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Aalto University

Department of Civil and Structural Engineering

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Bridge Life Cycle Optimisation Stage 3

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Preface

We have now finished the third part of inter Nordic project ETSI (life cycle conscious bridge) and have finally reached working tools and methods described in this report to evaluate and compare different life cycle issues of a bridge design.

ETSI was started in 2004 by Finnish, Norwegian and Swedish road authorities together with technical universities from Helsinki (TKK/Aalto University), Stockholm (KTH) and Trondheim (NTNU). Denmark joined in the project at Stage three with Danish Road Authority and consultant company COWI.

Life cycle issues of a bridge are numerous and in this project we concentrated on a new bridge and its life cycle costs (LCC), environmental impacts (LCA) and cultural values (LCE). Issues related to existing bridges are very important as well as safety features of a bridge, but they were left for the future projects. These tools and methods are discussed in detail in the following chapters and here I try to give a general view of the process and its applications.

Figure 1. ETSI provides tools to evaluate different aspects of life cycle. The best compromise is left to be done manually by owner or designer

The very heart of this new methodology is the *Life Cycle Plan* bridge designer adds to his bridge plan. This is sort of a maintenance plan where bridge designer plans the maintenance actions during the bridge's service life, i.e. interval of the actions, what is done and how much traffic disturbance is caused during maintenance works.

Life cycle plan is based on *standardized data base* maintained by the whole industry and distributed by road authorities. From this data base bridge designer finds the life cycle values of different bridge parts. For example an edge beam made from this grade of concrete with this kind of surface treatment in this environment must be overhauled every 10 years and replaced every 40 years and the costs and maintenance times are like this.

From this life cycle plan**,** *comparable* life cycle costs and environmental burden may be calculated.

Life cycle tool LCC is calculating the present value of future actions and maintenance and traffic disturbance are taken from the maintenance plan. The program is very flexible, interest rate may be varied and actions may be inputted in various ways and also the investment cost may be calculated.

Life cycle assessment tool LCA is calculating several values of environmental impact like toxicity, global warming, etc. from the on life cycle plan and bills of quantities. Values for major materials like steel and concrete are taken from the standardized data base and minor materials directly from Ecoinvent. These environmental impact factors may be combined to one factor once the national weighting factors are determined.

The third part in the compromise is the cultural value of a bridge, LCE. To be able to evaluate and compare aesthetical values of different bridge alternatives, we have developed tools and methods to calculate an aesthetical factor of a bridge. With this factor aesthetical values may be connected to cost comparison.

Bridge designer may apply these tools and methods in search of the best alternative and to show to the client the benefits of his design. Client's applications might guide the design process and set targets for design. The life cycle plan might also be used in maintenance planning but its major role is to make LCC and LCA calculations possible. It is also aiding to a more life cycle aware design culture as the maintenance becomes an integral part of the design.

Perhaps the very key in this project though is to be able to use these tools and methods in procurement of design and construction. Possibility to compare life cycle issues instead of just looking at the investment phase truly opens vast possibilities for new innovations in bridges.

Matti Piispanen

Finnish Transport Agency
Chairman of the ETSI Project Steering Group

ETSI Project Stage 3

ETSI Project Stage 3 was a co-operation project between four Nordic countries as Denmark decided to join in. The two new members in the Project organization were the Danish Road Directory and COWI Consult.

Four national Road Authorities were the main financing units for the ETSI Project Stage 3. The funding between Nordic Road Authorities was organised by NordFou. Aalto University acted as a coordinator between the universities and companies.

The project plan was established and most agreements were signed so that the Stage 3 could start on the first of June 2009. The project was designed to finish in the end of the year 2011 and last altogether 31 months. However, the Project delayed and the final seminar to conclude the Project was decided to arrange on May 14-15 2012 in Malmö. So the total duration of the ETSI Project Stage 3 was approximately three years.

Besides the Road Authorities, the following universities and enterprises were involved in the ETSI Project Stage 3:

Aalto University
Norwegian University of Science and Technology NTNU
Royal Institute of Technology KTH
COWI Consult Denmark
WSP Finland
Extraplan Oy
VR Track Oy

Persons who deeply influenced to the success of the ETSI Project Stage 3 were:

Helge Brattebø	*Norwegian University of Science and Technology NTNU*
Birit Buhr Jensen	*COWI Consult Denmark*
Kirsten Erikssen	*COWI Consult Denmark*
Johanne Hammervold	*Norwegian University of Science and Technology NTNU*
Carsten Henrikssen	*Danish Road Directorate*
Marianne Hvaal Larsen	*Norwegian Public Road Administration*
Linda Høibye,	*COWI Consult Denmark*
Aarne Jutila	*Extraplan Oy*
Raid Karoumi	*Royal Institute of Technology KTH*
Risto Kiviluoma	*WSP Finland*
Otto Kleppe	*Norwegian National Road Administration*
Riku Kytö	*VR Track Oy*
Iben Maag	*Danish Road Directorate*
Anne Nieminen	*Aalto University*
Yishu Niu	*Aalto University*
Sami Noponen	*Aalto University*
Matti Piispanen	*Finnish Transport Agency*
George Racutanu	*Swedish Transport Administration*
Marte Reenaas	*Norwegian University of Science and Technology NTNU*
Mohammed Safi	*Royal Institute of Technology KTH*
Lauri Salokangas	*Aalto University*
Håkan Sundquist	*Royal Institute of Technology KTH*

Timo Tirkkonen *Finnish Transport Agency*
Minna Torkkeli *Finnish Transport Agency*

Project Leader during ETSI Stage 3 was *Lauri Salokangas* from Aalto University. As the Chair of the Project Steering Group (PSG) during the ETSI Stage 3 has been *Matti Piispanen* from Finnish Transport Agency. The Project Steering Group held ten meetings before the Final Seminar in Malmö in May 2012. The practical work in the project was divided into five groups, named Task Groups. The duties, the leaders and persons in charge of the Task Groups were:

- *TG 1: Testing of the developed tools* — *Lauri Salokangas, Birit Buhr Jensen*
- *TG 2: Establishing the data base* — *Minna Torkkeli, Timo Tirkkonen*
- *TG 3: Updating and completing LCC tool* — *Håkan Sundquist, George Racutanu*
- *TG 4: Updating and Completing LCA tool* — *Helge Brattebø, Otto Kleppe*
- *TG 5: Implementing ETSI Tools* — *Matti Piispanen, Lauri Salokangas*

Project home pages have been kept up in the Internet on Aalto University's web server and can be found from address: etsi.aalto.fi. The tools are available on home pages as well as this Project Report and the two earlier ETSI reports from stages 1 and 2.

Current report is divided into five chapters and appendices. Chapter 1 is a short introduction of the ingredients. Chapter 2 deals with LCC methodology and introduces the updated LCC tool, which was developed by *Håkan Sundquist* and *Raid Karoumi*. Chapter 3 introduces the methodology how the environmental impacts of bridges can be taken into account and the updated application tool, *BridgeLCA* is presented. It is written by *Helge Brattebø* assisted by *Johanne Hammervold* and *Marte Reenaas.* Chapter 4 introduces a computer program for evaluation of bridge aesthetics written by *Aarne Jutila* and *Yishu Niu.* Chapter 5 contains an example application of LCC and LCA for a real concrete motorway bridge project and is a part of "Demonstration Report" authored by *Birit Buhr Jensen* and the workgroup at COWI Denmark. Appendix A includes five abstracts of the academic studies completed during the Project's Stage 3.

Thanks to all those who wrote and sent literal material for this project report. The original manuscripts of the chapters 2-5 can be found on ETSI home page. Some editorial amendments were made in the originals to make the printed report more readable and uniform. Thanks belong to *Yishu Niu*, who assisted in editing this report into its final form.

The success of the project is also due to the high level presentations of the speakers in the Final Seminar in Malmö. Special thanks must be targeted to two excellent keynote lecturers: *Anne M. Benzon* from COWI Denmark and *Pekka Vuorinen* from the Finnish Association of Construction Product Industries. Presentations of the Final Seminar are available on ETSI home pages.

Finally, thanks belong to all persons who contributed ETSI Project Stage 3 to reach its goal. It is always a pleasure to collaborate with Nordic colleagues in a common Nordic Project. The tools for the life cycle analysis of the bridges are now available, but the feedback is still needed. The next steps are to disseminate the ETSI knowledge, use the tools in pilot projects and gradually take them into practical use.

Lauri Salokangas

Aalto University
ETSI Stage 3 Project Leader
Editor

Contents

Notations and Symbols

Acronyms and abbreviations

AAB	The Road Directorate's general specifications for concrete works
ADP	Abiotic Depletion Potential
ADT	Average Daily Traffic [vehicle/day]
AP	Acidification Potential
BaTMan	The Swedish bridge and tunnel management system
BridgeLCA	Name of the LCA tool for environmental life cycle assessment of road bridges
BLCCA	Bridge Life-Cycle Cost Analysis
BMS	Bridge Management System
CC	Condition class
CUR	A general notation for currency
DANBRO	Danish Codes for Bridges
DKK	Danish currency
ECC	Engineered Cementitious Composites
EIA	Environmental Impact Assessment
EN	European standards
EOL	End of Life
EP	Eutrophication Potential
EPD	Environmental Product Declarations
ET	Ecotoxicity Potential
ETSI	Bridge Life-cycle Optimisation
FD	Fossil Depletion potential
GHG	Greenhouse Gas
GWP	Global Warming Potential
HTC	Human Toxicity potential – Cancer
HTNC	Human Toxicity potential – Non Cancer
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCE	Life Cycle AEsthetics
LCI	Life Cycle Inventory

LCIA	Life Cycle Impact Assessment
LCP	Life Cycle Plan
MR&R	Maintenance, Repair & Rehabilitation
ODP	Ozone Depletion Potential
O&M	Operation and Maintenance
OR&M	Operation, Repair & Maintenance
PCR	Product Category Rules
POCP	Ground level Ozone-Creating Potential
POP	Photochemical Oxidation Potential
RPM	Rotation per Minute
SEK	Swedish currency
TrV	Trafikverket, the Swedish Transport Administration
VD	Danish Road Directorate (Vejdirektoratet)
WebHybris	Software navigation tool that can access BaTMan database
WLC	Whole-Life Costing
Class I, II ...	Classification categories for bridge site

Upper case roman letters (quantities)

ADT_t	The average daily traffic, measured in numbers of cars per day at time t
$A_{L,r}$	Annuity factor
A_n	The normal accident rate per kilometre
A_r	The accident rate during the roadwork
C	The sum of the time for one red and one green light in one direction
C25	Concrete type with 25MPa cylinder strength
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]

C_{LCC} Life cycle cost

C_{LCA} Environmental value

C_{total} Total cost used in Bridge Life-cycle optimization calculation [CUR]

EAC Equivalent Annual Cost [CUR]

I The traffic intensity per direction

L Service life-span in years [a],
The length of affected roadway on which cars drive [km]

LCC Life-cycle cost [CUR]

LCI Life-cycle income [CUR]

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 The length of affected roadway on which cars drive due to MR&R actions

S_{Detour} Detour length [m]

T Time period studied in years [a]. Usually the life-span (L) of the bridge

WLC Whole life cost [CUR]

Lower case roman letters (quantities)

a One year

a Scaling factor

b The average time for finishing one vehicle (usually 2 s/vehicle-unit)

c_{jk} Characterisation factor for substance j with respect to impact category k

d_k Total potential impact in environmental category k

e_{ij} Amount of substance or stressor j (e.g. CH_4, in kg) caused by the total consumption of input resource i (e.g. concrete)

f_{ij} Emission of substance j per unit of resource i (e.g. kg CH_4 per kg concrete)

Δl The difference between the original distance and the alternative route [km]

l_r The distance of the alternative route (diversion) [km]

l_n The distance of the original route [km]

k_{rel} Reduction coefficient

m_k	Per capita normalised potential impact of environmental category k
n_k	Normalisation factor for category k
o_D	Average hourly operating cost for one passenger car [CUR/h]
o_G	Average hourly operating cost for transported goods [CUR/h]
o_{L}	Average hourly operating cost for one commercial traffic vehicle [CUR/h]
p_i	Grading point for item i
p_{L}	The amount of commercial traffic [%]
q_L	The cost for commercial traffic [DKK/km]
q_D	The cost for cars [DKK/km]
r	Real interest rate [%] or The time when the traffic light is red
r_{i}	Inflation rate [%]
r_{L}	Discount rate [%] for loans with long duration
r_{TG}	Traffic growth rate [%]
t	Time in years [a]
v	Weighted single score LCA result
v_{n}	Normal traffic speed [km/h]
v_{r}	Traffic speed during bridge work activity [km/h]
w_i	Weight factor for item i
w_k	Weighting factor of environmental impact category k
w_{D}	Hourly time value for one passenger car [CUR/h]
w_{L}	Hourly time value for one truck [CUR/h]
x_i	Consumption of resource i (concrete, in kg)

1 Introduction

The main goal at the start of ETSI Project Stage 3 was to develop practical tools by which the designers, contractors or authorities etc. can compare different solutions in life cycle sense. It can be said, that the goal has been reached. In this report three standalone computer programs are introduced. The theory, background and user instructions are given separately for each program in next Chapters 2-4.

The LCC(Life Cycle Cost) tool developed is an Excel based individual program, which covers the calculation of the total costs of the bridge during its service life, including the direct construction costs and the costs of operation, maintenance and repair. Besides, one can also take account so called indirect user costs, which are caused by traffic delays or disturbance, for example. The methodology and the theory behind the LCC tool with many examples are explained in detail in Chapter 2.

New refined LCA(Life Cycle Assessment) tool is an Excel based individual program by which it is possible to calculate the total energy consumption, the carbon oxide emission, the ozone depletion, the acidification and many more harmful emissions to the environment during the service life of the bridge. Significant progress in proposing international standardized methods in LCA field has been going on during the last few years. The developed LCA tool takes the advantage of latest state-of-the-art of LCA methodology. An overview of the theory, methodology, references to LCA studies on bridges and the introduction of the program itself, BridgeLCA, can be found in Chapter 3.

The methodology for evaluating aesthetics and cultural values of a new bridge project was first presented during the ETSI Project Stage 2. The methodology was refined and new Excel based individual program is introduced in Chapter 4. Using developed tool the aesthetical values can be related to the bridge life cycle costs. This is done by determining a single coefficient, which depends on parameters as: class of the bridge site, weights and points given to the selected parts of the bridge by the aesthetic evaluators. Detailed application example is included. The program is used for the evaluation of the aesthetics of bridge design competition proposals.

The Chapter 5 is a review of the applicability of the developed LCC and LCA tools. The ETSI tools are applied to calculate life cycle costs and life cycle environmental burden caused by the construction of two-span, six lane concrete motorway bridge in a bridge project in Denmark. The input values needed in calculations are explained and especially material data for concrete is considered. The effect of different traffic models to the results are examined in Danish circumstances. The results from LCC and LCA calculations are presented in graphical form. Suggestions for the application of ETSI tools in different phases of bridge design are given. General and detailed recommendations are listed for the future development of the tools.

Chapter 6 gives short conclusion and considers future development of ETSI tools.

The Appendices contains five abstracts (A1 – A5) of academic studies and works completed during ETSI Stage 3. In abstract A1 the ETSI Tools were applied to large seven-span steel-concrete composite bridge. The results of the LCC and LCA calculations, determined in construction phase, were compared to the earlier results, obtained in the design phase of the bridge. Abstract A2 deals with concepts of structural database and life cycle plan. By using the database the designer can optimise between different structural solutions and by using life cycle plan he can organise repair actions at optimum time interval. Abstract A3 considers the expected repair intervals of structural parts of a bridge and Abstract A4 life cycle cost calculations of concrete bridge deck surface structures. Abstract A5 introduces general applications of LCC calculations for short-span bridges.

2 Life Cycle Cost Methodology and LCC Tools

2.1 What is Bridge Life Cycle Costing

2.1.1 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 using as little of not renewable material resources as possible. Very important values are also all kinds of traffic security issues. Other "values" could be aesthetical 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 at the early design stage.

2.1.2 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. It means that, at least for individual bridges, the LCC can be seen as a tool within the BMS and 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 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 constrains on the available resources for 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 to be built unless it contributes to the social and economic development of the society.

2.1.3 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 of the program with more functionality will be discussed later as well.

2.1.4 How to use the LCC tools

The LCC tools are intended to be a part of the design process of bridges. The definitions, notations, "ETSI-definitions" 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" 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. Moreover, the plan can contain different options like variation of interest rate, use of different material qualities etc. The LCC tool is then used for getting economical information on the options. Since the entity consistency of LCP and LCC is a prognosis of the future, no exact values are expected, thus the LCC tools are mainly intended to use for comparison of different designs.

2.2 Methodology for LCC calculation analysis

2.2.1 The idea behind Life Cycle Cost

The classical task for the Bridge Engineer is to find a design giving the lowest investment cost for the bridge, taking the functional demands into consideration. This process is shown in *Fig. 2.1* schematically.

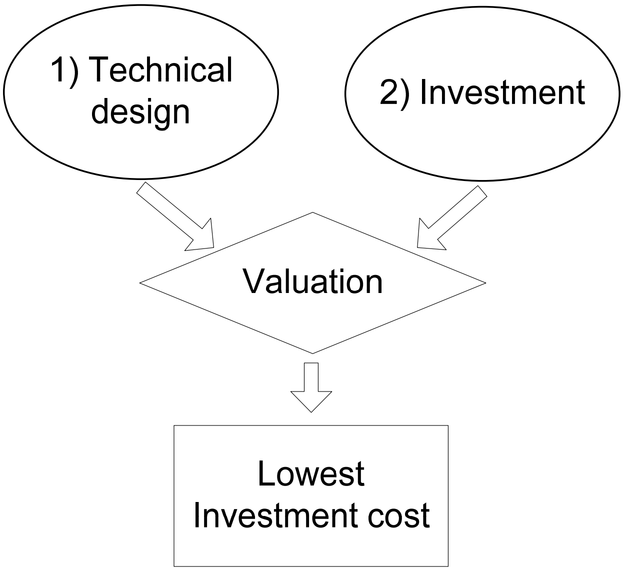

Figure 2.1. The classical task for the bridge engineer is to find the design giving the lowest investment cost for the bridge.

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

A comprehensive definition of 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. 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.

To make 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 divided into separate parts (*Table 2.1*).
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.
4. Time for interventions and incidents during the life-time of the bridge.

Item 4 is the most complicated in LCC calculation, since it must be based on known future events and behaviour of the bridge. These things can be found in *Jutila A., & Sundquist H. (*2007). In this report it is assumed that the time between different maintenance and repair actions is decided by the user of the system.

2.2.2 Basic calculation methods for LCC

The different contributions in a complete LCC analysis of a structure could be divided into parts, mainly because that the different bodies in the society will be responsible for the costs caused by constructing or using the structures. There are many reports in this field i.e. *Burley Rigden* (1997), *Hawk* (1998), *Siemens* et al. (1985), *Veshosky D., Beidlenan C.* (1992). The following presentation follows *Troive* (1998). 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. Different parts of the LCC calculation are shown in *Fig. 2.2*.

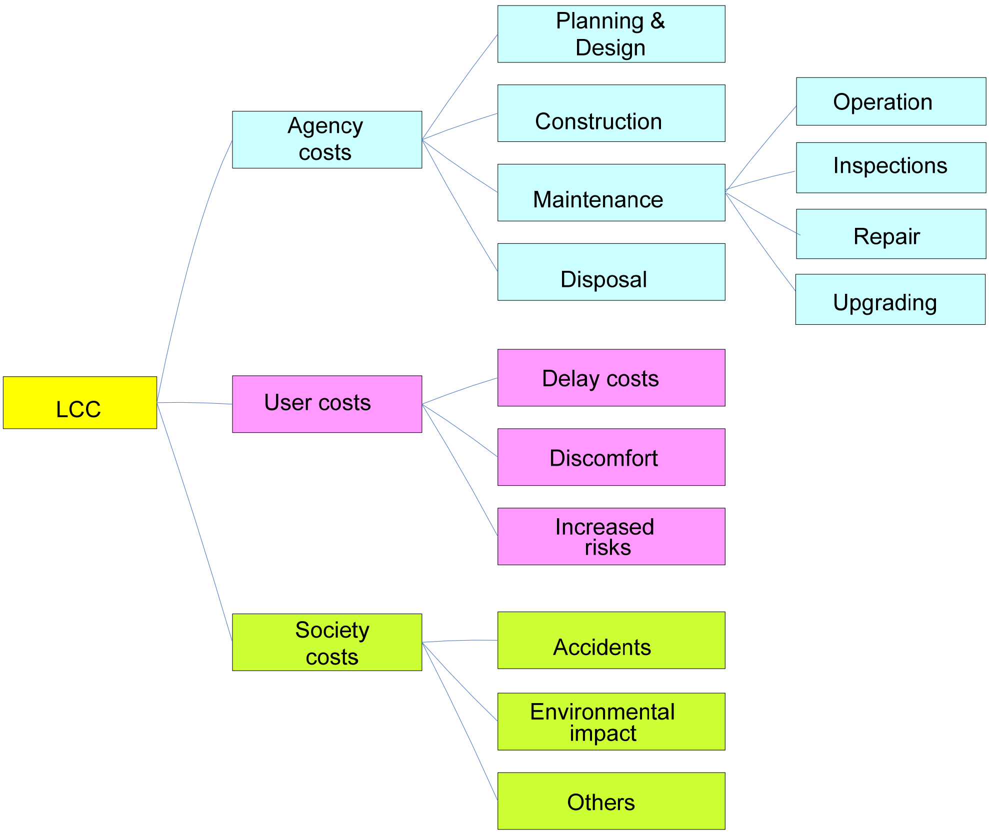

Figure 2.2. Schematic presentation of the different items in a complete LCC analysis.

The owner - or in the case of an Agency like a Road or Railway Administration - takes the responsibility for investments, operation and MR&R costs. The user is the one who gains the benefit of the road system and thus the bridges, but 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 malfunction. The income for the society of the road and thus the bridge could be called as 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 times of LCC, see Section 2.2.7.

It is 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, though seemingly illogical, only the user costs will be included in the analysis. The society cost will only be included regarding accidents due to structural malfunction.

2.2.3 Agency costs

LCC_{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

$$LCC_{\text{agency}} = LCC_{\text{acquisition}} + LCC_{\text{MR\&R}} + LCC_{\text{consequence}} \quad , \tag{2.1}$$

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 using 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 using the net present value at a specified time.

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

LCC_{society} is the future costs for possible negative consequences for the society, by using the net present value at a specified time.

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

$$LCC_{\text{MR\&R}} = C_{\text{equipment}} + LCC_{\text{MR\&R,future}} \tag{2.2}$$

where

$C_{\text{equipment}}$ (CI) is the investment cost 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 using the net present value at a specified time (usually the opening of the bridge).

The investment cost of the maintenance, $C_{\text{equipment}}$ could be divided according to

$$C_{\text{equipment}} = C_{\text{spare parts}} + C_{\text{tools}} + C_{\text{documentation}} + C_{\text{training}} \tag{2.3}$$

where

$C_{\text{spare parts}}$ is cost of spare parts and material,

C_{tools} is cost of instrument, tools, vehicles that is needed for inspection and maintenance,

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

C_{training} is cost of employment and education of personnel for operation and maintenance.

Usually the $C_{\text{equipment}}$ costs for a bridge are small and mostly cannot be coupled with a specific bridge. The agency costs 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 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

$$LCC_{\text{agency}} = \sum_{t=0}^{T} \frac{C_{\text{t}}}{(1+r)^t} \tag{2.4}$$

where

C_t is the sum of all costs incurred at time *t*,

r is 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.

Eq. (2.4) is schematically visualised in *Fig. 2.3*.

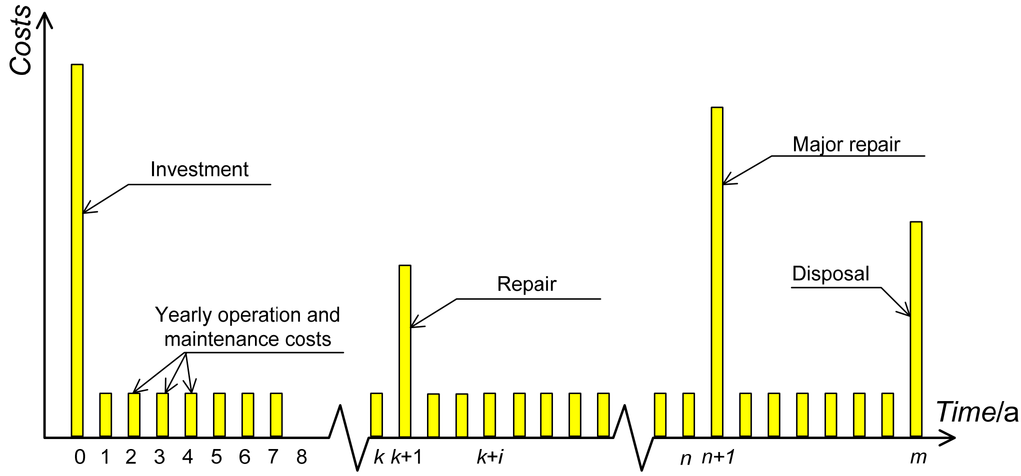

Figure 2.3. Schematical representation of agency costs for a bridge. The costs in this figure are not recalculated using the present value method.

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 LCC_{net} annuity factor $A_{L,r}$ in Eq. (2.5) :

$$EAC = LCC_{net} \cdot A_{L,r} = LCC_{net} \frac{r}{1-(1+r)^{-L}} \tag{2.5}$$

In an optimisation context the task which takes only the agency costs into consideration, is to design a bridge to find the lowest Life-cycle cost. This phase of the LCC optimisation is visualised in

Fig. 2.4.

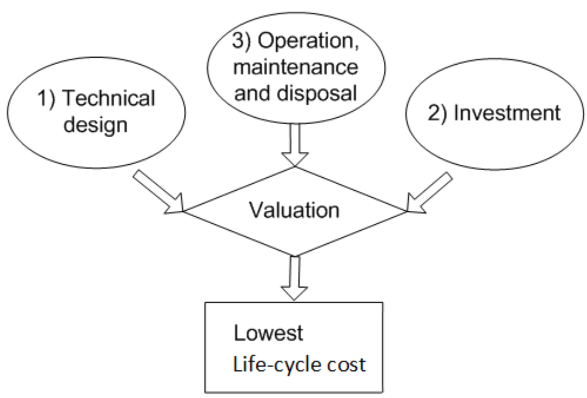

Figure 2.4. The figure shows schematically the costs taken into consideration in a classic LCC analysis not including society and user costs.

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. Another uncertainty 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 seem not to be feasible at this stage. However, combination of historical data with *Markov-chain methodology* seems to be feasible, if enough data is available.

2.2.4 User costs

User costs (LCC_{user}) are typically costs for drivers, cars and transported goods on or under the bridge due to delays caused by the 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, since they are better related to the bridge itself.

Driver delay cost is the cost for the drivers who are delayed due to the roadwork. Vehicle operating cost is capital cost for the vehicles, which are delayed due to the roadwork. Cost for goods is all kinds of costs for delay of delivering. Other user costs might be cost of damage to the vehicles and humans due to the roadwork, which are not included in the cost for the society. Travel delay costs can be computed by

$$LCC_{\text{user,delay}} = \sum_{t=0}^{T} \left(\frac{S}{v_{\text{r}}} - \frac{S}{v_{\text{n}}} \right) ADT_t \cdot N_t \left(p_{\text{L}} w_{\text{L}} + (1 - p_{\text{L}}) w_{\text{D}} \right) \frac{1}{(1+r)^t} \tag{2.6}$$

where

S	is the length of affected roadway on which cars drive due to MR&R actions,
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 the 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 by

$$LCC_{\text{user,operating}} = \sum_{t=0}^{T} \left(\frac{L}{v_{\text{r}}} - \frac{L}{v_{\text{n}}} \right) ADT_t \cdot N_t \left(p_{\text{L}} (o_{\text{L}} + o_{\text{G}}) + (1 - p_{\text{L}}) o_{\text{D}} \right) \frac{1}{(1+r)^t} \tag{2.7}$$

In Eq. (2.7) the same parameters are used as in Eq. (2.6) except for

L is the length of affected roadway on which cars drive,

o_{L} is average hourly operating cost for one commercial traffic vehicle,

o_{G} is average hourly operating cost for transported goods and

o_{D} is average hourly operating cost for one passenger car.

The costs should be calculated to the present value and added up for all foreseen maintenance and repair work for the studied time interval T.

There might be an accident cost due to the roadwork for the user, which is not included in the cost for the society. Eq. (2.6) could be used also for including the accident cost by merely adjusting the cost parameter.

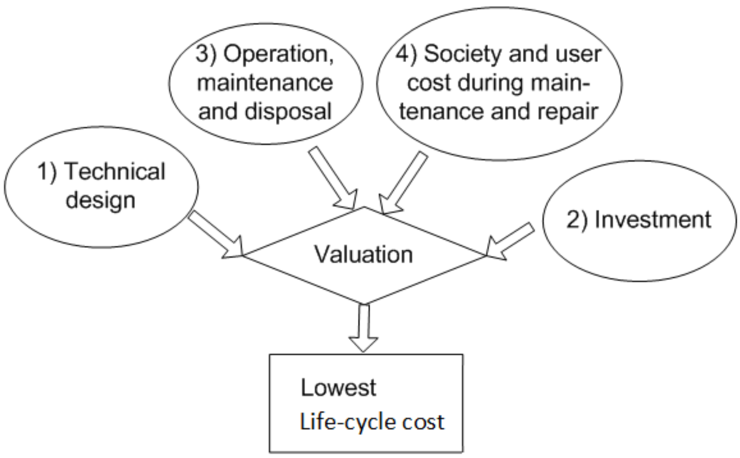

Figure 2.5. The figure shows schematically the costs taken into consideration in a classic LCC analysis for including society and user costs.

2.2.5 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 caused by traffic accidents.

Most construction materials consume energy for production and transportation. One possibility to take this into account is to multiply all costs for materials of construction and repair with some factors due to energy consumption of 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 are probably real, but only in case when two different types of bridges are mutually compared and the risks for accidents differ between them. The accident costs can be caused by the roadwork and calculated by

$$LCC_{\text{society, accident}} = \sum_{t=0}^{T} \left(A_{\text{r}} - A_{\text{n}} \right) ADT_t \cdot N_t \cdot C_{\text{acc}} \frac{1}{(1+r)^t} \tag{2.8}$$

where

A_{n}	is the normal accident rate per kilometre,
A_{r}	is the accident rate during the roadwork,
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 Transport Administration uses a cost of about 3 million US dollars for deaths and a third of this sum for serious accidents.

2.2.6 Failure costs

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

$$LCC_{\text{failure}} = \sum_{j=1}^{n} K_{\text{H},j} R_j \frac{1}{\left(1+r\right)^j} \tag{2.9}$$

where 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. How the cost for serviceability limit failure can be taken into account is discussed in *Radojičić* (1999).

2.2.7 Comparing cost and benefit, Whole Life Costing (WLC)

Bridge is built because the project is considered beneficial to the society. The income for the society of the bridge could be called LCI (Life Cycle Income) and certainly should be greater than the total Life-cycle cost, shown in *Fig. 2.6*. However, calculation of the LCI is not a part of this project.

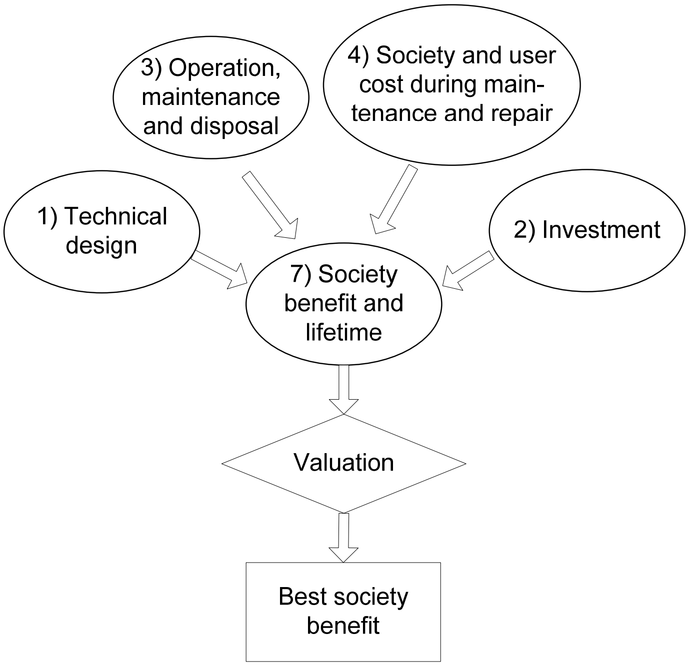

Figure 2.6. A total cost benefit analysis shall certainly include both the total cost and the benefit for the society as well.

2.2.8 Interest rate

The most important factor in Eq. (2.4) is the interest rate *r*, besides the costs. The real interest rate is usually calculated as the difference between the current discount rate for long loans and the inflation or more exact as

$$r = \frac{r_L - r_i}{1 + r_i} \tag{2.10}$$

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 (taking the uncertainties into consideration) is 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 (*Fig. 2.7*). This fact shows a decrease in the productivity, which also can be explained by stricter rules for safety measures that must be applied at the construction sites. This is applicable for maintenance and repair work on existing structures along the roads as well.

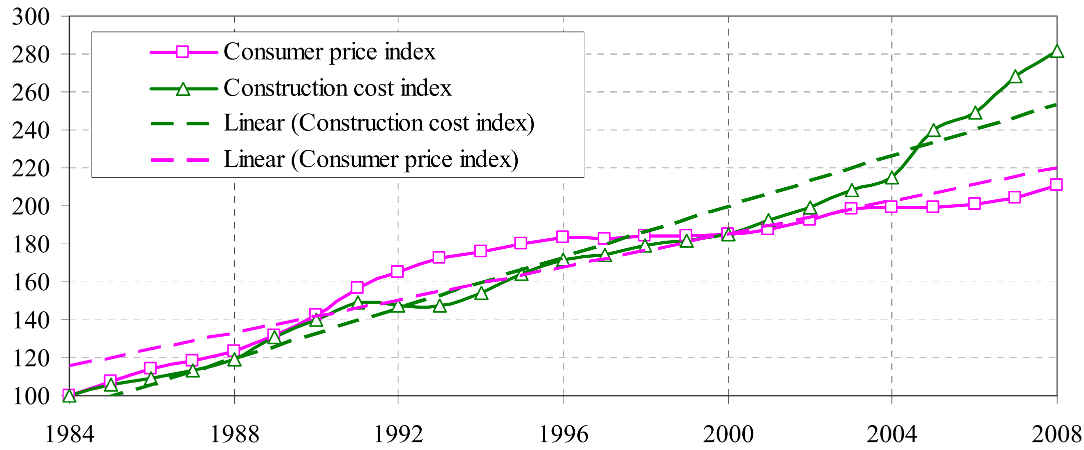

Figure 2.7. The "inflation rate" in the construction field in Sweden is higher than the general inflation rate in the society.

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

$$r = \frac{r_L - r_i - r_{TG}}{1 + r_i} \tag{2.11}$$

where

r_{TG} is the increase in traffic volume using the structure.

On the other hand, if there is a risk of decrease in the usage of the structure, this factor should have a negative sign. For example, this could 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 % in *Jutila A., & Sundquist H.* (2007).

2.2.9 Time between different MR&R actions

To be able to calculate costs at different times and discount these costs to the present values, one has to assume the time intervals for different measures which have 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. In standards, life-spans of bridges are given from 40 to 120 years. Standards do not usually define the parameter "life-span" exactly. According to *Mattson* (2008), 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 *Fig. 2.8*.

In reality very few bridges survive 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.

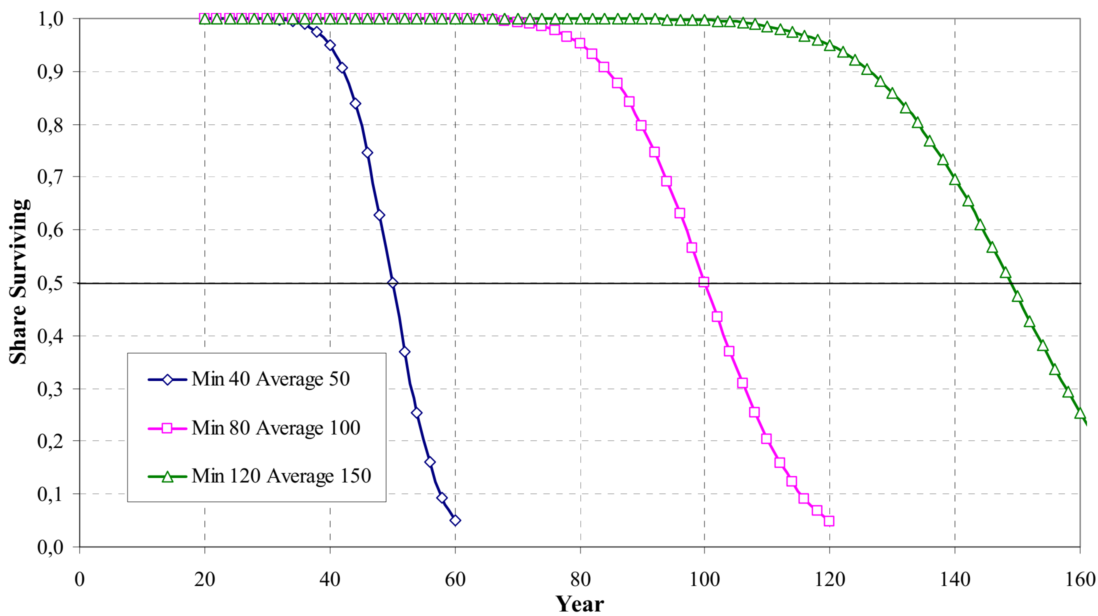

Figure 2.8. Requirement of standards for designing life-span of bridges. In Sweden the design life-span is defined as the lower 5 % fractile of a distribution which can be assumed to be normally distributed.

Time intervals for inspection and standard maintenance

All structures have to be inspected and maintained. The time intervals among these measures depend on the type of bridge, the experience in different countries, the available economic resources, the ADT value, the usage of de-icing salt etc.

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 inevitably vary among different countries and different owners. Simultaneously, these inspections and maintenance will build up a part of the Whole Life Costing (WLC) for the owner of the bridge.

Inspection intervals in different countries are discussed in *Jutila A., & Sundquist H. (*2007). Definitions of the different types of inspections are different from country to country, so it is not possible to directly compare the denomination and the intervals. In Nordic countries only three main types of inspections are performed. Yearly superficial inspection, general inspection every 5 to 6 year and special inspection which must be performed for more complicated cases.

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

Railings are often damaged due to car collisions. The time intervals and the probability for different kinds of incidents are largely dependent on the bridge type and the ADT value.

Degradation models

The equations presented earlier depend on the information of lots of parameters, many of which are uncertain. One all-important factor is the time interval between repair and maintenance work. The intervals for remedial actions are not fixed values as they are affected by the degradation and considerations of the most economical intervals. It also has to be considered that bridges usually do not just break down, but their structural elements degrade.

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

- One method is to use mechanical or chemical models for diffusion of chlorides, carbonation rates, number of frost cycles and combinations to forecast degradation. Such method is used *by Vesikari, E.* (2003) and *Söderqvist M-K. and Vesikari E.* (2003). This approach is used in combination with the *Markov-chain methodology* as a tool for analysis.
- Another method is to use and evaluate results from field observations, *Racutanu G.* (2000), *Mattsson, H. & Sundquist, H.* (2007).
- Nowadays the most applied method is to use experience from specialists and people deeply involved in inspection of bridges.

