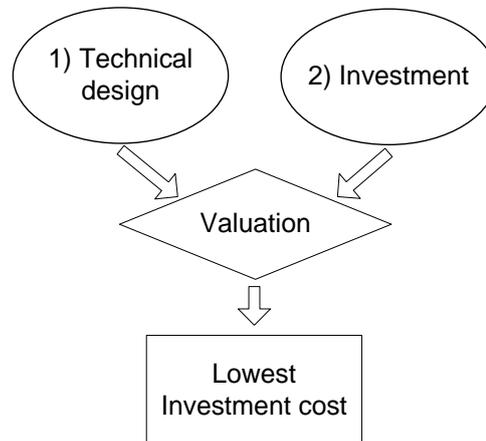
Before starting the LCC calculation a “Life Cycle Plan” see the chapter on this issue, can be designed. This plan can contain the same type of information as the LCC program, but could

be more elaborated and the different items like actions could be explained and motivated. The plan can contain different options like variation of interest rate, use of different material qualities and so on. The LCC tool is then used for getting economical information on the options. Since the Life Cycle Plan and the LCC is a prognosis of the future, no exact values are expected, thus the LCC tools are mainly intended for comparison of different solutions.

## 2. Methodology for LCC calculation

### 2.1 The idea behind Life Cycle Cost analysis

The classical task for the Bridge Engineer was to find a design giving the lowest investment cost for the bridge, taking the functional demands into consideration. **Figure 2.1** shows this process schematically.



**Figure 2.1** *The classical task for the bridge engineer was to find the design giving the lowest investment cost for the bridge.*

This process could result in a bridge design giving a low investment cost but high maintenance costs. A LCC analysis aims in finding an optimal solution weighting investment and maintenance.

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 and maintenance 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. 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.

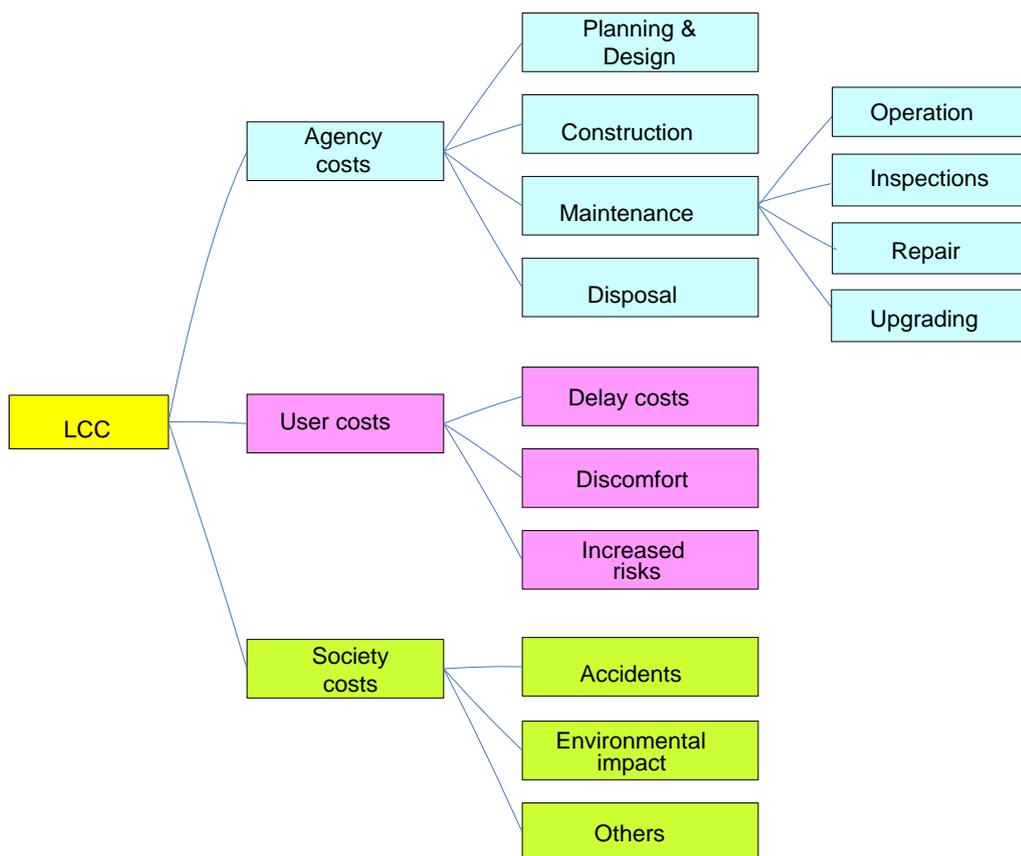
For making a complete LCC calculation for a bridge, at least the following parameters are needed:

1. Functional demands for the bridge. The most important of these demands are the safety, planned life-span and accepted traffic interruptions and user costs.
2. Physical description of the bridge. The structure is usually divided in parts, i.e. according to **Table 2.1** 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 Sections 2.3 to 2.7.
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 Section 3.8. In *Jutila & Sundquist (2007)* Sections 4.6 and 4.6 a more thorough discussion on this question is presented. In this report it is assumed that the time between different maintenance and repair actions is decided by the user of the system, even if the WebLCC program presented in Chapter 4 has a module for modifying the time for actions depending on climate classes.

## 2.2 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)*. In all these reports *LCC* is a general variable describing a cost, usually by using the net present value method calculated to the time of opening the bridge. The different parts of the calculation can be described in **Figure 2.2**.



**Figure 2.2** Schematic presentation of the different items in a complete LCC analysis.

The owner - or in the case of an Agency like a Road or Railway Administration - has the responsibility for investments, operation and MR&R costs. The user is the one who has the benefit of the road system and thus the bridges, but has also has to pay for lost working hours

due to traffic interruptions, risks and other problems. The society has to pay for accidents, environmental impacts and if the road network does not function for the welfare of a country. The income for the society of the road and thus the bridge could be called *LCI*, Life Cycle Income.

In a general term the *LCC* should be smaller than the *LCI*. Typically a road system should not being built unless *LCI* is larger than  $1,5 \cdot LCC$ , see Section 2.7.

It is very easy to use a toll bridge as an example for this scheme. The Income from tolls over a specified period of time should be larger than the depreciations, rents and MR&R costs for the bridge.

In the following only *LCC* will be discussed, and what can seem illogical, only the user costs will be included in the analysis. The society cost will only be included regarding accidents due to structural malfunction.

The environmental aspects will be treated in a special subproject (SP2) of the ETSI project. Cultural and aesthetic issues will be discussed in another subproject (SP3) of the ETSI project.

## 2.3 Agency costs

$LCC_{\text{agency}}$  is the part of the total *LCC* cost that encumbers the owner of the project. This cost can in turn be divided into different parts according to Eq. (4-1)

$$LCC_{\text{agency}} = LCC_{\text{acquisition}} + LCC_{\text{MR\&R}} + LCC_{\text{consequence}} \quad (2-1)$$

Where

$LCC_{\text{acquisition}}$  (sometimes denoted *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.

$LCC_{\text{MR\&R}}$  (sometimes denoted *LSC* Life Support Cost) = is the cost for future operation, maintenance, repair and disposal of the bridge, by the net present value calculated to a specified time usually the opening of the bridge.

$LCC_{\text{consequence}}$  (sometimes denoted *LCCC* = Life Cycle Cost Consequence) = is the future costs for possible negative consequences, by the net present value calculated to a specified time, usually the opening of the bridge. This kind of costs could possibly be a part of the user ( $LCC_{\text{user}}$ ) or the society costs ( $LCC_{\text{society}}$ ), see below.

$LCC_{\text{society}}$  = is the future costs for possible negative consequences for the society, by the net present value calculated to a specified time, usually the opening of the bridge.

The  $LCC_{\text{MR\&R}}$ , the Life Support Cost (LSC), can in turn be divided into two parts according to Eq. (2-2)

$$LCC_{\text{MR\&R}} = C_{\text{equipment}} + LCC_{\text{MR\&R,future}} \quad (2-2)$$

where  $C_{\text{equipment}}$  ( $CI$ ) is the investment in the necessary equipment and other resources for the future operation and repair.

This distinction between the cost for acquisition and cost for equipment for MR&R will not be used in the following.

$LCC_{\text{MR\&R, future}}$  is the future cost for operation, maintenance, inspection and repair, by the net present value calculated to a specified time, usually the opening of the bridge.

The investment part of the maintenance,  $C_{\text{equipment}}$  could be divided according to eq. (2-3)

$$C_{\text{equipment}} = C_{\text{spare parts}} + C_{\text{tools}} + C_{\text{documentation}} + C_{\text{training}} \quad (2-3)$$

where

$C_{\text{spare parts}}$  = spare parts and material,

$C_{\text{tools}}$  = instrument, tools, vehicles that is needed for inspection and maintenance,

$C_{\text{documentation}}$  = documentation i.e. drawings and instruction manuals needed for inspection and maintenance and also

$C_{\text{training}}$  = employment and education of personnel for operation and maintenance.