2.3 Definitions and measures used in the ETSI LCC and LCA programs

2.3.1 Background

In order to have a consistent set of definitions for in- and output in ETSI LCC and LCA, there is a need to define and explain all the parameters in the system. Mainly based on the Swedish system, the definitions are described in the BaTMan system.

2.3.2 Definition of bridge parts and their measures

Notions for bridge main structures and its elements are presented in *Table 2.1.*

Table 2.1. Notions for a typical girder bridge with ordinary bearings and expansion joints.

Description in English	Explaining figure
Foundation	
Foundation slab (base slab), plinth, pile cap	
Excavation, soil	
Excavation, rock	
Pile	
Erosion protection	
Slope and embankment	
Embankment, embankment end, backfill	*Fig. 2.9*
Soil reinforcement and slope protection	
Abutments and piers	
All concrete structures belonging to the substructure excl. foundation and including the foundation slabs	*Fig. 2.9*
Main load-bearing structure	
Slab / deck	
Beam, girder	
Truss	
Arch, vault	
Cable system	
Pipe, culvert	
Secondary load-bearing structures	
Secondary load-bearing beam, cross beam	
Secondary load-bearing truss, wind bracing	
Equipment	
Bearing and hinge	
Edge beam	
Insulation, water proofing	
Surfacing	
Parapet, railing	
Expansion joint	
Drainage system	

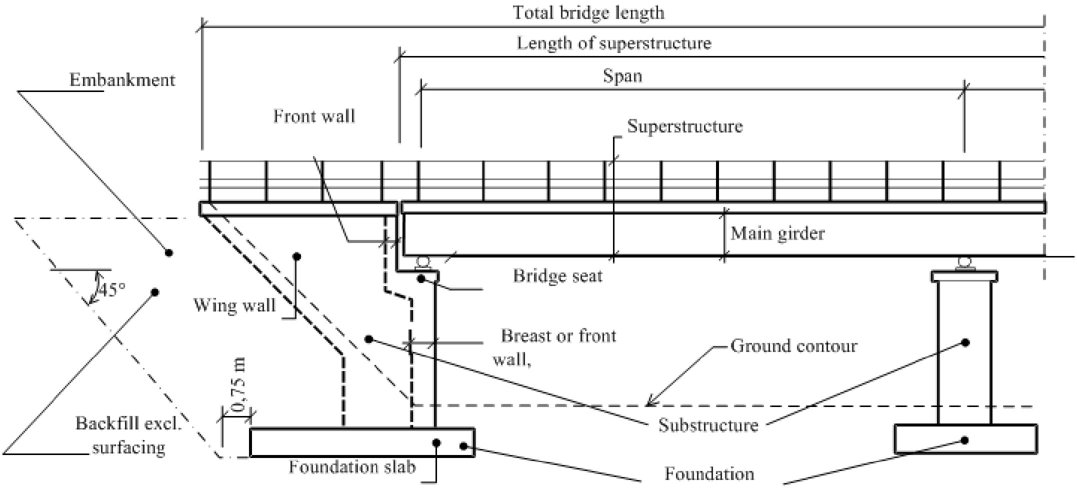

Figure 2.9. Notations and measures of a typical beam girder bridge with ordinary bearings and expansion joints.

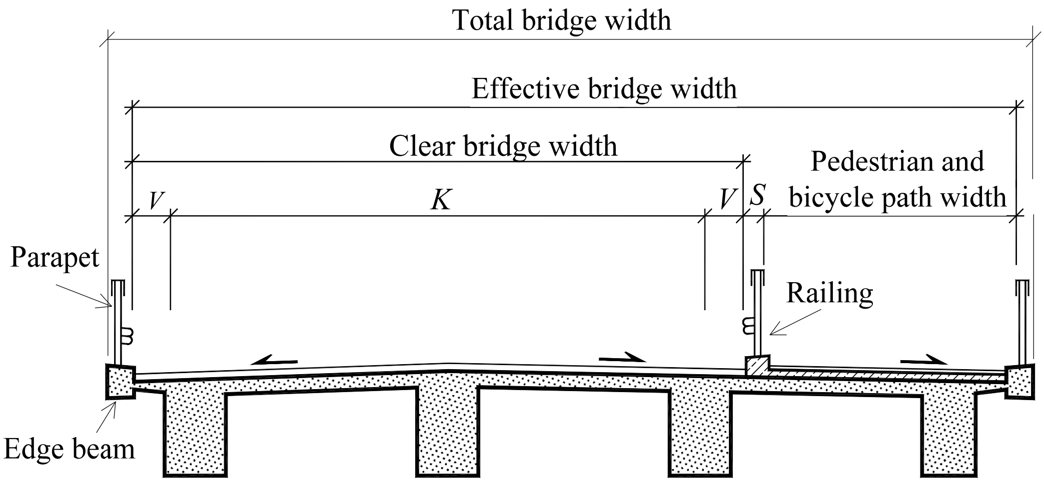

Figure 2.10. Notations and measures in cross direction of typical beam girder bridge carrying a roadway and a pedestrian and bicycle path.

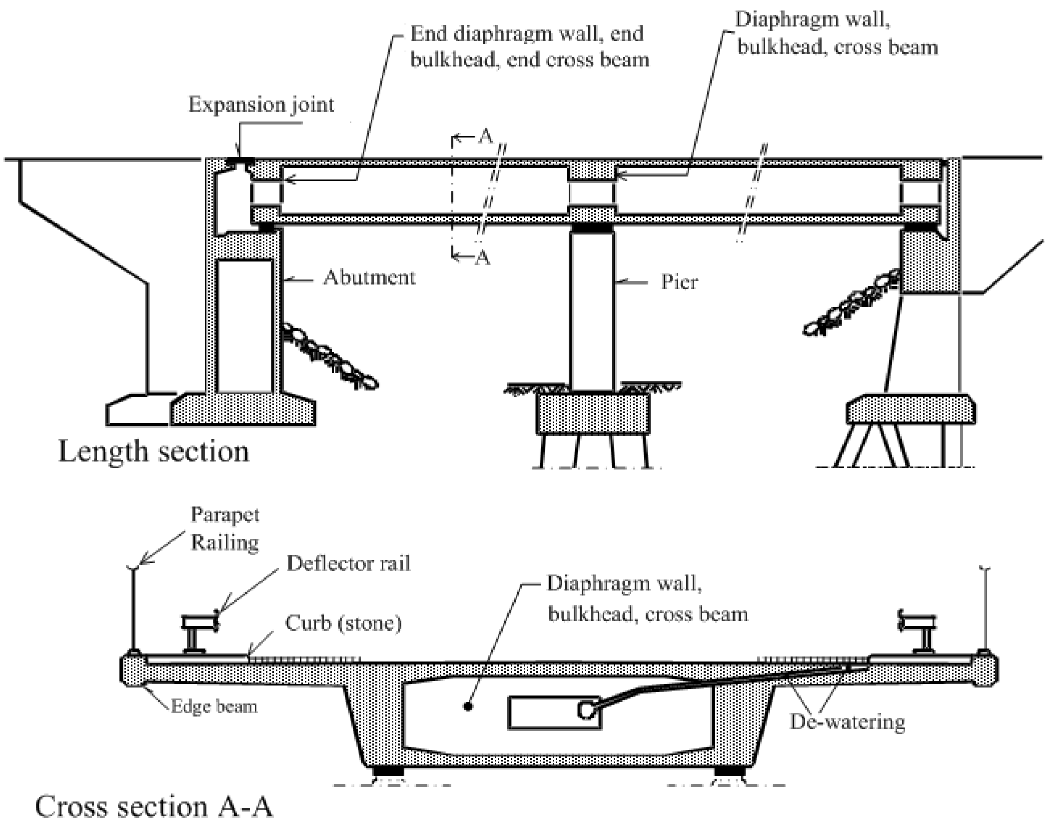

Figure 2.11. Notations in the longitudinal direction and in the cross direction for a typical box girder bridge with ordinary bearings and expansion joints.

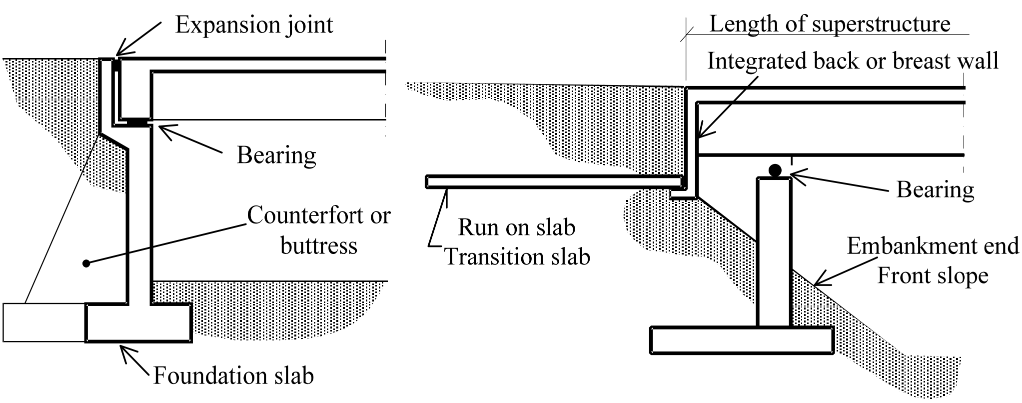

Figure 2.12. Notations for abutment elements in an ordinary bridge and in an integral bridge with integrated back walls.

2.3.3 Definitions of the materials

In *Table 2.2* the materials included in the LCC and LCA systems are defined.

Table 2.2. Materials that should be input in the LCC and LCA programs.

Material	Unit	Quality	Description
Concrete	m^3	C25[1)]	Cylinder strength in MPa
Reinforcing steel	ton	500	Yield strength in MPa
Steel for pre-stressing, tendons, cables	ton	1700	Yield strength in MPa
Steel	ton	350	Yield strength in MPa
Sawn Timber	m^3		
Glued laminated timber	m^3		
Impregnated timber	m^3		
Backfill soil	m^3		
Pile	m	Type[2)]	Coupled to the structural element

The following items are only used in the LCA module:

Asphalt	m^3		Thickness should be given
Mastic	m^3		Thickness should be given
Membrane	m^2		
Epoxy	m^2		Thickness should be given
Plastic	m^3		
Paint	m^2		Thickness should be given
Zink coating	m^2		Thickness should be given
Rubber	m^3		
Glass	m^3		

2.3.4 Definitions of the 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:

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

[1)] Example of notation. For LCC and LCA analysis an approximate value can be used.

[2)] Type of pile should be defined. Pile driving is a very energy consuming task.

Management

It is the owner’s task to keep the bridge inventory and manage the bridge stock. Usually this work can be assigned as a percentage of the actual new construction value of bridges in the bridge stock.

Inspection actions

Typical inspection actions and the intervals are given in *Table 2.3*.

Table 2.3. Inspection types and frequency of inspections.

Inspection type	Frequency	Aims	Remark
Regular	Often	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	Usually considered as part of the operation main-tenance
Major inspection	Every five to six years		
Special inspection	When needed		

Operation

Operation is the every-year duty to inspect, clean and to repair small damages of the bridges superficially and regularly.

Maintenance actions could be divided into actions, which are 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 maintenance actions” are listed in *Table 2.4,* but usually these can be calculated as a percentage of the cost to re-build the bridge stock. A typical value could be 0,2 %.

Table 2.4. Examples of “operation maintenance actions”.

Action	Frequency	Aims	Remark
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, etc.	Once a year		

Repair actions

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

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 not an action included in the LCC calculations.

Final demolition and reuse of material

Final demolition is a complicated issue and few researches are performed regarding the reuse of material. Interesting point 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_2-emissions from the cement production phase. The reused reinforcement steel requires less energy than the original steel. It is not known that how many materials from the demolition are really reused.

2.3.5 Environmental classes

The degradation of structures due to different climate actions is a complicated issue and has been a theme for an enormous amount of research in recent years. Degradation is usually a combination of material properties in interaction with climate and issues related to the use and wear of the structure.

In LCC aspect, the material properties are defined by the used material as defined earlier. However, the environment and the use of the bridge must be described in a way that the degradation can be assessed by the user of the program.

A very condensed subdivision of external deterioration factors is:

- Damage and wear during the service life of bridge caused by usage.
- Environmental damage.

Damage and wear during the service life of bridge caused by usage i.e.:

- Fatigue.
- Progressive cracking.
- Wear due to i.e. studded tires (mainly affect 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.
- Reinforcement corrosion.

The physical deterioration typically contains

- Frost swelling (in cracks).
- Repeated frost-thaw cycles.
- Salt crystallisation.

The climate conditions affecting the physical deterioration are mainly the number of frost cycles and the salting. In northern and 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.

To a large extent, the chemical deterioration is dependent on the material properties, but some factors such as

- carbonisation,
- chloride ingress,
- reinforcement corrosion,

are highly dependent on

- moisture,
- road salting and/or rain with high content of salt and
- high temperature.

In conclusion, the following parameters can approximately define the climate and the external conditions in relation to the internal conditions.

A default value of all parameters is 1,0, i.e. factor = 1. A *factor* > 1,0 increases the time interval between repair actions, while a factor < 1 reduces the time interval between repair actions.

Factor depending on daily traffic (ADT)	ADT	$factor_{ADT}$
	ADT < 2000	1,1
	2000 < ADT < 5000	1,0
	ADT> 5000	0,9
Factor depending on climate zone (ENV)	Climate zone (ENV)	$factor_{ENV}$
	Northern Sweden (ekvi.)	1,1
	Central Sweden (ekvi.)	1,0
	Southern Sweden (ekvi.)	0,9

Factor to take account of salting:

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

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

2.4 Program descriptions

2.4.1 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 of the program, 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 need input.

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

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

Data: This sheet contains important data that the program uses during calculation. The user is not allowed to alter any of the cells in this sheet, when this sheet is not shown at 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 need to choose a larger text using "ZOOM" in 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. For each case, the values must 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 would not be done if you enter the 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. I.e., you can choose to repair some part of the superstructure without replacing the whole deck.
11. As for road user cost, the program includes only costs in the form of reduction in service benefits, as long as work is underway on the bridge.
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 the time of the actions being carried out. If necessary, also change the number of days that the road users are disturbed by the OR&M activities, so that these will not lead to an overestimation of the road user costs. For example, if two activities are meant to be performed simultaneously, only the activity of the longest duration gives any road user cost. Undoubtedly, this depends on what activities are planned to be carried out and may not apply generally, therefore, the program does not make this correction automatically.

2.4.2 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 with using the net present value method.

In the case of a bridge the LCC includes the construction, operation, repair work and the demolishment of the bridge at the end of the life-time. The calculation also includes indirect costs for the road users due to traffic interruption during repair work.

WebLCC is sufficiently general for making LCC analysis even for small parts of a large project. WebLCC also offers you 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, since all input is made dynamic. Therefore, there is no restriction on how many inputs for actions that can be analysed.

However, there are many practical problems with systems where all calculations are made on a central server. Unwished results may occur when the user inputs wrong type of letters or numbers, leads the server to break down.

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

2.4.3 Case Study of LCC calculations

To describe the use of the Bridge-Stand-Alone-LCC program, a case study is performed. This case study is also shown when opening the program for the first time. The program should be saved as a new name.

The bridge is depicted in *Figs 2.13* and *2.14.* The main properties of the bridge are compiled in the following section.

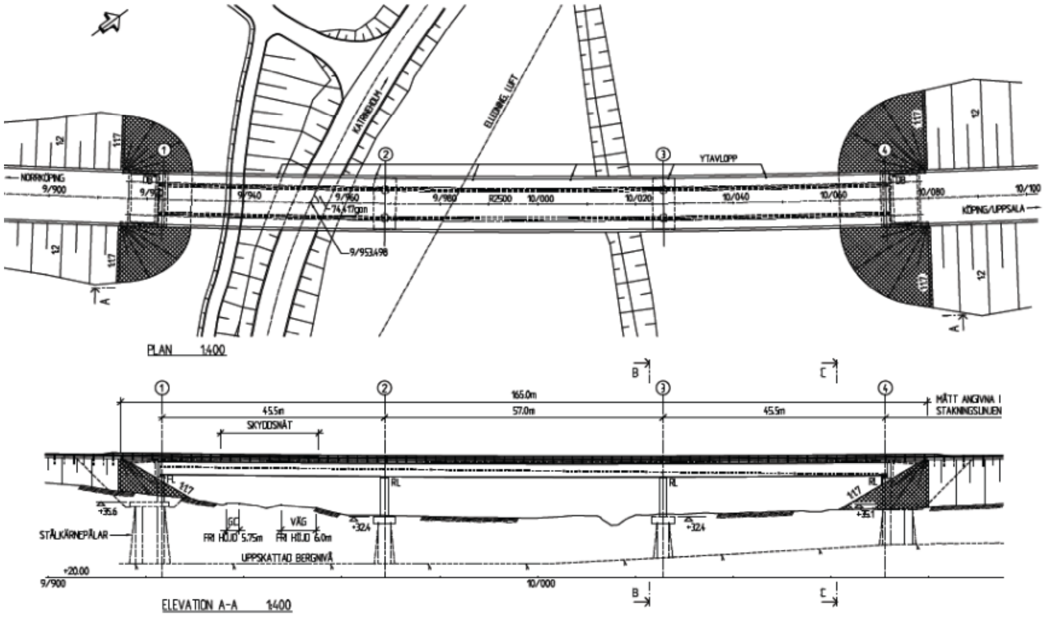

Figure 2.13. Plan and side view of the studied bridge.

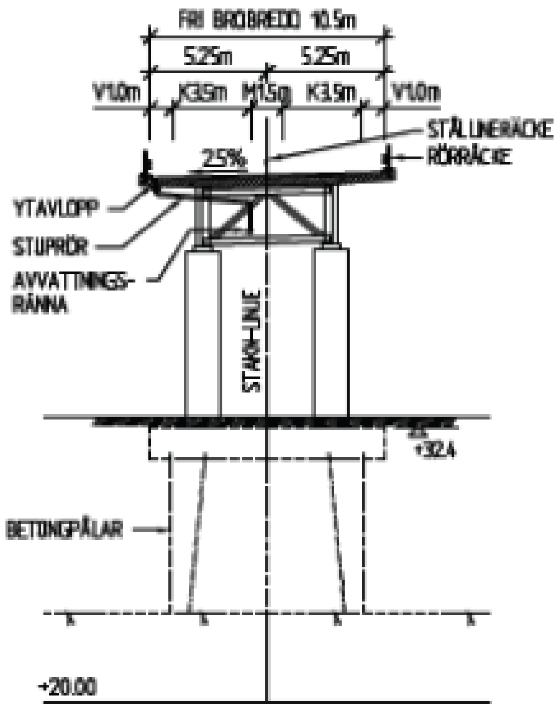

Figure 2.14. Cross-section of the studied bridge.

Input data:

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

Bridge effective width is 10,5 m, total bridge width including edge beams 11,3 m, assuming that the edge beams have an area of $0{,}4 \cdot 0{,}4 = 0{,}16\,\mathrm{m}^2$.

Bridge area used for comparisons is $149{,}2 \cdot 11{,}3 = 1686\,\mathrm{m}^2$

Bridge quantities are calculated using a methodology based on *Rautakorpi, H.* (1988).

Quantities:

For a steel concrete composite bridge deck the following applies:

L_0 = sum of bridge spans = 148 m

b = effective width of bridge = 10,5 m

auxiliary factors:

$k_1 = 0{,}243 m$

$k_2 = 0{,}7 m^2$

$k_3 = 2.17 m$

$m_1 = 53.6 kg/m^2$

$m_2 = 1.59 kg/m^3$

The quantity of concrete is

$$Q_c = bL_0\left(k_1 + 0.0072b + \frac{k_2}{L_0}\right) \approx bL_0 0.32 = 502m^3$$

Formwork

$$Q_f = bL_0\left(0.93 + \frac{k_3}{b}\right) = 1781m^2$$

Reinforcement

$$Q_r = bL_0(m_1 + m_2 b) = 110124kg$$

$$Q_r/Q_c = 219kg/m^3$$

Amount of steel

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

The designation stands for an "average" span length calculated by using the formula $\frac{1}{L_0}\sum_{i=1}^{n} L_i^2$,

where the lengths of the spans are denoted as L_i and n is the number of spans.

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

Calculation of quantities and investment cost

The formulas for calculation of quantities are presented in previous section which are used and compiled in *Table 2.5.*

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

Quantities using the formulas above are compiled in an Excel file, together with the cost calculation. The total cost per square metre turns out to be the current average cost for this kind of bridges in Sweden, in spring 2010.

Table 2.5. Invest cost calculation of 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_f/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/m²**		
Bridge concrete incl temp control and after treatment	CUR/m³	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/m²	1 300	1781	2 314 913	1 373		
Railing/parapet	CUR/m	5 000	298	1 492 000	885		
Surfacing + insulation	CUR/m²	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		
Sum of bridge slab system				**13 074 936**	**7 755**		
Steel structure incl. painting and launching	CUR/kg	55	300 721	**16 539 664**	**9 810**		
Two Intermediate piers incl. foundation	**Unit cost**		***Quantity***	**CUR**	**CUR/m²**		
Concrete columns	CUR/m³	4000	36	144 691	86		
Reinforcement	CUR/kg	40	4 522	180 864	107		
Formwork	CUR/m²	1300	121	156 749	93		
Foundation slab concrete	CUR/m³	4 000	158	630 000	374		
Reinforcement	CUR/kg	40	3 617	144 691	86		
Formwork	CUR/m²	700	158	110 250	65		
Number of piles per pier			43		0		
Piles	CUR/m	1 800	687	1 236 294	733		
Sum intermediate piers				**2 603 540**	**1 544**		
Two abutments incl. foundation	**Unit cost**		***Quantity***	**CUR**	**CUR/m²**		
Concrete front and wing walls and bridge seat	CUR/m³	4000	141	563 200	334		
Reinforcement	CUR/kg	40	21 120	844 800	501		
Formwork	CUR/m²	1300	128	166 400	99		
Foundation slab concrete	CUR/m³	4 000	158	630 000	374		
Reinforcement	CUR/kg	40	14 080	563 200	334		
Formwork	CUR/m²	700	158	110 250	65		
Number of piles per pier			49		0		
Piles	CUR/m	1 800	785	1 412 908	838		
Sum intermediate piers				**4 290 758**	**2 545**		
Excavation							
Backfilling							
Total earthworks				**1 000 000**			
					CUR/m²		
Total cost				**37 508 898**	**22 248**		

Life cycle costs

Based on the given quantities (above) and simplified Excel scheme, LCC calculation is shown in *Table 2.6*. The interest rate is used as 3 %.

Table 2.6. Calculation of life cycle cost.

Example: Steel Concrete composite bridge

Input data		
Bridge length L **=**	149,2	
Bridge effective width b **=**	10,5	
Bridge total width **=**	11,3	
Exposed area of each edge beam **/m²/m =**	1,4	The edge beams are assumed to have an exposed area of 400+400+400+200/each
Total bridge area **/m² =**	1 686	
Area of surfacing **/m² =**	1 567	
Painted area steel beams **/m²/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*p
Management + Operation 0,3 %	112 527	1	3 549 865	99,00	99,00	99
Careful inspection 100 CUR/m²	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
Sum LCC cost			**4 883 284**			

LCC Repair and replacements	Cost year 0	Quantity	Cost year 0	Year 13	25	37	50	63	75	88	Sum
Edge beam, rep 0 - 30 mm/m²	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/m²	400	1566,6	626 640	426 711				97 336			524 047
Surfacing + insulation replacement/m²	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/m²	4 000	120,6	482 304				110 017				110 017
Front and wing walls repair 0 - 30 mm/m²	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**
			Total:							**6 143 546**	

Investment	37 508 898	77%
Periodic activities	4 883 284	10%
Repair and replacements	6 143 546	13%
Total LCC:	**48 535 728**	**100%**

The 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 are not paid much attention to in this example.

The result is presented in *Fig. 2.15*.

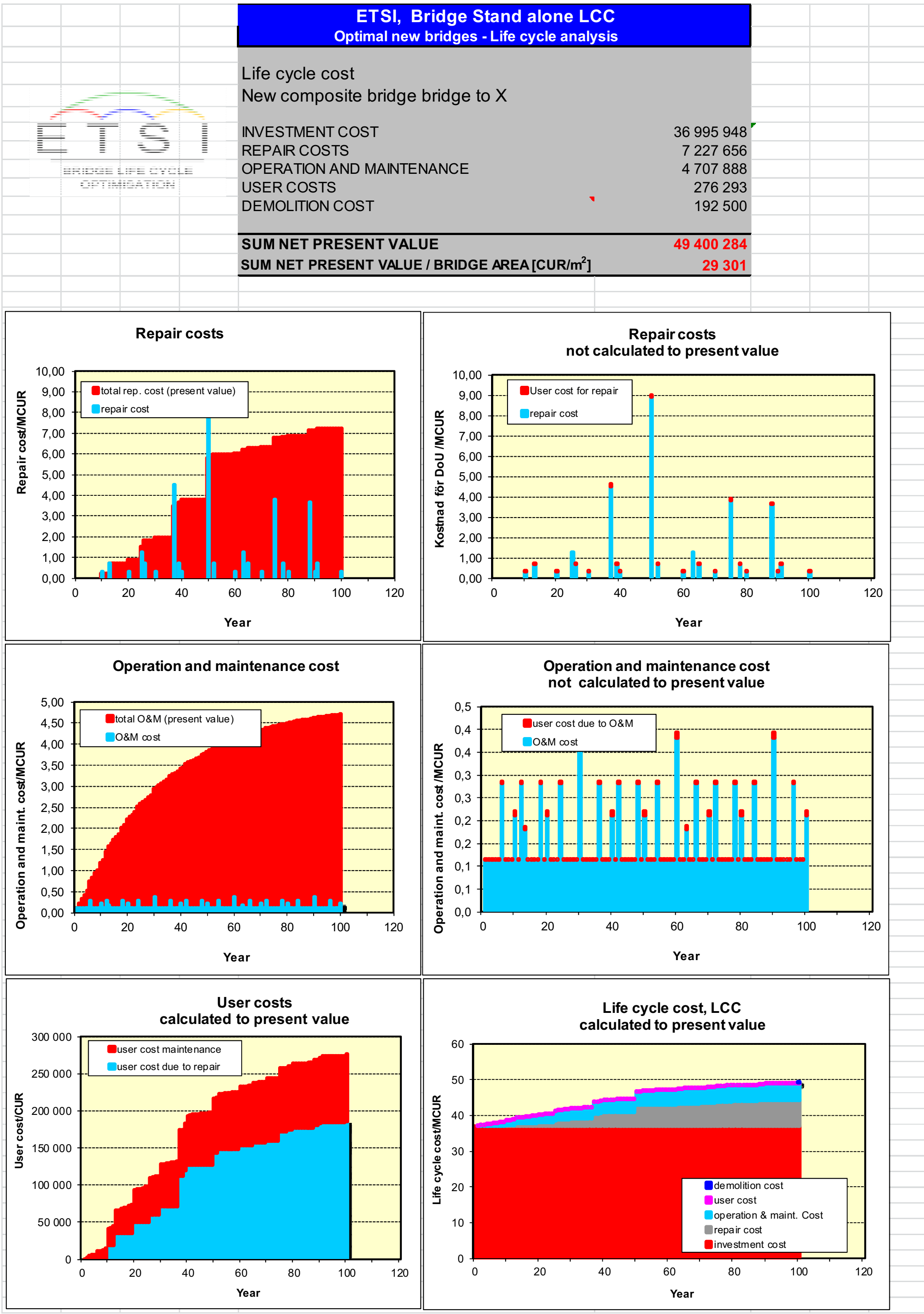

Figure 2.15. Presentation of LCC results from the stand-alone-Bridge-LCC program.

2.5 Discussion and proposal for future work

Making LCC calculations is an estimation work of the future, and the only thing we know about the future is that we don't know anything. The big problem is guessing the degradation of the structures and the time between maintenance and repair actions. Also, we must guess rates of interest and inflation in the future. Looking at in the rear-view mirror, we know that rates have changed dramatically over time. One positive thing is that the authorities in many cases have decided what rates are used.

Another all-important factor is the structural degradation rate. An enormous amount of research work 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 have been studied for years, but the results are difficult to use as a prognosis for the required maintenance and repair actions in the future. In *Jutila A., & Sundquist H.*, (2007), a methodology based on *Markov Chains* in turn developed by *Vesikari, E.* (2003) was presented. However, the input for this method is complicated, simple usage leads to wrong curvature for the degradation curve if not enough data are given.

Usually when guessing the future, we have to use history and regression analysis based on this data. However, the problem is 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 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, which therefore should be rather reliable. For more information about these methods see *Safi et al.* (2012a,b).

Another possible 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. In the future, if the WebLCC program is developed for better stability, this feature can be used for "research".

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3 Life Cycle Assessment of Bridges

3.1 What is Bridge Life Cycle Assessment

3.1.1 General

The environmental effects of road projects, including the location and design of road elements such as bridges, have played an important role in road planning in many decades. However, this focus has more or less exclusively covered local environmental impacts as part of Environmental Impact Assessment (EIA) documentation in the early-phase planning of road projects. Due to the increasing focus on life cycle issues, both the global environmental problems (climate change, ozone depletion or scarce resource) and regional problems (acidification, eutrophication and toxicity) must be taken into account. Thus, the traditional scope on local environmental impacts of road and bridge projects had to be extended to more system-based philosophy and Life Cycle Assessment (LCA) calculation approach.

Bridge LCA is a calculation methodology and a life cycle thinking concept taking account of all potential environmental impacts of a bridge project. The impacts are quantitatively determined, regardless where or when they occur during life cycle including also the whole service life of the bridge and the life cycle of bridge materials and energy inputs. The aim of applying LCA for a bridge is to quantify the impacts of a bridge design, taking into account a large number of environmental impact categories (types of problems) according to internationally standardised methodologies. After such quantification, it is possible to understand that what the elements are contributing to critical environmental impacts during bridge life cycle. These can be reduced as much as possible leading to better bridge design or location in environmental sense. In reality, however, it is important to note that such environmental qualities of a bridge design will have to be evaluated in parallel to the life cycle costing and the life cycle aesthetic qualities of the bridge. Hence, there is surely a trade-off between such bridge qualities.

In this chapter, LCA methodology described is applicable to a new bridge project. Therefore, the LCA tools in this chapter are only applicable at this stage, where costs, environmental, aesthetical and cultural values are evaluated together and the “best” bridge solution is to be selected at the early design stage.

3.1.2 Life Cycle Assessment and Bridge Management System

Life Cycle Assessment, LCA, is a technique that enables comparative environmental assessments to be made over a specified period of time, taking account of a predefined selection of environmental factors. The methodology considers all phases of a bridge life cycle including:

- Production of bridge materials and components.
- Transportation to the bridge site and construction of the bridge.
- Operation, repair and maintenance (OR&M) during the bridge’s service life.
- The End-of-Life (EOL) of a bridge includes demolition, waste disposal and material recycling.

LCA can be one important tool in a Bridge Management System (BMS), and although this is definitely not a common practice today, it is believed that LCA will gain much interest in future. LCA methods may differ in scope and depth; depending upon which planning phase it is used in and for what purpose. LCA methods are required in order to quantify the whole life cycle energy consumption and the carbon footprint, for which there is already a practical demand today. Moreover, LCA is also needed for verifying other environmental impacts of a bridge.

As outlined in Chapter 2, BMS is usually divided into the country or county level, the road network level and the project level usually interpreted as a BMS for individual bridges. Similar to what is needed for LCC calculations, there has to be a close interaction between bridge LCA and BMS, since much of the same information is needed. This includes information related to:

- The definition of the bridge, its parts, elements, details and equipment with measures and quantities.
- Planned OR&M measures for the bridge parts and elements.
- Planned information on the use of the bridge, such as the amount and type of traffic flow.
- A planned demolition scheme.

Information could be collected into a Life Cycle Plan (LCP) which is the basis for calculating the inputs of physical resources (materials and energy carriers) that become a direct consequence of activities during the service life of a bridge.

3.1.3 LCA tools

There are numerous LCA tools available internationally which are used for a large number of applications and purposes in various sectors (industrial and governmental) and in research. A common observation is that existing LCA tools are not at all specifically developed for road infrastructure; hence, one has to rely on the use and adaptation of generic, commercially available and usually complex LCA software packages. Therefore, LCA is traditionally working for LCA experts only. During ETSI project, an Excel-based LCA tool – *BridgeLCA* was developed by the Norwegian University of Science and Technology (NTNU). This is a program that bridge designers with some environmental competence are able to use without a long learning phase on LCA theory or methodology.

3.2 Methodology for LCA calculation

3.2.1 General principles and structure of LCA

According to standard ISO 14040:2006, LCA is defined as *compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*. The life cycle is defined as *consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal* and a product is defined as *goods or service*. In ETSI project, the purpose of the bridge design, location and service during service life, is the product to study.

LCA considers the entire life cycle of a product, from raw material extraction through energy, material production and manufacturing to the use of product and end-of-life treatment and final disposal. Through such a systematic overview and perspective, the shifting of a potential environmental burden between life cycle stages or individual processes can be identified and possibly avoided.

LCA addresses the environmental aspects and impacts of a product system (*Fig. 3.1*) and could be a given bridge system in a life cycle perspective.

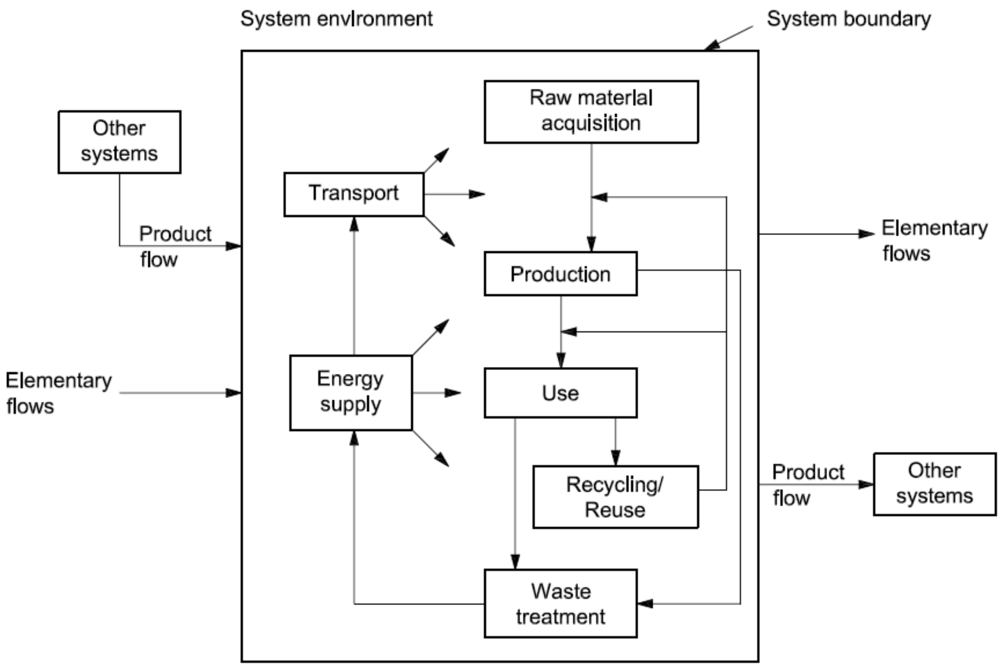


Figure 3.1. Illustration of a product system in LCA (ISO (2006a)).

As schematically shown in *Fig. 3.1*, the system boundary of the product system includes all phases of the product's life cycle (raw material acquisition, production, use, recycling/reuse and waste treatment), as well as the transport and energy supply needed to support all the other activities. It means that all processing and transport of materials and energy for the given product system can be included in the LCA. There may be product flow inputs from and outputs to other product systems and there are elementary flows entering and leaving the system. Elementary flows are defined as "*material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation*" (European Commission 2006a). These flows are interested in examined, determined and quantified in LCA analysis and their potential environmental impacts.

The structure of LCA consists of four phases (*Fig. 3.2*):

1) Goal and scope definition.

2) Inventory analysis.

3) Impact assessment.

4) Interpretation.

The goal and scope definition is a phase during which the purpose of the assessment is decided and the system is defined. The inventory analysis Life Cycle Inventory (LCI) is the phase involving the compilation and quantification of elementary flow inputs and outputs for a given product throughout its life cycle. The impact assessment, i.e. Life Cycle Impact Assessment (LCIA) is the phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for the product system throughout its life cycle. Interpretation is a systematic procedure to identify, qualify, check, evaluate and present the conclusions from the study. It is iterative with other three phases of the LCA.

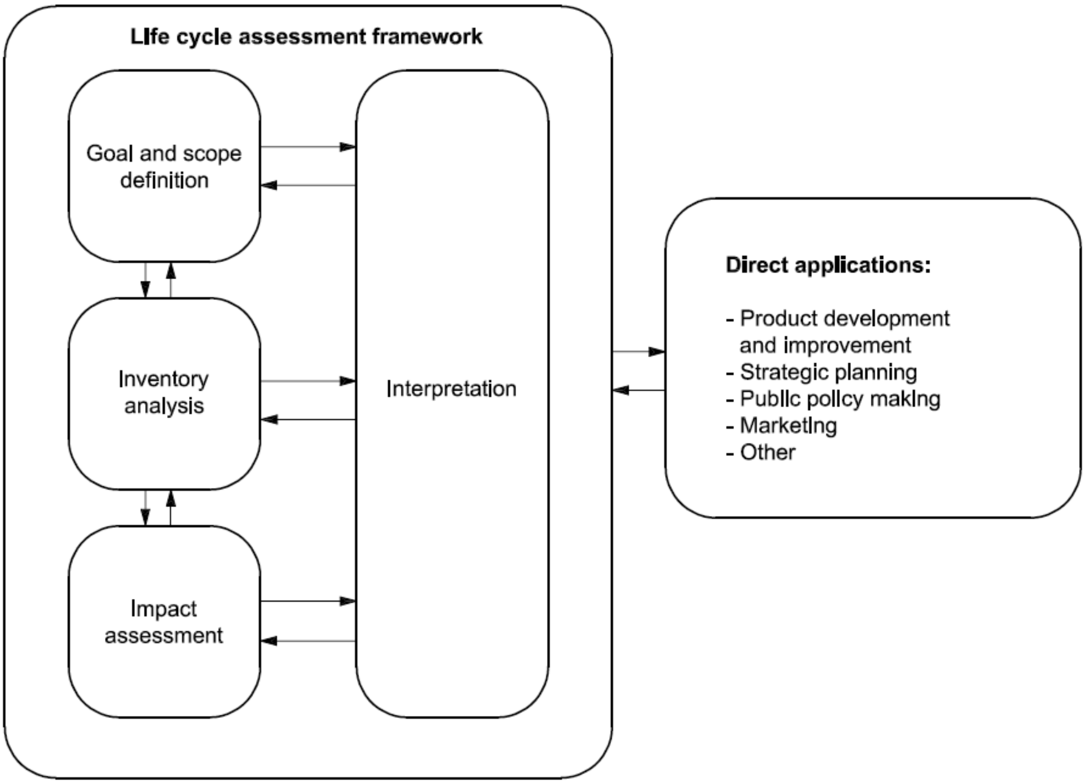


Figure 3.2. The four phases of LCA (ISO (2006a)).

3.2.2 Goal and scope definition

LCA starts with defining the problem formulation and system definition, which are parts of defining the goal and scope of LCA. The assessment can be used for a variety of objectives, but common ones are to document potential environmental impacts as a basis for focusing possible improvements, comparing alternative designs, identify waste management solutions, and develop environmental documentation for use in external communication (such as in environmental product declarations, EPD).

The goal of an LCA should clarify the intended application and the reason of carrying out the study. It should also identify the intended audience, and whether the results are being used for comparative purposes and communicated to the public. With reference to the ETSI project, the goal of an LCA would be to examine the environmental effects of a bridge design, so that one could choose the best alternative among different design options, for given bridge location(s) and traffic.

The goal of an LCA, and the way of carrying out the analysis (particularly in the inventory analysis) is closely linked to the decision context of the study. *Fig. 3.3* is taken from the ILCD Handbook (European Commission 2010b) detailed guide on how to carry out LCA, and it presents three different situations – A, B and C – or decision contexts, depending on whether or not the LCA is actually used to support decisions regarding future policies, and if so, whether or not one expects large-scale process-changes in the background system or other systems, as a consequence of possible changes to be implemented in the (foreground) product system.

<table>
<tr><td rowspan="5">Decision support?</td><td rowspan="2"></td><td colspan="2">Kind of process-changes in background system / other systems</td></tr>
<tr><td>None or small-scale</td><td>Large-scale</td></tr>
<tr><td>Yes</td><td>Situation A
"Micro-level decision support"</td><td>Situation B
"Meso/macro-level decision support"</td></tr>
<tr><td>No</td><td colspan="2">Situation C
"Accounting"
(with C1: including interactions with other systems, C2: excluding interactions with other systems)</td></tr>
</table>

Figure 3.3. The decision context of LCA (European Commission 2010b).

If the LCA results are being used for decision support, the decision context is either Situation A or B. Hence, to carry out an LCA of alternative road bridge designs for selecting the best design or location of a bridge. LCA results are used as active decision support, and are applied in Situation A or B, in Situation C one only accounts the environmental impacts of an existing product system without affecting the decision.

In cases A and B, one sometimes has to consider the possibility that there will be potential large-scale and structural consequences of the decisions taken on the basis of the LCA. This could for instance occur if the market has a limited production capacity for materials X and Y, or energy carrier Z, and decisions in our product system will lead to consumption of them beyond what the market can supply without mobilising the extra production capacity from plants using marginal technologies. This might even mean that new production facilities utilising distinct technologies need to be built.

In case A, none or only small-scale, non-structural consequences in the background system and potentially on other systems of the economy are considered. These cases imply that only the extent is changed to which the already installed equipment i.e. of a production facility is used (e.g. the existing technologies that produce material X). In the LCI model, the additional demand from our system would then be modelled with the processes of the existing equipment (technologies). In most cases, LCI modelling in Situation A is based on the assumption of average technologies, for instance the average electricity mix (relative composition of electricity-generating technologies in the electricity market) within a limited region (e.g. the Nordic or European electricity market).

In case B large-scale structural effects may be consequent. This implies that the decision may result in large-scale market changes; such as additionally installed or decommissioned production capacity. If so, we may have the installation of new production plants and technologies for material X, or we may have some existing ones taken out of operation, both of them as direct market change consequences of the given decision. The result is that at least parts of the technologies in background or other systems in the economy, outside our foreground product system, change as consequence of actions taken according to the analysed decision. Often only few processes actually have these large-scale effects and only those processes need the respective modelling; most of the background systems will only have small-scale effects. However, for those processes affected, the difference between the 'large-scale' and 'small-scale' cases can be substantial, as newly installed technologies may differ fundamentally from the currently installed technologies that are modelled in the case of small-scale consequences. A typical example of LCI model in case B would be the assumption of marginal electricity technologies, including their relative specific greenhouse gas emissions, in a market where excess power generation capacity is needed.

It is important to stress that the above mentioned refers to changes in the background or other systems that are caused via market-mechanisms, i.e. market changes in response to changed demand and supply results from the decision within product foreground system. Direct changes in the foreground system, such as the installation of a new technology being installed at the producer's site as part of the analysed product system, are to be modelled as explicit scenarios in both cases.

The scope analysis in LCA is about what to analyse and how. The scope of LCA should be that the breadth, depth and detail of the study are sufficient to address the stated goal. The scope includes the product system, the functions of the product system (or the functional unit), the system boundary, allocation procedures, selected impact categories and the methodology of impact assessment. It also addresses data and data quality requirements, assumptions and limitations.

The functional unit is a key feature of LCA and it is important to define the functional unit in a way which is mostly possible. A system may fulfil different functions, and the one selected for a given LCA study depends on its goal and scope. According to standard ISO 14040:2006 (ISO 2006a) it is explained as "*The functional unit defines the quantification of the identified functions (performance characteristics) of the product. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis. It is important to determine the reference flow in each product system, in order to fulfil the intended function, i.e. the amount of products needed to fulfil the function*".

The functional unit shall be identified and specified in detail, including the following aspects:

- Function provided.
- Quantity.
- Duration.
- Quality (in what way and how well the function is provided?).
- Changes in the functional performance over time shall be explicitly considered and quantified, as far as possible.

The system boundary must be selected so that it is consistent with the goal of the study. The deletion of life cycle stages, processes, inputs or outputs is only permitted when it does not significantly change the overall conclusions of the study. When the functional unit and boundary of a system is defined, one can determine the corresponding reference flow, which by definition is the "*measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit*", i.e. the amount of products needed to fulfil the function.

With reference to the ETSI project we assume that the location and traffic capacity of a given bridge is known, hence also its length, width and effective area. Therefore, the functional unit of the *BridgeLCA* can be simply defined as: 'Given bridge (name) over its service life of 100 years'. With this functional unit one can easily carry out LCA for a number of different design options, and compare the designs for selecting the best.

3.2.3 Life Cycle Inventory (LCI) analysis

The LCI involves data collection and calculations to quantify relevant inputs and outputs of a product system. Meanwhile, it is an iterative process that may lead to the need for better data and revisions of the goal or scope of the study. *Fig. 3.4* illustrates this by giving a simple example of three unit processes within a product system.

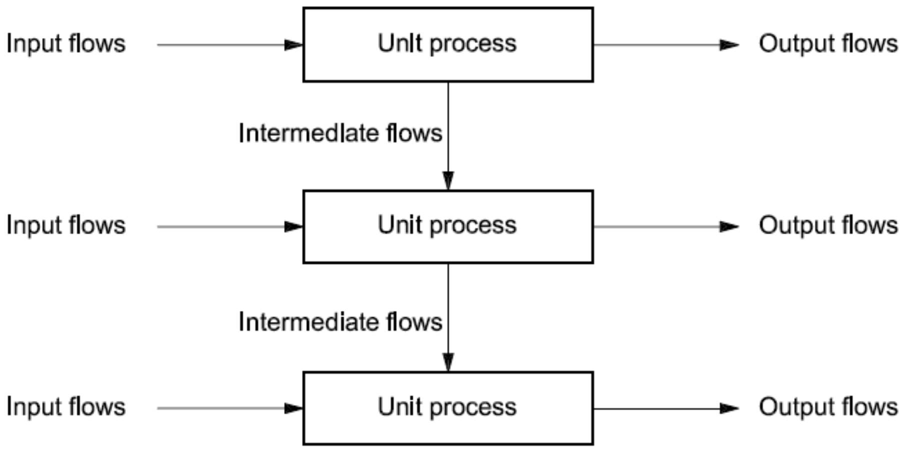


Figure 3.4. Example with a set of unit processes within a product system. (European Commission (2010b).

Data must be collected for each unit process within the system's boundary, which can be a resource-intensive process. However, the use of commercial LCA software and databases (such as the SimaPro LCA software and the Ecoinvent v2 database) help reducing time and work for such data collection, but these represent average data for technologies that are not often sufficiently specific for the given product system being studied.

The calculation of energy flows are of particular importance in LCA and one needs to account for the use of different fuels and electricity sources, energy conversion and distribution efficiencies, and the inputs and outputs related to the generation and use of different energy flows.

According to the decision context in *Fig. 3.3,* the choice between case A and B lead us to two different principles of LCI modelling, which are called "*attributional LCI modelling*" and "*consequential LCI modelling*", respectively. Attributional modelling is a modelling frame which inventories the input and output flows of all processes as they occur. Hence, in this modelling one normally uses project's specific or average technology foreground LCI data and assumes average technology LCI data for the background system. Consequential modelling is a principle which identifies and models all processes in the background system of a system in consequence of decisions made in the foreground system. Hence, in this modelling one normally have to use marginal technology LCI data for selected parts of the background or other systems in the economy, i.e. those systems that are likely to be large-scale influenced by decisions in product system.

In the context of the ETSI project, when carrying out LCA to determine which is environmentally the best design of a new bridge, one is normally in a situation of type A – the given bridge is not a project with sufficient size to influence market technologies. Only in extreme cases, such as for the very long *Öresund* bridge for example, one may come into a situation of type B, where project can cause a demand for bridge materials beyond the current production capacity in the market, thereby mobilising marginal production technologies. It is crucial to note that this issue is important, since there is lots of confusion on how to carry out LCA with respect to the choice of technology assumptions and the choice of average or marginal technologies of a given material, or energy carrier can influence the LCA results strongly, by reason that sometimes emissions from various technologies are very different in type and magnitude.

Another comment of importance is that one should use as exact and project-specific assumptions as possible, including emission data from production processes that supply major materials consumed in the bridge project. This implies that one should use emission data from Environmental Product Declarations (EPD) of defined material suppliers to the bridge, if the suppliers are known or can be assumed with a high degree of certainty. Furthermore, if such project-specific data are not known, average technology assumptions of the specific country can be used rather than average technology assumptions for a larger region (like Western Europe) or for the entire world.

Industrial processes usually give more than only one output product, e.g. products and co-products which may be recycled intermediate or discarded products and used as raw materials. In such situations/cases??? a multifunctional process is in question (*Figure 3.5*).

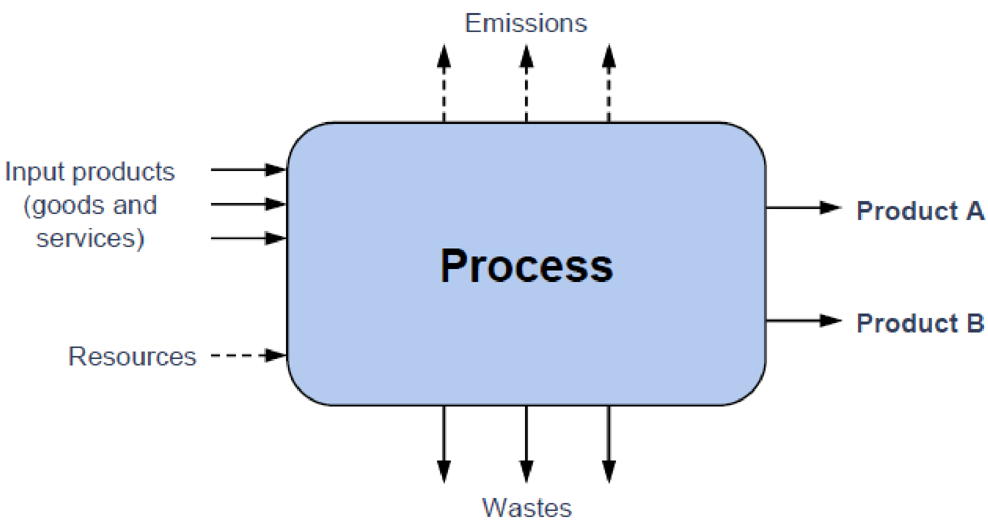


Figure 3.5. Example of a multifunctional process, with several inputs, emissions and wastes, and providing two co-products A and B (Source: European Commission 2010b).

In order to cope with such issues, the use of allocation procedures is needed. According to the standard ISO 14040:2006, allocation is defined as "*partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems*". The point is that, if a product (including co-product, reused product or recycled materials from a product) has a value (benefit) for another product system, part of the environmental impacts from the processing of this should be accounted for in the other system. The study shall identify the processes shared with other product systems and deal with them in the following ways:

- Wherever possible, allocation should be avoided by 1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or 2) expanding the product system to include the additional functions related to the co-products.
- Where allocation cannot be avoided, the inputs and outputs should be partitioned between their different products or functions in a way that reflects the underlying physical relationships between them.
- Where physical relationship alone cannot be established or used as the basis for allocation, other relationships can be used, such as the economic value of each of the co-products.
- The inventory is based on mass balances between input and output.

It is particularly important to use the correct allocation procedure when carrying out an LCA for product systems where recycling is involved, since open and closed loop recycling is an important issue. Reuse and recycling may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system. Reuse and recycling may change the inherent properties of materials that might be used later and a care should be taken when defining system boundary with regard to recycling and recovery processes.

With reference to the ETSI project, it believed that it is so important to decide upon a principle for how to deal with recycling and recovery which is also in agreement with the state-of-the-art rules for Environmental Product Declarations (EPD) and Product Category Rules (PCR). PCR is a predefined and internationally standardized set of rules, specifying how one should develop EPDs within different categories of goods and services. The International EPD®System (2010) provides a "PCR Basic Module" for Constructions, which covers EPDs for buildings and civil engineering works including:

- Highways, streets, roads, railways and airfield runways.
- Bridges, elevated highways and tunnels.
- Harbours, waterways, dams, irrigation and other waterworks, etc.

The International EPD®System (2009) also provides a more detailed PCR document for railways, but they have not yet developed PCR documents for bridges.

In *Fig. 3.6*, it is shown the general presentation of the boundaries of the construction project, it consists of processed in Core module, Upstream and Downstream modules of constructions, according to the International EPD®System 2010.

The Upstream processes include the following inflow of raw materials and energy needed for the production of the construction product:

- Extraction and production of raw materials for all main parts and components.
- Recycling process of recycled material used in the product.
- Transportation of raw material.

The Core processes includes:

- Manufacturing process for main parts and components.
- Assembly of the final product.

- Treatment of waste generated from the manufacturing of main parts and assembly of the product.
- The core process includes external transportation of materials to the factory and internal transportation within the factory.

The Downstream processes includes:

- Transportation from final manufacturing to customer.
- Lifetime operation of the product including power losses and emissions.
- Maintenance, replacements of parts, during life time.
- Recycling of material after EOL.

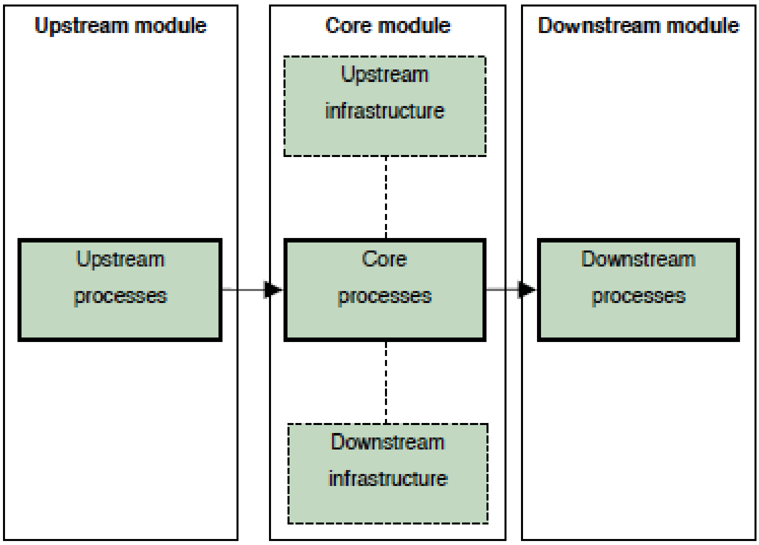


Figure 3.6. General system boundaries of construction project with Upstream and Downstream processes (International EPD®System 2010).

The PCR Basic Module for Constructions document (International EPD®System 2010) states that allocation between different products and co-products shall be based on physical relationships, if possible. The document also states that EPDs for constructions should use an allocation cut-off criterion of 99 percentages, which means that LCI data for a minimum of 99 percentages of total inflows to the core module shall be included.

The document does not explain how to allocate when recycling materials after end of life, but states that the PCR shall specify which allocation rules should be used. Because of the PCR for bridges are not available today, PCR for railways can be applied (International EPD®System 2009):

"*For resource inputs that come from recycling processes and waste outputs that go to recycling processes, no allocation should be made*". It means that inputs of recycled materials or energy to a product system shall be included in the data set without adding their environmental impact caused in "earlier" life cycles. However, potential environmental impact from recycling processes (e.g. collection, treatment etc.) shall be included in the system under study. Consequently, outputs of products subject to recycling shall be regarded as inputs to the "next" life cycle. It means that they will not carry any environmental impact to the next life cycle and the environmental impact from recycling processes shall be included in the next life cycle. If it is difficult to decide whether recycling processes should be included in the previous or the next life cycle, the delineation between the product systems shall be drawn where the waste has its lowest market value.”

There are some important implications when applying to bridges:

- When the construction of a given bridge is consuming components or materials that are recycled from scrap from earlier life cycles, i.e. using secondary materials (such as reinforcement steel from arch furnace technologies, based on scrap steel), the LCA of the bridge shall include the emissions and environmental impacts from collection, transport and processing of these secondary materials. This will give an advantage to the bridge system, compared to the alternative of using virgin steel. Hence, when using secondary (recycled) materials in a bridge, one should use the emission data for those given secondary materials, such as from the EPD of a secondary materials supplier.
- When a bridge is demolished and its construction materials are reused, the using material recycling or energy recovery process, the emissions and environmental impacts from collection, transport and processing of these materials shall be allocated to the next life cycle system, instead of the current bridge system. This also means that the advantage of recycling and energy recovery, compared to the use of virgin materials, is credited to the next life cycle, instead of the current bridge. Hence, one should not include the fate of recycled materials or recovered energy in another product system, after the end of the bridge.
- If the materials of the bridges, after the demolition are not recycled, but disposed in landfills or given any other end treatment (such as incineration without energy recovery), one must include the emissions and impacts from such disposal or end treatment. In this case, such emissions are included in the LCA of the bridge system.
- Likewise, the demolition activity itself must be included in the LCA of the bridge system.

The final outcomes from LCI is a quantified list of all elementary inflows from nature and outflows back to nature shown in *Fig. 3.1*, allocated to the given product system, as well as a consequence of the overall life cycle activity in the system for fulfilling its function as defined by the functional unit. This quantification is in physical units only, without any assessment of the corresponding potential environmental impact.

3.2.4 Life Cycle Impact Assessment (LCIA)

The next phase of LCA, Life Cycle Impact Assessment (LCIA), serves the purpose of determining the potential environmental impacts that may be caused by inputs and outputs from LCI. There are lots of various problematic environmental effects, which may cause problems and have to be included in the impact assessment analysis.

LCIA methods such as described in *Fig. 3.7* exist for midpoint and endpoint level of the environmental impact pathway. These two levels have advantages and disadvantages. In general, on midpoint level a higher number of impact categories is differentiated (typically around 10 items) and the results are more accurate and precise compared to the three areas of protection at endpoint level commonly used for endpoint assessments.

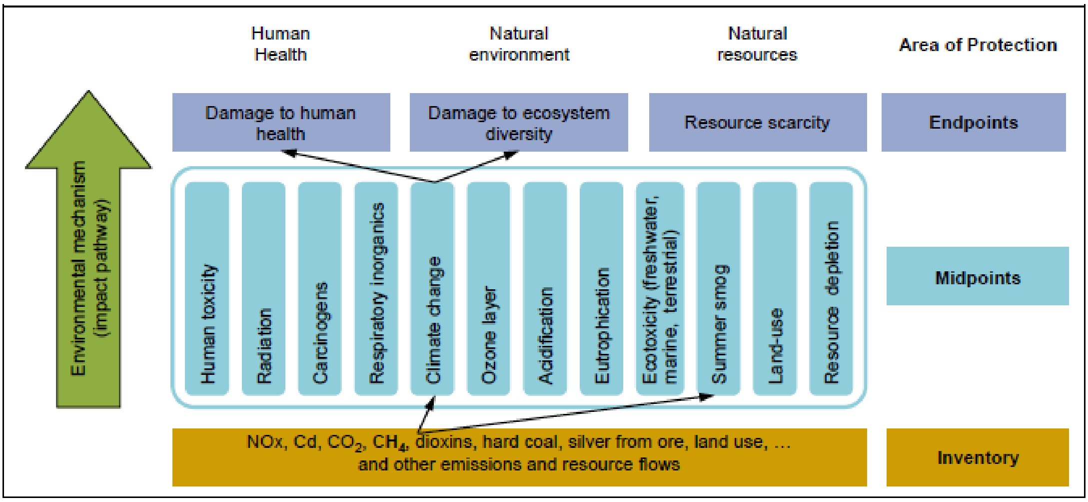


Figure 3.7. Life Cycle Impact Assessment (LCIA) on the basis of inventory data (European Commission 2010b).

The following environmental impact categories are to be included in an EPD for constructions (International EPD®System 2010) and should be included in an LCA as well:

- Emissions of greenhouse gases expressed as Global Warming Potential (GWP).
- Emissions of ozone-depleting gases expressed as the sum of Ozone-Depleting Potential (ODP).
- Emissions of acidification gases expressed as the sum of Acidification Potential (AP).
- Emissions of gases that contribute to the creation of ground level ozone expressed as the sum of Ozone-Creating Potential (POCP).
- Emissions of substances to water contributing to oxygen depletion expressed as Eutrophication Potential (EP).

All these emissions are to be measured in gas equivalents given in EPD. Many other environmental impact categories besides those listed above are part of a comprehensive LCIA. For instance, *Fig. 3.7* shows twelve midpoint indicators, each represents a different environmental impact category. In practice, the choice of how many, and which, indicators are to be included in an LCA should be decided as part of the goal and scope definition, and refer to the purpose of the analysis.

It is common to say that the LCIA methodology has four steps shown in *Fig. 3.8*. The first two are classification and characterisation, and transform of LCI results (amounts of input and output elementary flows, such as NH_3, NO_x, SO_2, P, etc.) to the midpoint level equivalent values (such as acidification potential AP, eutrophication potential EP, global warming potential GWP, etc.). One environmental stressor, i.e. substance from LCI, may contribute to several midpoint indicators, such as NO_x (contributing both to AP and EP), and several stressors can certainly contribute to the same midpoint indicator, such as different greenhouse gases (CO_2 and CH_4, contributing to GWP).

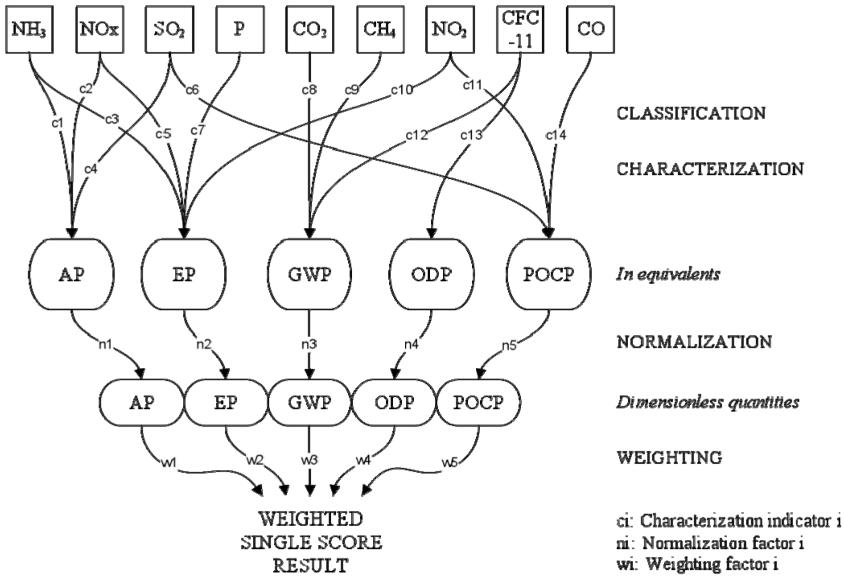


Figure 3.8. Steps in the Life Cycle Impact Assessment (LCIA) methodology.

In classification, it is decided which of the stressors are contributing to which of the midpoint environmental impact categories. In characterisation, their relative importance with respect to that impact potential is determined, in equivalent units. For instance, methane CH_4 has a global warming potential GWP100 of 25 CO_2-equivalents (over a 100 years' time horizon), which means that methane is 25 times stronger than carbon dioxide with respect to GWP, and therefore has a characterisation factor (*c*) of 25.

Classification and characterisation are the steps needed for categorising the numerous LCI results into a limited number of known environmental impacts. These two steps have to be included in any LCIA methodology. However, there are several different LCIA methods on how to calculate the midpoint indicator values on the basis of a given LCI dataset. These include LCIA methods such as the IPCC baseline model of 100 years for GWP, the USEtox model for human toxicity and eco toxicity, and the CML2002 method for several indicators. Similarly, there are different methods available for transforming midpoint indicators to endpoint level results. The ILCD Handbook (European Commission 2011b) contains recommendations for the methods which are to be used (as the preferred ones) for each midpoint and endpoint indicator. It is expected that commercial LCA software systems will adapt this in the near future.

As can be found from *Fig. 3.8*, midpoint level results may be further processed, through the steps of normalisation and weighting to obtain one weighted single score result. In the normalisation process, midpoint equivalent results (such as for GWP) are multiplied by a normalisation factor (*n*) equal to the inverse value of the per capita equivalent of the same indicator (GWP) for a given region (such as the global or European per capita level GWP contributions). In the weighting process, normalised values are multiplied by a weighting factor (*w*), which reflects the stakeholder or political priority of relative importance of the different environmental impact categories. These two steps are not compulsory parts of LCIA, and in fact, if LCA results are to be disclosed to the public, normalisation and weighting are not to be carried out. The reason is that these two steps are much less objective, and therefore without a scientific basis but subjective and strongly related to stakeholder priorities and policy preferences. On the other hand, many stakeholders do not (of course) understand much of the details of LCA, and therefore they also prefer a limited number of dependent variables (results) to take into account in their decision-making process.

3.2.5 Mathematical description of LCA

At first, the amount of each input and output must be calculated as part of LCI. The stressors with respect to environmental impact are shown in *Figs 3.7 and 3.8.*

$$e_{ij} = x_i \cdot f_{ij} \tag{3.1}$$

where

e_{ij} is the amount of substance or stressor j (e.g. CH_4, in kg) caused by the total consumption of resource i (e.g. concrete),

x_i is the consumption of resource i (concrete, in kg),

f_{ij} is the emission of substance j per unit of resource i (e.g. kg CH_4 per kg concrete).

Classification is calculated by

$$d_k = \sum_{i=1,j=1}^{i=o,j=p} (e_{ij} \cdot c_{jk}) \tag{3.2}$$

where

d_k is the total potential impact in environmental category k, and

c_{jk} is the characterisation factor for substance j with respect to impact category k.

Normalisation is carried out by

$$m_k = d_k \cdot n_k \tag{3.3}$$

where

m_k is the per capita normalised potential impact of environmental category k, and

n_k is the normalisation factor for category k.

The normalisation factor is the inverse value of the per capita sum of emissions (contributions) to the given impact category, e.g. GWP in kg CO_2-eq per capita per year.

Finally, weighted single score result is determined as a sum

$$v = \sum_{k=1}^{k=q} (m_k \cdot w_k) \tag{3.4}$$

where w_k is the weighting factor of environmental impact category k (*Fig. 3.8).*

The first two steps, using Eqs 3.1 and 3.2, are required parts of any LCIA method, in order to come to midpoint indicators. On the other hand, the last two steps, using Eqs 3.3 and 3.4, are voluntary options that can be skipped, and must be skipped of the LCA results are to be used for external communication and competition (such as in a product EPD). The advantage of including these last steps is that LCA results are aggregated into one indicator only, which is easier to relate to by a non-environment expert. However, then this requires that a set of normalization factors n_k and weighting factors w_k are agreed upon. Common normalisation factors in LCA are the ones developed for Western Europe or the entire world, which then represent the inverse of per-capita annual emissions of the given impact category indicator, such as CO_2-equivalents in Western Europe or the entire world. In LCA Handbook (European Commission 2010 b), it is stated that if normalisation is applied, the used weighting factors must be shown. These can relate to an equal weighting (1:1:1:etc) of all environmental midpoint indicators, or one can define a project-specific or sector-specific set of weighting factors according to the policies. Hence, the weighting factors are clearly subjective choices.

3.2.6 Interpretation

The Interpretation phase in LCA has two main purposes (European Commission 2010b):

- During the iterative steps of the LCA and for all kinds of deliverables, the interpretation phase serves to steer the work towards improving the LCI model to meet the needs derived from the goal definition (*Fig. 3.9*).
- If the iterative steps of the LCA have resulted in the final LCI model and results, especially for comparative LCA studies, the interpretation phase is used to derive robust conclusions and recommendations.

The final outcome of the interpretation should be conclusions or recommendations, which are to respect the intentions and restrictions of the goal and scope definition of the study. The interpretation should present the results of the LCA in a comprehensible way and help the user of the analysis to evaluate the robustness of the conclusions and comprehend any potential limitations.

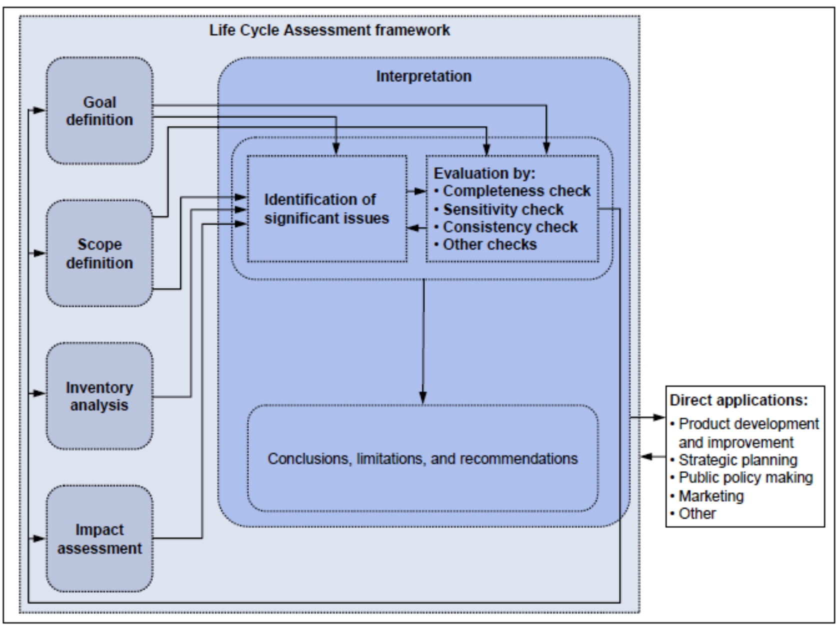


Figure 3.9. Activities in the interpretation phase of LCA.

The interpretation phase includes three activities as shown in *Fig. 3.9*:

- The significant issues are identified.
- The identified issues are evaluated with regard to their sensitivity or influence on the overall results of the LCA. This includes an evaluation of the completeness and consistency which have been handled according to LCI or LCA analysis.
- The results of the evaluation are used in the formulation of conclusions and recommendations from the LCA study.

It is important to understand that LCA, despite the fact that it is based on internationally standardised and recognised methodology, several assumptions and value choices must be taken into account. Due to uncertainties in data, the reliability, accuracy and robustness of the LCI and LCIA results are somewhat inaccurate, and influence the reliability of conclusions and recommendations of the LCA study. Hence, it is all-important to carry out the completeness check, the sensitivity check and the consistency check in the evaluation step of LCA interpretation as shown in *Fig.3.9*.

3.3 Literature review on LCA of road bridges

A thorough examination of the international literature on LCA for bridge studies was carried out during ETSI Project Stage 2. The main findings from literature are presented also in a more recently published paper by *Hammervold J., Reenaas M.* and *Brattebø H.* (2012), in addition to a comparative study of three case bridges, using an earlier version of the *BridgeLCA* model. The three case bridges analysed have already been built and in service in Western Norway: steel box girder, concrete box girder and wooden arch bridge. Thus, one could get hold of detailed facts of resource consumption in the production and construction phase of the bridges.

3.3.1 Comparison of different bridge type alternatives

Gervásio H., da Silva L.S. (2008) compared a prestressed concrete box girder bridge and a steel-concrete composite I-girder bridge. The emissions of equivalent considered were CO_2, SO_2, NO_x, VOC, CO, CH_4 and particles, classified into six categories of environmental impact: global warming, acidification, eutrophication, criteria air pollutants, smog formation and water intake. These categories were normalised using US emissions per capita and per year. The results from LCA analysis showed that the composite bridge had the best overall environmental performance, but for the categories such as global warming, water intake and eutrophication the concrete bridge was best alternative.

Collings, D. (2006) made an environmental comparison between bridge types in two studies. The first study was a comparison of three alternative bridge designs for the same construction site (a major creek crossing in the Middle East). The second study was similarly on three alternative bridge types crossing a 120-metre wide river in the United Kingdom.

The first study comprised a concrete cantilever bridge, a concrete cable-stayed bridge and a steel arch bridge. The obtained results showed that the concrete cantilever bridge was the most beneficial in environmental sense. The concrete cable-stayed bridge caused 30% and the steel arch bridge caused 90% more environmental burden than the concrete cantilever bridge. The study also concluded that paint, waterproofing and plastics used in construction influence strongly energy consumption and CO_2 emission. The second study considered three basic bridge types with different material choices for each alternative. The alternatives are: girder, arch and cable stayed bridges made of steel, concrete or steel-concrete composite. It was found that bridges made of concrete had the lowest embodied energy and CO_2 emission values, but for short-span structures, the difference between concrete and steel-concrete was found to be insignificant. Emissions during the service phase of the bridge are approximately at the same level for the three superstructures choices, and most of the emissions were related to resurfacing of the bridge.

*Horvath, A. and C. Hendrickson (*1998) presented a comprehensive environmental assessment on steel and concrete bridges. Three groups of environmental impacts were quantified in the study: TRI chemical emissions, hazardous waste generation and conventional air pollutant emissions. The concrete bridge according to this study had lower overall environmental effects. Environmental effects calculated for the lifetime of the bridge can be highly important, as SO_2, NO_x, CH_4 and VOC emissions were significantly higher for paint manufacturing than for the production of the girders for example the bridge made of steel.

Itoh, Y, and T. Kitagawa. (2003) used a modified life cycle methodology to evaluate and compare two types of steel bridges; a conventional and a minimised girder bridge. The bridges are compared regarding CO_2 emissions and costs.

3.3.2 Comparison of different bridge component alternatives

Keoleian, G. A., A. Kendall, et al. (2005) compared two deck systems, a concrete deck with conventional steel expansion joints and a concrete deck with a link slab design in which Engineered Cementitious Composites (ECC) was used as concrete alternative. Various pollutants to air (CO_2, CH_4, CO, PM10, NMHC, NO_x, SO_x) and water (BOD, NH_x, PO_4^{3}-, oils, suspended matter and dissolved matter) were considered. The analysis shows that the ECC deck yields significantly lower environmental impacts.

Steele, K., G. Cole, et al. (2003) presents a methodology applicable to all kinds of bridges. It was concluded in the paper that material reduction is important, but one should not compromise durability and longevity of the structure. Steel and concrete are major constituents in new bridges. Manufacturing of these materials is the biggest cause to environmental impact over the life cycle of the structure. Joints, bearings and parapets are often made of other materials and have much less impact, even when allowing for service life renewal. According to the report, it is unlikely to see that either steel or concrete is inherently better from the environmental point of view. Good maintenance prevents deterioration and extends structural life. Mostly, refurbishment and strengthening represent a lower environmental impact than structure replacement. At structure closures, traffic disruption can represent higher environmental impact than the maintenance activity and in some cases higher than the actual construction of the bridge. Foreseeable future needs, e.g. the need for extra deck or abutment width, homogenous load capacity or use of loose-fit components gives allowance for increase capacity. Findings indicate that this raises initial impacts, but will reduce impact in the long run. However, it is remarked that this must be balanced with over-design.

In *Martin, A. J.* (2004) environmental issues regarding concrete bridges are described and two earlier studies comparing different alternatives for bridge decks (including girders) are presented. The first study presented comparison of two bridge deck designs. Concrete deck on steel girders and concrete deck on concrete girders. The decks are compared regarding the energy use and Greenhouse Gas (GHG) emissions. The results showed that the original concrete deck alternative consumes 39 % less energy and yields 17 % less CO_2 emission than the deck where steel girders were used. The latter was more beneficial in recycling sense, partly because it is easier to separate in EOL. The second study compared three deck alternatives using lightweight, normal and high-strength concrete. It was concluded that there is no significant difference in energy consumption. However, the high-strength concrete has supposedly longer durability, and thus probably is the environmentally preferred alternative.

In *Bouhaya, L., R. Le Roy,* et al. (2009) an innovative bridge structure made of wood and ultra-high performance concrete is studied using LCA methodology. The study includes energy use and GHG. For wood, CO_2 uptake during growth is included, and three scenarios for EOL treatment are assessed; Scenario 1) burying in landfills, assuming that only 15 % deteriorates and emits CO_2 and CH_4, the remaining 85 % constitutes a stock of carbon, Scenario 2) Incineration, compared to burning of natural gas and Scenario 3) Recycling (zero emissions). The total results for the three scenarios showed that the inclusion of CO_2 captured during tree growth offsets the emissions stemming from other parts of the system. For scenarios 1 and 3, the uptake of CO_2 during tree growth is actually higher than the emissions in the remaining of the bridge life cycle, and hence the total life cycle GHG emissions for the bridge are negative. Another finding is that the transportation and the construction phase contribute small amounts to the total energy use and GHG emissions (savings), while it is the production phase that contributes most energy use and GHG emission savings.

As a conclusion from the reference literature referred to above, it may be agreed that there are several LCA studies carried out on bridges, providing helpful information to designers. On the other hand, it may be difficult to extract a set of few generic recommendations for environmentally benign bridge design, due to the fact that the studies are carried out under various assumptions. One observation is that no study yet documented the environmental life cycle performance of bridges, comparing different designs by using a standardised bridge design classification, where consumption of materials and energy carriers in a more systematic way are related to the various bridge parts (components).

The work of *Hammervold J., Reenaas M. and Brattebø H.* (2012) also examined three case bridges, shown in *Table 3.1*.The main results of the LCA studies are given in *Figs 3.10* and *3.11*, respectively.

Table 3.1. Basic data for three Norwegian case bridges.

	Klenevaagen	**Fretheim**	**Hillersvika**
Type	Steel box girder	Wooden arch	Concrete box girder
Bridge span	42.8 m	37.9 m	39.3 m
Effective width	7.5 m	6.1 m	10.6 m
Traffic lanes	2	1	2
Pavement	0	1	1
Bridge deck area	321 m^2	229 m^2	417 m^2

Hillersvika is the largest bridge, with the deck area of 417 m^2. This bridge has two traffic lanes and one pavement, while *Klenevaagen* has two traffic lanes and no pavement and F*retheim* has one traffic lane and one pavement. *Klenevaagen* has a surface area of 321 m^2 and Fretheim has a surface area of 229 m^2. These three bridges are chosen as they represent bridges of three material choices: steel, concrete and wood. In this way, important parameters affecting environmental performance for these types of bridges can be identified. The production of the bridges consumed different amount of inputs (materials and energy), and different OR&M schedules were also assumed. More detailed information is available in the published paper (*Hammervold* et al. 2012) and in the previous ETSI Stage 2 report.

Total weighted results per functional unit for all the three bridges are shown in *Fig. 3.10*, relative to *Klenevaagen* Bridge. After normalisation and weighting, the impact categories GWP, ADP and to some extent AP turn out to be the most important factors. There are some impacts to EP and POP, but insignificant impacts to ODP. *Hillersvika* (concrete bridge) performs best compared to the other two bridges. Fig. 3.11 shows the total weighted impacts split up into input parameters for each bridge.