Usually the  $C_{\text{equipment}}$  costs for a bridge is small and can often not be coupled to a specific bridge. The Agency cost for Operation could however be referred to this cost, because the cost for operation is probably proportional to the number and complexity of the bridge stock.

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

$$LCC_{\text{agency}} = \sum_{t=0}^T \frac{C_t}{(1+r)^t} \quad (2-4)$$

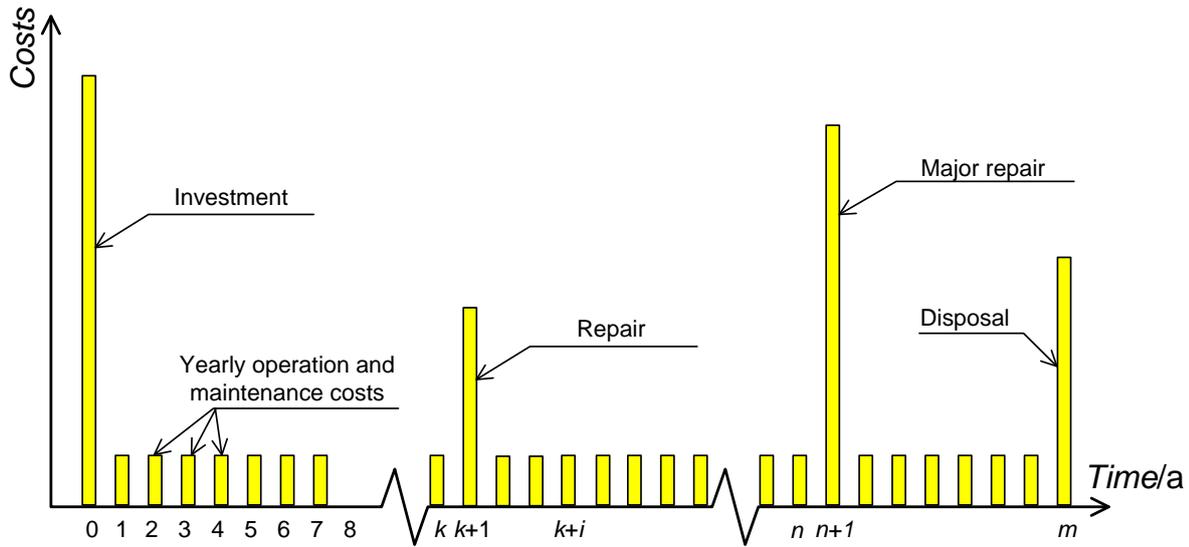
In Eq. (3-4) is

$C_t$  the sum of all costs incurred at time  $t$ ,

$r$  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.

Equation (2-4) is schematically visualised in **Figure 2.3**.

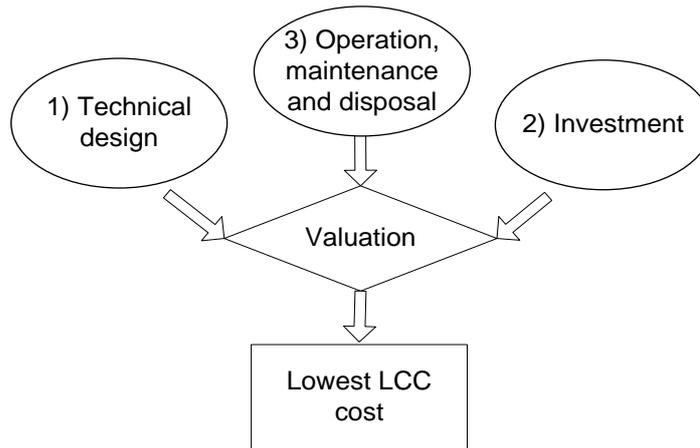


**Figure 2.3** Schematically representation of agency costs for a bridge. The costs in this figure are not recalculated using the present value method.

When comparing investment projects of unequal life-spans, it would be improper to simply compare the net present values of the two projects unless neither project could be repeated to let all projects have the same analysis period. Equivalent Annual Cost (*EAC*) is often used as a decision support-tool in capital budgeting when comparing investment projects of unequal life-spans. In finance the *EAC* is the cost per year of owning and operating an asset over its entire life-span. The alternative associated with the lowest annuity cost is the most cost-effective choice. The *EAC* is calculated by multiplying the *LCC* calculated by the net present value by the annuity factor  $A_{L,r}$ :

$$EAC = LCC_{\text{net}} \times A_{L,r} = LCC_{\text{net}} \frac{r}{1 - (1+r)^{-L}} \quad (2-5)$$

In an optimisation context the task, only taking the agency costs into consideration, is to design a bridge to find the lowest *LCC*. This phase of the *LCC* optimisation is visualised in **Figure 2.4**.



**Figure 2.4** *The figure shows schematically the costs taken into consideration in a classic LCC analysis not including society and user costs.*

Eq. (2-4) is usually used to calculate the owners cost for investment, operation, inspection, maintenance, repair and disposal.

The  $C_t$  costs 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  $r$ -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 be feasible. Combination of historical data with Markov-chain methodology seems however to be feasible if enough data is available.

## 2.4 User costs

User costs ( $LCC_{\text{user}}$ ) are typically costs for drivers, the cars and transported goods on or under the bridge due to delays due to roadwork. There are different kinds of user costs, like detours needed when the bridge is closed for repair etc., but these costs are very site-specific. Some other user costs are easier to calculate, because those are better related to the bridge itself.

Driver delay cost is the cost for 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. (2-6)

$$LCC_{\text{user, delay}} = \sum_{t=0}^T \left( \frac{S}{v_r} - \frac{S}{v_n} \right) ADT_t \cdot N_t (p_L w_L + (1 - p_L) w_D) \frac{1}{(1+r)^t} \quad (2-6)$$

In Eq. (2-6)

$S$  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  $t$ ,

$p_L$  is the amount of commercial traffic,

$w_L$  is the hourly time value for commercial traffic and

$w_D$  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 for transported goods can be calculated using Eq. (4-7)

$$LCC_{\text{user,operating}} = \sum_{t=0}^T \left( \frac{L}{v_r} - \frac{L}{v_n} \right) ADT_t \cdot N_t (p_L(o_L + o_G) + (1 - p_L)o_D) \frac{1}{(1+r)^t} \quad (2-7)$$

In Eq. (4-7) the same parameters are used as in Eq. (4-6) except for

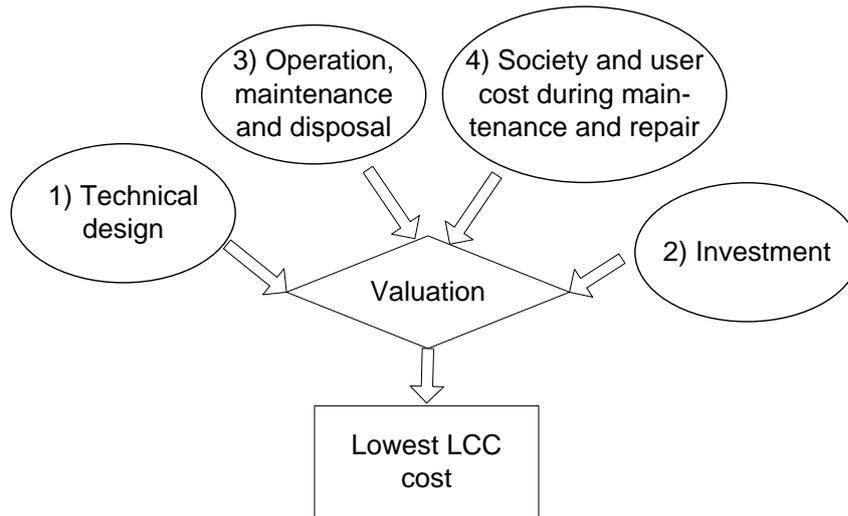
$o_L$  which are operating cost for the commercial traffic vehicles,

$o_G$  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. (2-6) could be used also for this by just adjusting the cost parameter for this case.



**Figure 2.5** The figure shows schematically the costs taken into consideration in a classic LCC analysis not including society and user costs.

## 2.5 Costs for the society

Typical costs, not clearly visible for the Agency 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. These issues are discussed in the TG4 subproject on Life Cycle Assessment.

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

$$LCC_{\text{society, accident}} = \sum_{t=0}^T (A_r - A_n) ADT_t \cdot N_t \cdot C_{\text{acc}} \frac{1}{(1+r)^t} \quad (2-8)$$

In Eq. (2-8)  $A_n$  is the normal accident rate per vehicle-kilometres,  $A_r$  is the accident rate during roadwork and  $C_{\text{acc}}$  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 3 million \$ for deaths and a third of that sum for serious accidents.