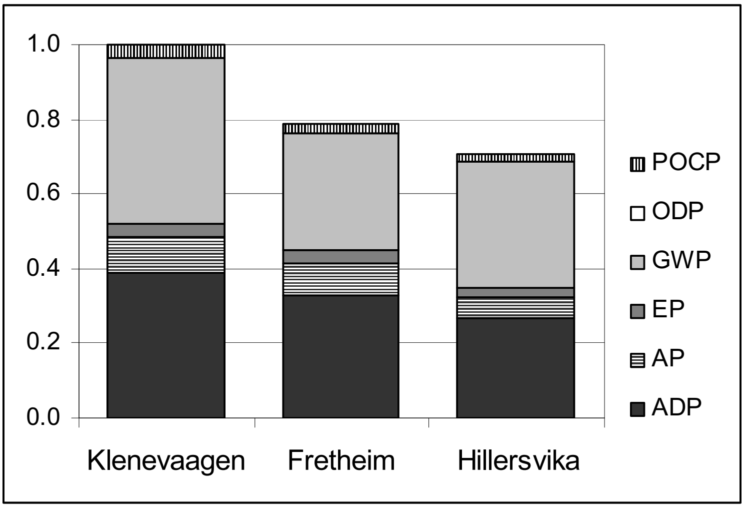


Figure 3.10. Total weighted impacts, relative to results for Klenevaagen Bridge (calculated on a per m^2 effective bridge area basis).

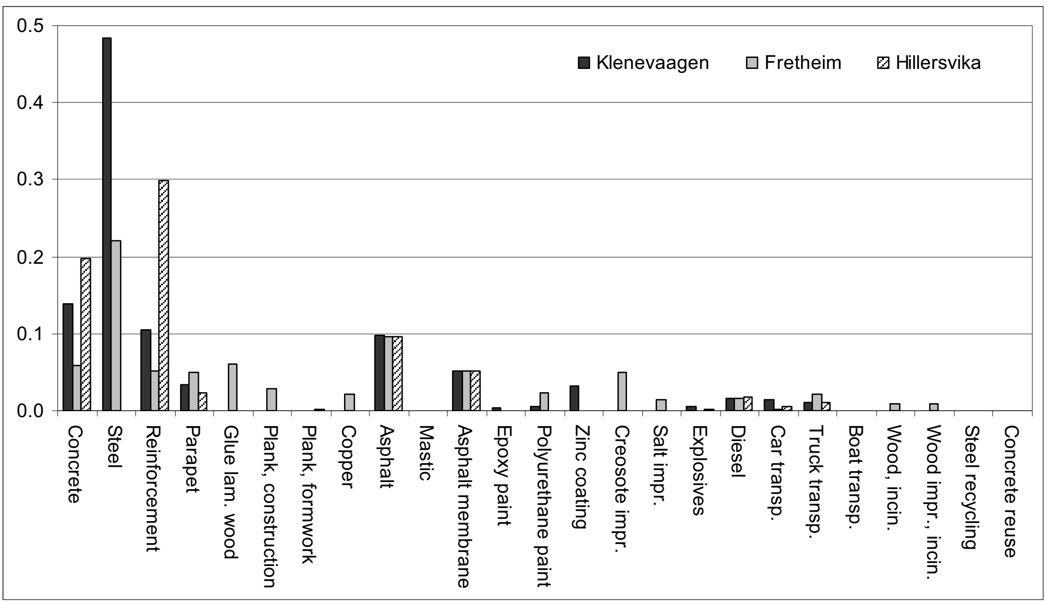


Figure 3.11. Total weighted impacts per functional unit, split up into input parameters.

The main materials concrete, steel, wood and asphalt are contributing to the major share of the emissions. Some of the materials used in smaller quantities are contributing to somewhat as well, like asphalt membrane, copper, creosote and zinc coating, together with car, truck and diesel consumption. The analysis showed that *Hillersvika* concrete box girder bridge was in this case the environmentally preferred alternative, but *Hammervold J., Reenaas M. and Brattebø H.* (2012) noted that one cannot draw general conclusions.

From literature it can be concluded that the most important materials regarding environmental performance are the materials in the main load bearing structures (construction steel, concrete, reinforcement, glue laminated wood, copper), followed by the concrete and reinforcement in the abutments, and finally the parapets and the surfacing materials as asphalt and asphalt membranes. Impregnation treatment or painting of the wood and the surface treatment of steel (at least zinc coating) are also of relevance. Use of building equipment and transportation of materials and personnel during the construction phase of the bridges are of minor importance. This is also the case for use of formwork, mastic, blasting and the incineration of wood at EOL. It is also worth paying attention to the diesel consumption in the construction phase, as this parameter varies a lot for different bridge designs and construction site conditions.

3.4 Definitions and measures used in the ETSI BridgeLCA tool

3.4.1 Background

To use effectively developed LCA tool – *BridgeLCA* for bridges, a few parameters have to be defined and explained, some of these are already in Chapter 2, where LCC tool was introduced.

3.4.2 Definition of bridge parts and their measures

The definition of bridge parts and their measures are presented in Chapter 2.

BridgeLCA is structured with use of an "*Input sheet*", where the user can manually input the actual amounts of materials and energy carriers that are consumed in the production of the bridge parts in *Table 2.2*. It is essential that the user of the program after having run *BridgeLCA,* can spot back on exactly which bridge parts contribute to the total environmental or a given midpoint indicator impact of a bridge.

In addition to the production phase of bridge parts, the bridge system also includes the construction phase, the OR&M phase, and the EOL phase, where there will be also consumption of material and energy inputs.

Moreover, all masses in the system have to be transported, either by ship, lorry or train. Emissions from transportation within the production phase are normally included in the emission data from production of a given material, therefore such transportation will not have to be specified explicitly in *BridgeLCA*. However, one must define the transportation mode and distance for:

- Materials from production (factory) gate to site in the construction phase.
- Replacement materials during the OR&M phase.
- Waste materials to dispose during the EOL phase.

3.4.3 Definition of bridge materials

Bridge materials are defined and listed in *Table 2.3* and some of them are common for both LCC and LCA.

BridgeLCA distinguishes among:

- Materials with major LCA impact (concrete, construction steel, reinforcement steel, prestressing steel, timber and asphalt).
- Materials with minor LCA impact (asphalt membrane, epoxy, rubberised bitumen lotion, asphalt mastic, polyurethane, zinc coating, paint, glass, creosote impregnation, salt impregnation, acryl, polycarbonate and plastic).
- Other input factors (energy – electricity or diesel, and blasting and transportation).

The materials with major LCA impacts are selected on the basis of what has been learned in ETSI Stage 2, using the philosophy that one would want to keep the LCA fairly simple using only country-specific or project-specific emission data for a limited number of materials. These definitely should be the materials that are likely to contribute to the largest share of environmental impact for a bridge system, regardless of the specific design of the bridge. Hence, it was decided to select concrete and construction steel, both with the option of specifying different qualities, as well as reinforcement steel, prestressing steel, timber and asphalt.

The materials with minor LCA impacts are selected due to the fact that these materials may also be consumed in quantities so that they give a significant added contribution to the environmental impact of a bridge. Hence, in a detailed LCA of bridge, the analyst may also choose to input good estimates of such materials. However, materials with minor LCA impact do not need the use of country- or project-specific emission data. In such case one may rely on emission data from commercial LCA databases.

Other input factors like electricity and diesel, blasting explosives and transportation are important to be included, because they may give substantial contributions to environmental impact from the construction phase, the OR&M phase or the bridge demolition in the EOL phase.

3.4.4 Definition of actions

Actions after the bridge is built are fairly much the same in LCC calculations, but in LCC analysis, not all these actions are of main importance as the consumptions of materials and energy are the direct reasons for environmental impacts in LCA perspective.

In *BridgeLCA* the following actions as defined:

- OR&M with all actions lumped together in one phase regardless of when they occur during the service life of the bridge.
- The action of the EOL phase is defined as:
    - input to demolition,
    - materials to landfill,
    - materials to material recycling and
    - materials to energy recovery.

The estimated consumption of inputs (materials and energy) related to the actions in the OR&M phase of a bridge should be taken from the Life Cycle Plan (LCP) of the bridge. In ETSI Project (Appendix 2), the default service life of a road bridge is set to 100 years, and the LCP should reflect this when calculating how many times certain bridge parts (like bearings and parapets) or layers (like asphalt and surface coating) have to be repaired or replaced.

The consumption of inputs to the demolition of the bridge will have to be estimated, if such information is not included in the LCP of the given bridge.

3.4.5 Extra traffic caused by repair and maintenance actions

When bridge deck is under repair or maintenance actions, usually extra traffic is generated. It can lead to partly or full closure of the bridge, in one or both driving directions. When this occurs, extra traffic is generated, due to slowing down the average speed of traffic caused by congested driving patterns or traffic stops. In such situations part of the traffic may choose alternative routes, e.g. detours giving a longer driving distance.

BridgeLCA of a bridge is able to take account of impacts of traffic due to planned OR&M actions, according to LCP of the bridge. This is particularly important when heavy traffic is using the route. Different bridge designs cause different OR&M actions and lead to different emissions from the traffic.

BridgeLCA offers the possibility to calculate vehicle fuel consumption due to extra traffic generated by planned OR&M activities. The user of the program needs to input the number of days that is duration of planned OR&M action in the whole bridge service life which leads to partly or full bridge closure. In addition, the user of the program needs to input assumptions on the traffic pattern during OR&M actions:

- Assumed consumption of the vehicles using the route (percentage share of passenger petrol cars, passenger diesel cars, buses and lorries).
- Assumed extra driving distance, average driving speed, Average Daily Traffic (ADT) and assumed traffic load driving pattern (free flowing traffic, average flowing traffic, congested traffic).

Accordingly, the fuel consumption from the extra traffic generated by planned OR&M actions are calculated based on ADT, the mix of the vehicle fleet, distance, average speed and assumed traffic load driving pattern. This fuel consumption (petrol or diesel) is then used to calculate emissions and environmental impacts caused by the extra traffic due to planned OR&M actions.

3.4.6 Environmental impact categories and LCIA method

BridgeLCA includes a selection of eight different environmental impact categories which is shown in the *Table 3.2*.

Table 3.2. Environmental impact categories and corresponding LCIA characterisation method.

Environmental impact category		**LCIA method**
Climate change	unit : GWP	ReCiPe, kg CO_2 eq
Ozone depletion	unit : ODP	ReCiPe, kg CFC-11 eq
Terrestrial acidification	unit : AP	ReCiPe, kg SO_2 eq
Freshwater eutrophication	unit : EP	ReCiPe, kg P eq
Fossil depletion (FD)	unit : FD	ReCiPe, kg oil eq
Human toxicity, cancer (HTC)		USEtox, CTUh
Human toxicity, non-cancer (HTNC)		USEtox, CTUh
Eco toxicity (ET)		USEtox, CTUe

The first five categories are all calculated by use of the ReCiPe LCIA method, while the last three categories are calculated by use of the USEtox method.

The chosen impact categories are based on principles given in PCR Basic Module for Constructions (International EPD®System 2010), referred in Section 3.2.4 and earlier ETSI Project result:

- *BridgeLCA* includes environmental impact categories that are commonly important to construction projects proposed by PCR.
- Climate change, Acidification and Abiotic resource depletion were the most important impact categories for bridges, according to results from ETSI Stage 2. Eutrophication was found to be less important, and the creation of ground level ozone unimportant.
- Energy consumption and toxicity are new considered impacts. *BridgeLCA* includes now impact categories Fossil depletion, Human toxicity (cancer and non-cancer) and Eco toxicity.

As methods for LCIA calculation, *BridgeLCA* uses the methods that are recommended for the best-practice LCA in the LCA Handbook (*European Commission* (2010b)). According to this, ReCiPe is used for the calculation of midpoint indicator values for the first five impact categories of the *Table 3.2* and USEtox is used for the calculation of the three toxicity midpoint indicators. Both methods are available in the *SimaPro LCA* software and the Ecoinvent v2 Database, which can be used in calculating the LCI stressors of the inputs for a bridge system.

Midpoint indicator impact values in BridgeLCA are specified for each input values (material or energy) for a bridge system. There are three alternatives as shown in *Table 3.3*. The default values in the program are taken from the Ecoinvent v2 Database. Hence, the user of *BridgeLCA* needs a licence from Ecoinvent. These default values are always used as input materials of minor LCA impact. For materials of major LCA impact, *BridgeLCA* also offers the possibility of using either country-specific or project-specific impact values. Country-specific average impact values for major materials have been developed during ETSI Project, and can be inserted in *BridgeLCA* as soon as they are finally reported (Appendix 2). Project-specific impact values could be inserted on the basis of more local precise information, such as EPD data for given materials. The calculations are coded in such a way that project-specific data will always be preferred and used if available. If not, the program asks for country-specific values. If these are yet not present, the program automatically tells the user to use Ecoinvent values in the calculations.

Table 3.3. Options for use of midpoint indicator impact values in BridgeLCA.

Input type	**Ecoinvent**	**Country specific**	**Project specific**
Materials of major LCA impact	X	X	X
Materials of minor LCA impact	X		
Energy	X	X	X
Blasting	X	X	X
Transportation	X	X	X

BridgeLCA midpoint indicator values for the first five environmental impact categories listed in *Table 3.2* are also calculated further by normalisation and weighting, according to Eqs (3.3) and (3.4). Normalisation is calculated by using latest ReCiPe normalisation factors on a per capita emission basis in EU 25+3 for the year 2000. Default weighting in *BridgeLCA* is equal weighting among all impact categories, but the user of the program can change this according to future policy priorities defined by the national road administrations. The values of normalization and default weighting factors used in the LCA model are shown in *Table 3.4*.

Table 3.4. Normalisation and weighting factors used in BridgeLCA.

Environmental impact category		**Normalization factors**	**Weighting factor**
Climate change	unit : GWP	8,92E-05 kg CO_2 eq	1 (default value)
Ozone depletion	unit : ODP	4,55E+01 kg CFC-11 eq	1 (default value)
Terrestrial acidification	unit : AP	2,91E-02 kg SO_2 eq	1 (default value)
Freshwater eutrophication	unit : EP	2,41E+00 kg P eq	1 (default value)
Fossil depletion (FD)	unit : FD	6,01E-04 kg oil eq	1 (default value)
Human toxicity, cancer (HTC)		Not included	Not included
Human toxicity, non-cancer (HTNC)		Not included	Not included
Eco toxicity (ET)		Not included	Not included

Toxicity impact values are not subject to normalisation and weighting, and therefore are not included in the calculation towards a single score aggregated impact result. The reason is that toxicity impacts are still subject to much higher uncertainties today.

3.4.7 Energy consumption

Energy consumption is calculated more specifically divided into two categories:

- Non-renewable energy consumption, which are fossil energy, nuclear energy and non-renewable biomass energy.
- Renewable energy consumption, which are renewable biomass energy, wind-, solar- and geothermic energy and hydropower.

The share of these different energy sources is calculated as absolute values (MJ) and in percentage (%) values of the total consumption. It is also shown how much each bridge part or activity during the service life of the bridge, contributes to the energy consumption.

3.5 BridgeLCA program description

The renewed LCA tool – *BridgeLCA* is an Excel-based tool for calculating the life cycle environmental impacts of a bridge system based on the methodology explained earlier.

The key features of *BridgeLCA* are as following:

- The goal of the analysis is intended to get information how will the design of a new bridge influence the environmental life cycle quality of the bridge, so that the bridge design can be improved.
- The scope covers all life cycle phases of the bridge: production, construction, OR&M and EOL.

- Environmental impacts consumption of inputs, which are grouped in: materials of major LCA impact, materials of minor LCA impact and other input factors (energy, blasting and transportation).
- For materials of major LCA impact, project-specific emission data is to be used; otherwise, use national average emission data; or else, use default values from the Ecoinvent LCA Database. For materials of minor LCA impact, only Ecoinvent default data are used. For other input factors one can use project- or country-specific emission data.
- *BridgeLCA* includes eight impact categories, five environmental and three eoxicity categories.
- Benefits from materials recycling and energy recovery to other product systems after the EOL of the bridge, are credited to the other systems instead of LCA of the bridge.
- The *BridgeLCA* calculates midpoint impact indicator values, so that one can identify their causes in the bridge system.
- The *BridgeLCA* can also be used to calculate a normalised and weighted single-score indicator, but the result will be far more subjective and rely upon a consensus on weighting factors among key bridge stakeholders. In order to reduce further uncertainty, toxicity impact categories are not part of such single-score calculations.

The *BridgeLCA* has altogether 18 worksheets, linked into a complete model:

- Worksheet No. 1 is starting sheet containing welcome information and links to the User Manual.
- Worksheets No. 2 and 3 are for the bridge input data for materials and traffic. Consumption of input materials, energy, blasting and transportation amounts, related to each phase of the bridge life cycle are inserted to the cells of the worksheet No. 2, and data on the generation of the extra traffic due to bridge closures in the OR&M phase are inserted in worksheet No. 3.
- Worksheets No. 4 and 5 give the calculated results. Worksheet No. 4 presents LCA results (in figures and tables) as a single score normalised and weighted value, and as parallel midpoint values for each environmental midpoint indicator. Worksheet No. 5 shows results for consumption of various types of energy carriers from renewable and non-renewable sources.
- The following worksheets are mainly for the background information and used in calculation basis. Worksheet No. 6 gives the actual impact matrix that is used in given LCA calculations, Midpoint indicator values are listed for all inputs to the bridge system, according to what information is provided regarding either project- or country-specific emission data, and Ecoinvent data. Worksheets No. 7 to 14 provide opportunity of giving data for each midpoint indicator (GWP, ODP, AP, EP, FD, HTC, HTCN and ET). These data are then fed automatically into Worksheet No. 6.
- Worksheet No. 15 collects an overview of all Ecoinvent data that are used in the model.
- Worksheet No. 16 collects an overview of all energy consumption results that are related to each input to the bridge system.
- Worksheet No. 17 contains a menu-set for macros used in the model.
- Worksheet No. 18 contains codes for calculating fuel combustion on the basis of composition of vehicles in the traffic module, used as the basis for calculating how extra traffic is due to bridge closure during OR&M actions.

Examples of the Worksheets in *BridgeLCA* are shown in *Figs 3.12* to *3.17*.

In *Figs 3.12* and *3.13* the left- and the right-hand parts of a large table are shown, where the user inserts into the white cells: the quantities of inputs to the bridge system, transportation (one-way) distances by each transportation mode (ship, lorry, train). Four different phases of the bridge life cycle (material production, construction, OR&M and EOL) are distinguished. This table is the place where most of the input data from the user is to be inserted, and the user can decide to carry out a rough (simplified) LCA with little information merely, or a detailed LCA with lots of information inserted.

In *Fig. 3.14* the Input traffic worksheet is shown. The user is expected to manually insert data related to the assumptions on bridge closure duration due to OR&M actions, and traffic disturbances caused by the closures. This represents a simple traffic calculator with 4 waypoints and 4 different paths for traffic. The user inserts also assumptions on detour driving distance, speed of traffic, ADT, the type of traffic load (congested traffic, average flowing traffic or free flowing traffic), as well as the assumed mix of the vehicle fleet.

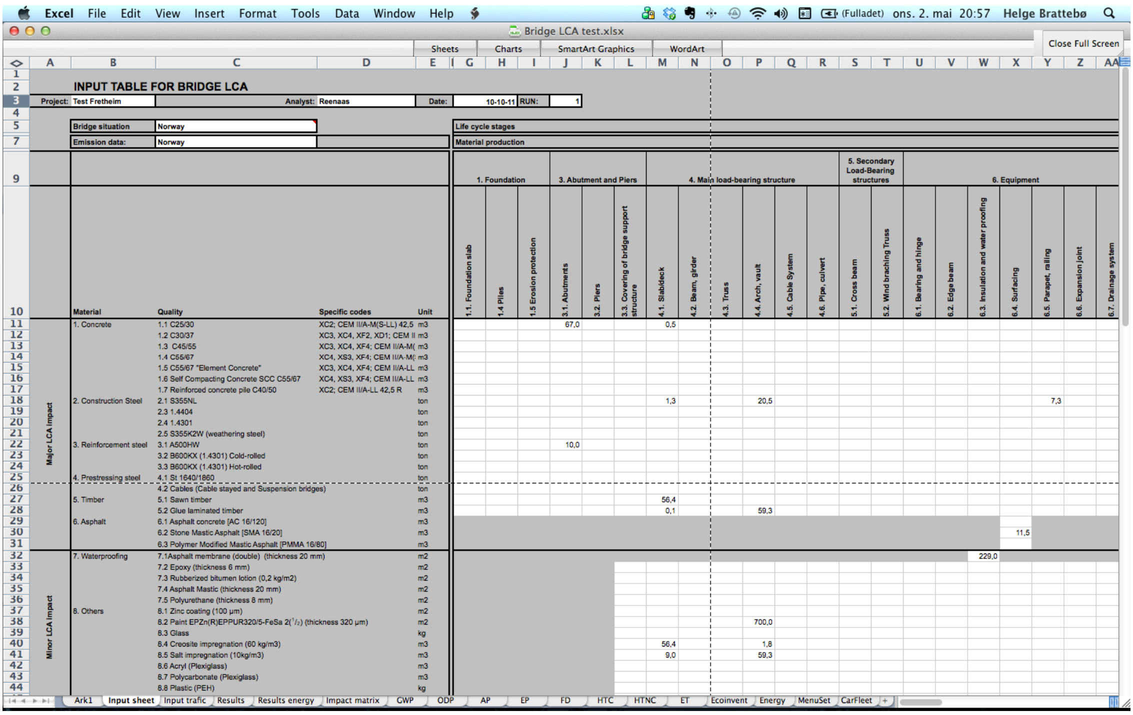


Figure 3.12. The left-hand side of the Input worksheet, for the user to manually insert data.

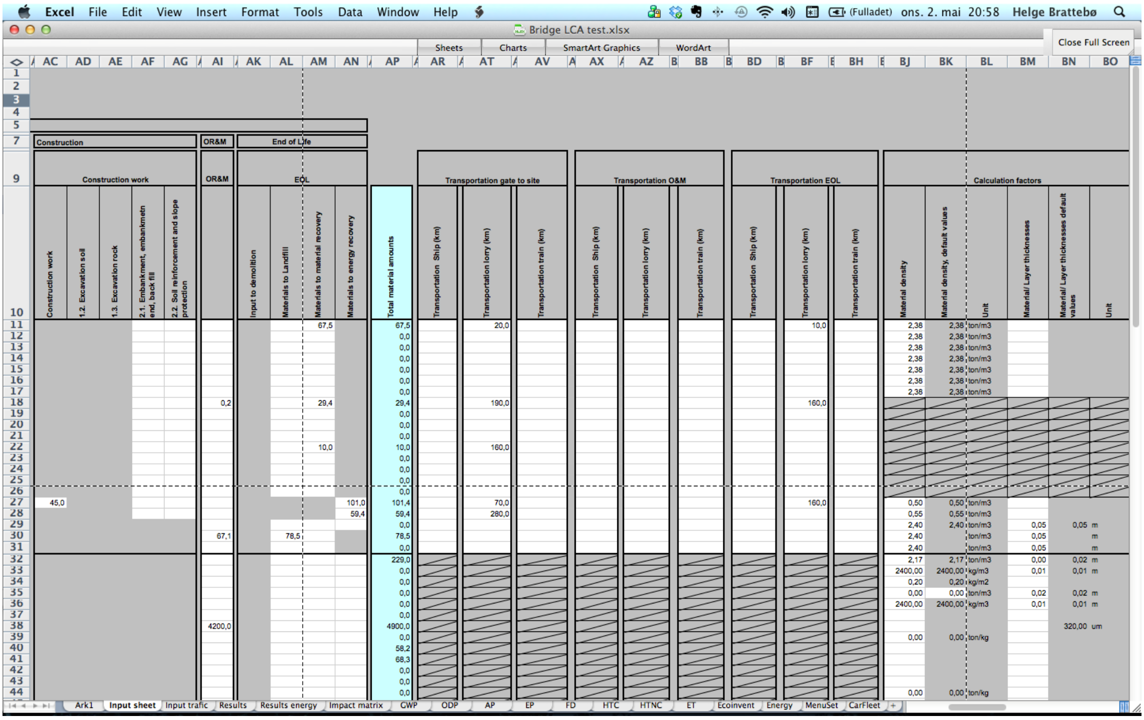


Figure 3.13. The right-hand side of the Input worksheet, for the user to manually insert data.

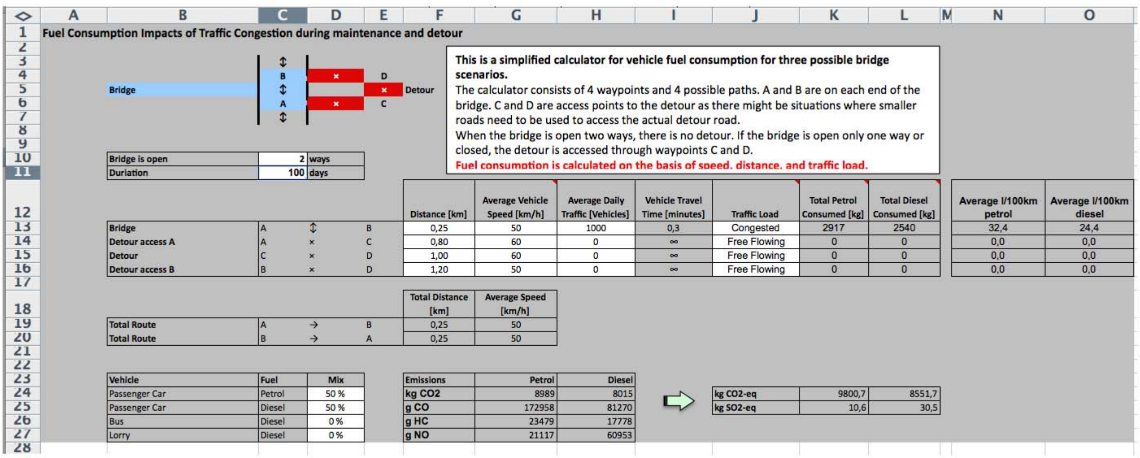


Figure 3.14. The Input traffic worksheet, for the user to manually insert data.

In the example shown in *Fig. 3.14*, the bridge is never assumed to be fully closed, either driving direction, but there is OR&M actions during the service life for 100 days, causing congested traffic load pattern for 1000 ADT vehicles of which 50% are supposed to be passenger petrol cars and 50% passenger diesel cars, respectively. The distance of disturbance is 250 meters at speed of 50 km/hour. In this example, total petrol consumption is 2917 kg and total diesel consumption is 2540 kg.

The user is free to assume any combination of traffic disturbances, within the framework of this calculator method (4 waypoints and 4 possible paths). The calculator method can be used to examine different OR&M actions of the bridge with likely consequences during its service life. Hence, one may estimate the corresponding impacts of different life cycle plans for a given bridge, which will certainly depend on where the bridge is located in relation to traffic loads, disturbances and extra driving distances.

In *Figs 3.15* and *3.16* the Results worksheet is shown, the upper part (aggregated LCA results) and the lower part (detailed LCA results) of the worksheet, respectively. The aggregated results represent values after normalisation and weighting. On the left side of *Fig. 3.15*, the histogram shows the results of normalised LCIA and weighted LCIA. In this example, no difference can be seen, since equal weighting factors (1:1:1:etc) were used for all midpoint impact categories. If non-equal weighting factors were used, there would be a difference between these graphs. The example displays that the aggregated impact is mainly due to FD and GWP emissions. In the upper graph on the right "*Relative midpoint LCIA results*", each environmental impact indicator is presented on a relative basis, to illustrate which of the four phases of the bridge system are most important. It can be seen that the material production phase of bridge components (lower blue part) dominates in all indicators, but also a significant contribution from the OR&M phase can distinguish some indicators.

AGGREGATED RESULTS

Overall LCIA results - Midpoint results / Normalized results / Weighted results

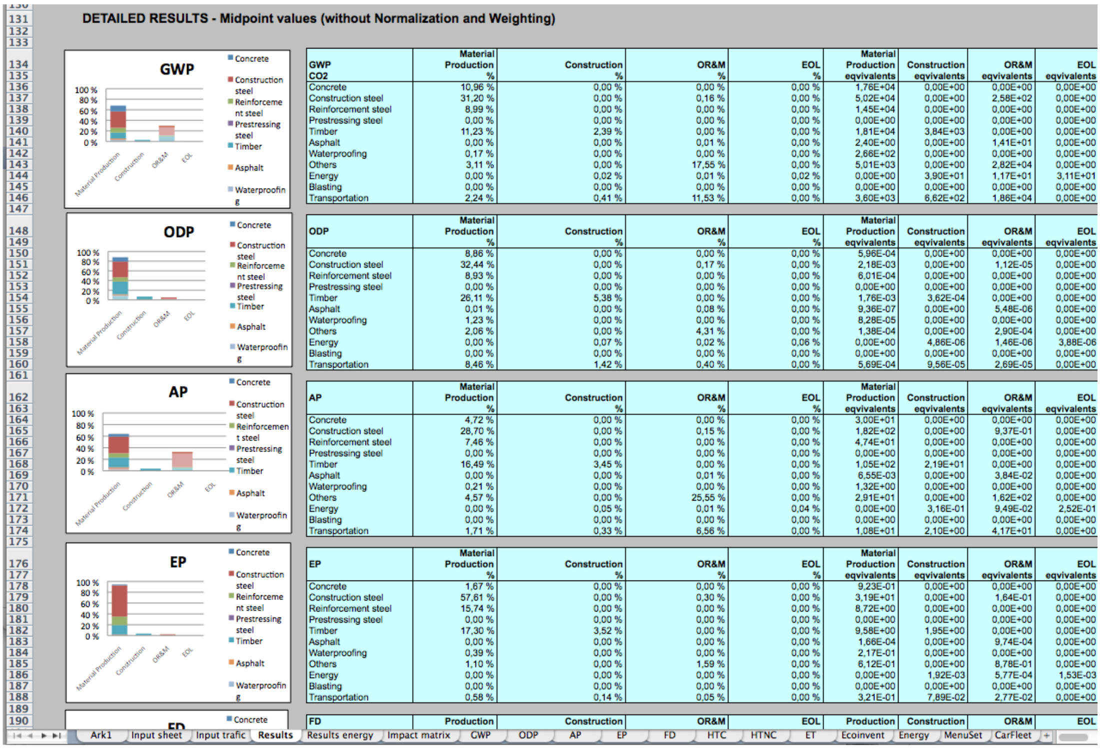
Emission category		Equivalent	Method	Midpoint results (kg eq.)	Normalised (PE)	Weighted (PE)
Climate change	GWP	kg CO2 eq	ReCiPe	1,61E+05	1,80E+09	9,02E+09
Ozone depletion	ODP	kg CFC-11 eq	ReCiPe	6,73E-03	1,48E-04	1,48E-04
Terrestrial acidification	AP	kg SO2 eq	ReCiPe	6,36E+02	2,18E+04	6,55E+04
Freshwater eutrophication	EP	kg P eq	ReCiPe	5,54E+01	2,30E+01	2,30E+01
Fossil depletion	FD	kg oil eq	ReCiPe	4,67E+04	7,78E+07	1,56E+08
Human toxicity, cancer	HTC	CTUh	USEtox	3,95E-05		
Human toxicity, non-cancer	HTNC	CTUh	USEtox	1,74E-05		
Ecotoxicity	ETX	CTUe	USEtox	1,15E+03		

Midpoint LCIA results - Distributed over bridge life cycle stages

Emission category		Equivalents	Method	Material Production	Construction	OR&M	EOL	Total
Climate change	GWP	kg CO2 eq	ReCiPe	1,09E+05	4,54E+03	4,71E+04	3,11E+01	1,61E+05
Ozone depletion	ODP	kg CFC-11 eq	ReCiPe	5,93E-03	4,62E-04	3,35E-04	3,88E-06	6,73E-03
Terrestrial acidification	AP	kg SO2 eq	ReCiPe	4,06E+02	2,43E+01	2,05E+02	2,52E-01	6,36E+02
Freshwater eutrophication	EP	kg P eq	ReCiPe	5,23E+01	2,03E+00	1,07E+00	1,53E-03	5,54E+01
Fossil depletion	ADP	kg Sb eq	ReCiPe	3,29E+04	1,53E+03	1,23E+04	1,09E+01	4,67E+04
Human toxicity, cancer	HTC	CTUh	USEtox	3,91E-05	2,69E-07	1,31E-07	2,48E-10	3,95E-05
Human toxicity, non-cancer	HTNC	CTUh	USEtox	1,68E-05	3,44E-07	2,35E-07	2,95E-10	1,74E-05
Ecotoxicity	ETX	CTUe	USEtox	1,05E+03	9,76E+01	1,63E+00	4,00E-02	1,15E+03

Figure 3.15. Screen-print of upper part of the Results worksheet, with aggregated LCA results.

In *Fig. 3.16* more detailed results can be seen, i.e. how do selected inputs to the bridge system, in each phase of the life cycle, contribute to each impact indicators. Such results provide basis for locating the most important causes to each environmental impacts and may be used to minimise emissions in bridge design.



DETAILED RESULTS - Midpoint values (without Normalization and Weighting)

GWP CO2	Material Production %	Construction %	OR&M %	EOL %	Material Production eqvivalents	Construction eqvivalents	OR&M eqvivalents	EOL eqvivalents
Concrete	10,96 %	0,00 %	0,00 %	0,00 %	1,76E+04	0,00E+00	0,00E+00	0,00E+00
Construction steel	31,20 %	0,00 %	0,16 %	0,00 %	5,02E+04	0,00E+00	2,58E+02	0,00E+00
Reinforcement steel	8,99 %	0,00 %	0,00 %	0,00 %	1,45E+04	0,00E+00	0,00E+00	0,00E+00
Prestressing steel	0,00 %	0,00 %	0,00 %	0,00 %	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Timber	11,23 %	2,39 %	0,00 %	0,00 %	1,81E+04	3,84E+03	0,00E+00	0,00E+00
Asphalt	0,00 %	0,00 %	0,01 %	0,00 %	2,40E+00	0,00E+00	1,41E+01	0,00E+00
Waterproofing	0,17 %	0,00 %	0,00 %	0,00 %	2,66E+02	0,00E+00	0,00E+00	0,00E+00
Others	3,11 %	0,00 %	17,55 %	0,00 %	5,01E+03	0,00E+00	2,82E+04	0,00E+00
Energy	0,00 %	0,02 %	0,01 %	0,02 %	0,00E+00	3,90E+01	1,17E+01	3,11E+01
Blasting	0,00 %	0,00 %	0,00 %	0,00 %	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transportation	2,24 %	0,41 %	11,53 %	0,00 %	3,60E+03	6,62E+02	1,86E+04	0,00E+00

ODP	Material Production %	Construction %	OR&M %	EOL %	Material Production eqvivalents	Construction eqvivalents	OR&M eqvivalents	EOL eqvivalents
Concrete	8,86 %	0,00 %	0,00 %	0,00 %	5,96E-04	0,00E+00	0,00E+00	0,00E+00
Construction steel	32,44 %	0,00 %	0,17 %	0,00 %	2,18E-03	0,00E+00	1,12E-05	0,00E+00
Reinforcement steel	8,93 %	0,00 %	0,00 %	0,00 %	6,01E-04	0,00E+00	0,00E+00	0,00E+00
Prestressing steel	0,00 %	0,00 %	0,00 %	0,00 %	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Timber	26,11 %	5,38 %	0,00 %	0,00 %	1,76E-03	3,62E-04	0,00E+00	0,00E+00
Asphalt	0,01 %	0,00 %	0,08 %	0,00 %	9,36E-07	0,00E+00	5,48E-06	0,00E+00
Waterproofing	1,23 %	0,00 %	0,00 %	0,00 %	8,28E-05	0,00E+00	0,00E+00	0,00E+00
Others	2,06 %	0,00 %	4,31 %	0,00 %	1,38E-04	0,00E+00	2,90E-04	0,00E+00
Energy	0,00 %	0,07 %	0,02 %	0,06 %	0,00E+00	4,86E-06	1,46E-06	3,88E-06
Blasting	0,00 %	0,00 %	0,00 %	0,00 %	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transportation	8,46 %	1,42 %	0,40 %	0,00 %	5,69E-04	9,56E-05	2,69E-05	0,00E+00

AP	Material Production %	Construction %	OR&M %	EOL %	Material Production eqvivalents	Construction eqvivalents	OR&M eqvivalents	EOL eqvivalents
Concrete	4,72 %	0,00 %	0,00 %	0,00 %	3,00E+01	0,00E+00	0,00E+00	0,00E+00
Construction steel	28,70 %	0,00 %	0,15 %	0,00 %	1,82E+02	0,00E+00	9,37E-01	0,00E+00
Reinforcement steel	7,46 %	0,00 %	0,00 %	0,00 %	4,74E+01	0,00E+00	0,00E+00	0,00E+00
Prestressing steel	0,00 %	0,00 %	0,00 %	0,00 %	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Timber	16,49 %	3,45 %	0,00 %	0,00 %	1,05E+02	2,19E+01	0,00E+00	0,00E+00
Asphalt	0,00 %	0,00 %	0,01 %	0,00 %	6,55E-03	0,00E+00	3,84E-02	0,00E+00
Waterproofing	0,21 %	0,00 %	0,00 %	0,00 %	1,32E+00	0,00E+00	0,00E+00	0,00E+00
Others	4,57 %	0,00 %	25,55 %	0,00 %	2,91E+01	0,00E+00	1,62E+02	0,00E+00
Energy	0,00 %	0,05 %	0,01 %	0,04 %	0,00E+00	3,16E-01	9,49E-02	2,52E-01
Blasting	0,00 %	0,00 %	0,00 %	0,00 %	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transportation	1,71 %	0,33 %	6,56 %	0,00 %	1,08E+01	2,10E+00	4,17E+01	0,00E+00

EP	Material Production %	Construction %	OR&M %	EOL %	Material Production eqvivalents	Construction eqvivalents	OR&M eqvivalents	EOL eqvivalents
Concrete	1,67 %	0,00 %	0,00 %	0,00 %	9,23E-01	0,00E+00	0,00E+00	0,00E+00
Construction steel	57,61 %	0,00 %	0,30 %	0,00 %	3,19E+01	0,00E+00	1,64E-01	0,00E+00
Reinforcement steel	15,74 %	0,00 %	0,00 %	0,00 %	8,72E+00	0,00E+00	0,00E+00	0,00E+00
Prestressing steel	0,00 %	0,00 %	0,00 %	0,00 %	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Timber	17,30 %	3,52 %	0,00 %	0,00 %	9,58E+00	1,95E+00	0,00E+00	0,00E+00
Asphalt	0,00 %	0,00 %	0,00 %	0,00 %	1,66E-04	0,00E+00	9,74E-04	0,00E+00
Waterproofing	0,39 %	0,00 %	0,00 %	0,00 %	2,17E-01	0,00E+00	0,00E+00	0,00E+00
Others	1,10 %	0,00 %	1,59 %	0,00 %	6,12E-01	0,00E+00	8,78E-01	0,00E+00
Energy	0,00 %	0,00 %	0,00 %	0,00 %	0,00E+00	1,92E-03	5,77E-04	1,53E-03
Blasting	0,00 %	0,00 %	0,00 %	0,00 %	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transportation	0,58 %	0,14 %	0,05 %	0,00 %	3,21E-01	7,89E-02	2,77E-02	0,00E+00

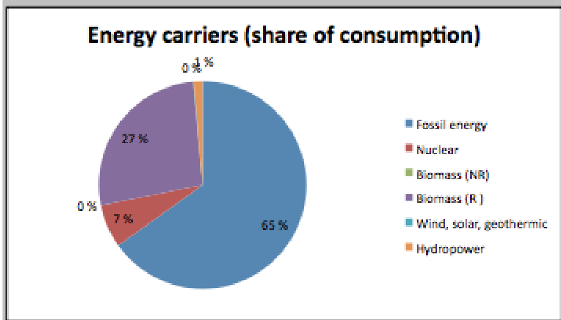
Figure 3.16. Lower part of the Results worksheet, with detailed LCA results.

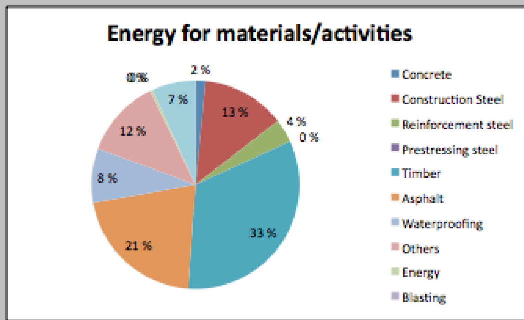
In *Fig. 3.17* results for life cycle energy consumption within the bridge system are shown, i.e. what are the absolute and percentage amounts of energy consumed (MJ and %) for different energy sources (renewable and non-renewable), and which inputs are caused by the energy consumption. Fossil energy is the main source followed by biomass energy.

RESULTS FROM ENERGY CALCULATIONS

Energy	Unit	MJ	%
Non-renewable energy	Fossil energy	4,11E+06	65,1 %
	Nuclear	4,27E+05	6,8 %
	Biomass (NR)	6,64E+00	0,0 %
Renewable energy	Biomass (R)	1,68E+06	26,7 %
	Wind, solar, geothermic	6,43E+03	0,1 %
	Hydropower	8,58E+04	1,4 %
Total		**6,31E+06**	**100,0 %**

	Energy consumption (MJ)						
Material / activity	**SUM**	**Fossil**	**Nuclear**	**Biomass (NR)**	**Biomass (R)**	**Wind, solar, geothermal**	**Hydropower**
Concrete	9,78E+04	7,28E+04	1,95E+04	2,37E-01	6,17E+02	6,64E+01	4,76E+03
Construction Steel	8,19E+05	6,89E+05	8,67E+04	4,80E-01	5,84E+03	1,59E+03	3,52E+04
Reinforcement steel	2,31E+05	2,02E+05	2,34E+04	1,21E-01	1,57E+03	4,28E+02	3,84E+03
Prestressing steel	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Timber	2,08E+06	3,18E+05	9,33E+04	9,62E-01	1,66E+06	1,59E+03	1,19E+04
Asphalt	1,33E+06	1,24E+06	6,38E+04	3,34E+00	1,30E+04	3,69E+02	1,44E+04
Waterproofing	5,32E+05	4,71E+05	5,13E+04	6,51E-01	3,20E+03	1,69E+03	5,08E+03
Others	7,68E+05	6,79E+05	7,63E+04	9,25E-02	2,80E+03	5,42E+02	8,62E+03
Energy	2,77E+04	2,70E+04	5,38E+02	3,57E-02	2,30E+01	9,97E+00	7,24E+01
Blasting	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transportation	4,27E+05	4,13E+05	1,19E+04	7,11E-01	4,03E+02	1,40E+02	1,85E+03
Sum	**6,31E+06**	**4,11E+06**	**4,27E+05**	**6,64E+00**	**1,68E+06**	**6,43E+03**	**8,58E+04**





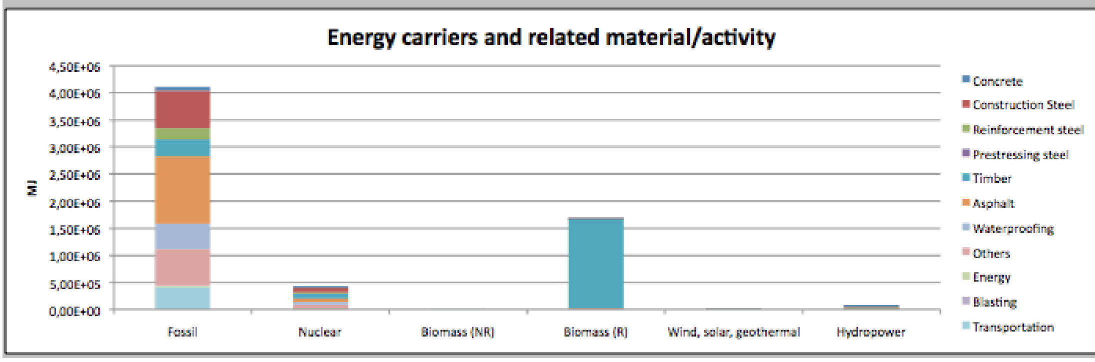


Figure 3.17. Results energy worksheet, showing energy consumption.

BridgeLCA gives different results for different bridges. For comparative purposes, the tool can be used to examine alternative design options with their own LCP and OR&M actions. The tool may also be used to test alternative bridges, using different designs and locations based on effective bridge area basis.

There are several possible ways to use the *BridgeLCA* to support decisions in the planning and design phase. This could be used already at early-stage planning when only a little information about the bridge is available. Then, many assumptions have to be taken. On the other hand, the tool can be used in detailed-planning phase, or even after the bridge has been built, when accurate data of all inputs are available.

In order to speed up the process of applying LCA for bridges, it is highly recommended that *BridgeLCA* is tested for a large number of case studies in all Scandinavian countries. This would provide a good basis for understanding better the following critical questions for the future-design - environmental friendly bridges:

- What types of environmental impacts do the bridges cause?
- What are the main contributions to environmental impacts during the life-cycle of a bridge?
- Which bridge parts and which materials are the most initial ones in environmental sense?
- How are different design options effective in reducing environmental impacts?
- What are the strengths and the weaknesses of *BridgeLCA* for a robust analysis?
- For which elements of the bridge system, do better data are needed?
- What are the priorities of databases for *BridgeLCA*?
- How can bridge designers most actively take the methodology and the *BridgeLCA* into use.
- What is the needed support from LCA experts and from the national road administrations?

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4 Bridge Aesthetics and Cultural Values

4.1 Introduction

When evaluating a bridge for its whole life cycle, it is not enough to consider only the construction and managements costs, environmental and aesthetic values should be given attention as well. One difficulty is then, how to measure, express and evaluate the aesthetic aspects so that they would be commensurable. The present study is an attempt into that direction and a continuation of the development work started in ETSI Stage 2 (2009). The basic principles and the methodology are presented and explained in detail in published project report.

4.2 Background for the aesthetics evaluation

For the life cycle cost, for which a symbol C_{LCC} is used here, the money is the only thinkable unit. Through some manipulations, environmental values can also be transferred to be expressed as money, here C_{LCA}. For aesthetical values, however, a similar manipulation is not relevant, but this difficulty can be overcome by introducing a *reduction coefficient* k_{rel} so that aesthetical values may be related to the construction cost. Consequently, the total costs could be calculated by

$$C_{total} = k_{rel} \cdot C_{LCC} + C_{LCA} \tag{4.1}$$

The current computer program is developed to calculate the value of the *reduction coefficient* k_{rel}. For such calculation, four main aspects are needed:

- Classification of the bridge site.
- A scaling *factor a.*
- The *weights* w_i for selected items.
- Grading the items by using the *points* p_i.

Classification of the bridge site is based on a system developed by the *Finnish Road Administration* (*Finnra*). It considers the value of the environment, landscape and scenery. A publication: *Siltapaikkaluokitusohje (2007) Guide for Grading a Bridge Site* is available.

A four-grade system is used for evaluation of a bridge site:

Class I	Very demanding considering the landscape and city view.
Class II	Demanding considering the landscape and city view.
Class III	Remarkable considering the landscape and city view.
Class IV	Ordinary considering the landscape and city view.

Bridge sites belonging to the highest class, *Class I,* are considered as "*very demanding*". This means that the site includes nation-wide valuable views or city views, culturally valuable landscape or the most important joints in the transport network. Also the most remarkable waterway crossings within the country and museum bridges belong to this group.

Bridge sites belonging to *Class II*, "*demanding*", possess similar characteristics as those belonging to the previous class but their importance is local, for instance remarkable city or village objects and big bridges crossing waterways with less modest views.

Class III, "*remarkable*", consists of bridge sites including ordinary waterway crossings and bridge sites at crossings with heavy traffic located outside city or village areas.

Class IV, "*ordinary*", consists of bridge sites including roads with low amount of traffic located in an ordinary landscape outside city or village areas as well as sites with low importance where a road or railway crosses a waterway. These kinds of bridge sites usually do not require any special environmental or aesthetical consideration or design.

The basic equation in the calculation is

$$k_{rel} = 1 - a \frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_i p_{i\max}} \tag{4.2}$$

where *scaling factor a* is a non-dimensional factor, which defines generally how much value is given to aesthetical aspects. It varies between 0 and 1. The higher value, the more aesthetics is appreciated.

The *weight values* w_i in Eq. (4.2) consider, how important different *items i* are in relation to each other. The higher value, the more important *item* is in question.

Points p_i indicate, how well the requirements of each *item i* are fulfilled for a bridge under evaluation. Five values are accepted, namely -2, -1, 0, +1 and +2, corresponding: "*poor*", "*modest*", "*medium*", "*good*" and "*excellent*" attributes, respectively.

The system described above enables comparison between different design proposals, existing bridges and bridge types as well as the evaluation of different construction methods.

4.3 Program for evaluating aesthetics

4.3.1 The evaluation procedure

An Excel-based program was developed to incorporate aesthetical, environmental and cultural values in bridge design or construction projects and to make them comparable with construction and lifecycle costs. The program can be utilised in following cases:

- Evaluation of aesthetical, environmental and cultural values respect to the construction costs.
- Comparison of different bridge design proposals within a project or in engineering skills - including bridge design - competitions.
- Comparison of different routes where bridges are involved during the feasibility study stage or construction phase.

The practical use of the program is simple and can be used either by individual experts or group of evaluators. The process can be divided into four steps as shown schematically in the flowchart of the program in *Fig. 4.1.*

At the beginning, the user has to give some general information (*Block 1* and *Block 2*). The importance of the aesthetical or cultural value of the bridge site must be evaluated firstly. It means that the user must decide to which class-category the bridge site belongs. In the program this decision making is helped by introducing the evaluation of the bridge site with using four items.

In the second stage (*Block 3*) the user must select the *items* that will be used in the evaluation and also the *weights f*or them. This should be done at the beginning of the evaluation. In the program some default items and weights are given, but the user is free to change, discard or choose new items and weights. After the items and weights have been determined, these should then be considered as "*fixed*" during the evaluation.

A similar value as the weights is the *scaling factor a*. It also needs to be determined in advance, because it has a decisive influence on the level of appreciation of the aesthetical values compared to costs. Initial values depending on the bridge site classification are given, but the user is free to change also this factor.

The final block, *Block 4,* includes the evaluation itself. The evaluator gives credits, *points* p_i for the items of each bridge proposal. Before that, however, the scale to be applied has to be determined. The developed computer program is tuned to use a fixed scale from -2 to + 2 as a default. By allowing the user to input integers values only and between the interval [-2, +2], one has to input p_i from one of the five values, *i.e.*, -2, -1, 0, 1 and 2. Although the system allows any other scale, it is not recommended, because changing the scale may cause the need of reprogramming. After the evaluator has graded and inserted the points p_i for the items, the program calculates the final result, k_{rel} for each proposal.

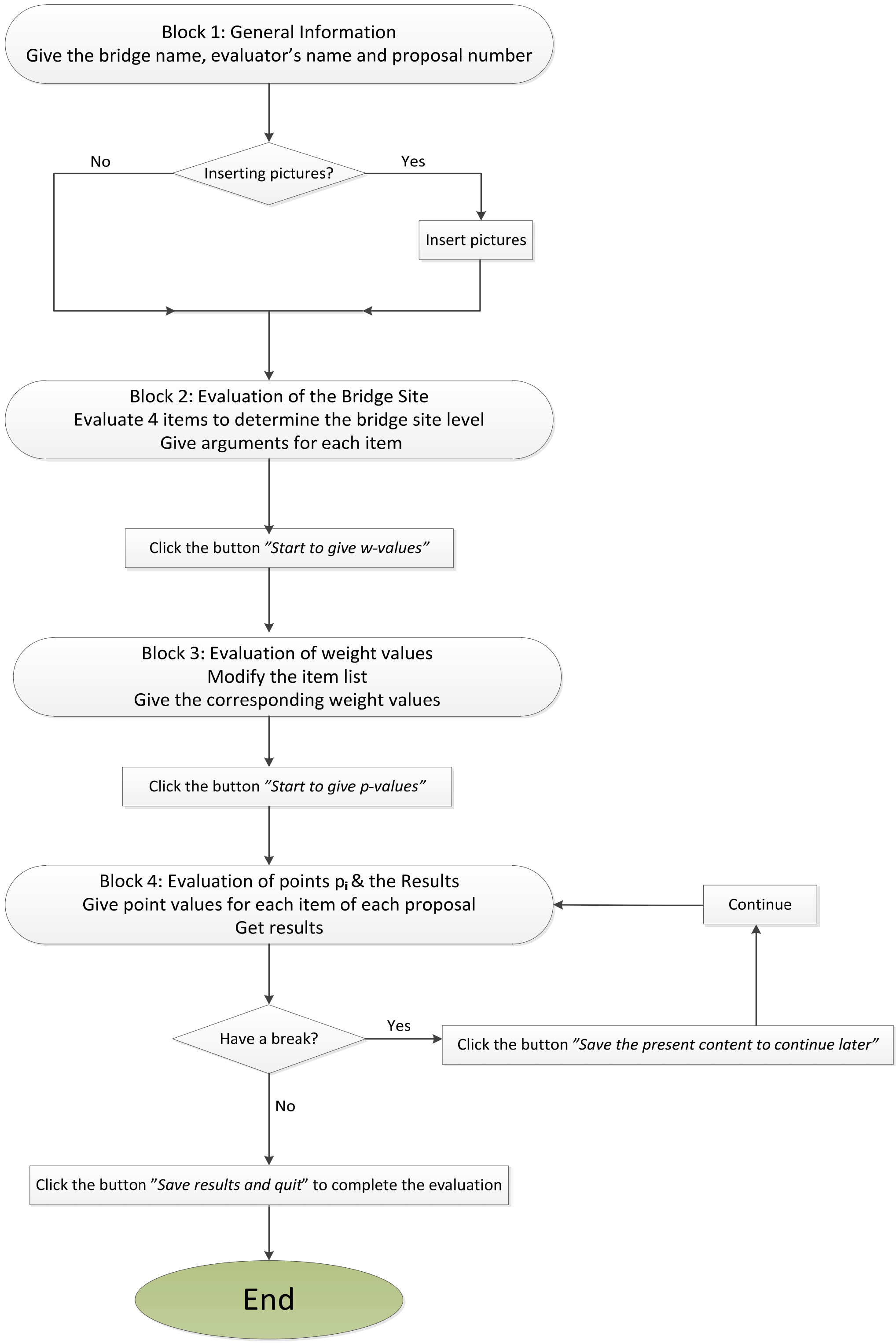


Figure 4.1. Flowchart of the developed computer program.

4.3.2 Saving data and getting results

Before starting to use the program, the user is recommended to move or copy the program into a new file folder, whose name could be the user's name for example. The purpose is to collect all files related to the evaluation into the same folder and make possible to distinguish the results of evaluators.

The program contains 3 sheets, the names of which are: "*Sheet1"*,"*Alldrawings"* and "*p-value"*, respectively. The evaluation procedure is carried out in the first sheet, which is activated automatically when opening the program. The function of each sheet will be explained in more detail in the section "Application example".

4.4 User instructions for the program

The use of the computer program in evaluation can be divided into four modules or blocks:

1. General information.
2. Bridge site classification.
3. Determining the weight values.
4. Grading by points.

4.4.1 General Information

In "*General information"*- block the name of the bridge, the name of the evaluator and the date of evaluation are given. Also the number of proposals to be evaluated must be given. The maximum number of bridges to be evaluated is limited to 10.

Throughout the program, pink shaded cells are the ones which content or input value the user may or is expected to change. Cells with other colours are protected.

The last part of this block is requested, if the pictures are to be used in the evaluation process. Usually pictures are available and the user activates the "*Alldrawings*"-sheet to get the pictures.

4.4.2 Bridge site classification

In the evaluation of a bridge site, four-level classification system is used. To make it easier to judge, into which *Class* bridge site should be classified, four sub-blocks and items are introduced:

- Location.
- Value of the landscape.
- Cultural value of the environment.
- Aesthetical demands set to a bridge at this particular bridge site.

In each sub-block the user determine, which of the four *Classes* is most appropriate considering the *item* related to that particular sub-block. For motivation and remembering, an empty cell is reserved for writing down some text describing, what was in the user's mind when making the decision.

After this part of the block the average of the sub-block values is calculated to determinate the bridge site class, but still can be changed later by the user.

Finally, the recommended value for *scaling factor a* is presented for each class. These are as follows:

Class I $a = 0{,}4$
Class II $a = 0{,}3$
Class III $a = 0{,}2$
Class IV $a = 0{,}1$

The user can input the scaling factor, but if using recommended values above, the *reduction coefficient* k_{rel} will vary between the limits 0,6 and 1,4.

To complete the *Block 2* and continue to *Block 3* the button "S*tart to give w-values*" should be clicked.

4.4.3 Determining the weight values

In B*lock 3* the *weight values* w_i for selected items are to be given. These values are dependent on the *Bridge Class* and the *item*.

The *weights* w_i indicate the importance of each item or aspect of the bridge or design. The user should change the weight values to adjust them to each particular case. The default *items* and values are shown in *Table 4.1*.

Table 4.1. Proposed list of items and suggested weights for them in each class.

List of items	**Class I**	**Class II**	**Class III**	**Class IV**
Integration between the bridge and the site	9	8	7	6
Overall harmony	9	8	7	6
Horizontal and vertical geometry	4	3	2	1
Structural simplicity and order	8	7	6	5
Transparency	6	5	4	3
Slenderness	7	6	5	4
Appearance of substructures and pylons	8	7	6	5
Surfaces, colours and finishing	5	4	3	2
Railing and vehicle barriers	4	3	2	1
Lighting	5	4	3	2
Appearance of access bridges, embankments and cones	6	5	4	3

One can change items or discard them (only for the content of the cell), but *Delete* or *Insert Lines* - operations are not allowed, when using the program. Under default items shown, 9 empty rows for additional items are available for the evaluator. The maximum number of rows in this block is always 20 and cannot be exceeded. So the user can have 20 different items to be considered in the evaluation.

To complete *Block 3* and continue to next step, the cell "S*tart to give p-values*" should be clicked. Consequently, the current file will be saved as a new file named according to the bridge.

4.4.4 Grading by using points

In *Block 4* of the program numerical values called *point* shall be given to each *item*. Only the five categories and values presented in *Table 4.2* are accepted. The higher value, the better the bridge or design corresponds to the *item* in consideration.

Note: It is not allowed to change the content of items.

Table 4.2. Acceptable numerical values of points p_i and the corresponding explanation.

Category	Explanation
2	Excellent
1	Good
0	Medium
-1	Modest
-2	Poor

If several proposals are to be evaluated one by one, *points p_i* can be given for each proposal in the sequence of evaluation, but finally all values will be seen in *Block 4*. By these means the different proposals can be easily compared.

4.4.5 Getting results

When *Block 4* is completed, program calculates the final result from the Eq. (4.2) and the relative coefficient k_{rel}, is obtained. This is the coefficient which is needed in cost calculations (Eq. (4.1)). In the program the coefficient is printed on the result row of each proposal. This ends the evaluation process.

When quitting the program the user has two options, either to continue later with the given values or to finish and save obtained results.

In the former case the user should press the button "*Save the present content to continue later"*. Then the values given during the conducted evaluation can be examined and changed later.

In the latter case, the user is satisfied to the obtained results and finishes the program by pressing the button "*Save results and Quit*". In this case the current results will be saved as a new file which name is constructed from the bridge name, user name and the number of the proposal so that it can be identified later.

4.5 Application example

As a practical calculation, three bridge proposals presented for a bridge design competition in Tampere, Finland, carried out in 2007, are evaluated. Each proposal includes several drawings and pictures. The evaluation is based on this given material.

The bridge called *Laukonsilta* is located in the middle of the town and crosses a 150 m wide river (*Fig. 4.2*). The three proposals used in this example are all based on a cable-stayed bridge solution, with main span varying between 65 and 112 meters. Here the proposals and the corresponding bridges are numbered as 1, 2 and 3. The drawings and pictures used are shown in *Figs 4.3…17*, respectively.

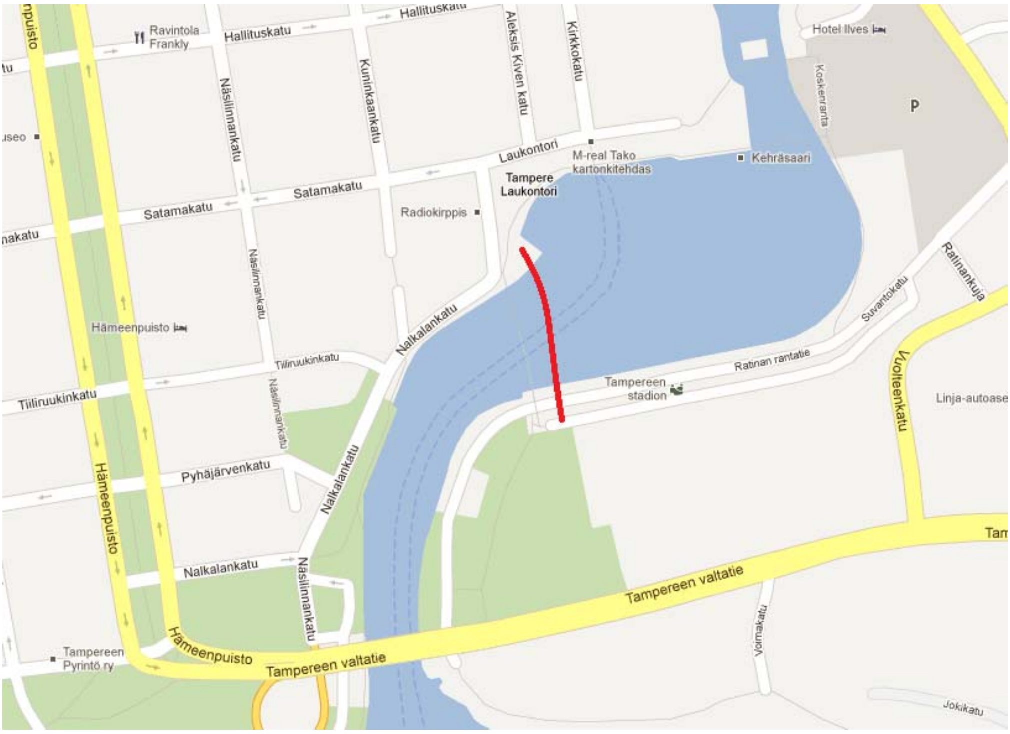


Figure 4.2. Location of the Laukonsilta Bridge.

Proposal No. 1 pictures:

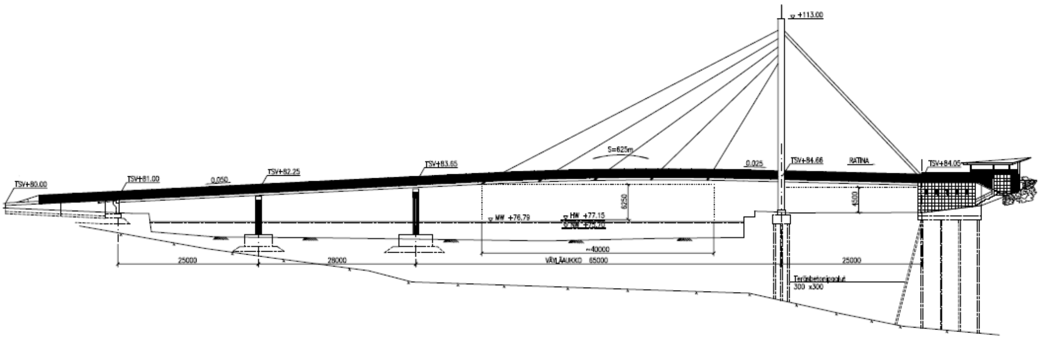


Figure 4.3. Side view drawing of Bridge No. 1.

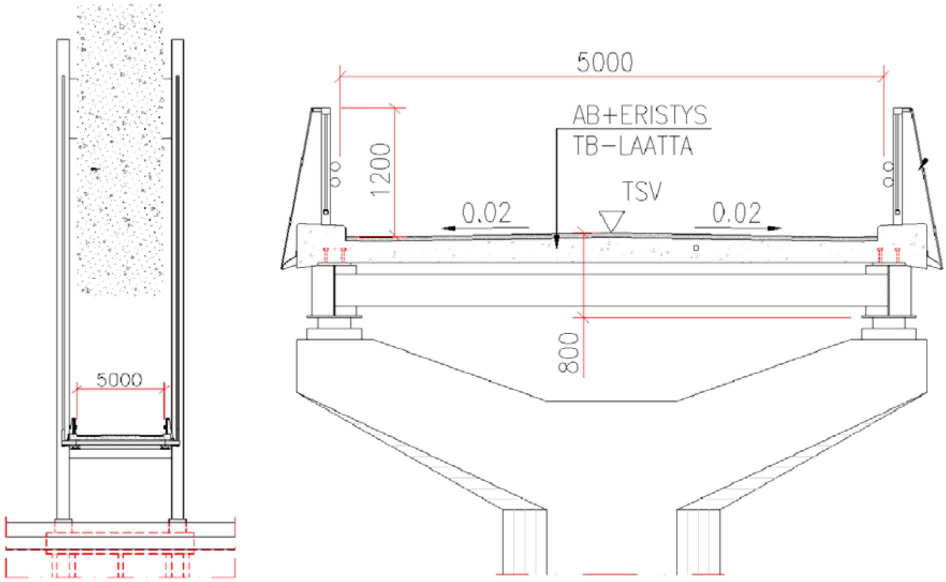


Figure 4.4. Cross-sections of Bridge No. 1.

Figure 4.5. Photomontage A of Bridge No. 1.

Figure 4.6. Photomontage B of Bridge No. 1.

Figure 4.7. Photomontage C of Bridge No. 1.

Proposal No. 2 pictures:

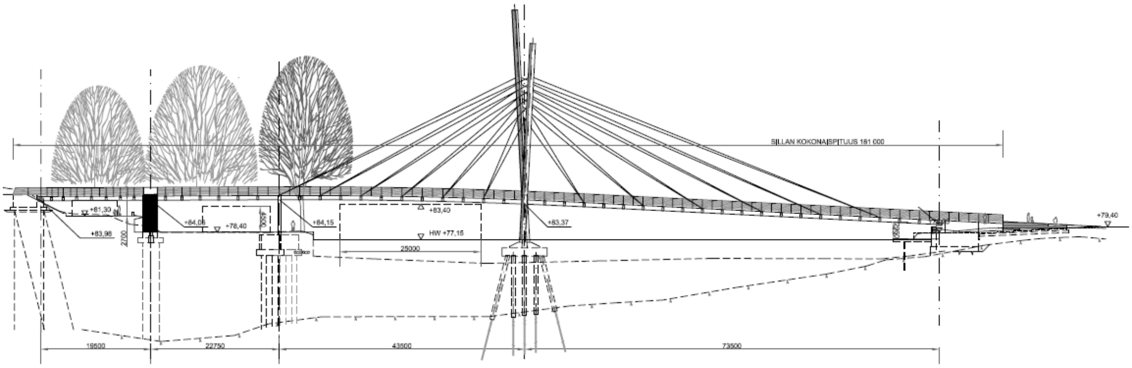


Figure 4.8. Side view drawing of Bridge No. 2.

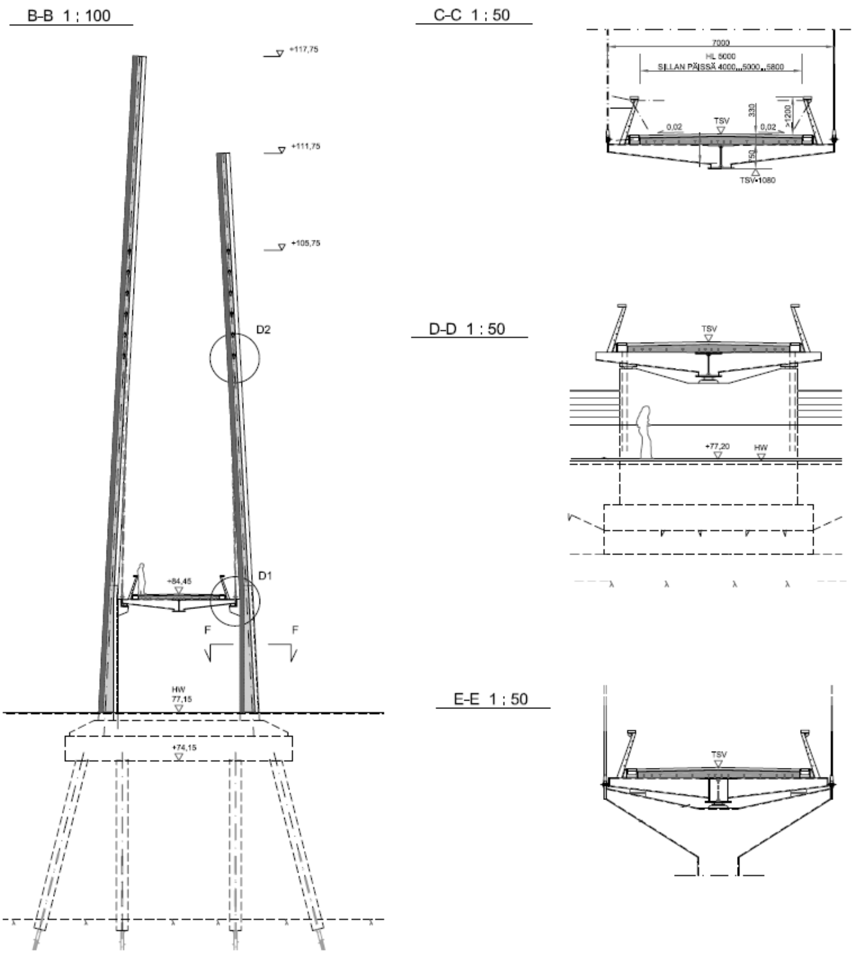


Figure 4.9. Cross-sections of Bridge No. 2.

Figure 4.10. Photomontage A of Bridge No. 2.

Figure 4.11. Photomontage B of Bridge No. 2.

Figure 4.12. Photomontage C of Bridge No. 2.

Proposal No. 3 pictures:

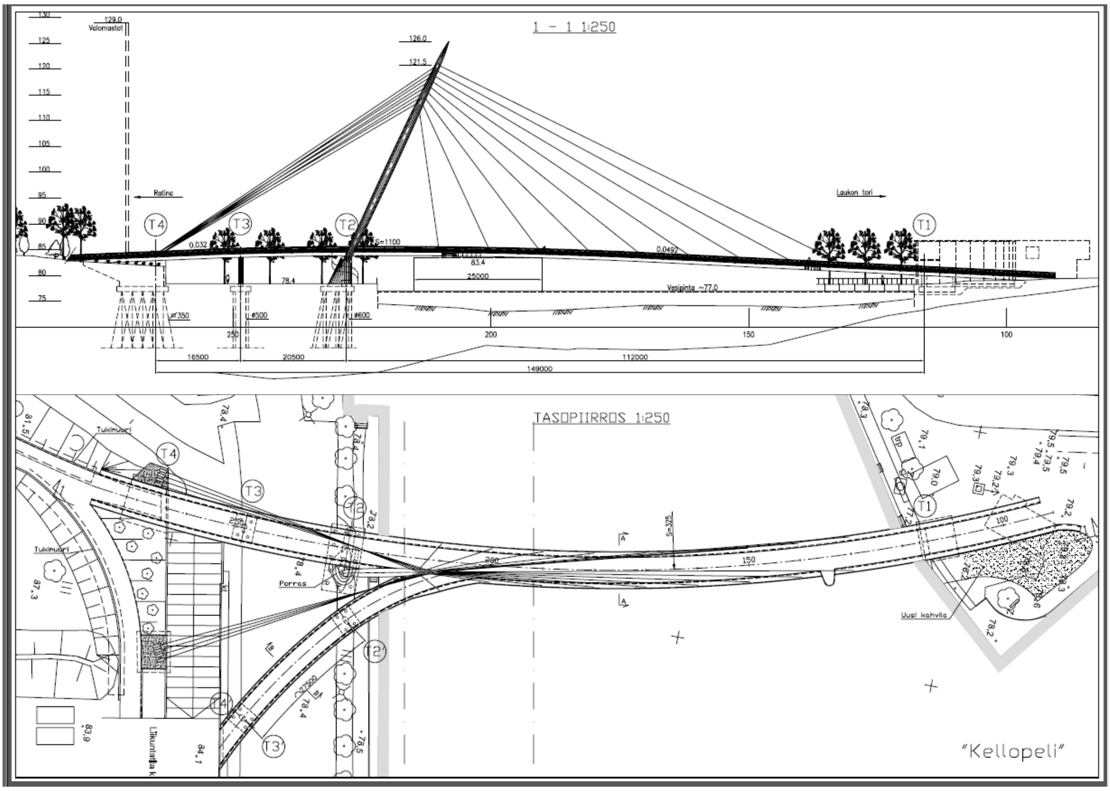


Figure 4.13. General drawing of Bridge No. 3.

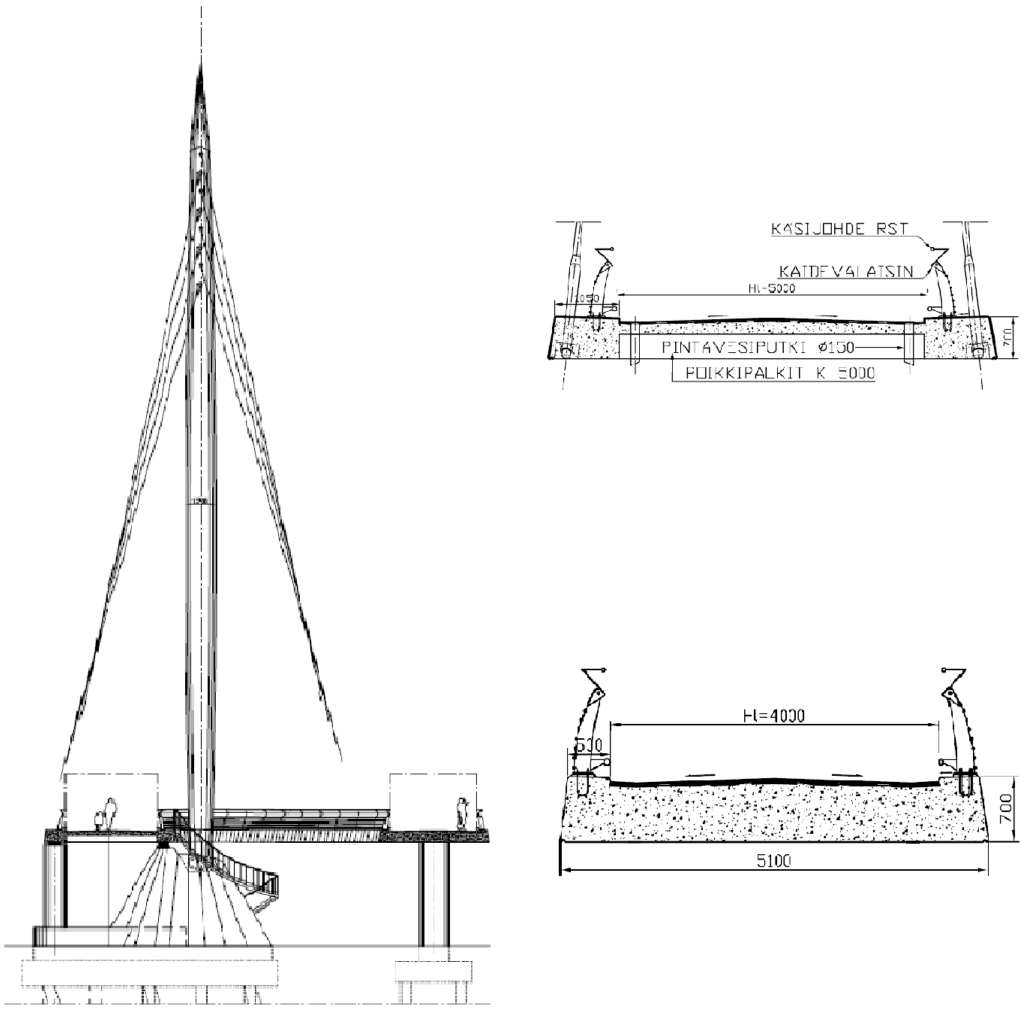


Figure 4.14. Longitudinal view and cross-sections of Bridge No. 3.

Figure 4.15. Photomontage A of Bridge No. 3.

Figure 4.16. Photomontage B of Bridge No. 3.

Figure 4.17. Photomontage C of Bridge No. 3.

Actions related to *Block 1*:

As the first step, open the basic program and click button "*Enable content*" above the Formula Bar. Then give general information for the evaluation in Block 1.

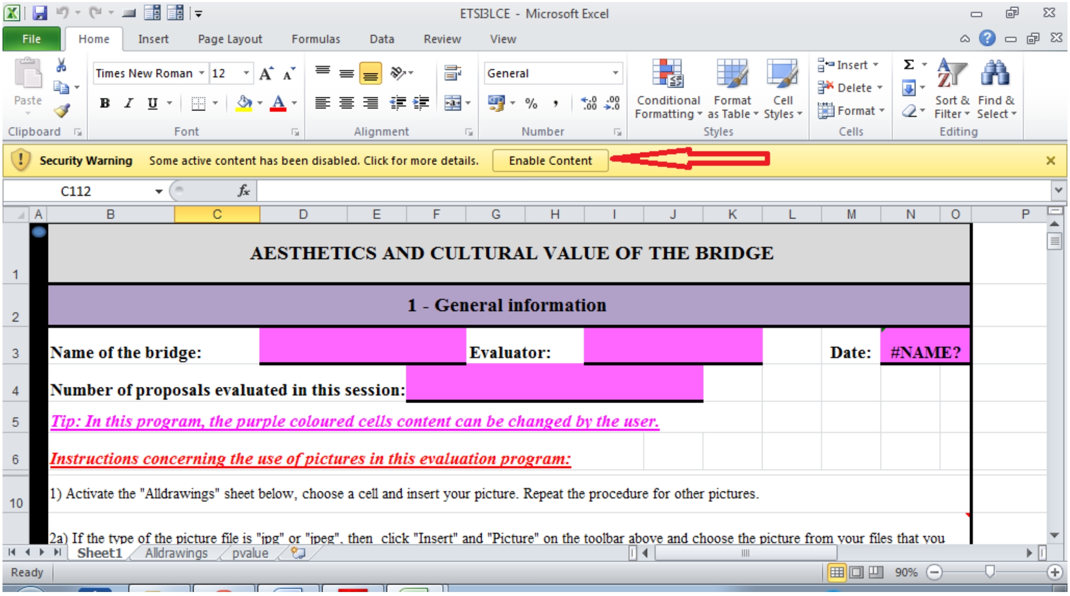


Figure 4.18. Clicking "Enable Content".