## 2.6 Failure costs

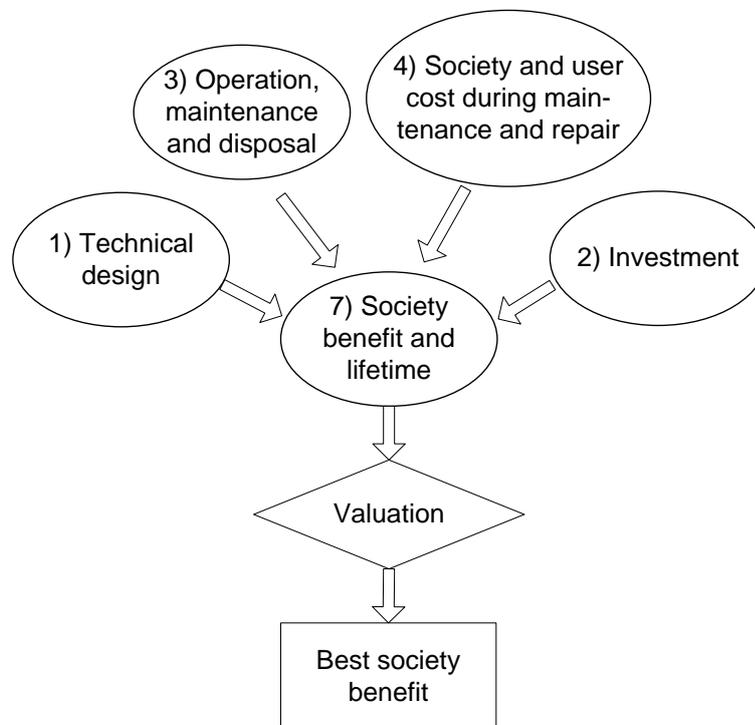
There is a small risk for the total failure of a structure. To get the cost for failure one has to calculate all costs ( $K_{H,j}$ ) for the failure, accidents, rebuilding, user delay costs and so on and then multiply these costs with the probability for failure and with the appropriate present value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

$$LCC_{\text{failure}} = \sum_{j=1}^n K_{H,j} R_j \frac{1}{(1+r)^j} \quad (2-9)$$

In Eq. (2-9),  $R_j$  is the probability for a specified failure coupled to  $K_{H,j}$ . 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.

## 2.7 Comparing cost and benefit, whole life costing (WLC)

Why a bridge – as a part of a road or railway – is built is of course that the project is considered beneficial for the society. The income for the society of the road and thus the bridge could be called *LCI*, Life Cycle Income, and should of course be greater than the total *LCC* cost, see the schematically **Figure 2.6**. Calculation of the *LCI* is however not a part of this project.



**Figure 2.6** A total cost benefit analysis shall of course also include both the total cost and the benefit for the society.

## 2.8 Interest rate

The most important factor in Eq. (2-4) is, except of course the costs, the interest rate  $r$ . The real interest rate is usually calculated as the difference between the current discount rate for long loans and the inflation or more exact

$$r = \frac{r_L - r_i}{1 + r_i} \quad (2-10)$$

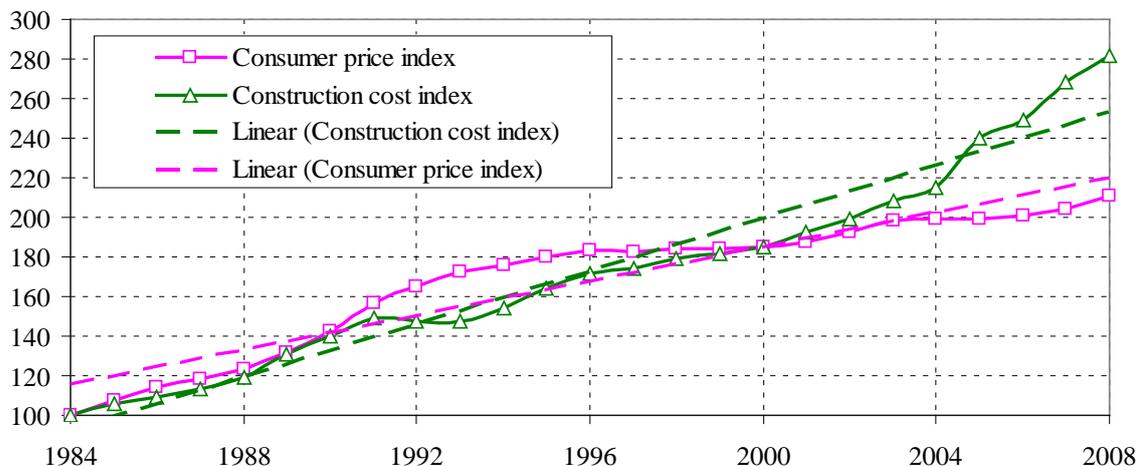
where

$r_L$  is the discount rate (%) for loans with long duration and

$r_i$  is the inflation rate (%).

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

The inflation rate in the society might not be the same as the inflation rate for the construction sector. An investigation presented in *Mattsson (2008)* showed that the inflation in the construction sector in Sweden during the period was 1 % - 1,5 % higher than the general inflation rate, see also **Figure 2.7**. This fact shows a decrease in the productivity, but can also be explained by stricter rules for safety measures that must be applied at the construction sites. This is especially true for maintenance and repair work on existing structures along the roads.



**Figure 2.7** The “inflation rate” in the construction field in Sweden is higher than the general inflation rate in the society.

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

$$r = \frac{r_L - r_i - r_{TG}}{1 + r_i} \quad (2-11)$$

where  $r_{TG}$  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  $r$ -value should be called “calculation interest rate” or likewise. Typical values for  $r$  are in the order from 3 % to 8 %, see *Jutila & Sundquist (2007)*.

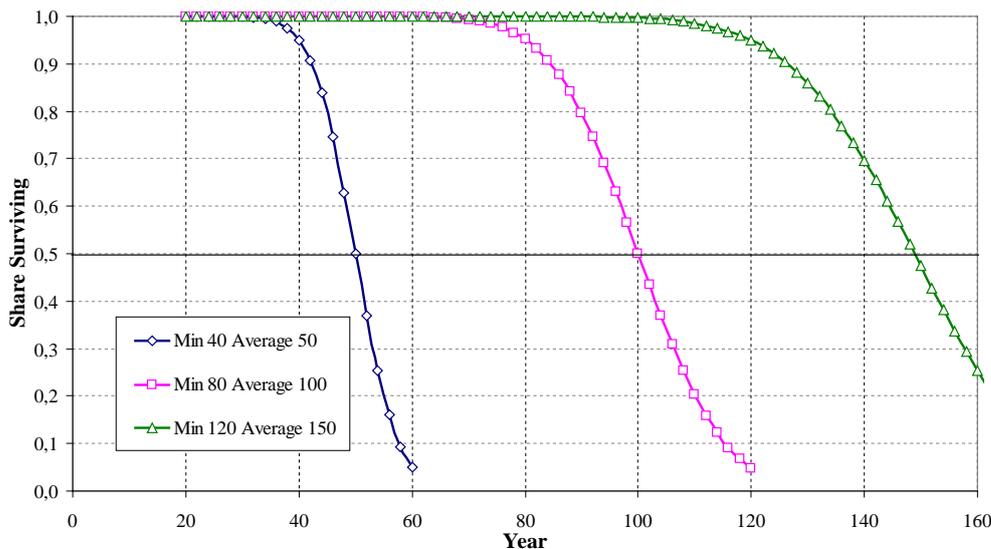
## 2.9 Time between different MR&R actions

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 40 to 120 years. Standards do not usually define the parameter “life-span” exactly. According to *Mattson (2008)*, which is an interpretation of VBR Standard, the definition of life-span is the lower five percentile of the distribution of the life span. This interpretation means that the life span for 40, 100 and 120 year distribution is as shown in **Figure 2.8**.

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 average time for decommissioning bridges is in the order of 60 to 70 years.



**Figure 2.8** Standards calls for design life span of bridges, but at least in Sweden the design life span is defined as the lower 5 % fractile of a distribution that could be assumed to be normal distributed.

### ***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 economic 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.

Inspection intervals in different countries are discussed in *Jutila & Sundquist (2007)*. 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. In the Nordic countries only three main types of inspections are performed. Yearly very superficial inspection and general inspection every 5 to 6 year are performed. Special inspection must also be performed for more complicated cases. This must also be made allowances for in an LCC analysis.

Regular maintenance will of course always be needed. Typically railings, lampposts and other steel details need repainting regularly and this is could be considered being part of the yearly inspections.

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.