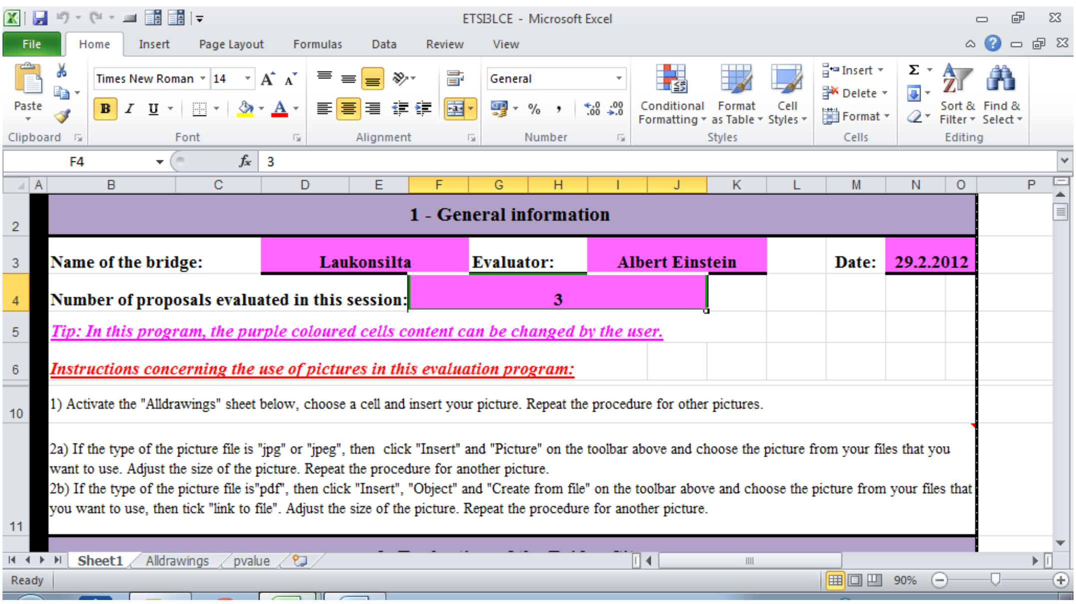


Figure 4.19. Giving information: the bridge name, user name, etc.

For inserting pictures, activate sheet "*Alldrawings*" next to "*sheet1*". Activate one cell, then click button "*Insert*" and choose "*Picture*" (*Fig. 4.20*).

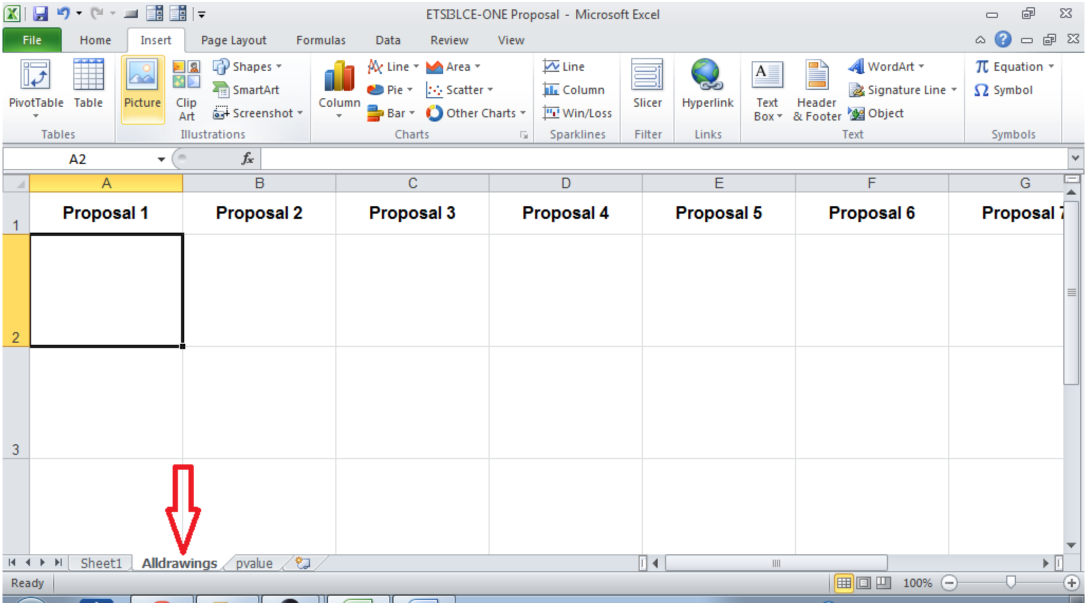


Figure 4.20. Activating one cell and clicking button "Insert" and then "Picture", respectively.

A new window will pop up, from here choose the picture you want to insert and then click "*Insert*" in the right upper corner (*Figs 4.21 and 4.22*).

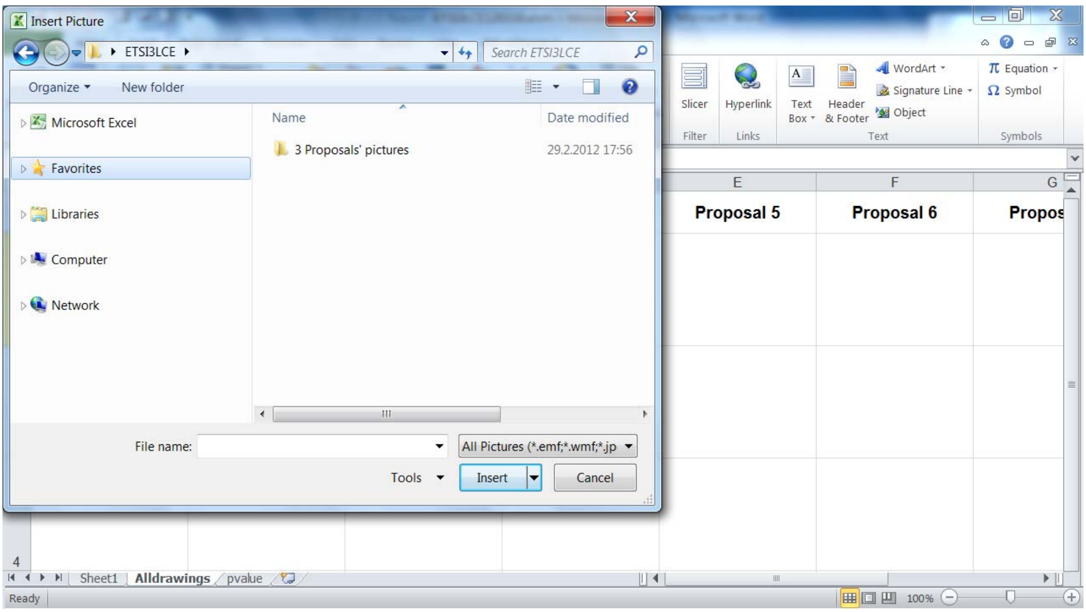


Figure 4.21. Choosing file that is being inserted.

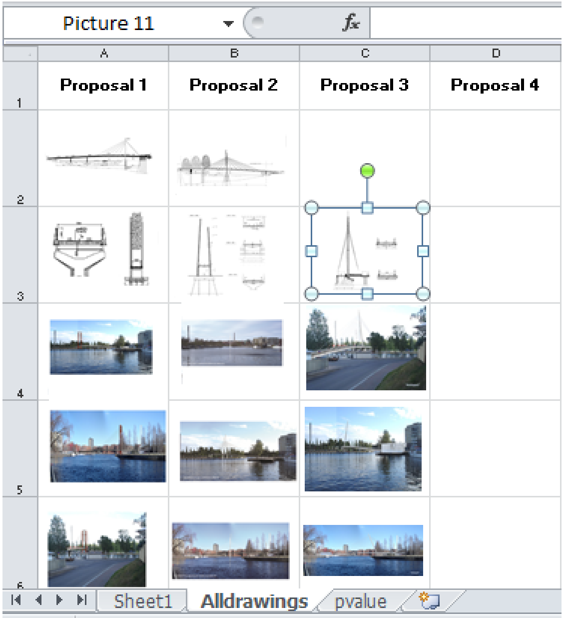


Figure 4.22. Adjusting the size of the picture or drawing.

If the pictures are of "*pdf*" type, then activate one cell by clicking "*Insert*" and choosing "*Object*". Now, a new window will pop up, then activate "*Create from file*" and "*browse*" the "*pdf*" file. Finally, tick "*Link to file*" and click "*OK*" in the end (*Figs 4.23, 4.24 and 4.25*).

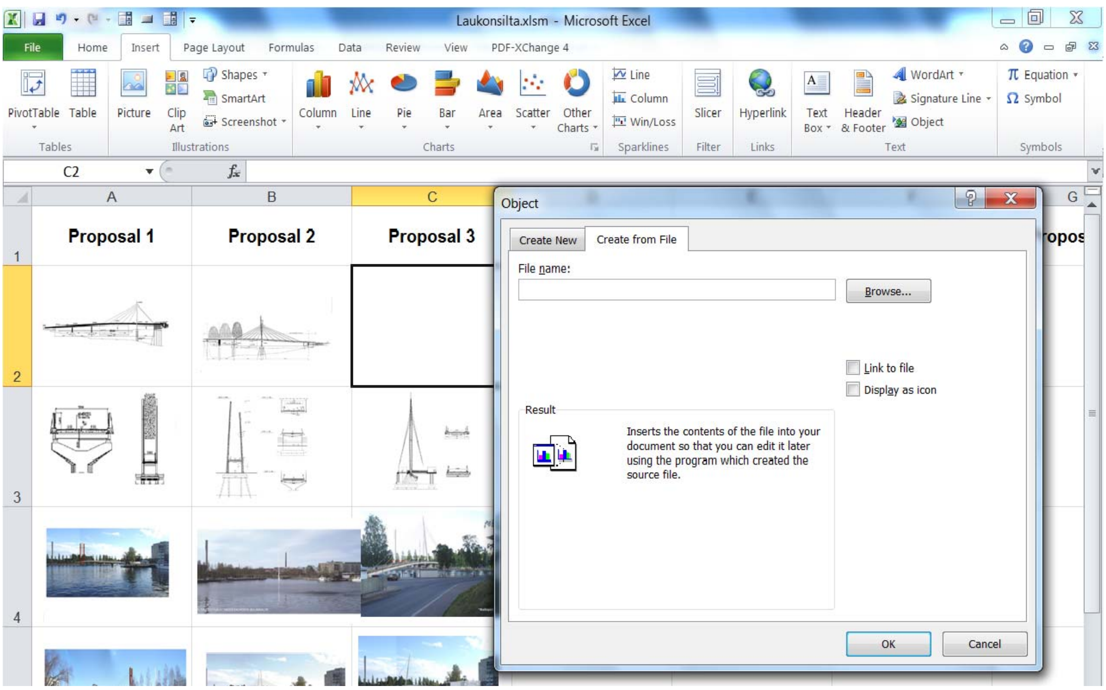


Figure 4.23. Clicking "Insert" button and then "Object".

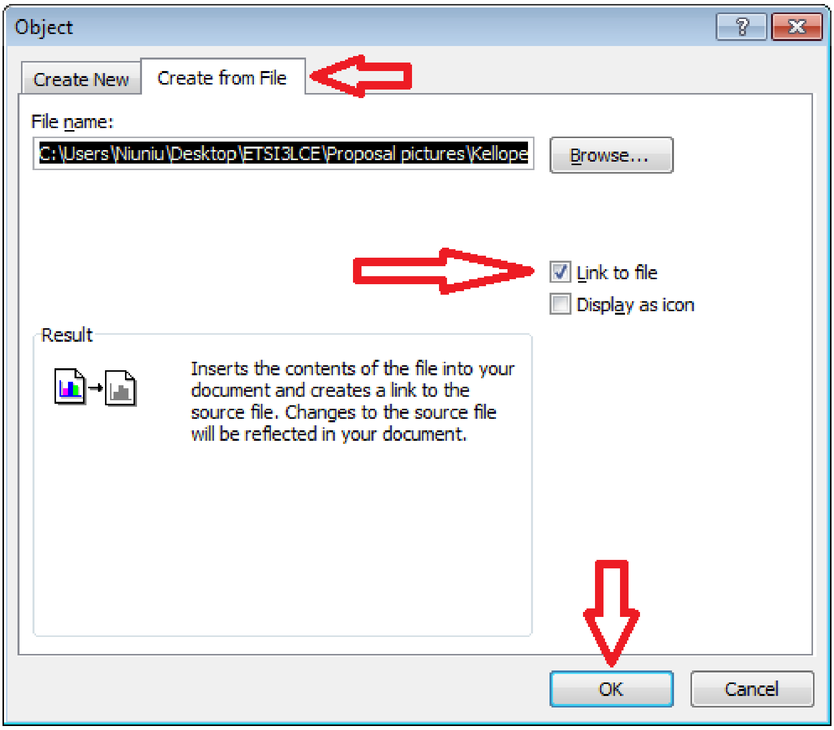


Figure 4.24. Activating "Create from file" and choosing the file to be inserted.

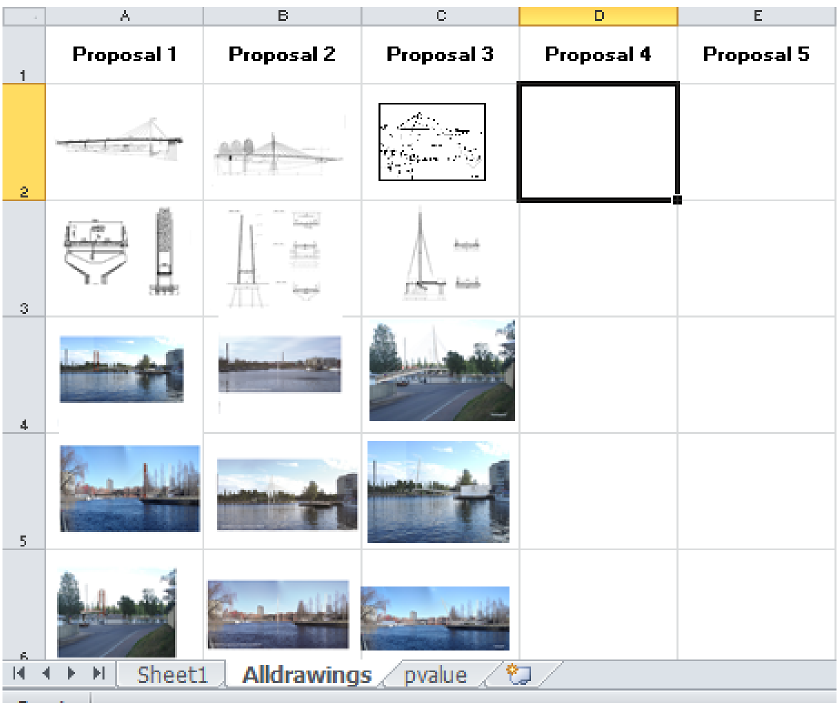


Figure 4.25. The "pdf" file example (cell B2).

Actions related to *Block 2*:

Choose *Class Level* relevant to the bridge site by utilising the four aspects (*Figs 4.26, 4.27 and 4.28*). The recommended *Class Level* and the corresponding *a-value* are automatically calculated, but they can be changed by the evaluator.

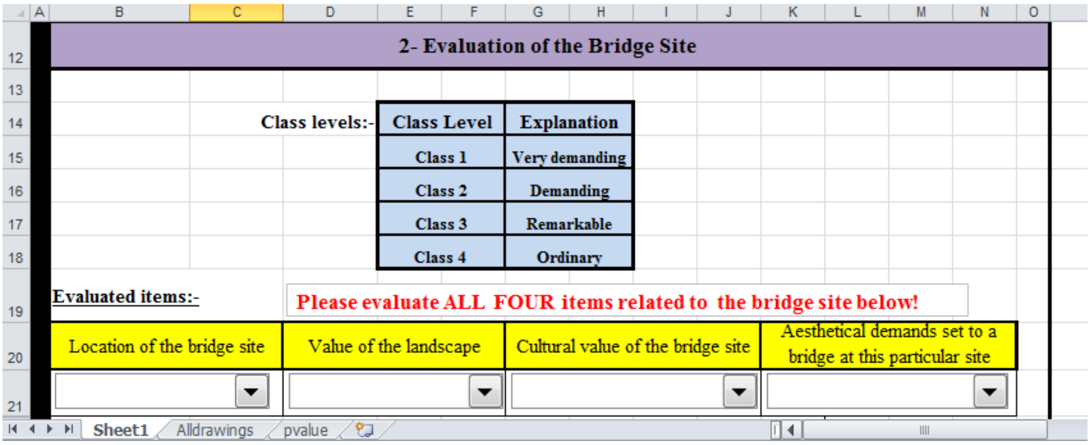


Figure 4.26. Choosing Class Levels.

Note: In this example calculation, the following *Class Levels* are chosen:

Location of bridge site: 2

Value of the landscape: 1

Cultural value of the bridge site: 2

Aesthetical demands set to a bridge at this particular site: 1

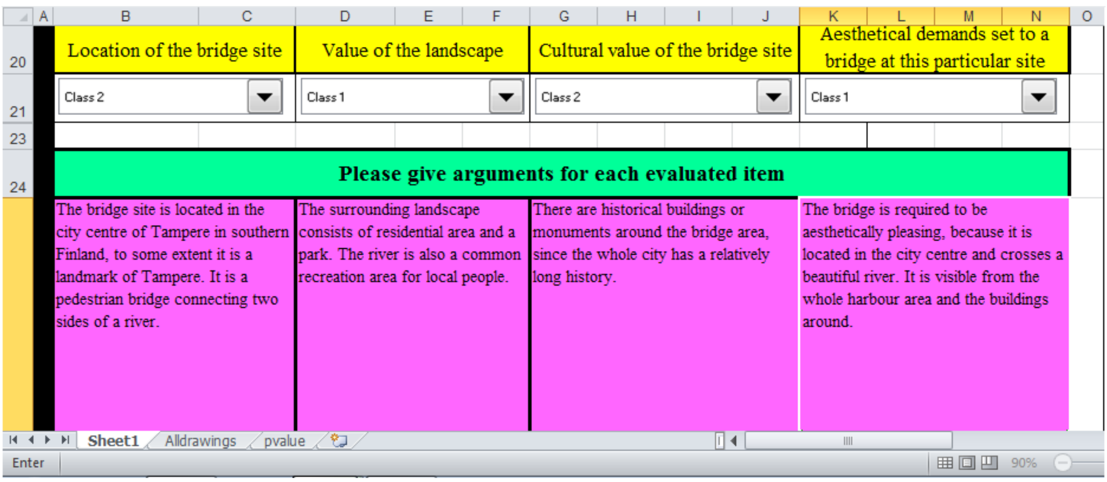


Figure 4.27. Giving description of each item.

Thus the recommended *Bridge Site Class* will be “1” as shown in *Fig. 4.28*. Correspondingly, the recommended “*a-value*” is “0,4”.

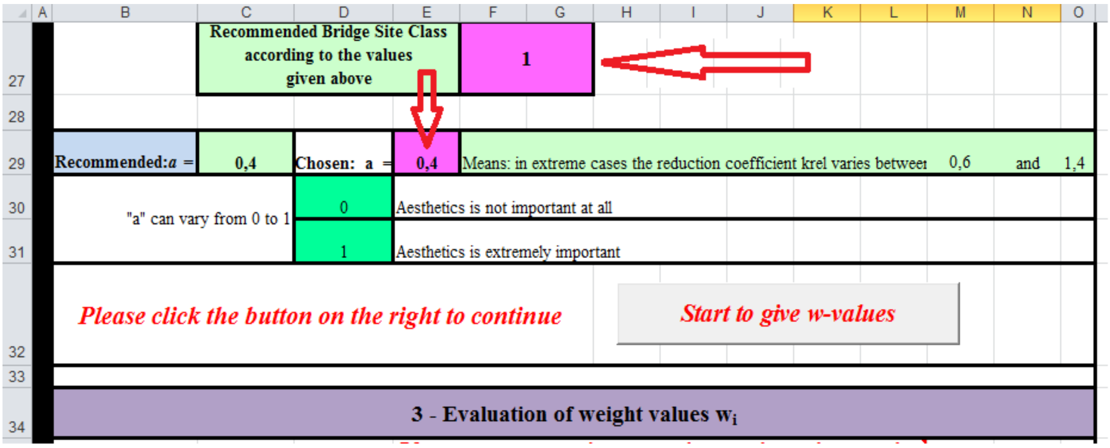


Figure 4.28. Display of Bridge Site Class Level and "a-value".

Actions related to *Block 3:*

Click the button "*Click to start to give w-values*". In this example, one item, "*Others*", is added to the basic item list (*Fig. 4.29*).

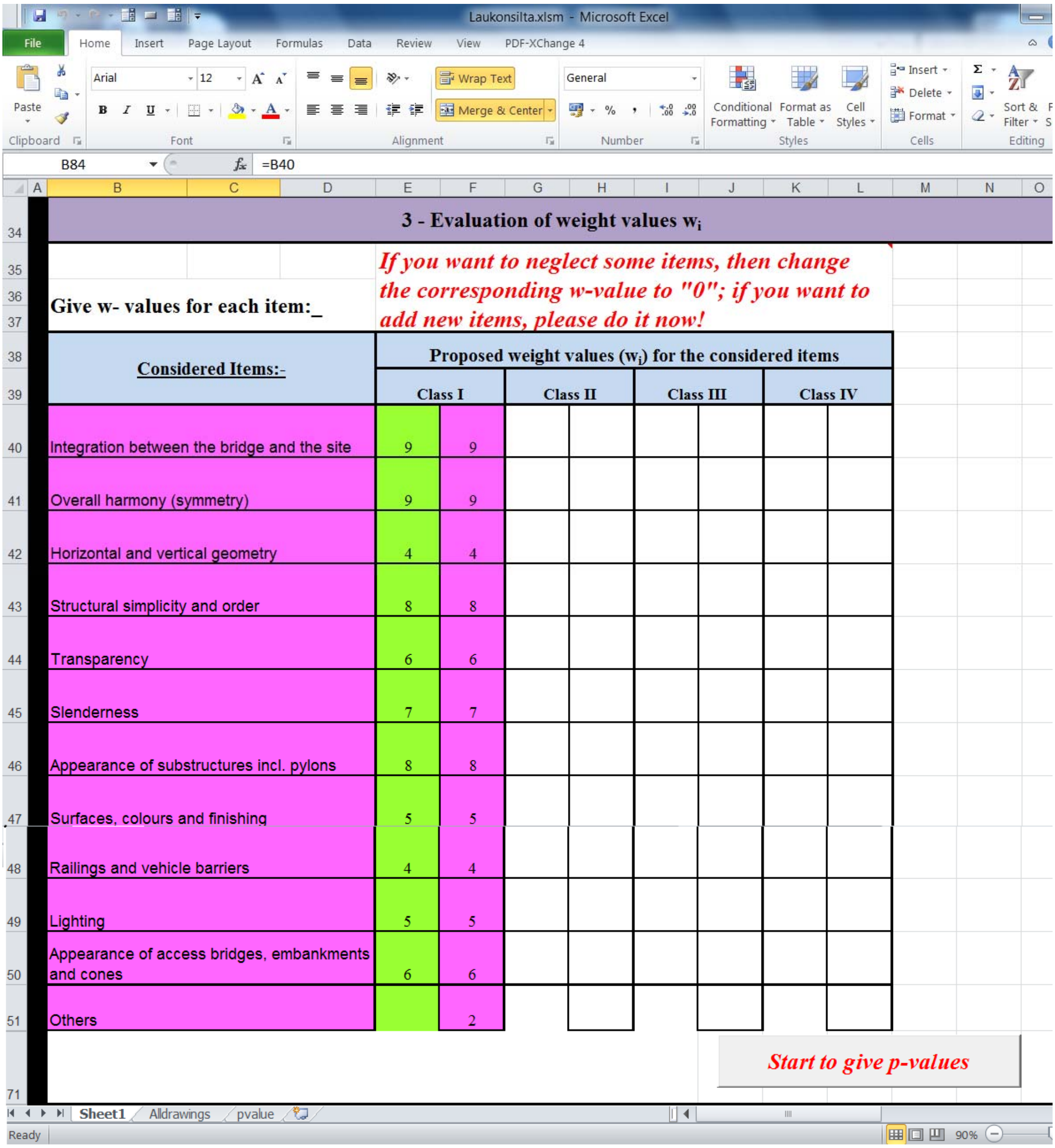


Figure 4.29. Giving w-values in pink cells.

Give a *w-value* for each item. If the user adds an item, but forgets to give the *w-value* for it, a window will pop up after clicking button ”*Start to give w-values*” (*Fig. 4.30*).

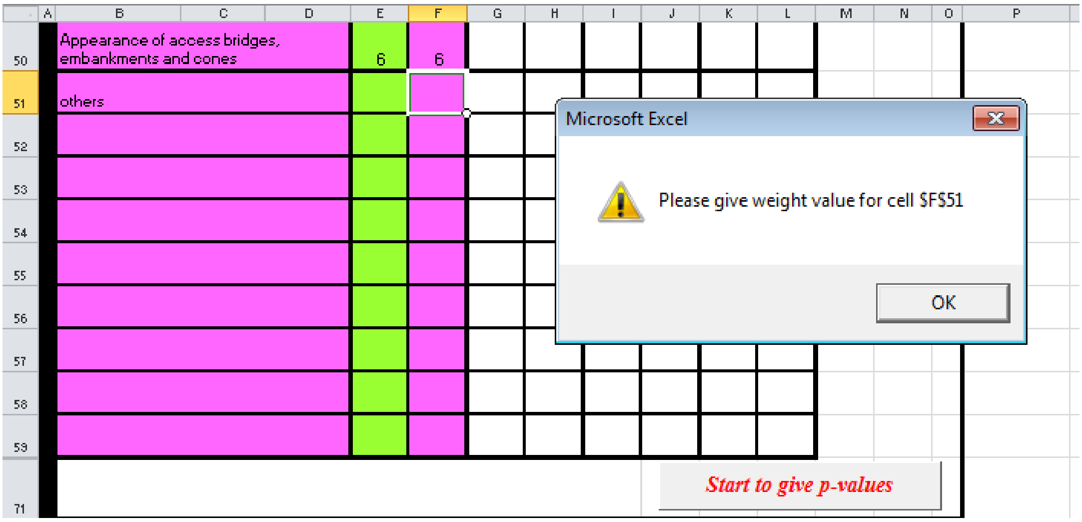


Figure 4.30. If there is a missing w-value, an alert window will pop up.

After giving the *weight values* for each item, click the button ”S*tart to give p-values*” (*Fig. 4.31*).

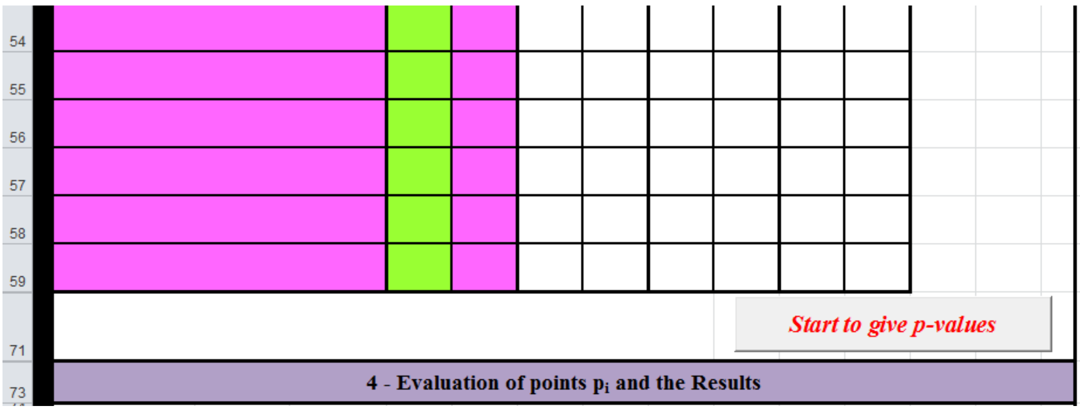
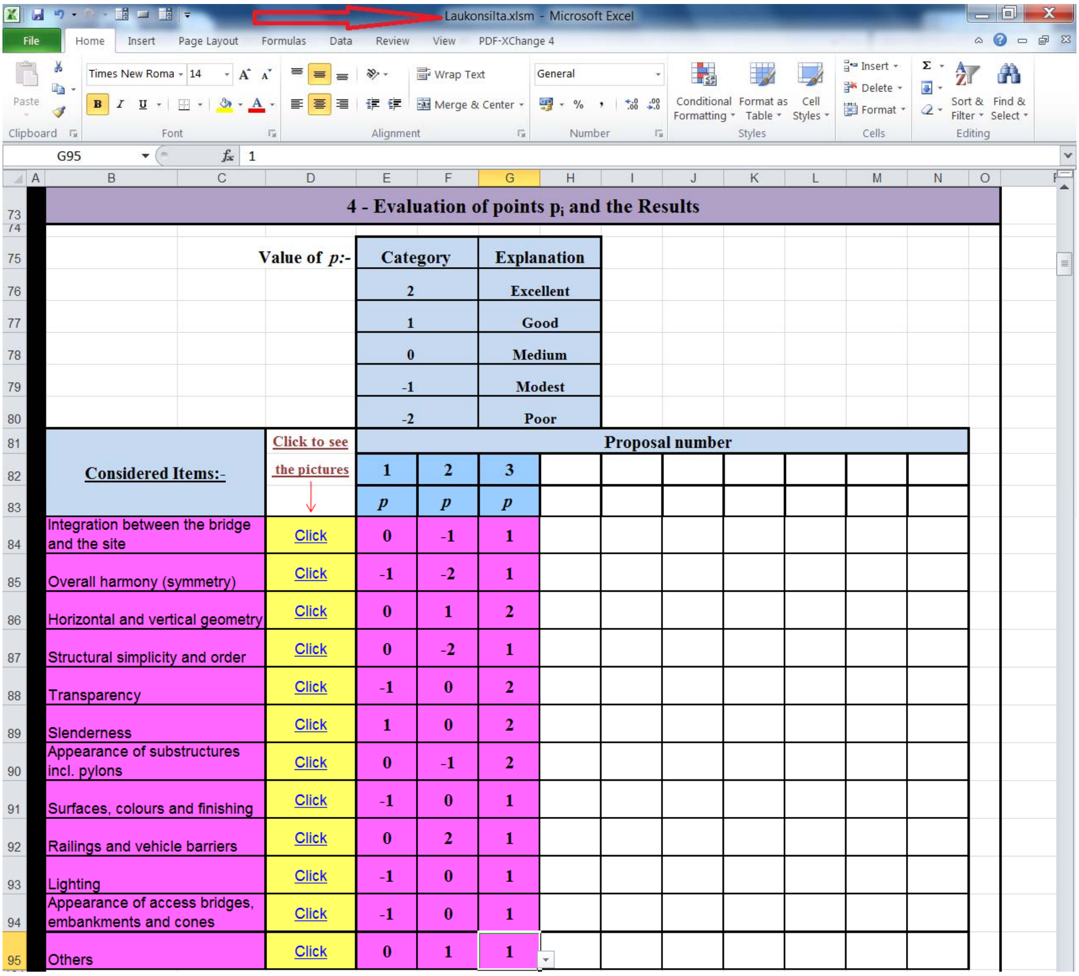


Figure 4.31. Clicking the button “Start to give p-values”

Actions related to *Block 4*:

Now the *p-values* related to the different items and proposals, respectively, will be given (*Fig. 4.32*). Then the current file's name is changed into "*Laukonsilta*".



Value of *p*:-	Category	Explanation
	2	Excellent
	1	Good
	0	Medium
	-1	Modest
	-2	Poor

Considered Items:-	Click to see the pictures	Proposal number 1	2	3
		p	*p*	*p*
Integration between the bridge and the site	Click	0	-1	1
Overall harmony (symmetry)	Click	-1	-2	1
Horizontal and vertical geometry	Click	0	1	2
Structural simplicity and order	Click	0	-2	1
Transparency	Click	-1	0	2
Slenderness	Click	1	0	2
Appearance of substructures incl. pylons	Click	0	-1	2
Surfaces, colours and finishing	Click	-1	0	1
Railings and vehicle barriers	Click	0	2	1
Lighting	Click	-1	0	1
Appearance of access bridges, embankments and cones	Click	-1	0	1
Others	Click	0	1	1

Figure 4.32. Giving p-values for each item in pink cells.

In this step, if the user has inserted pictures into the program, the program provides more convenience for the user. When clicking the picture which the user wants to see, the chosen picture will be enlarged; when clicking another picture, the previous one will be reduced to a suitable size, and the new chosen picture will be enlarged and so on. Also, if the user wants to see all suitable size pictures in suitable sizes, s/he just needs to click any empty *cell* (not an inserted picture) to let them back. The effect will be like shown in *Figs 4.33* and *4.34*, respectively.

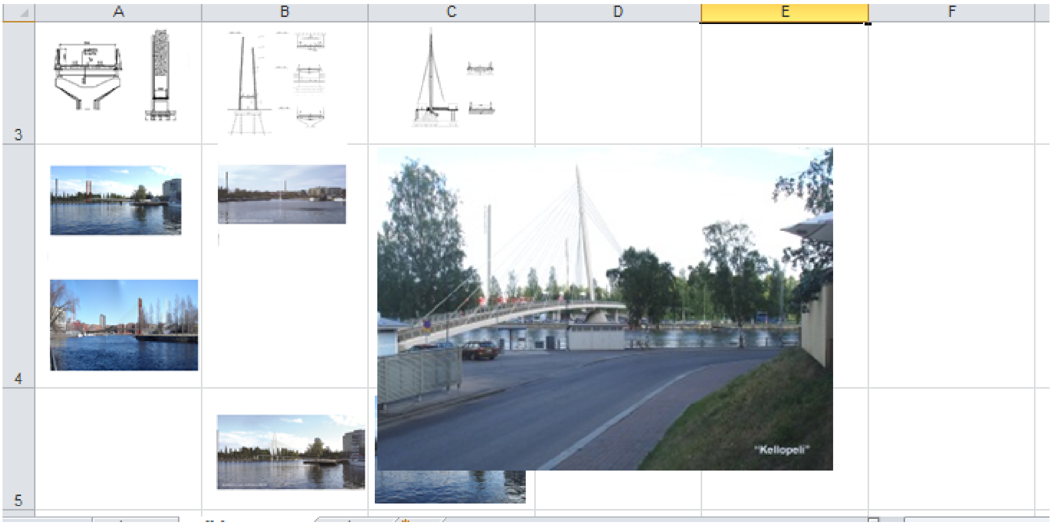


Figure 4.33. Clicking the picture to enlarge.

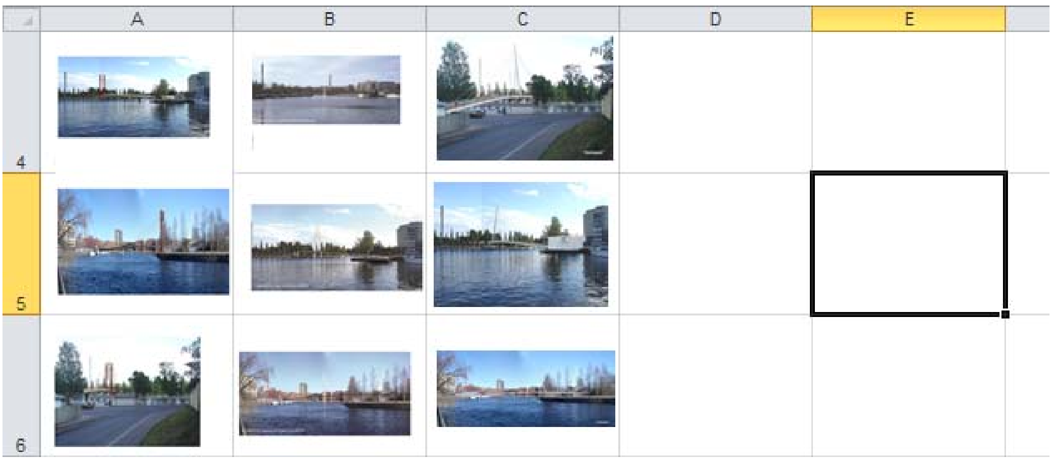


Figure 4.34. Activating one empty cell to let the picture be reduced to a suitable size.

After giving all *p-values*, the results will be shown under each *p-value* column (*Fig. 4.35)*.

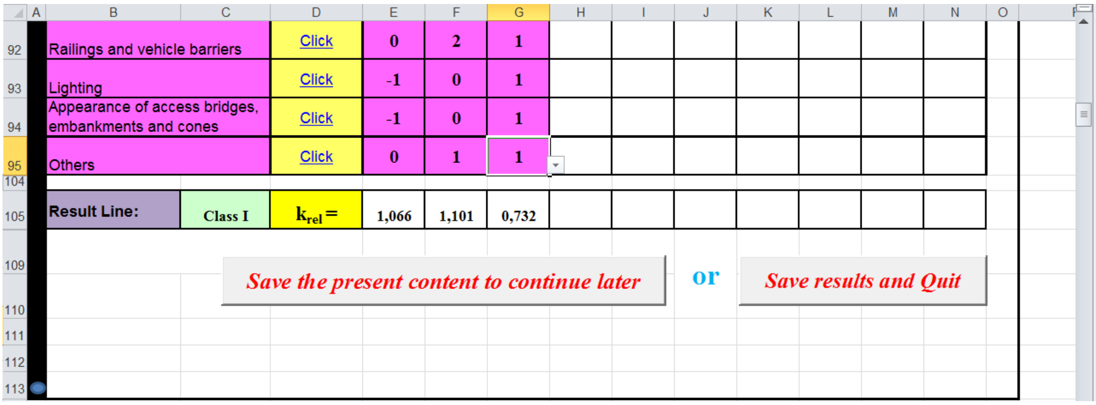


Figure 4.35. Relative coefficient k_{rel} of each proposal will be calculated after giving all p-values.

Please note that if the user inserts a *p-value* outside the range of the five pre-set values, for example "*3*", then an error message box will pop up (*Fig. 4.36*).

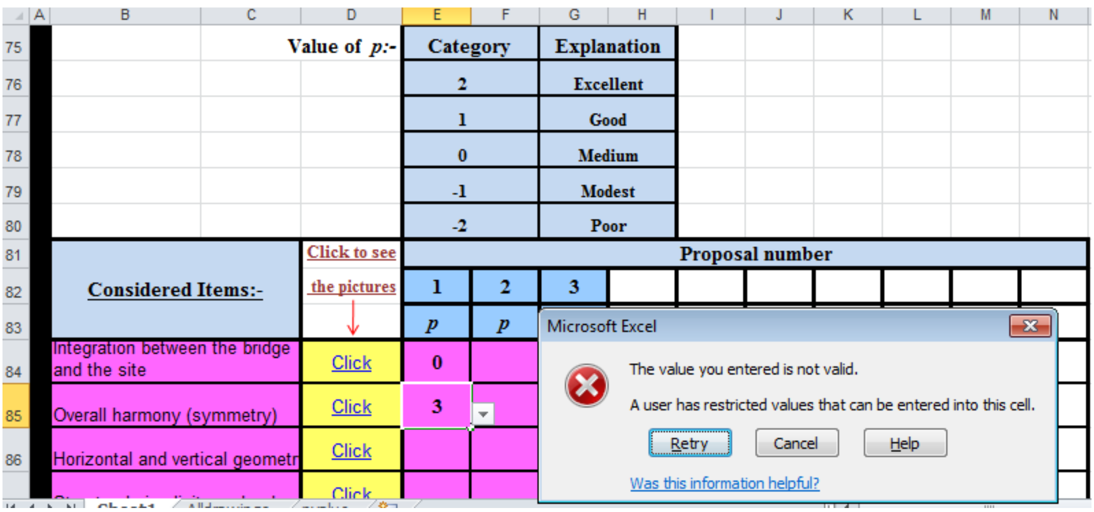


Figure 4.36. Alert window will pop up, if the p-value is given outside the 5 categories.

If the user wants to have a break during evaluation, then the button "*Save the present content to continue later*" should be pressed. Then the file will be saved as a new file. The name of the new file is "*Continue---Not finished yet!*" (*Fig. 4.37*).

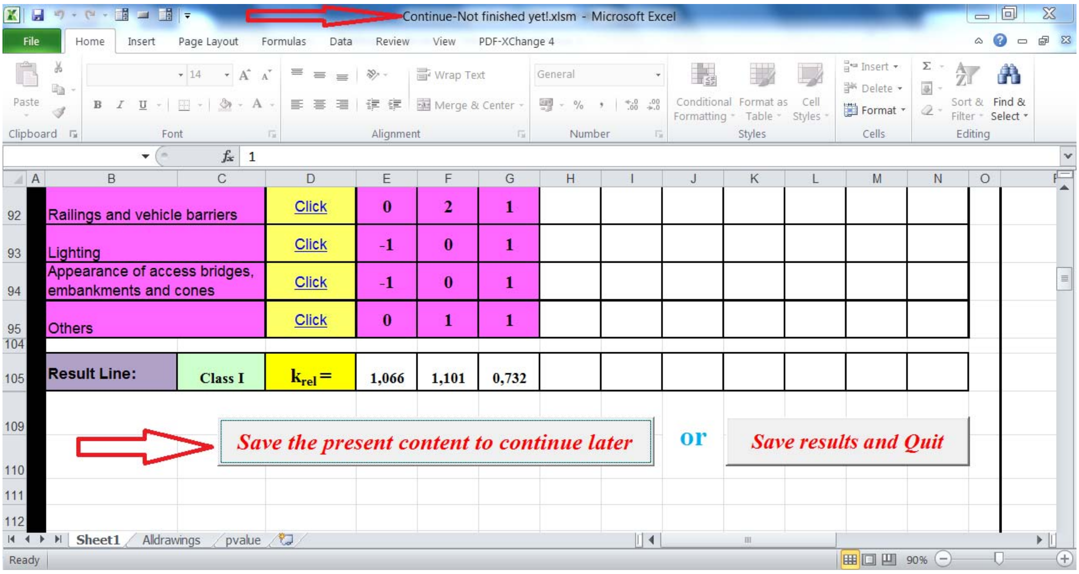
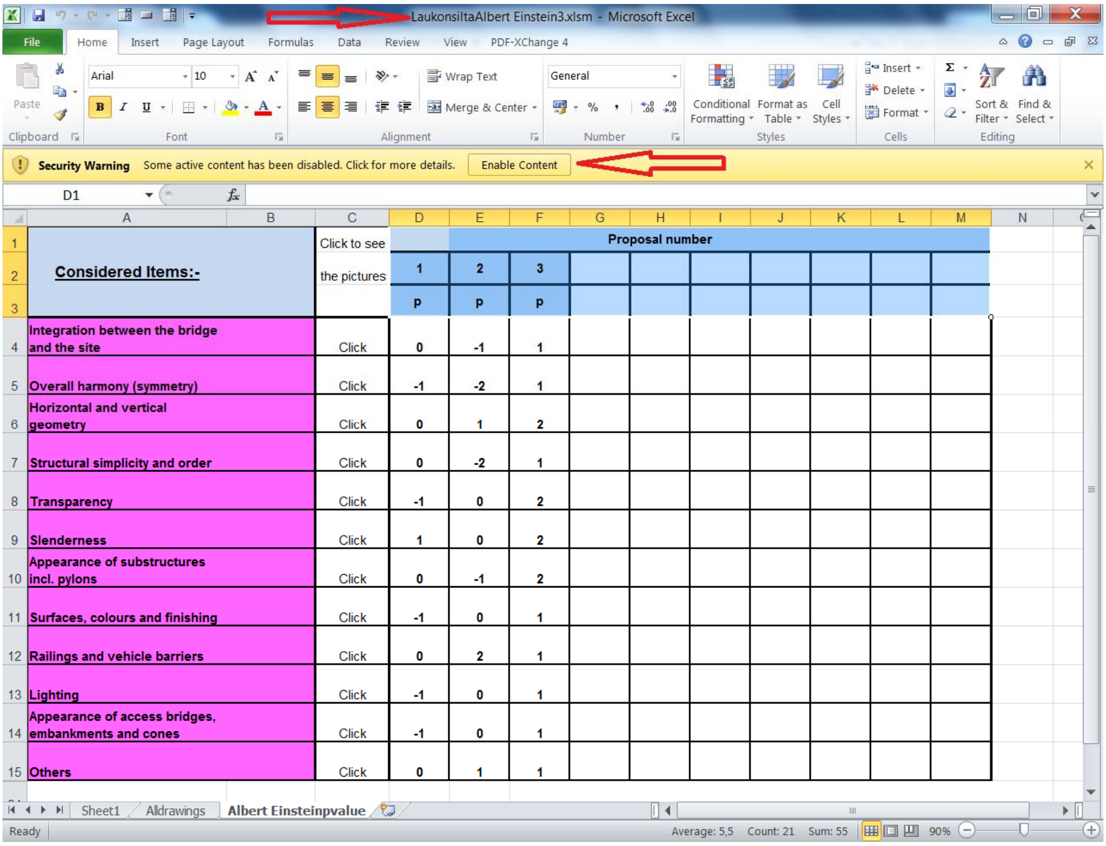


Figure 4.37. Clicking the button "Save the present content to continue later" for having a break.

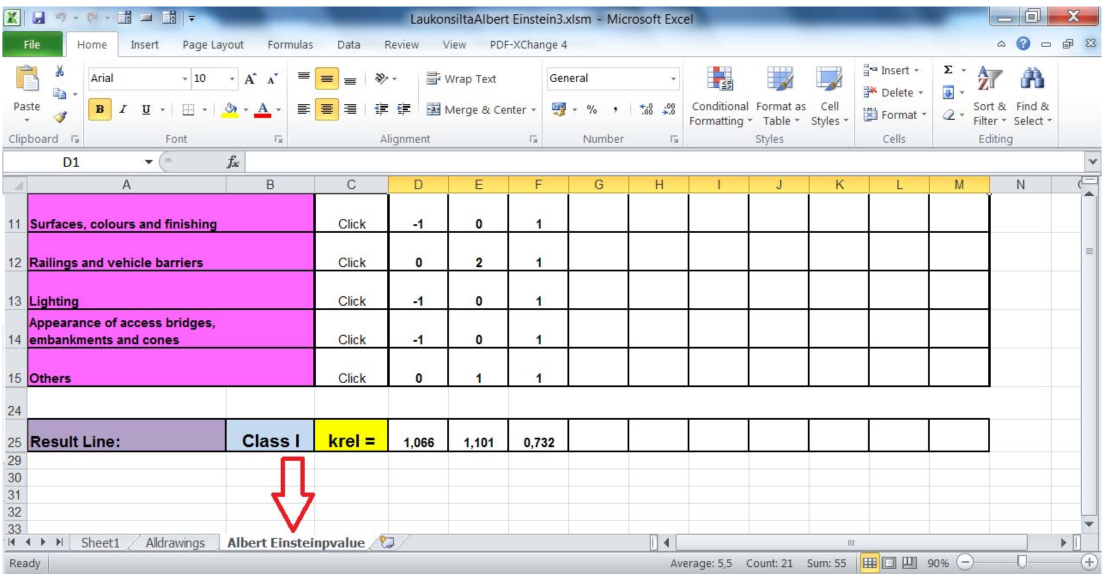
To complete the evaluation, click the lower right corner button "*Save results and quit"* to close the program. Consequently, *Block 4* will be copied in the third sheet "*pvalue*" and the sheet's name will be changed as the *user's name* & "*pvalue*". This is done to make comparison with other evaluators' results easier.

After that a new Excel file under the current file folder will be created. In the current example the name is "*LaukonsiltaUser1*". Now open this workbook, click button "*Enable content*", and the interface will be like shown in *Figs 4.38 and 4.39*. Finally, the third sheet's name is "*Userpvalue*".



Considered Items:-	Click to see the pictures	Proposal number		
		1	2	3
		p	p	p
Integration between the bridge and the site	Click	0	-1	1
Overall harmony (symmetry)	Click	-1	-2	1
Horizontal and vertical geometry	Click	0	1	2
Structural simplicity and order	Click	0	-2	1
Transparency	Click	-1	0	2
Slenderness	Click	1	0	2
Appearance of substructures incl. pylons	Click	0	-1	2
Surfaces, colours and finishing	Click	-1	0	1
Railings and vehicle barriers	Click	0	2	1
Lighting	Click	-1	0	1
Appearance of access bridges, embankments and cones	Click	-1	0	1
Others	Click	0	1	1

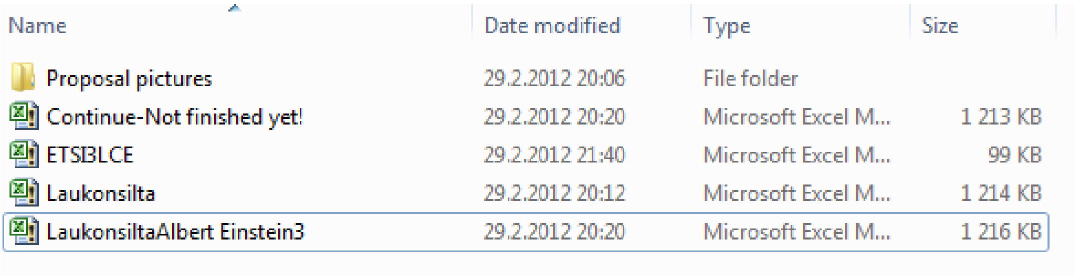
Figure 4.38. Clicking "Enable Content".



Surfaces, colours and finishing		Click	-1	0	1
Railings and vehicle barriers		Click	0	2	1
Lighting		Click	-1	0	1
Appearance of access bridges, embankments and cones		Click	-1	0	1
Others		Click	0	1	1
Result Line:	Class I	krel =	1,066	1,101	0,732

Figure 4.39. All p-values and k_{rel}-values are shown in the third sheet.

Finally, close the workbook and check the file folder. After completing the evaluation, there will be 4 Excel files in the same file folder (*Fig. 4.40*).



Name	Date modified	Type	Size
Proposal pictures	29.2.2012 20:06	File folder	
Continue-Not finished yet!	29.2.2012 20:20	Microsoft Excel M...	1 213 KB
ETSIBLCE	29.2.2012 21:40	Microsoft Excel M...	99 KB
Laukonsilta	29.2.2012 20:12	Microsoft Excel M...	1 214 KB
LaukonsiltaAlbert Einstein3	29.2.2012 20:20	Microsoft Excel M...	1 216 KB

Figure 4.40. All files in the file folder.

If the user did not press "S*ave the present content to continue later*", then the file folder will have only 3 Excel files without the file "*Continue---Not finished yet!"*.

4.6 References

L. Salokangas (ed.). (2009). *Bridge Aesthetics and Cultural Effects*. ETSI Project (Stage 2), Bridge Life Cycle Optimisation. TKK Structural Engineering and Building Technology Publications B, TKK-R-BE3. Espoo. P. 111-135.

Niu, Y., (2011) *Development of a Computer Program for Bridge Aesthetics*. Special Assignment, Aalto University, School of Science and Technology.

S*iltapaikkaluokitusohje* (Guide for grading the Bridge Site). (2007). Tiehallinto - Vägförvaltningen. Helsinki. 53 p. (in Finnish).

Criticism Report of the Laukonsilta Bridge Design Competition. (2007). City of Tampere. 19 p. (in Finnish).

5 Review of LCC and LCA Tools

5.1 Introduction

The present chapter is extracted and edited from the full report published by COWI (*Demonstration of ETSI LCC and LCA tools*, 2012). It comprises an actual application of the tools on Life Cycle Costs (LCC) and Life Cycle Assessment (LCA) for bridges – tools that were developed and finalised during the ETSI 3 Project.

5.2 Possible Applications of the ETSI Tools

The possible applications of the ETSI tools in different bridge design phases are listed below:

- Feasibility study – different possible alignments and links (different bridge types and design).
- Tender – architects – comparison of bids, which often include evaluation of aesthetical values.
- Tender – consultant tender design – optimization, minimizing life cycle costs and environmental impact.
- Tender – construct and built and maybe operate – optimization, minimizing life cycle costs and environmental impact.
- Construction – monitoring, declaring and documenting costs and impacts in relation to actual suppliers, etc.

5.3 Testing the ETSI Tools in a Bridge Project

This section provides background information of the bridge project which is used in this report for the review of the applicability of the developed LCC and LCA tools.

The actual bridge considered in this project is a new bridge across M11, Holbækmotorvejen, bridge no. 72.10, Overpass of *Vindingevej*. A bridge already existed at that location. Demolition and disposal of that bridge are included in the LCC but not in the LCA calculations. The traffic on motorway M11, Holbækmotorvejen, near Roskilde has increased over the years. To match the future traffic needs, it was decided to widen the motorway from 4 lanes to 6 lanes at the bridge location, where *Vindingevej* passes over the motorway.

The existing bridge was replaced with a new standard 2-span concrete bridge. The bridge was cast on site and reinforced with pre-stressed reinforcement. The new bridge and the location are shown in *Figs 5.1* and *5.2*, respectively.

Figure 5.1. Photo showing the bridge viewed from the motorway, shortly before the new bridge was finished.

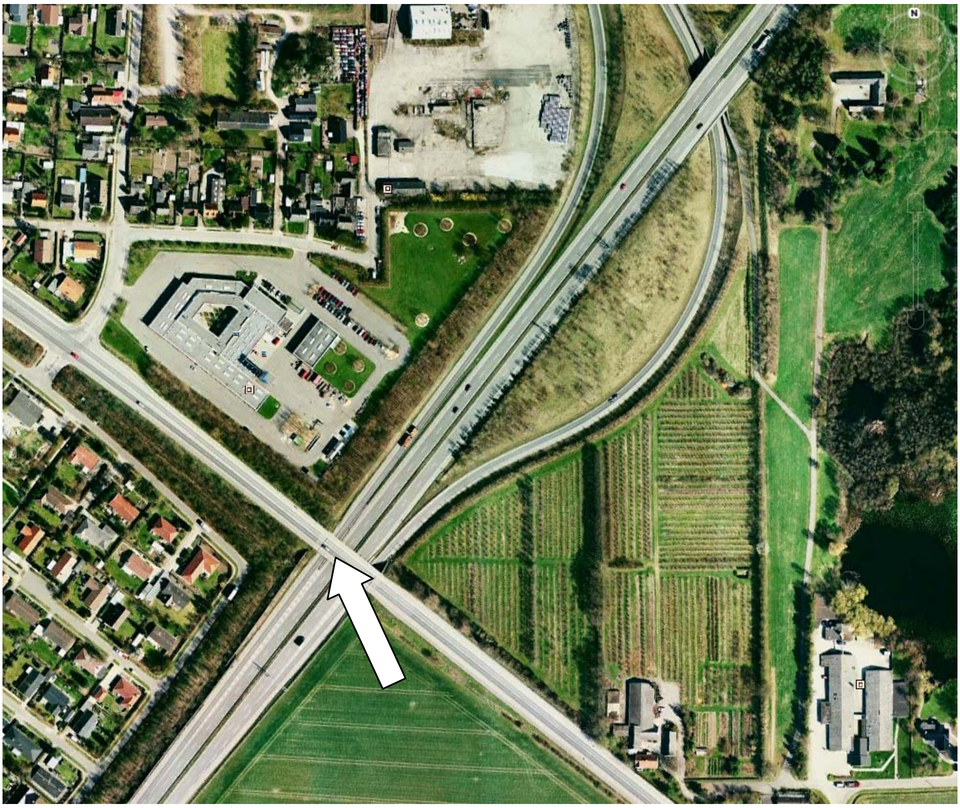


Figure 5.2. Aerial photo with the old bridge marked by an arrow.

In the design phase of the project, three parameters were investigated and optimized.

1st: The cost of the bridge itself. In order to minimize the cost of the bridge, an optimized design solution was used - based on client's specific aesthetic-, bridge type- and material demands.

2nd: The thickness of the bridge deck (the construction height). By reducing the thickness of the deck, more reinforcement steel has to be used than normal. But on the other hand, a reduced construction height leads to a reduced amount of earth works, which overall reduces the total cost of the whole project.

3rd: The traffic disturbances in which two alternative construction scenarios were considered:

- The first scenario was to construct the new bridge next to the end locations of the old bridge, and then - after demolishing the old bridge - push the new bridge into place. This would lead to a closure of Vindingevej for a very short period of time.
- The second scenario was to construct the bridge in several construction phases (using 2 parallel pieces of bridge deck) hereby reducing the traffic disturbance of the traffic on Vindingevej. This would lead to a prolonged construction period.

For both the above mentioned scenarios, the added construction cost was significant, and the overall reduction of traffic disturbances was considered too small. Therefore, it was decided to construct the bridge as a whole, while diverting the traffic on Vindingevej by using an interim road. It took approximately a year to construct the new bridge.

5.4 Input for LCC and LCA Models

The main input for the LCC and LCA calculations consists of three separate items:

- Construction of the bridge.
- Operation and Maintenance during the service life.
- The influence of traffic.

5.4.1 Construction of the bridge

Input quantities and prices of the materials, used for the calculations of the LCC and LCA during the construction phase have been retrieved from the bill of quantities (*Demonstration of ETSI LCC and LCA tools*, 2012).

The quantities of construction materials and the associated costs might not be the same as the real costs and a comparison with the actual quantities and costs were carried out. Based on this comparison it was seen that this difference was negligible.

The unit price of the main materials as concrete and steel was calculated as a weighted average, based on the different prices and quantities of the materials which are included in the bill of quantities. For instance there is a difference in price on formwork of the deck and the abutment.

The division into bridge elements in the LCC tool is also based on the bill of quantities. There are some differences between nomenclature in the LCC program and nomenclature used by the Danish Road Directorate (VD). The program INPUT has been adjusted for this application to match VD.

In the "Construction cost" sheet of the program, an estimate of the quantities in the section called "Road project" was made. The bill of quantities for this part of the project contains the sum of quantities for roads leading up to two bridges. Based on project drawings it is estimated that 75% of the quantities are used as part of the "*Vindingevej*" project. This estimate contains some level of uncertainty.

5.4.2 Operation and Maintenance

The input for the O&M plan used for the service life of structural components is based on engineering judgements and recommendations of the Danish practise (*Demonstration of ETSI LCC and LCA tools*, 2012).

Quantities of materials contained in the different repairs are calculated, as they are needed as input in the LCA tool. The quantities of materials are calculated based on the values given in Danish design codes for Bridges, DANBRO. The cost of the repair is also based on the values provided by DANBRO for the year 2012.

For each type of repair which is included in the "DANBRO price", there is an amount for administration and an amount for the construction site including the cost of materials and labour. This means that amount for administration and amount for running the construction site are included twice, if two types of repairs are carried out at the same time. Therefore the total price of repair is subject to some level of uncertainty.

The amount and frequency of repairs are based on engineering judgements and experience (*Demonstration of ETSI LCC and LCA tools*, 2012).

5.4.3 The influence of traffic

The influence of traffic is taken into account in different ways in the LCC and LCA tools. The basis of those calculations is given in the following sub-sections. Moreover, a description of the traffic models used by VD is given along with a brief discussion of the differences between those models and the models forming the basis of the ETSI LCC and LCA tools.

Traffic models for LCC tool

In the LCC tool, the influence of traffic on the total cost during the service life of the bridge corresponds to the delay of the users and/or goods on the affected road section. A rather simplified model for this delay is proposed in the LCC tool assuming that the delay is due to a speed reduction on the affected road section. It is assumed that the road section has sufficient capacity, i.e. there is no tail back due to the road works. Finally, it is assumed in the tool that the traffic and number of cars and trucks are constant throughout the service life of the bridge. The LCC corresponding to the delay of the users is calculated by

$$LCC_{\mathrm{user,delay}} = \sum_{t=0}^{T} \left(\frac{S}{v_{\mathrm{r}}} - \frac{S}{v_{\mathrm{n}}} \right) ADT_t \cdot N_t \left(p_{\mathrm{L}} w_{\mathrm{L}} + (1 - p_{\mathrm{L}}) w_{\mathrm{D}} \right) \frac{1}{(1+r)^t} \tag{5.1}$$

where

S is the length of affected roadway on which cars drive due to MR&R actions,

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 works at time t,

p_L is the amount of commercial traffic,

w_L is the hourly time value for commercial traffic [CUR/h],

w_D is the hourly time value for drivers [CUR/h] and

r is the real interest rate.

The annual daily traffic on the road section is provided by the road-owner. In specific cases where operation, maintenance and repair works affect other roads, e.g. roads below the bridge, the owner of that road should provide information about ADT as well. The LCC calculations presented in this report are based on the average daily traffic, ADT_d and N_t is changed to N_d which is the number of days of road works.

Relevant values for the input parameters given above are presented in *Table 5.1*.

Table 5.1. Parameters for LCC calculations.

ADT_d (Vindingevej)	9,554 vehicles/day
ADT_d (M11)	40,400 vehicles/day
v_n (Vindingevej)	50 km/h
v_r (Vindingevej)	30 km/h
v_n (M11)	110 km/h
v_r (M11)	70 km/h
w_D	105.25 DKK/h *
w_L	344.87 DKK/h *
p_L	0.15
R	5 %

** 2010 values provided by VD*

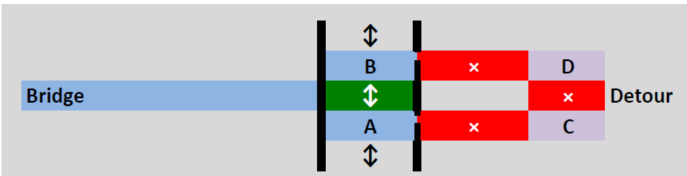
Numbers concerning ADT_d for *Vindingevej* and M11 were provided by *Roskilde Kommune* and VD, respectively. The amount of trucks, p_L, is assumed based on experience from similar calculations. The value for the annual real interest rate, r, is the value used by VD.

The LCC concerning the impact of traffic are calculated for the bridge (*Vindingevej*) and the highway (M11) in separate simulations.

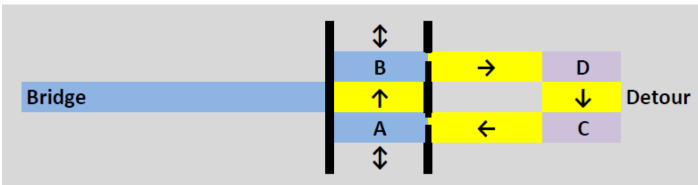
Traffic models in LCA tool

The traffic model for the LCA tool is capable of simulating three different scenarios:

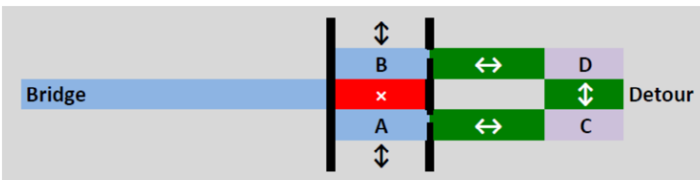
1. Two way traffic across the bridge during O&M:



2. One way traffic across the bridge and diversion of traffic in the other direction:



3. Diversion of the traffic in both directions:



The illustrations below each scenario are screen dumps from the LCA tool.

For each scenario the total emission measured in CO_2, CO, HC and NO is calculated taking into account the following parameters:

- Length of detour (if there is a detour).
- Duration of the road works (in days).
- Average vehicle speed.
- Average daily traffic.
- Traffic load.
- Amount of passenger cars (petrol and diesel), buses (diesel) and trucks (diesel).

Input for the LCA calculations, such as the CO_2 emission per unit of construction material etc., are based on tabular values from Ecoinvent which are an integrated part of the LCA tool.

The traffic load is used to describe the Rotation per Minute (RPM) of the engine, which in this case is directly linked to the fuel consumption. The fuel consumption for cars, buses and trucks is based on a weighted average of the fuel consumption of the most common vehicles.

At present, the LCA tool calculates the total emission during the road works, not only the extra emission due to the road works i.e. subtracting the average daily emission from the total emission.

The impact of the traffic in the LCA is calculated for the bridge (*Vindingevej*) and the motorway (M11) in separate simulations. The results of the LCA calculations cover the impact of the traffic on both roads.

In the present Vindingevej case the LCA calculations are based on two way traffic on and under the bridge. The distance travelled by the cars is calculated as a weighted average of the distance corresponding to each road work.

Traffic models used by VD

Three models are used by VD to estimate the expenses related to disturbances in the traffic caused by road works.

- Maintain the traffic on affected road by reducing the speed.
- Diversion of the traffic.
- Maintain the traffic on affected road by regulating the traffic with traffic lights.

All the models are based on simplified formulations and assumed that the capacity of the roads used for diversion is sufficient and that there is no creation of queues, etc. All the models are capable of extrapolating the amount of traffic.

The model used for calculating the costs associated with a reduction of the speed is similar to the model used within the LCC calculations in this project, Eq. (5.1), and for that reason the model is not further discussed in this section.

The cost due to a diversion of the traffic via an alternative route is calculated as the sum of the cost due to the increased travel time and the cost related to extra wear of vehicles. Costs due to the increased travel time are calculated by

$$LCC_{traffic\ time} = \sum_{t=0}^{T} \left(\frac{l_r}{v_r} - \frac{l_n}{v_n}\right) ADT_t \cdot N_t (p_L w_L + (1 - p_L) w_D) \frac{1}{(1+r)^t} \tag{5.2}$$

where

l_r is the distance of the alternative route (diversion)[km],

l_n is the distance of the original route [km],

v_r is the speed on the alternative route [km/h],

v_n is the speed on the original route [km/h],

ADT_t is the average daily traffic, measured in numbers of cars per day at time t,

w_L is the hourly time value for commercial traffic [CUR/h], and

w_D is the hourly time value for drivers [CUR/h].

The cost associated with increased wear of the vehicles due to extra distance via the alternative route is calculated by

The cost associated with increased wear of the vehicles due to extra distance via the alternative route is calculated by

$$LCC_{traffic,distance} = \sum_{t=0}^{T} \Delta l \cdot ADT_t \cdot N_t (p_L q_L + (1 - p_L) q_D) \frac{1}{(1+r)^t} \quad (5.3)$$

where

- Δl is the difference between the original distance and the alternative route [km],
- q_L is the cost for *commercial traffic* [DKK/km], and
- q_D is the cost for *cars* [DKK/km].

The final model concerns the increased costs due to regulation of traffic by the use of traffic lights. The model is based on the assumption that there is no tailback due to the regulation, and the difference between travel-time on the distance with/without the traffic light is calculated.

The average delay per vehicle due to the regulation is calculated by

$$F_{avg} = \frac{r^2}{[2 \cdot C \cdot (1 - b \cdot I)]} \quad (5.4)$$

where

- r is the time when the traffic light is red,
- C is the sum of the time for one red and one green light in one direction,
- b is the average time for finishing one vehicle (usually 2 s/vehicle-unit), and
- I is the traffic intensity per direction.

Further information about the calculations of the time of green light, the average delay per vehicle, etc. is given in (*Demonstration of ETSI LCC and LCA tools*, 2012).

Based on the average delay of the vehicles the total costs related to traffic regulation are calculated for cars and trucks from Eqs (5.5) and (5.6), respectively

$$LCC_{\text{light,car}} = \sum_{\text{t}=0}^{\text{T}} F_{avg} \cdot ADT_t \cdot N_t \cdot (1 - p_L) w_D \cdot \frac{1}{(1+r)^t} \quad (5.5)$$

$$LCC_{light,lorry} = \sum_{t=0}^{T} F_{avg} \cdot ADT_t \cdot N_t \cdot p_L \cdot w_L \cdot \frac{1}{(1+r)^t} \quad . \quad (5.6)$$

Discussion of traffic models

A short discussion of the traffic models incorporated in the ETSI LCC and LCA tools is provided in the following. Moreover, the possibility of implementing the traffic models used by Danish Road Directorate (VD-models) into the existing LCC and LCA tools is discussed.

Taking account of the cost which is related to the traffic in the LCC program is very user-friendly. The simple formulation considering a general reduction of the speed over a specified distance is apparent. However, the traffic model used in the LCC tool does not provide a possibility of taking delays due to traffic-light regulation into account, which is often used during maintenance and repair of a bridge.

Associated cost due to diversions of the traffic during the construction phase is not an option within the LCC model. Such cost can be, as explained in a separate section of this report, substantial. Finally, the existing LCC tool is not capable of taking account of cost associated with traffic both **on** the bridge and **under** the bridge at the same time.

The traffic model used within the *BridgeLCA* takes account of the emission due to a diversion of the traffic. It is easy to use and the formulation is rather detailed since it takes account of the emission as a function of the speed, the type of cars (petrol or diesel), etc. However, as for the model used in the LCC tool, it is not possible to take account of traffic lights. In addition, it is not possible to include emission associated with idle running of the cars and a general reduction of the speed cannot be considered. Moreover, it is not possible to take account of traffic **on** and **under** the bridge.

The costs related to three typical scenarios can be calculated by the (simple) models used by VD, which makes the tool very useful. At present there is no link between the VD tool and the LCC tool, which can however be implemented.

In addition, the VD-model does not calculate the emission from traffic.

5.5 Results from LCC and LCA calculations

5.5.1 Results from LCC calculations

Prior to presenting the results from the LCC analysis the basis of those calculations is described.

At a relatively early stage in this project it was clear that some limitations of the LCC tool existed, e.g. traffic diversion during the construction phase is not considered, and the model in relation to the traffic-costs only considers a general reduction of speed, etc. However, taking into account that the aim of this project was to show how the existing tool for LCC can be implemented, it was decided not to make any major changes to the tool, as the relevance of changes to a large extend would be country dependent. The things that have been implemented into the LCC tool are the possibility of taking into account traffic under the bridge, the possibility of calculating costs for O&M and repair based on an O&M plan.

The bridge project used for the review of the LCC and LCA tools described in this report concerns the demolition of an existing bridge and the subsequent construction of a new bridge at the same location. Diversion of the existing traffic via an alternative route and the associated costs while the new bridge is constructed are not considered in the results shown in *Figs 5.3 – 5.8*. The reason for this is that the existing LCC tool does not allow for such calculations.

Calculations of the costs associated to a diversion of the traffic were calculated using the models and corresponding unit-costs provided by VD. The difference between the alternative route and the actual route was approximately 1 km. Taking account of the cost due to increased use of the vehicles and the delay of the users, the cost associated to that diversion of the traffic was more than 40.000 DKK per day, resulting in more than 13 million DKK over the construction period of the bridge. In this context it is of relevance to mention that this diversion of the traffic is the best alternative. Thus, the cost related to diversion of existing traffic is substantial and the LCC tool can benefit from implementing methods for calculation of diversion.

Though the O&M plan prescribes that the regulation of traffic during parts of the road works should be done by the use of traffic-lights, this has not been done in the calculations since the LCC tool does not allow for this. Consequently the associated cost due to those delays is solely based on a general speed reduction from 50 km/h to 30 km/h without considering the time of waiting for green light.

The LCC tool summarises the results in one table and six graphs. Results are calculated for 100 years life span of the bridge assuming an annual real interest rate, *r = 5%.*

In *Fig. 5.3* the total cost is divided into five sub-categories, of which the investment cost in this case is the major cost-driver (88 % of the total sum in net present value). In the case that diversion of the traffic was included, this would even comprise an ever higher percentage.

Bridge Stand alone LCC
Optimal new bridges - Life cycle analysis

Life cycle cost
Bridge at Vindingevej, across M11

INVESTMENT COST	11,411,987
REPAIR COSTS	1,104,784
OPERATION AND MAINTENANCE	263,324
USER COSTS	207,429
DEMOLITION COST	8,678
SUM NET PRESENT VALUE	**12,996,202**
SUM NET PRESENT VALUE / BRIDGE AREA [CUR/m^2]	**15,751**

Figure 5.3. Output from LCC tool - summary of costs in net present value.

The sum of repairs, operation and maintenance correspond to approximately 1.4 million DKK in net present value.

The user costs, i.e. the costs associated with delays of the road users, are at the same level as the costs for operation and maintenance. In this case operation and maintenance only cover the costs for inspection (general and special inspections) and minor cleaning. All other costs during the life span of the bridge, e.g. replacement of bearings, wearing course and waterproofing membrane, are considered as part of the repair costs. The cost for demolition of the bridge is calculated by the LCC tool as a predefined percentage (10%) of the total investment cost.

A more detailed illustration of the total cost during the service life of the bridge is presented in *Fig. 5.4*, showing the accumulated cost (in net present value) as a function of the service life.

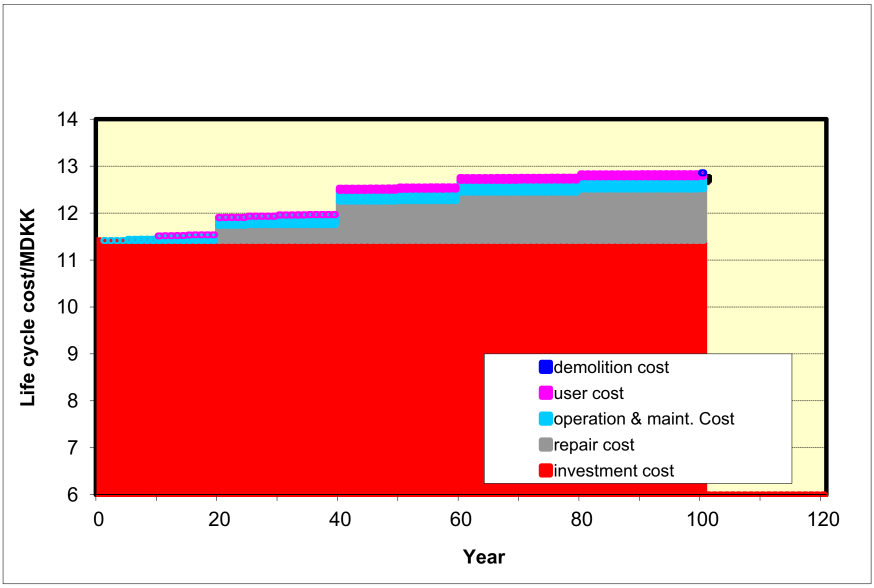


Figure 5.4. Whole life cycle cost for Vindingevej Bridge. Calculated to present value.

The accumulated cost (net present value) for repair during the entire service life of the bridge is shown in *Fig. 5.5* along with the repair cost (not calculated to net present value) at different intervals (in accordance with the O&M plan) along the service life.

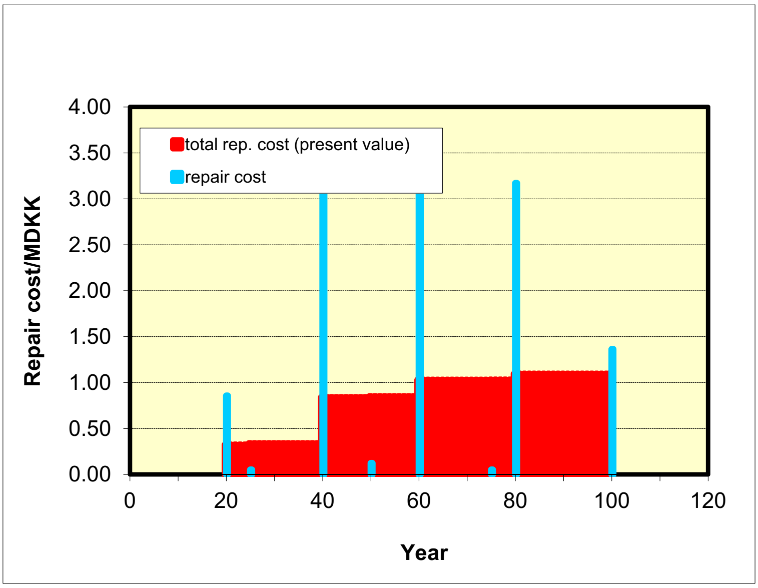


Figure 5.5. Accumulated repair cost (net present value) and repair cost (not calculated to net present value).

The repair costs presented in *Fig. 5.5* do not consider the associated user costs. Results showing the repair costs and the related costs due to traffic delays, i.e. user costs, are illustrated in *Fig. 5.6*. Those costs are not converted to net present value.

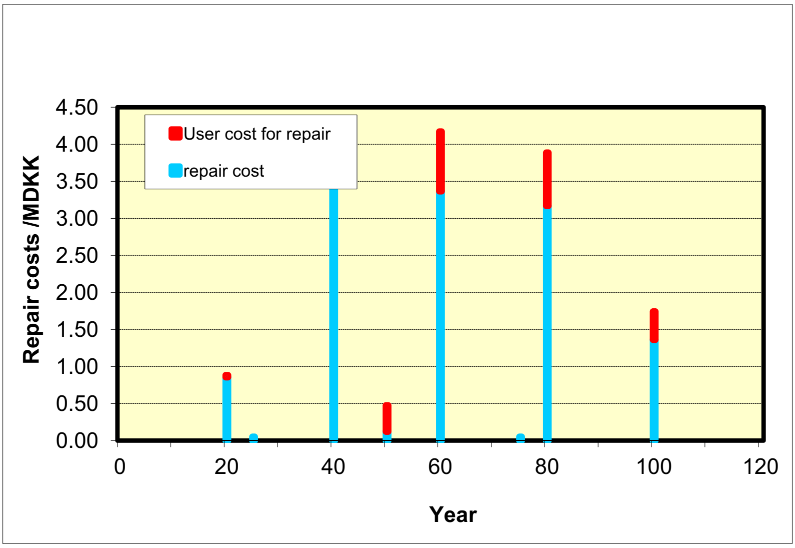


Figure 5.6. Repair costs and associated user costs. Not converted to net present value.

The accumulated cost for operation and maintenance (converted to net present value) is presented in *Fig. 5.7* along with the cost for operation and maintenance (not converted to net present value) in accordance with the O&M plan.

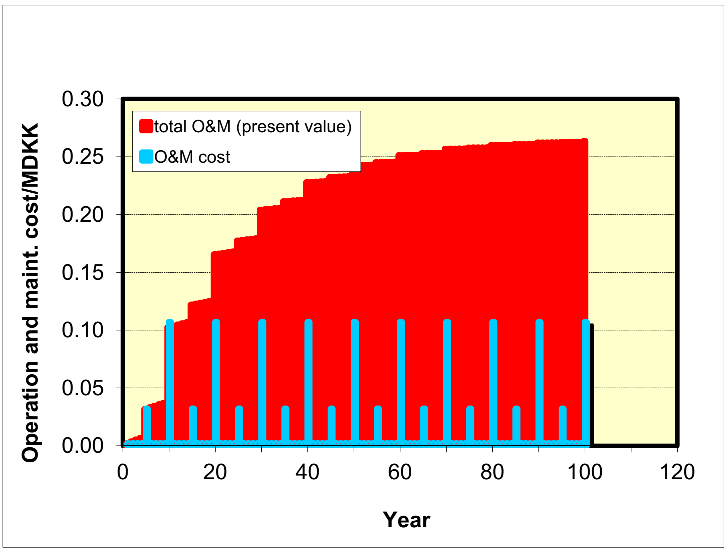


Figure 5.7. Accumulated cost for operation and maintenance (converted to net present value) and cost for operation and maintenance in accordance with O&M plan (not converted to net present value).