### ***Degradation models***

All the discussed equations in Section 2.3 – Section 2.6 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 do not just break down; 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. Definitions and measures used in the ETSI LCC and LCA programs

#### 3.1 Background

To be able to have a consistent set of definitions for in- and output in the planned ETSI LCC and LCA there is a need to define and explain all parameters in the system. This document, mainly based on the Swedish system for such definitions as described in the BaTMan system, is a first preliminary suggestion for such definitions.

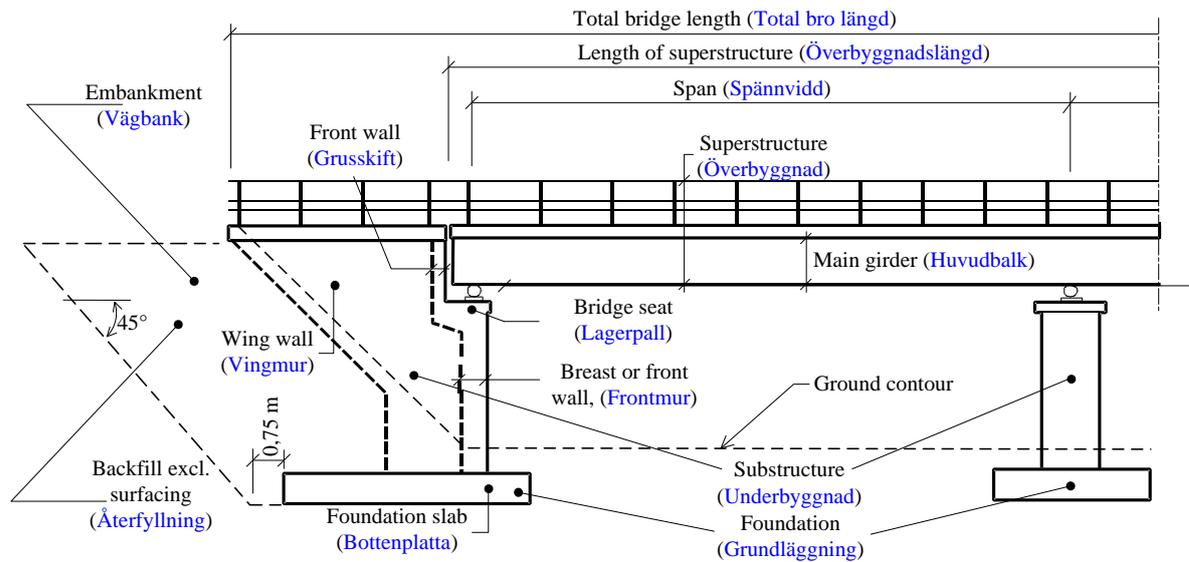
#### 3.2 Definition of bridge parts and their measures

Notion for bridge main structures and its elements are presented in **Table 3.1**.

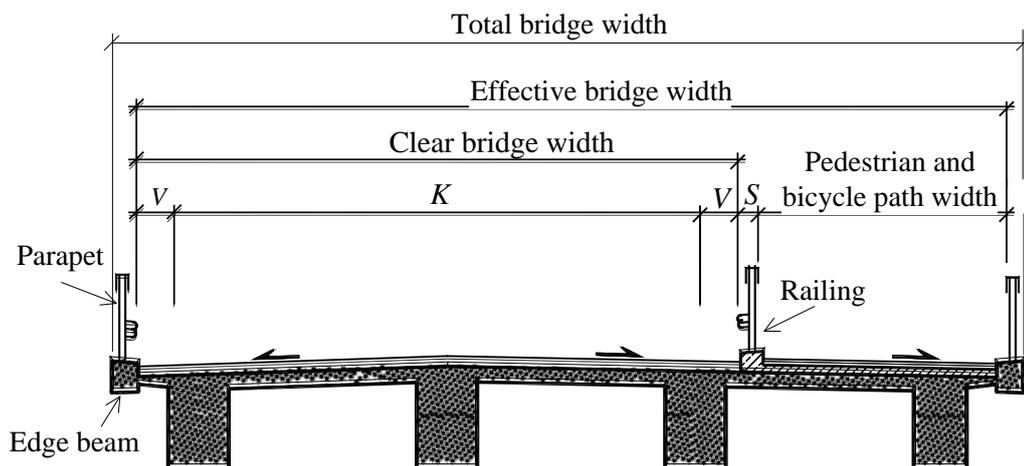
**Table 3.1** *Notations for a typical girder bridge with ordinary bearings and expansion joints.*

<b>Description in English</b>	<b>Explaining figure</b>
<b>Foundation</b>	
Foundation slab (base slab), plinth, pile cap	
Excavation, soil	
Excavation, rock	
Pile	
Erosion protection	
<b>Slope and embankment</b>	
Embankment, embankment end, backfill	<b>Figure 3.1</b>
Soil reinforcement and slope protection	
<b>Abutments and piers</b>	
All concrete structures belonging to the substructure excl. foundation and including the foundation slabs	<b>Figure 3.1</b>
<b>Main load-bearing structure</b>	
Slab / deck	
Beam, girder	
Truss	
Arch, vault	
Cable system	
Pipe, culvert	
<b>Secondary load-bearing structures</b>	
Secondary load-bearing beam, cross beam	
Secondary load-bearing truss, wind bracing	
<b>Equipment</b>	
Bearing and hinge	

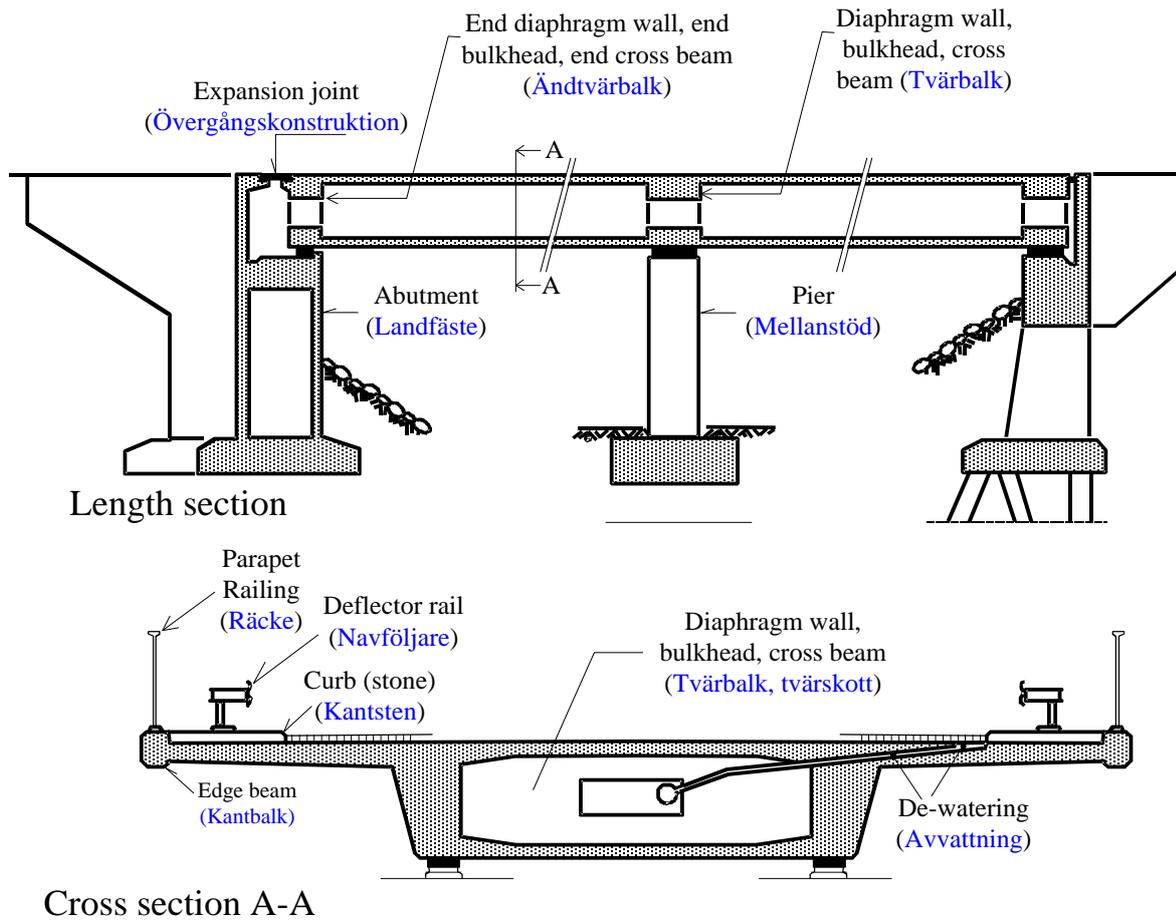
Edge beam	
Insulation, water proofing	
Surfacing	
Parapet, railing	
Expansion joint	
Drainage system	



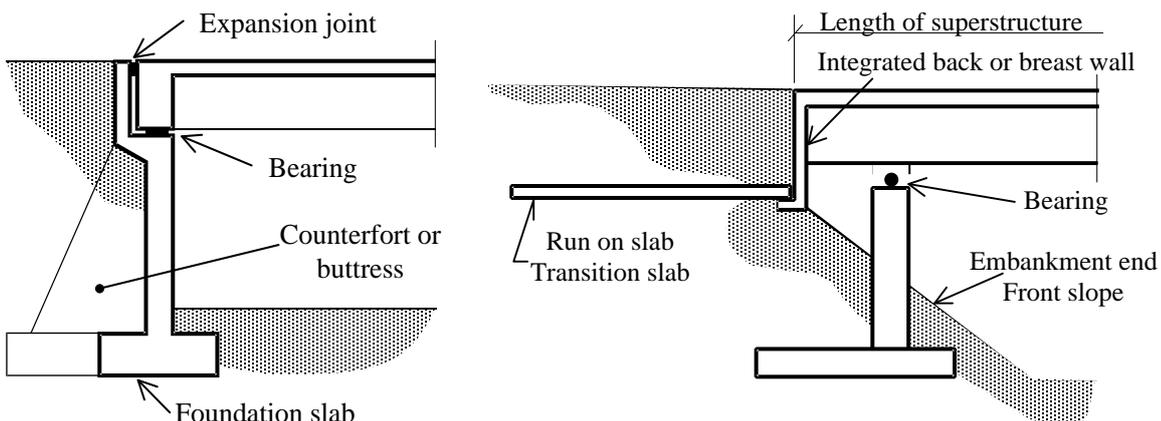
**Figure 3.1** Notations and measures of a typical beam girder bridge with ordinary bearings and expansion joints.



**Figure 3.2** Notations and measures in cross direction of typical beam girder bridge carrying a roadway and a pedestrian and bicycle path.



**Figure 3.3** Notations in the longitudinal direction and in the cross direction for a typical box girder bridge with ordinary bearings and expansion joints.



**Figure 3.4** Notations for abutment elements in an ordinary bridge and in an integral bridge with integrated back walls.

### 3.3 Definition of materials

In **Table 3.2** the materials included in the LCC and LCA systems are defined.

**Table 3.2** *Materials that should be inputted in the LCC and LCA programs.*

Material	Unit	Quality	Description
Concrete	m <sup>3</sup>	C25 <sup>2</sup>	Cylinder strength in MPa
Reinforcing steel	ton	500 <sup>3</sup>	Yield strength in MPa
Steel for pre-stressing, tendons, cables	ton	1700	Yield strength in MPa
Steel	ton	350 <sup>4</sup>	Yield strength in MPa
Sawn Timber	m <sup>3</sup>		
Glued laminated timber	m <sup>3</sup>		
Impregnated timber	m <sup>3</sup>		
Backfill soil	m <sup>3</sup>		
Pile	m	Type <sup>5</sup>	Directly coupled to the structural element

*The following items only used in the LCA module (in the LCA only surfacing and insulation in m<sup>2</sup> is given)*

Asphalt	m <sup>3</sup>		Thickness should be given
Mastic	m <sup>3</sup>		Thickness should be given
Membrane	m <sup>2</sup>		
Epoxy	m <sup>2</sup>		Thickness should be given
Plastic	m <sup>3</sup>		
Paint	m <sup>2</sup>		Thickness should be given
Zink coating	m <sup>2</sup>		Thickness should be given
Rubber	m <sup>3</sup>		
Glass	m <sup>3</sup>		

### 3.4 Definition of actions

After the inauguration and during the lifetime of a bridge different actions and interventions must be performed. At least the following actions are usually performed during the lifetime of a bridge:

<sup>2</sup> Example of notation. For LCC and LCA analysis an approximate value can be used.

<sup>3</sup> Example of notation. For LCC and LCA analysis an approximate value can be used.

<sup>4</sup> Example of notation. For LCC and LCA analysis an approximate value can be used.

<sup>5</sup> Type of pile should be defined. Pile driving is a very energy consuming task.

- Management
- Inspection
- Operation
- Repair
- Upgrading
- Final demolition

*Management* is the owners own work for keeping the bridge inventory, the planning and other actions to manage the bridge stock.

*Operation* is the *yearly work* to superficially and regularly inspect, clean and to repair small damages of the bridges. The Swedish term is “Drift”. See also **Table 3.4**.

### 3.4.1 Management

Usually this work can be assigned as a percentage of the actual new construction value of the bridges in the bridge stock.

### 3.4.2 Inspection actions

**Table 3.3** shows typical inspection actions and the intervals.

**Table 3.3** *Inspection types and intervals between inspections.*

Inspection type	Frequency	Aims	Remark
Regular	Often (actually always!?)	Detect acute damages	Usually considered as part of the operation action
Superficial inspection	Twice a year (probably only once a year)	Following-up of the yearly operation maintenance (properties)	Usually considered as part of the operation maintenance
Major inspection	Every five to six years		
Special inspection	When needed		

### 3.4.3 Operation

Maintenance actions could be divided into actions performed as part of the yearly operations and real repair actions needed when some of the structures or elements are severely damaged. Examples of such “Operation actions” are listed in **Table 3.4**, but could usually be calculated as a percentage of the cost to re-build the bridge stock. A typical value could be 0,2 %.

**Table 3.4** *Examples of “operation maintenance actions”. In the Swedish system this is called “Egenskaper” or “properties”.*

<b>Action</b>	<b>Frequency</b>	<b>Aim</b>	<b>Remark</b>
Regular inspection	Often	Detect acute damages	
Cleaning of the bridge	Once a year	Removal of de-icing salt	
Rodding of dewatering system	Once a year		
Cleaning of expansion joints	Once a year		
Removal of plants and bushes,...	Once a year		

#### **3.4.4 Repair actions**

Reference is made to BaTMan. (Just now I don't have reference to these files). The Swedish word for these actions is “Åtgärder” or maybe in English “Measures”.

In Sweden the yearly average repair actions are in the order of 1 % to 1,3 % of the renewal value of the bridge stock.

#### **3.4.5 Upgrading**

Since the programs developed are to be used at an early stage of the bridge life, upgrading is not an issue at this stage and is not an action included in the LCC and LCA calculations.

#### **3.4.6 Final demolition and reuse of material**

Final demolition is a complicated issue, and very little research is performed regarding the reuse of material used for structures. Interesting points is the carbonisation of concrete during the demolition phase, especially if the concrete is crushed and used for road sub-grade. An approximate value is that the completely carbonated concrete “eats” half of the CO<sub>2</sub>-emissions from the cement production phase. The reused reinforcement steel requires less energy than the virgin steel. How much of the material from the demolition that is really reused is something nobody knows.

### **3.5 Environmental classes**

The degradation of structures due to different climate actions is a very complicated issue and has been a theme for an enormous amount of research during recent years. Degradation is

usually a combination of material properties in interaction with climate and issues coupled to the use and wear of the structure.

In the LCC aspect the material properties are defined by the used material as defined in Section 3.3. The environment and the use of the bridge must however be described in a way so that the degradation can be assessed by the user of the program. A very condensed subdivision of external deterioration factors is:

- Damage and wear due to use and
- Environmental damage.

Damage and wear due to use e.g.:

- Fatigue
- Progressive cracking
- Wear due to i.e. studded tires (mainly affecting the insulation and surfacing)

can approximately be set in proportion to the amount of traffic e.g. the average traffic volume *ADT*.

The environmental damage can be subdivided into

- Physical deterioration,
- Chemical deterioration and
- Reinforcement corrosion

The physical deterioration is typically

- Frost spalling (in cracks)
- Repeated frost-thaw cycles and
- salt crystallization.

The climate conditions affecting the physical deterioration are mainly the number of frost cycles and the salting. In the northern and in the most southern part of Scandinavia the number of cycles is not so large, so the severity of the climate in relation to physical deterioration is greatest in the central parts of the Nordic countries.

The chemical deterioration is to a large extent dependent of the material properties, but some factors as

- Carbonization,
- Chloride ingress,
- Reinforcement corrosion

Are highly dependent on

- Moisture,
- Road salting and/or rain with high content of salt and
- High temperature

In summary, the following parameters can very approximately define the climate and the external conditions in relation to the external conditions. A default value of all parameters is 1,0 i.e.  $factor = 1$ . A  $factor > 1,0$  increases the time between repair actions, while a  $factor < 1$  reduces the time between repair actions.

**ADT:**

$ADT < 2000$	$factor_{ADT} = 1,1$
$2000 < ADT < 5000$	$factor_{ADT} = 1,0$
$ADT > 5000$	$factor_{ADT} = 0,9$

**Climate zone:**

Northern Sweden (ekvi.)	$factor_{ENV} = 1,1$
Central Sweden (ekvi.)	$factor_{ENV} = 1,0$
Southern Sweden (ekvi.)	$factor_{ENV} = 0,9$

**Salting:**

For roads with  $ADT > 10\ 000$  and where lots of salt is used a  $factor_L = 0,9$  can be applied.

In total  $factor = factor_{ADT} \cdot factor_{ENV} \cdot factor_L$ .

## 4. Program descriptions

### 4.1 LCC Stand-alone-Bridge-LCC program description

The program Bridge-stand-alone-LCC consists of seven Excel spread sheets containing the following items:

Info: This sheet is always displayed at start-up and contains general information about the programme, as well as some important advice and instructions.

General conditions: In this sheet the general information necessary for the LCC analysis is input.

Investment cost: In this sheet the estimated investment cost based on the specified quantities and prices of materials is calculated.

Operation & Inspection cost: In this sheet costs and intervals for operation & maintenance activities and associated traffic disturbance is input.

Repair cost: In this sheet costs and the intervals for repairs and associated traffic disturbance is inserted and calculated. The calculation of the weighted intervals between actions is based on previously entered information about traffic, salt amount, concrete quality, etc.

Results: in this sheet a compilation of LCC costs presented both as tables and diagrams

Data: This sheet contains important data the program uses during calculation. The user is not allowed to alter any of the cells in this sheet, why this sheet is not shown on start-up.

#### *Things to consider*

The user should consider the following points:

1. In order not to change the default settings and "default" values, always save the file Bridge-Stand-Alone-LCC.xls under a new name before making changes / input for a new project.
2. Cells that have a small red triangle in the upper right corner contain the help text. The text becomes visible by hovering over the box. To view the help text clearly you might need to choose a larger text using "ZOOM" on the Excel window.
3. Never feed a space in a non-current cell. Enter instead a 0 (i.e. the number zero).
4. Users can choose the subdivision of bridge parts and elements as desired by changing the text in each cell.
5. If no data is given for calculating the investment cost, the invest cost coming from i.e. an offered cost from a contractor (entered in the General Conditions) will be used for the calculation of the total LCC.
6. At program start "default"-values are given in the new invented currency CUR for unit cost and intervals between actions. The default values at program start are approximate current (2010) units costs where CUR = SEK. The values must for each case be adapted to the project at hand, see point 1.

7. Repair and maintenance cost may also include cost for replacement of structural elements.
8. Repair intervals entered will be adjusted depending on the concrete quality, ADT, climate zone, salt amount, location of the bridge, and concrete cover. Weighting is not done if you enter yourself exact year for repair instead of intervals.
9. Repair interval should be chosen to receive a maximum of about 3 - 4 large steps during the bridge life by at least 10 years apart.
10. Quantities specified for calculating the cost of repair need not be the same as investment quantities. E.g. you can choose to repair some of the concrete of the concrete slab superstructure instead of replacing the whole thing.
11. As road user cost the program includes only costs in the form of reduction in service benefits for as long as work is underway on the bridge and limited accessibility for the road users.
12. The LCC analysis should be done iteratively. Once the user has made the first run, the performance charts should be examined. The graphs show clearly the years, repairs and maintenance and also when these actions are carried out and their size. Users can thus be determined to manually move forward or backward in time to perform several actions at once. Remember, if necessary, also to change the number of days the road users are disturbed by the activity so these do not accidentally be added together and result in an overestimation of the road user costs. For example, if two activities are meant to be performed simultaneously only the activity with the longest duration gives any road user cost. This is of course depending on what activities are planned to be carried out and may not apply generally, therefore, the program do not make this correction automatically.

## **4.2 Principle design of the WebLCC program**

WebLCC is a program for doing Life Cycle Cost (LCC) calculations on the web. A LCC calculation summarizes all costs occurring during the intended life-span of a structure and recalculates these costs to a certain point in time, usually the time of inauguration of the structure using the net present value method. In the case of a bridge the LCC includes the construction, operation, repair work and the demolishing of the bridge at the end of the lifetime. The calculation also includes indirect costs for the road users due to traffic interruption during repair work.

WebLCC is sufficient general for making LCC analysis even for a small part of a large project. WebLCC also lets you in a simple and fast way to copy one project and use the data for i.e. comparing two different solutions for a bridge or a bridge part.

The WebLCC has many theoretical advantages, because all input is made dynamic, so there is no restrictions on how many inputs for actions that can be analysed.

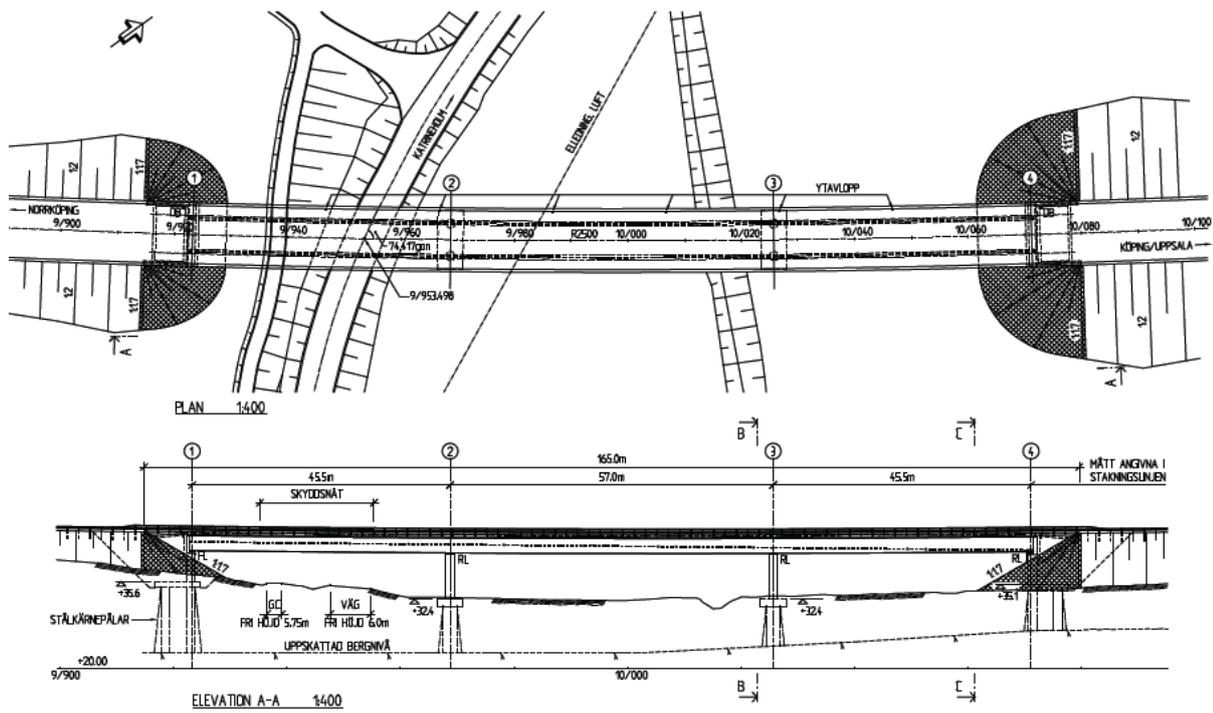
There are however many practical problems with systems where all calculations are made on a central server. Bad things can happen when the user input wrong type of letters or numbers leading the server to break down.

If this program should be used in the future a professional Web programmer must be involved – resource not available at the division of Structural Engineering at KTH. The program is more in detail described in *Salokangas L., (2009)*.

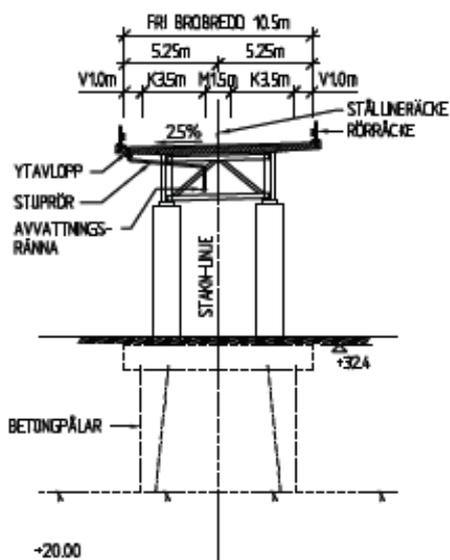
### 4.3 Case Study

To describe the use of the Bridge-Stand-Alone-LCC program, a case study is performed. This case study is also shown when you first open the program. Remember to save your program under a new name, see Section 4.1 point 1.

The bridge is depicted in **Figure 4.1** and **Figure 4.2**. The main properties of the bridge are compiled in the following section.



**Figure 4.1** Horizontal and vertical view of the studied bridge.



**Figure 4.2** Section of the studied bridge.

### 4.3.1 Input data:

Bridge Spans 45,5, 57,0 and 45,5, total bridge length incl. abutment structures 165,0 m. Length of the superstructure is  $2 \cdot 45,5 + 57 + 2 \cdot 0,6 = 149,2$  m

Bridge effective width is 10,5 m, total bridge width incl. edge beams 11,3 m, assuming that the edge beams have an area of  $0,4 \cdot 0,4 = 0,16 \text{ m}^2$ . Bridge area used for comparisons is  $149,2 \cdot 11,3 = 1686 \text{ m}^2$

Bridge quantities are calculated using a methodology presented in a Power Point File “The material quantities and cost models by studies of Heikki Rautakorpi”. The PP-file is partly based on Rautakorpi H., “Material Quantity and Cost Estimation Models for the Design of Highway Bridges”, *Acta Polytechnica Scandinavia – Civil Engineering and Building Construction Series*, No. 90, 1988. Some of the notations used are according to the Finnish system.

#### Quantities:

For a steel concrete composite bridge deck the following applies:

$$L_0 = \text{sum of bridge spans} = 148 \text{ m}$$

$$b = \text{effective width of bridge} = 10,5 \text{ m}$$

The quantity of concrete is

$$Q_c = bL_0(0,243 + 0,0072b + 0,7/L_0) = \\ 10,5 \cdot 148(0,243 + 0,0072 \cdot 10,5 + 0,7/148) \approx bL_0 0,32 = 502 \text{ m}^3$$

Formwork

$$Q_f = bL_0(0,93 + 2,17/b) = bL_0 \cdot 1,15 = 1781 \text{ m}^2$$

Reinforcement

$$Q_r = bL_0(53,6 + 1,59b) = bL_0 \cdot 71 \text{ kg/m}^2 = 110\,124 \text{ kg} = 219 \text{ kg/m}^3$$

Steel structure

$$Q_s = bL_0 \left( 31,3 + 286 \frac{h}{b} + 0,0914 \frac{l_e^2}{h} \right)$$

The designation stands for an “average” span length calculated using the formula

$$\frac{1}{L_0} \sum_{i=1}^n L_i^2, \text{ where the lengths of the spans are denoted } L_i \text{ and } n \text{ is the number of spans.}$$

The number of piles are also given in *Rautakorpi (1988)*, but are revised because of new higher allowed loads for piles.

### **4.3.2 Calculation of quantities and investment cost**

The formulas for calculation of quantities are presented in Section 4.2.1 are used and compiled in **Table 4.1** below.

The investment cost is based on a Design and build contract. The unit costs includes all costs of the main contractor (design, temporary, structures, machines, barracks, fee, unforeseen etc.) 62 % on subcontractors. Cost level February 2010.

Quantities using the formulas above are compiled in an Excel file, together with the cost calculation. The total cost/m<sup>2</sup> happens to be the current average cost for this kind of bridges in Sweden and if CUR = SEK, spring 2010 cost level.

**Table 4.1** Invest cost calculation for the example bridge.

Cost calculation, Steel composite bridge						
Design and build cost incl. all costs of the main contractor (design, temporary, structures, machines, barracks, fee, unforeseen m.m.) 62 % on subcontractors, Cost level February 2010						
Notations and calculation according to the Finnish system						
						Total quantities
Total length of superstructure	$L/m =$	149,2	$Q_c/bL_0 =$	0,32	$m^3/m^2$	502 $m^3$
Sum of spans (45,5, 57, 45,5)	$L_0/m =$	148	$Q_v/bL_0 =$	1,15	$m^2/m^2$	1 781 $m^2$
Bridge effective width	$b/m =$	10,5	$Q_a/bL_0 =$	71	$kg/m^2$	110 124 $kg$
Total bridge width incl. edge beams	$b_{tot}/m =$	11,3	$Q_s/bL_0 =$	194	$kg/m^2$	300 721 $kg$
Total bridge area ( $L \cdot b_{tot}$ )	$A_{calc}/m^2 =$	1686				
Equivalent average span	$l_e =$	49,9				
Height of steel beams ( $l_e/22$ )	$h =$	2,3				
Painted area steel beams	$A_{paint}/m^2 =$	6,9				1 033 $m^2$ , painting
			Concrete: $H_{med} =$	0,32	$m^3/m^2$	
			Reinforcement: $Q_a/bL/H_{med} =$	219	$kg/m^3$	
	Unit cost	Quantity	CUR	CUR/m <sup>2</sup>		
Bridge concrete incl temp control and after treatment	CUR/m <sup>3</sup>	4 000	502	2 009 818	1 192	
Reinforcement incl loss, bending and placing	CUR/kg	40	110124	4 404 966	2 613	
Formwork	CUR/m <sup>2</sup>	1 300	1781	2 314 913	1 373	
Railing/parapet	CUR/m	5 000	298	1 492 000	885	
Surfacing + insulation	CUR/m <sup>2</sup>	1 400	1567	2 193 240	1 301	
Expansion joints	CUR/m	20 000	23	452 000	268	
Bearings	CUR/no	26 000	8	208 000	123	
<b>Sum of bridge slab system</b>				<b>13 074 936</b>	<b>7 755</b>	
<b>Steel structure incl. painting and launching</b>	CUR/kg	55	300 721	<b>16 539 664</b>	<b>9 810</b>	
	Unit cost	Quantity	CUR	CUR/m <sup>2</sup>		
<b>Two Intermediate piers incl. foundation</b>						
Concrete columns	CUR/m <sup>3</sup>	4000	36	144 691	86	
Reinforcement	CUR/kg	40	4 522	180 864	107	
Formwork	CUR/m <sup>2</sup>	1300	121	156 749	93	
Foundation slab concrete	CUR/m <sup>3</sup>	4 000	158	630 000	374	
Reinforcement	CUR/kg	40	3 617	144 691	86	
Formwork	CUR/m <sup>2</sup>	700	158	110 250	65	
Number of piles per pier			43		0	
Piles	CUR/m	1 800	687	1 236 294	733	
<b>Sum intermediate piers</b>				<b>2 603 540</b>	<b>1 544</b>	
	Unit cost	Quantity	CUR	CUR/m <sup>2</sup>		
<b>Two abutments incl. foundation</b>						
Concrete front and wing walls and bridge seat	CUR/m <sup>3</sup>	4000	141	563 200	334	
Reinforcement	CUR/kg	40	21 120	844 800	501	
Formwork	CUR/m <sup>2</sup>	1300	128	166 400	99	
Foundation slab concrete	CUR/m <sup>3</sup>	4 000	158	630 000	374	
Reinforcement	CUR/kg	40	14 080	563 200	334	
Formwork	CUR/m <sup>2</sup>	700	158	110 250	65	
Number of piles per pier			49		0	
Piles	CUR/m	1 800	785	1 412 908	838	
<b>Sum intermediate piers</b>				<b>4 290 758</b>	<b>2 545</b>	
Excavation						
Backfilling						
<b>Total earthworks</b>				<b>1 000 000</b>		
					CUR/m <sup>2</sup>	
<b>Total cost</b>				<b>37 508 898</b>	<b>22 248</b>	

### 4.3.3 Life cycle cost calculation

Based on the quantities given in Section 4.2.2 using a simplified Excel scheme a LCC calculation is shown below. The interest rate is 3 %.

**Table 3.2** Calculation of life cycle cost.

Example: Steel Concrete composite bridge

<b>Input data</b>	Bridge length L =	149,2	
	Bridge effective width b =	10,5	
	Bridge total width =	11,3	
	Exposed area of each edge beam /m <sup>2</sup> /m =	1,4	The edge beams are assumed to have an exposed area of 400+400+400+200/each
	Total bridge area /m <sup>2</sup> =	1 686	
	Area of surfacing /m <sup>2</sup> =	1 567	
	Painted area steel beams /m <sup>2</sup> /m =	6,9	
	Life span /a =	100	
	Calculation interest rate /% =	3	
	Investment cost /CUR =	37 508 898	

LCC Periodic activities	Cost	is performed every	0,03	Help parameters		
				n/p	shortened	m <sup>2</sup> p
Management + Operation 0,3 %	112 527	1	3 549 865	99,00	99,00	99
Careful inspection 100 CUR/m <sup>2</sup>	168 600	6	808 082	16,50	15,00	90
Impregnation of edge beams	125 328	10	330 168	9,90	8,00	80
Demolition 10 %	3 750 890	100	195 169	1,00	1	100
<b>Sum LCC cost</b>			<b>4 883 284</b>			

LCC Repair and replacements	Cost year 0	Quantity	Cost year 0	Year						Sum	
				13	25	37	50	63	75		88
Edge beam, rep 0 - 30 mm/m <sup>2</sup>	3 000	417,8	1 253 280		598 574			194 672		793 245	
Edge beam replacement/m	9 000	298,4	2 685 600				612 604		199 235	811 839	
Parapets touch-up painting/m	1 100	298,4	328 240	223 515		109 955		50 985	24 351	408 807	
Parapets replacement	5 000	298,4	1 492 000				340 336			340 336	
Surfacing wearing course adjusting/m <sup>2</sup>	400	1566,6	626 640	426 711				97 336		524 047	
Surfacing + insulation replacement/m <sup>2</sup>	2 400	1566,6	3 759 840			1 259 482		409 617		1 669 099	
Expansion joint replacement/m	30 000	22,6	678 000			227 118			50 298	277 417	
Expansion joint replacement of rubber sealing/m	3 000	22,6	67 800	46 169		22 712		10 531	5 030	84 442	
Bearings minor repair + painting/no	7 000	8,0	56 000			18 759		6 101		24 860	
Bearings replacement/no	35 000	8,0	280 000				63 870			63 870	
Columns, repair 0 - 30 mm/m <sup>2</sup>	4 000	120,6	482 304				110 017			110 017	
Front and wing walls repair 0 - 30 mm/m <sup>2</sup>	4 000	157,5	630 000				143 707			143 707	
Steel touch-up patch painting 20 %	500	1032,8	516 396		246 634			56 259		302 892	
Steel re-painting	2 500	1032,8	2 581 979				588 968			588 968	
				696 395	845 207	1 638 026	1 859 502	353 524	471 976	278 914	6 143 546
Investment	37 508 898		77%	<b>Total:</b>						<b>6 143 546</b>	
Periodic activities	4 883 284		10%								
Repair and replacements	6 143 546		13%								
<b>Total LCC:</b>	<b>48 535 728</b>		<b>100%</b>								

This excel program gives the result

Investment: CUR 37 509 000  
 Periodic actions: CUR 4 883 000 (includes final demolition)  
Repair/replacement: CUR 6 144 000  
 LCC: CUR 48 536 000

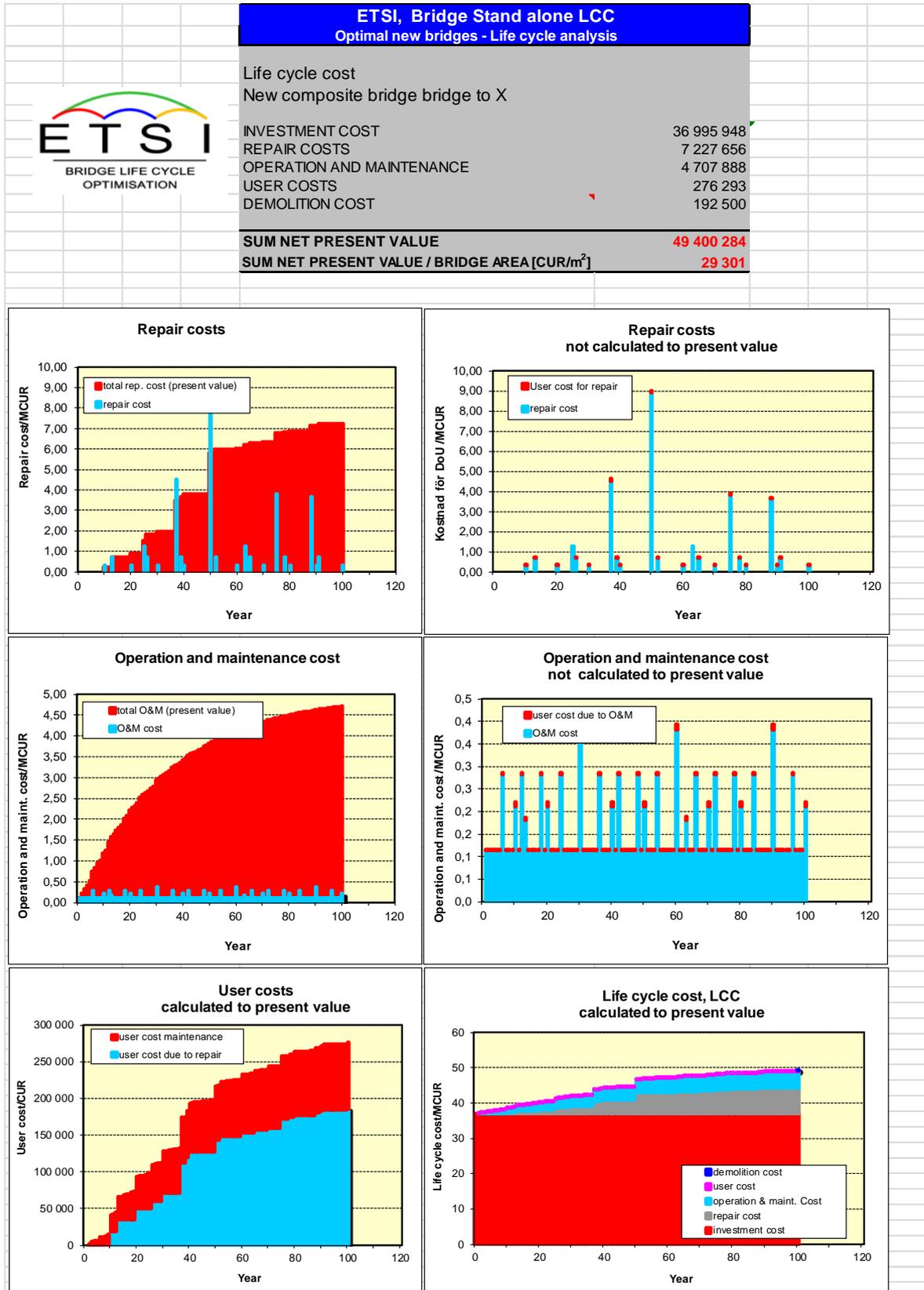
Using the Stand-alone-Bridge\_LCC tool

Investment: CUR 36 995 948  
 Periodic actions: CUR 4 681 757  
 Repair/replacement: CUR 6 889 933  
Demolition: CUR 192 500  
 LCC: CUR 48 693 233

The difference between the two results is due to a difference in definition of actions and a difference in definition of measures. The LCC Stand-alone Excel program calculates also the

user costs, which however is not paid much attention in this example. The result is also presented in diagrams, see **Figure 4.3** below.

**Figure 4.3** Presentation of LCC results from the Stand-alone-Bridge-LCC program.



## 5. Discussion and proposal for future work

Making LCC calculations are a guess work on the future, and the only thing we really know about the future is that we don't know anything. The big problem is guessing the degradation of the structures and thus the time between maintenance and repair actions. We must also guess rates of interest and inflation in the future. Looking in the rear-view mirror, we know that rates have changed dramatically over time. A good thing is though that the authorities in many cases have decided what rates to be used, but a discussion on this matter is Section 2.8.

Another factor of great importance is the structural degradation rates. An enormous amount of research has been devoted to physical and chemical degradation of concrete and steel structures. Especially the ingress of chlorides and moisture and the following possible corrosion of the reinforcement has been studied for years, but the results is difficult to use as a prognosis for the needed maintenance and repair actions in the future. In the ETSI I report, *Jutila A., & Sundquist H., (2007)*, a methodology based on Markov Chains in turn developed by Vesikari (2003) was presented. The input for this method is however complicated and with simple use it gave the wrong kind of curvature for the degradation curve.

As usual when guessing the future we have to use history and use regression analysis based on this data. A problem is however to find the historical data. A promising methodology for finding maintenance and repair historical data is to use the databases built up by the transport administrations. On-going research at the division of Structural Engineering and Bridges at KTH is by using historical data from the database BaTMan developed by the Swedish Transport Administration to predict future maintenance and repair actions and their associated cost. The costs in this database are calculated to current costs by the net present value method and should thus be rather reliable. For more information about these methods see *Safi et al. (2012a)* and *Safi et al. (2012b)*.

Another maybe very good method is to collect data from LCC calculations made by experienced specialists on bridge element degradation and maintenance. This was an idea included in the WebLCC program, because all data was stored in a database coupled to this program. If in the future the WebLCC program is developed for better stability, this feature can be used for "research".

After the research and development within the ETSI project, knowledge on LCC, LCA and "LCE" has been deepened, at least among the people involved in the three ETSI Stages. The next step is to bring the concepts and tools out in the practice. This will probably take a lot of effort, because the ideas on life cycle issues are not common practice among bridge engineers to-day. Probably the practical process of using LCC and LCA will influence the design of the tools, and new and better systems will be developed. Probably special tools will be developed for different purposes and for different stages in the design process for bridges, see e.g. *Safi et al. (2012a)*.

## 6. Literature

This literature list below refers mainly to bridge LCC studies. A more and complete general references to Bridge management systems, maintenance and management are given in *Jutila & Sundquist (2007)*, ETSI Stage 1 report and to *Salokangas (2009)*, ETSI Stage 2 report.

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