Apart from costs to maintenance of road lights every year, the total cost for operation and maintenance consists of costs for general inspection (every 5th year) and costs for special inspections (every 10th year). Special inspections are usually not planned in advance, but have been inserted in this way due to limitations of the LCC tool. The related user costs are not presented in *Fig. 5.7*. It is assumed in the O&M plan that most operation and maintenance work is carried out without interruptions of the traffic. Thus the user costs in this context are negligible, and therefore not included. This is seen from *Fig. 5.8*, which illustrates the user costs converted to net present value associated with repair and operation and maintenance, respectively.

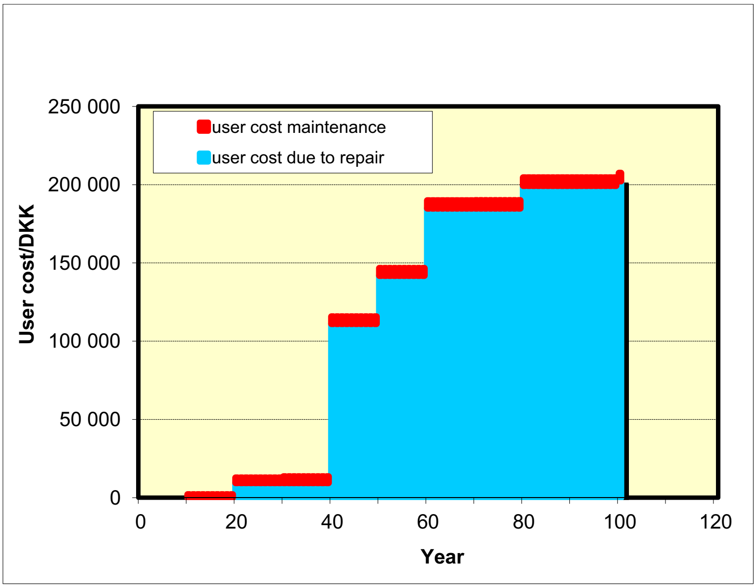


Figure 5.8. User costs related to repair and operation and maintenance, respectively (converted to net present value).

The illustrations of the results from the LCC calculations presented in *Figs 5.4 – 5.8* provide a general overview of the costs related to the project. However, it is not possible to identify the cost-drivers within a sub-category, e.g. repair. In order to evaluate the cost-drivers it is necessary to analyse the calculations forming the basis of the *results*-sheet, i.e. comparing the costs for different work.

5.5.2 Results from LCA calculations

Based on the quantities derived from the bill of quantities and the quantities from the operation, maintenance and repair, LCA results have been calculated. The results from assessing the *Vindingevej* Bridge by using *BridgeLCA* are depicted in *Figs 5.9 – 5.13*.

Environmental emissions

In *Fig. 5.9*, the relative midpoint LCIA results are presented.

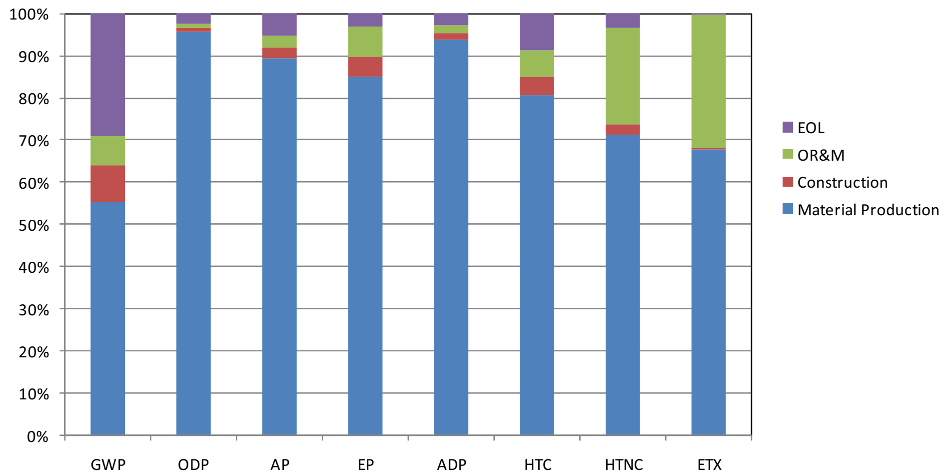


Figure 5.9. Relative midpoint LCIA results from assessing the Vindingevej Bridge.

Fig. 5.9 shows that the material production is contributing the most to the total potential environmental impact. Here, O&M shows significance for the potential impacts from toxicity.

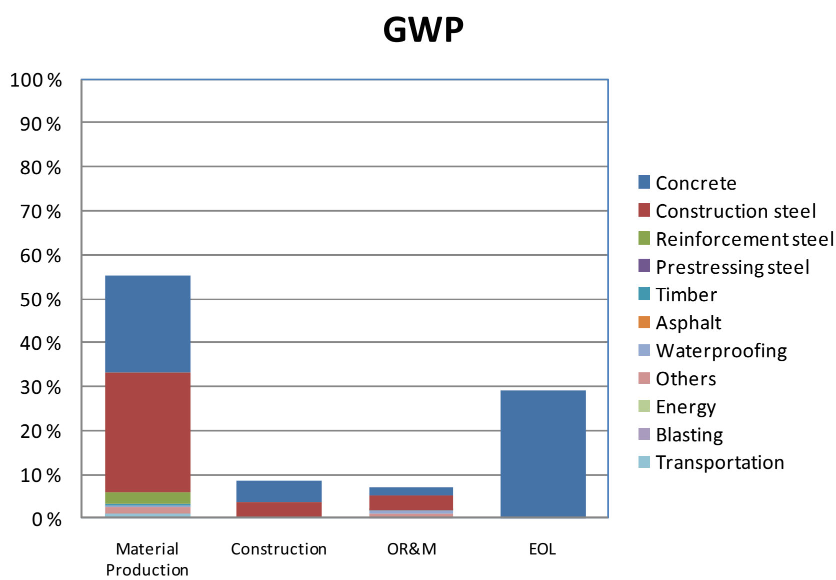


Figure 5.10. An example of the results from the LCA calculation in Bridge LCA. The figure shows normalised and weighted potential impacts on global warming.

From *Fig. 5.10* it can be concluded that concrete causes the largest potential environmental impacts. The second largest contributor to the potential environmental impacts is steel. Still, the emission factors for steel must be assessed further to be able to make a final conclusion.

Also, it can be concluded that the materials phase has the highest potential environmental impact. This is the case when the daily use of the bridge is not incorporated into the calculations. It is possible to insert data for the diesel consumption (in litres) but *BridgeLCA* has not been designed to incorporate this impact specifically.

The normalised figures show the same as the weighted figures due to the current incorporated weighting factors of 1.

The normalised impacts are divided into impact categories for the entire life cycle of the bridge:

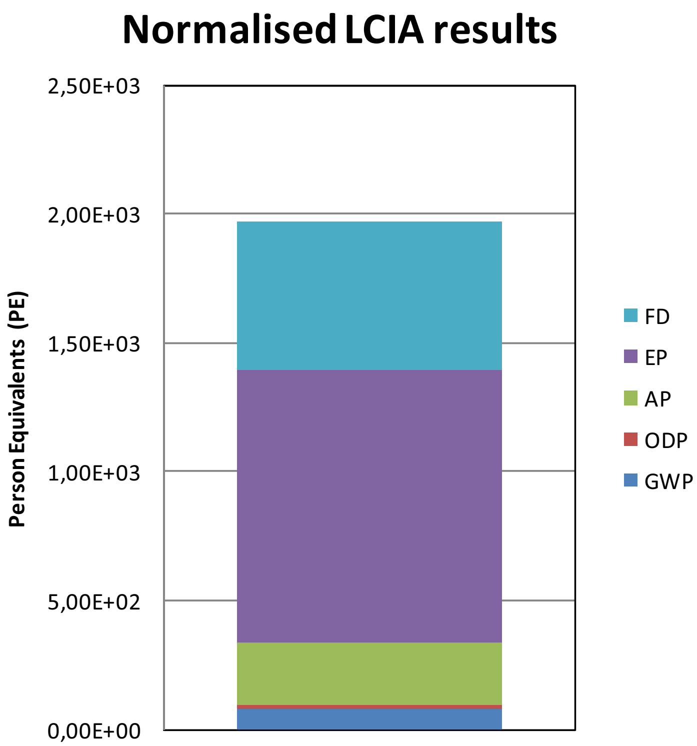


Figure 5.11. Normalised potential environmental impacts during the full life time of the bridge.

From *Fig. 5.11* it is clearly seen that the largest potential environmental impact is eutrophication. This impact primarily derives from the steel and zinc coating.

The importance of these potential environmental impacts is related to the average contribution from one average person per year.

FD expresses the fossil depletion and is the second largest potential environmental impact, also it is related to the energy consumption during the life time of the bridge.

Energy Consumption

It is possible to assess the energy consumption via *Figs 5.12 – 5.13*:

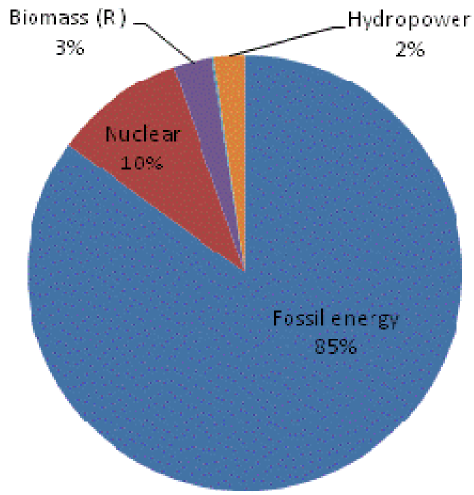


Figure 5.12. Energy consumption split into energy carriers.

As the data primarily derive from the Swiss database Ecoinvent, the energy carriers are primarily fossil fuels and nuclear power.

This picture will change when figures for Danish conditions are inserted.

The result can also be shown in another way where the user can see the large consumers of energy in the materials phase:

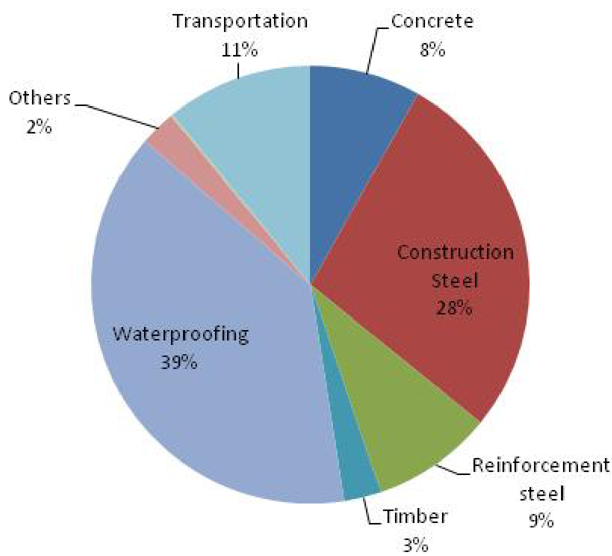


Figure 5.13. Energy for materials/activities.

It can be seen that, the waterproofing membrane uses the highest amount of energy, using data from Bridge LCA. The second largest consumer is steel. Data for the specific waterproofing membrane need a further evaluation as the result is higher than expected.

Effects of the Traffic

In *BridgeLCA* it is possible to insert traffic parameters during road works, but impossible to include effects of normal daily traffic on the bridge.

First of all, the importance of modelling and including potential environmental impacts from traffic during road works has been evaluated. It can be concluded that the traffic during road works has little potential impact compared to the daily traffic, 6% during the full lifetime of the bridge.

The daily traffic during the full life time of the project has great significance to the LCA result (the traffic during the phase of usage has by far larger potential impacts than the other phases of the project (materials phase, OR&M and end-of-life)). Thus, it is recommended to include daily traffic in the assessment - especially in the early stages of a bridge project where several traces/tracks with different lengths must be assessed.

Recommendations for the Development of *BridgeLCA*

During the test of *BridgeLCA* it can be concluded that some parts of *BridgeLCA* can be developed in the future. The possible areas for development are:

- Development of weighting factors.
- Expansion of the bridge to include roads, tunnels etc.
- Analyse the data to assess the significance of using generic data from Ecoinvent especially in relation to the use of energy (amount and type of fuel/energy carrier).
- Incorporation of values for steel which are relevant for bridge projects.
- Possibilities to incorporate daily traffic of the bridge.
- Development of a roadmap to maintain the tool including updating emission factors .
- Incorporation of the values for cement/concrete.
- Modelling the end-of-life of the bridge.

5.5.3 Material Data for Concrete

In the Nordic countries different approaches and requirements to concrete mixtures that are applied for various bridge parts exist, depending on national Annexes of Eurocode standards as EN 206-1, and local regulations from national authorities.

Such local regulations are typically based on long term experience with specific locally produced cement types which may differ substantially among countries. Therefore, environmental impacts from different concrete types may vary from country to country, and it is recommended that country specific values are applied in the *BridgeLCA*. The same applies for steel, along with concrete and steel being the largest single contributors to environmental impacts from bridges.

For Danish conditions not many degrees of freedom are left for the specification of concrete mixtures, following EN standards with national annexes and the Road Directorate's general specifications for concrete works (AAB). Moreover, ready mix concrete suppliers delivering standardized concrete mixtures which are certified means that any alternative concrete mix will have to undergo a new and extensive pre-testing programme before getting acceptance. This will not be feasible for smaller bridge projects.

For the actual bridge at *Vindingevej*, CO_2 contributions from cement have been calculated as an example only for CO_2, based on m^3 of concrete delivered for the construction of the bridge, which is shown in *Table 5.2*. The concrete mixtures typically include about 15-20% of added fly ash which does not add much to the CO_2 emission.

Table 5.2. Data for concrete used at Vindingevej based on CO_2 emission from cement.

Bridge part	Concrete , m^3	Cement content, kg/m^3	CO_2 emission* cement, kg/ton	CO_2 emission, total, ton
Foundation	54	285	926	14.3
Columns, walls	206	341	926	65.0
Bridge deck, edge beams	551	341	926	174.0
$\sum$				253.3

**Data from cement supplier*

It is worth to remark that only few years ago the single Danish cement type allowed for aggressive (A) and extra aggressive (E) exposure conditions due to earlier Danish having a CO_2 emission of 1,240 kg CO_2 per ton, e.g. the emission for the *Vindingevej* Bridge would have been 25 % higher. At the same time a requirement of maximum allowable CO_2 emission per m^3 of concrete was specified for the new Metrocity ring in Copenhagen, thus made it difficult to fulfil the requirement with the specific Danish cement type.

The 25 % reduction has been caused by altered and more energy effective production methods from the cement factory which in this case has expounded responsibility in reducing CO_2 emissions and continued efforts for further reductions for all cement products.

For maintenance activities during the estimated 100 years of service life about 40 m^3 of concrete needs to be replaced, following the O&M plan. This will imply an additional CO_2 contribution of 12.6 ton CO_2, which is ~5 % of CO_2 emission from concrete in the construction phase.

Service life

An overview of service life evaluations for concrete based on standards and guidelines and actual exposure conditions are attached in Appendix, in a Technical Note prepared earlier in the ETSI project on Methodology for LCC and LCA tools. Concrete durability and a long service lifetime are essential for large infrastructure investments involving concrete.

Service life estimation is a critical element in the development of LCC/LCA systems, not only to obtain accurate life cycle assessments but also to compare different options.

Future optimisation

For optimising and obtaining greener concretes for future bridge structures, a number of recommendations have already been available using larger mineral additions of e.g. fly ash and blast furnace slag cements, thereby reducing the content of Portland cement.

Inside existing standards and requirements, some CO_2 reductions can be obtained, especially by the use of blast furnace slag cements (reduction up to about 50 %) or high contents of fly ash. However, resources of blast furnace slag and fly ash are not large enough compared with the size of cement production.

Outside existing standards, reduction possibilities are larger, compromising service life time is not included, and moreover, test and trial bridges with innovative materials should be supported from relevant authorities to gain necessary experience.

Also, universities and the cement industry are involved in research of developing and introducing new low-energy cement types with similar properties as today. However, it will take decades before such new products are accepted and included into standards.

5.6 Conclusions and Recommendations

5.6.1 Conclusions

Conclusions in relation to results are described under LCC and LCA headings separately above. It has been a good learning process to implement the ETSI tools on an existing bridge project. The process has given valuable information in relation to:

- The tools themselves, impact of different input parameters and the ways the tools work.
- Possible improvements to the tools. Items and suggested actions are included in list under recommendation parts.
- The possible differences in how the tools are constructed and how the VD system works. Items and suggested actions are included in list under recommendation parts.
- How the tools can be used in connection with a tender design process (Expounded under recommendation parts).
- Ideas to how the tools can be applied also for feasibility studies, detailed design and during the construction phase.

5.6.2 Recommendations

The recommendations have been grouped under separate headings and shown in the *Table 5.3*.

Table 5.3. Recommendations for tools.

Items of general interest				
Tool	Sheet	Recommendation	Time term	Comment
LCC	General condition	Traffic below bridge should be included as supplement to traffic on bridge	Short	Included in amended calculations and reflected in separate O&M manual, weighting factors can be set as 1 as a starting point
		Weighting factors could be replaced with service lifes on different elements combined with deterioration models	Mid	Weighted prices can be included, the price on formwork for instance relate however hightly to location and extend in labor cost. Therefore it would be beneficial to provide more flexibility
	Investment costs	A more detailed price list should be provided for different structural elements	Mid	
	Operation & Inspection costs	Splitting of traffic costs into one on bridge and one under the bridge	Short	
		Repair should be combined with operation and maintenance as is the case with LCA	Short	
		Developed into more flexible tools, where it is possible to have a starting action year and intervals from there	Short	
		Repair should be % of surface area, so that sepatate calculations can be avoided	Short	
		Include annual increase in traffic in model	Short	
	Repair costs	Splitting of traffic costs into on the bridge and under the bridge	Short	
	Result	Graphic presentation should be uniformed with LCA	Short	
		Graphic should show net present values or actual costs not both in same graph	Short	
LCA		Modelling end of life	Short	
		Revise traffic impact in relation to operation, maintenance and repair, subtracting daily traffic from additional impact or include traffic impact in general throughout the life	Short	
		Analyse the data to asses the signigicance of using generic data from Ecoinvent especially in relation to the use of energy (amount and type of fuel/energy carrier)	Short	
LCC and LCA		Inclusion of tunnels and roads	Long	For possible evaluation of alignments and possible options in feasibility stage
		A web based tool could be considered	Long	Allowing for flexibility and uniform approach within Nordic countries
Items of Danish Road Directorate's interest				
LCC		Incorporation of Danish road directorate traffic model in LCC	Short	To match what is done within existing bridges
		Elaborate on prices for operation, maintenance and repair	Short	
LCA		Develop and incorporate specific Danish emission factors for the materials which contribute to the largest potential environmental	Short	
		Development of weighting factors	Mid	
		Include more materials in the tool (stainless steel, gravel, etc.)	Mid	
		Incorporate the possibility to insert daily traffic in Bridge LCA-especially for the use in the feasibility stage	Mid	
LCC and LCA		A web based tool could be considered	Long	

Detailed recommendations

a) The output from the results should be presented in net present value only. Existing figures in the LCC tool show costs calculated in net present value along with costs which are not calculated in net present value in the same figure, make the interpretation of the results difficult. It is suggested to change such figures to show results either calculated in net present value or not.

b) The results- sheet in the LCC tool automatically generates six graphs displaying the costs (user costs, repair costs, etc.). However, it is not possible to identify cost-drivers within those sub-categories, which is a major motivation for carrying out LCC calculations. Thus it is recommended to modify the LCC tool slightly for illustrating the contributions to each sub-category. In the result sheet it would be helpful to show the cost drivers in the construction phase as well, which will ease the optimisation process.

c) The LCC tool can calculate input parameters from traffic on the road in the present form. To make the tool more user-friendly, it could be supplemented by including traffic for both over and underpass. Moreover, it is recommended to implement the traffic models provided by VD. The reasons for this recommendation are:

- The VD-models comprise the typical scenarios, i.e. maintaining the traffic by reduced speed or regulations with traffic lights or diversions of the traffic.
- The VD-models are capable of extrapolating the amount of traffic, which is not the case in the existing LCC tool.

d) Operation & Inspection costs and Repair costs sheets should be converted into one, as they jointly comprise the O&M manual. The possibility of giving frequency for operation and maintenance is limited to either interval year with automatic start from the first year or three separate action years. To make it more user-friendly, it is recommended to increase the number of action years larger than 3. This solution may compromise the overview of the sheet.

e) Extension in repairs should be included in percentage instead of amounts, which require separate calculations. This will ease the input additionally.

f) The LCC tool may be expanded to calculate material quantities used in the O&M phase, as these are major input factors in the LCA tools.

g) The LCA calculations concerning the impact of traffic showed that the influence of the traffic on the total emission (calculated in CO_2 and SO_2 equivalents) is negligible compared to the emission from the remainder parameters. It is recommended to investigate this further as it may not be relevant to optimise the tool for usage with regard to traffic.

5.6.3 Recommendations for Applying ETSI Tools

It is concluded that there is a great potential for the Nordic Road Authorities in applying the updated ETSI tools to meet the actual needs.

It is recommended that a strategy and an action plan in bridge projects are developed for inclusion of the tools within the Nordic Road Authorities. This can comprise a series of pilot projects before implementing the tools. The possible actions could be taken in feasibility, tender and construction phases.

Feasibility phase

The earlier in the bridge design process the tools are applied the larger is the potential influence and impact. In the feasibility study phase, the road authority can use the tools to evaluate the cost optimum solution on links as well as the environmental optimum solution. At present the tools include bridges which will limit the use from comparing with tunnels, alternate routes etc.

Also alternative bridge solutions can be compared, concrete, steel, timber etc., where the possible effects of different investment and maintenance schemes can be compared.

Thus, recommendations for this part are:

- The tools are further developed to include tunnels and connecting roads.
- An option to include daily traffic is included in the LCA to provide input on effect on alternative alignments/routes.

Tender and construction phase

The tools can be used for different optimisation processes in the design process as a basis for a rational decision process compared to other decision process. This will provide a good basis for gaining knowledge on a rational basis for the benefit of future projects.

Also optimising material, durability and maintenance issues can be provided, for instance, as basis for setting the standard for requirements to suppliers of materials for certification and optimising the productions.

As for construction phase, the tools can be used to document not only the actual costs but also more important factor - the actual environmental impact. The costs in a new bridge design phase whether from a tender design or actual built situation from experience do not differ significantly. However, the environmental impact can be highly dependent on actual suppliers, and will be an important source for evaluation.

Thus, recommendations for this part are:

- National values for prices and emissions are further collected and database maintained simultaneously.
- A uniformed operation and maintenance plan has to be developed for the contractors and suppliers to provide tenders on the same basis.
- An evaluation of emission factors and corresponding weighing factors should be developed when knowledge and experience have been further gathered from pilot testing the LCA tool in conjunction with the LCC tool.

5.7 Reference

Demonstration of ETSI LCC and LCA tools. Danish Road Directorate. Report by COWI. May 2012. (Available as PDF on ETSI home Page: Etsi.aalto.fi/Etsi3/PDF/TG1/Verification_Report.pdf)

6 Conclusion and Future Development

6.1 Conclusion of ETSI Project Stage 3

In this report the methodology of life cycle analysis and three refined life cycle tools, developed during ETSI Project Stage 3, are presented. Individual tools that work reliably were reached and tested in pilot projects.

The LCC tool makes it possible to calculate the total costs of the bridge during its service life, including the direct construction costs and the costs of operation, maintenance and repair. Besides, it can also take account of so called indirect user costs, which are caused by traffic delays or disturbance. The methodology and the theory behind the LCC tool with many examples are explained in detail in Chapter 2.

Refined LCA tool may be used to calculate the total energy consumption, the carbon dioxide emission, the ozone depletion, the acidification and many other harmful emissions to the environment during the service life of the bridge. The program takes account of the effect of traffic due to repair works of the bridge as well. An overview of the theory, methodology, and the Tool *BridgeLCA*, can be found in Chapter 3.

For evaluation of aesthetics and cultural values of a new bridge project, a refined Excel based program was developed. Using this tool the aesthetical values can be related to the bridge life cycle costs. It shows how the program can be used for the evaluation of the aesthetics values of the bridge alternatives in Chapter 4.

In Chapter 5 the ETSI tools are applied to calculate life cycle costs and life cycle assessment in a real bridge project in Denmark. The effect of different traffic models to the results are examined in Danish circumstances. Suggestions for the application of ETSI tools in different phases of bridge design are given. Constructive recommendations are given for the practical use and for future development of the tools.

Five abstracts or studies were included in this report. In appendix A1 the LCC and LCA tools were applied to a large steel-concrete composite bridge. In appendix A2 the concepts of structural database and life cycle plan are introduced. In appendix A3 the expected repair intervals of structural parts of a bridge is discussed. Appendix A4 deals with life cycle cost calculations of concrete bridge deck surface structures. In the end, appendix A5 introduces general applications of LCC calculations for short-span bridges.

6.2 Future Development of ETSI Tools

There are still many things that need refinement to improve bridge design in life cycle sense. The methodology for life cycle plan needs further refinement as well as establishment and development based on reliable common database for estimating life cycle values of bridge parts. Similarly, the methodology to get environmental impact factors for LCA analysis from international or national databanks should be standardised.

ETSI tools may now be used in practice in bridge design. However, computer programs are never ready and the feedback is welcome to find out the remedies of the programs and to get the tools updated. Comments can be sent to developers through ETSI homepages, which can be found on the Internet from the link: etsi.aalto.fi .

Appendix

Abstracts of research related to ETSI Project

Aalto University
School of Engineering

Lövö Bridge - Life Cycle analysis using the ETSI Tools (Abstract)

Anne Nieminen

1 Introduction

This research was done to calculate the life cycle costs and environmental impacts of the Lövö Bridge and then compare them to earlier calculations. The earlier calculations were done when the bridge was still in the design stage. The calculations presented here were done when construction was on-going. The idea was to compare these two calculations to determine how accurately one can perform the life cycle analysis in the design stage. This research is also a part of the ETSI project. ETSI project stands for Bridge Life Cycle Optimisation which consists of bridge Life Cycle Cost methodology (LCC), Life Cycle Assessment of bridges (LCA) as well as bridge aesthetics and cultural effects evaluation. [1] The testing tools used in this research were produced for the ETSI project for the life cycle analysis.

LCC is an Excel based program which is used to determine the life cycle costs of a bridge, including maintenance and repair actions as well as traffic disturbances. LCA is an Excel based program used to calculate the environmental impacts of a bridge. Environmental impact calculations are performed by calculating emission of material manufacturing, construction, transportation, repair and maintenance. Used values for emissions are from EcoInvent database [1].

Lövö Bridge is a continuous girder bridge made of steel, with a concrete deck which makes it a composite structure. The Bridge connects the islands of Lövö and Söljeholmen replacing ferry [2].

2 Lövö Bridge

2.1 General

The Lövö Bridge is a continuous girder bridge of steel with a concrete deck. The bridge is situated in the archipelago of Dragsfjärd on the road number 1830. The total length of the bridge is 474 m consisting of 7 spans, 40+62+78+100+78+62+40 m. The width of the bridge is 8 m and vertical clearance 19 m. The bridge had to be founded on digging piles because the bed rock declines steeply towards the river bed in the longitudinal direction of the bridge. Steel I-girders are the primary load bearing structure. The bridge was opened for traffic in May of 2011 and was completed by the end of July of 2011 [2].

During the summer there is a lot of marine traffic in the vicinity of the bridge. 98 % of this traffic will be able to pass under the bridge through the 19 m vertical clearance, but taller sailing vessels will have to go around the islands [3].

The bridge has a very sturdy foundation. At the deepest point, the piles go nearly 10 metres below the water and the bridge columns reach almost the same height over the water.

The tolerance for impact is 300 tons at the most. Due to the water, ice pressure was a critical load for the foundations. [3]

Figure 1. The Lövö Bridge under construction.

2.2 Inputs Used in Applying ETSI LCC Tool

Life cycle costs of Lövö Bridge were calculated by using the interest rate of 2 %. The 2 % interest rate is recommended to be used for bridges with longer than 40 years life cycle periods [5].

The average daily traffic is 15155 of which 7.2 % is heavy traffic. The yearly traffic growth is expected to be 1.2 %.

The maximum speed limit of the Road 1830 is 80 km/h and reduced speed during maintenance and repair actions was assumed to 50 km/h. Hourly traffic cost for cars is 16.09 €/h and for lorries 56.02 €/h [4]. The total investment of the bridge was estimated to be 6 270 000 €. Investment cost was calculated by using the bill of quantities and unit prices.

The maintenance costs were estimated to consist chiefly of following actions:

- continuous inspections, 1 year interval
- general inspections, 5 years interval
- special inspections (repair designing included) circa 30 year intervals, before any major repair
- bridge cleaning, every year
- cleaning of dewatering system, every year
- exchange of rubber list in expansion joints, every 25 years
- maintenance of bearings, bridge seat, expansion joints, every year, and
- repainting the steel girders and stiffeners, 25 years interval.

This LCC calculation includes only some of the maintenance actions of the bridge because some of them are extremely difficult to predict and some don't have that great of impact on the total outcome of the calculation. In some cases default values of LCC were used due to the lack of more accurate information.

The repair costs consist chiefly of

- edge beam repairs, 25 years interval
- bearings and hinges changes, 35 years interval
- expansion joints reparations, 35 years interval
- reparations of railing (both parapet, railing and noise cover, parapets and railings were predicted to be changed to new ones), 50 years interval

- water proofing, 35 years interval and
- surfacing (asphalt layer renewal), 5 years interval.

This calculation includes only some of the repair actions of the bridge because some of them are extremely difficult to predict and some don't have that great of an impact on the total outcome of the calculation. Concrete quality and road salting were also included in the LCC calculations. Weighting factor for concrete quality was 1.10 and for road salting 1.00. In some cases default values of LCC were used due to the lack of more accurate information. In traffic disturbance calculations, default values of LCC were used.

2.3 Inputs Used in Applying ETSI *BridgeLCA* Tool

The *BridgeLCA* tool is an Excel table that considers the environmental impacts of the building materials, transportation of both materials and workers as well as impacts of maintenance and repair actions.

The transportation of materials was done by both trucks and boats, due to the difficult location of the bridge. The contractor was interviewed regarding the transportation distances. The distances for the primary materials are:

- concrete, truck 75 km
- construction steel, truck 55 km and boat 650 km
- stainless steel, truck, 100 km
- reinforcing steel, truck 100 km
- lower grade steel, truck 100 km
- sawn timber for formwork, truck 70 km
- rubber, truck 170 km
- asphalt, truck 100 km
- concrete deposit for end-of-life transportation, truck 200 km
- steel recycling for end-of-life transportation, truck 200 km.

The steel used in the bridge was provided by Ruukki. The steel parts are assembled and the surface was finished in the Ruukki factory in Ylivieska. After that it was transported to the Rahja Harbour in Kalajoki by trucks from where it was transported by a barge to the bridge site [2]. The total amount of steel used is 885 tons. The most part of the steel is in the steel girder of the bridge. Steel is also used in the foundation piles.

The concrete was pumped into the form by two concrete pumps. There were 10 concrete trucks transporting the concrete from the Salo factory to the bridge site day and night. [2]

For the main supports 116 m^3 of concrete, 9828 kg of reinforcing steel (A500HW) and 95 m^2 of formwork were used for the foundation and 144 m^3 of concrete, 12266 kg of reinforcing steel (A500HW) and 527 m^2 of formwork were used for the vertical parts. For the secondary supports 463 m^3 of concrete, 12114 kg of reinforcing steel (A500HW) and 625 m^2 of formwork were used for the foundation and 604 m^3 of concrete, 93291 kg of reinforcing steel (A500HW) and 1388 m^2 of formwork were used for the vertical parts. For the superstructure 1082 m^3 of concrete, 249 tons of reinforcing steel (A500HW) and 4168 m^2 of formwork were used. The painted area was 9690 m^2.

The total amount of excavation on the site was 60 m^3. The area paved with asphalt was 3729 m^2. The total length of the parapets was 964 m. Consumption layer is renewed every tenth year and the entire layer every 35th year during the replacement of the waterproofing.

For waterproofing rubber bitumen is used in the edge beam borders and asphalt membrane in the bridge life time. Waterproofing is renewed every 35th years.

Concrete is reused as a filling material in the end-of-life (EOL) management. It is assumed that parts of the concrete structures are contaminated. It is highly likely that the edge beams are too contaminated to be used as filling material, so they are ignored. The contaminated part of the concrete is calculated to be 300 m³. Reinforcing, construction and lower grade steels are recycled at the end of the bridge life. EOL transportation distances are assumed to be the same as in material transportation distances.

3 Life Cycle Analysis for Design and Construction Stage

3.1 Results of LCC Analysis

Total discounted value of Lövö Bridge in the calculations of the design stage with 2 % interest rate is 8 488 000 € and in the calculations of the construction stage 10 197 000 € (Table 1). Present values are discounted to year "zero"; in the other words commissioning year. Results from the calculation are shown in Fig. 2. The detailed calculations of design and construction stage can be found in the original paper [1].

Table 1. The results of the LCC calculations both in design stage and construction stage

	Results in design stage	Results in construction stage
Investment	**6 929 000 €**	**5 623 000€**
Maintenance costs	305 000 €	3 184 000 €
Repair costs	1 139 000 €	1 141 000€
Traffic disturbance	23 000 €	215 000 €
Demolition costs	96 000 €	58 000 €
Σ Present Value	**8 488 000 €**	**10 222 000 €**

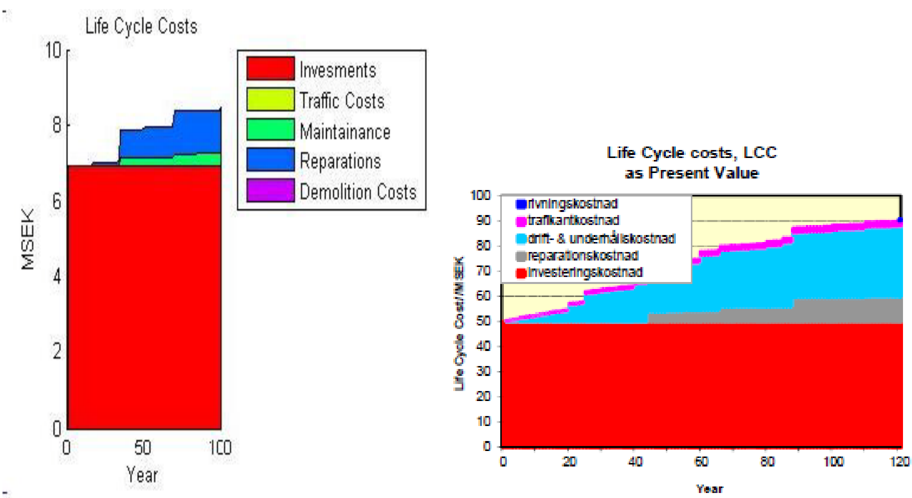


Figure 2. The LCC results in design (left) and construction (right) stage.

3.2 Results of LCA Analysis

BridgeLCA calculates the impacts of POCP, ODP, GWP, EP, AP and ADP. ADP stands for Abiotic Depletion Potential. The improved version of LCA also calculates values for HTC (human toxicity cancer), HTCNC (human toxicity non cancer) and ET (ecotoxicity). However the design stage calculations were done with the older version, hence only ODP, GWP, EP, AP and ADP are considered in this research so that comparison is possible.

In this case, ADP has a great impact on both calculations when compared to the other impacts (*Fig. 3*). EP stands for Eutrophication Potential. These impacts are related to process specific burdens for an incinerator [1]. In both cases this impact is one of the smallest. GWP stands for Global Warming Potential. With ADP it has the greatest impact (*Fig. 3*). AP stands for Acidification Potential, ODP Ozone Depletion Potential and POCP Photochemical Ozone Creation Potential. The ODP impact can be ignored completely, since the impact is very small compared to the others (*Fig. 5*).

The first histogram on the left hand side chart in *Fig. 3* is a result of total weight of LCA - calculation for a composite girder bridge in design phase and can be compared to the results obtained in the construction stage, the chart on the right hand side.

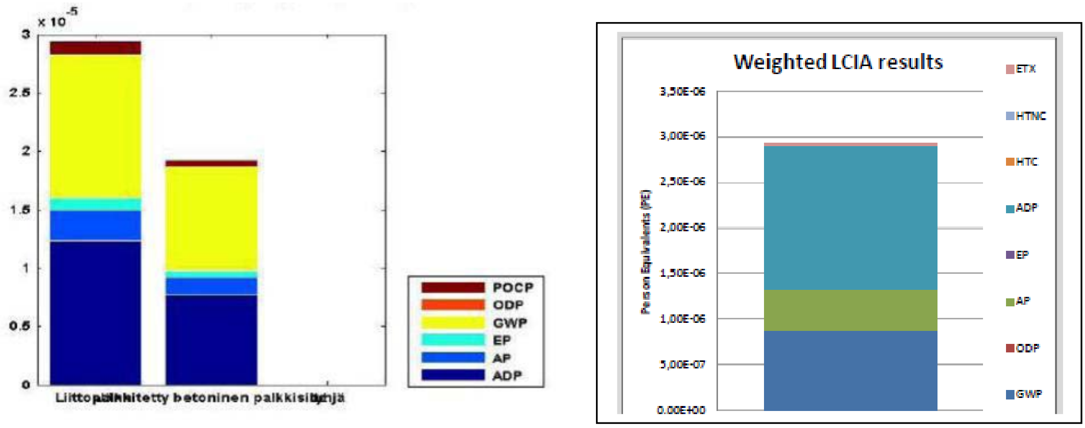


Figure 1: Total weighted impacts

Figure 3. Design (left) and construction (right) stage total weight impacts.

The environmental impact contributions of different bridge parts and actions at the design stage are shown in Fig 4. Using rough division it can be seen that superstructure is the biggest contributor to the environmental impacts.

Construction steel and its production are the biggest stress on the environment when considering bridge materials as can be seen from the Fig. 5. Bridge equipment and operations, maintenance and repair contribute a considerable part of the impact. This is caused by the surfacing of bridges. Asphalt, asphalt membrane and mastic are all bitumen products, which consume raw oil in production which again causes the ADP impacts. [1]

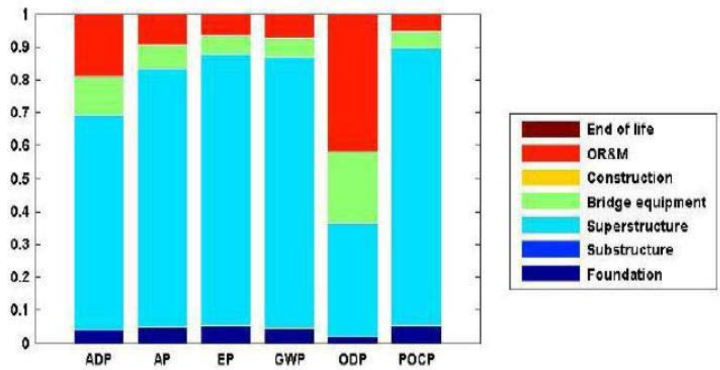


Figure 16: Relative contributions to environmental impacts, Empty

Figure 4. Environmental impact contributions of bridge parts at design stage.

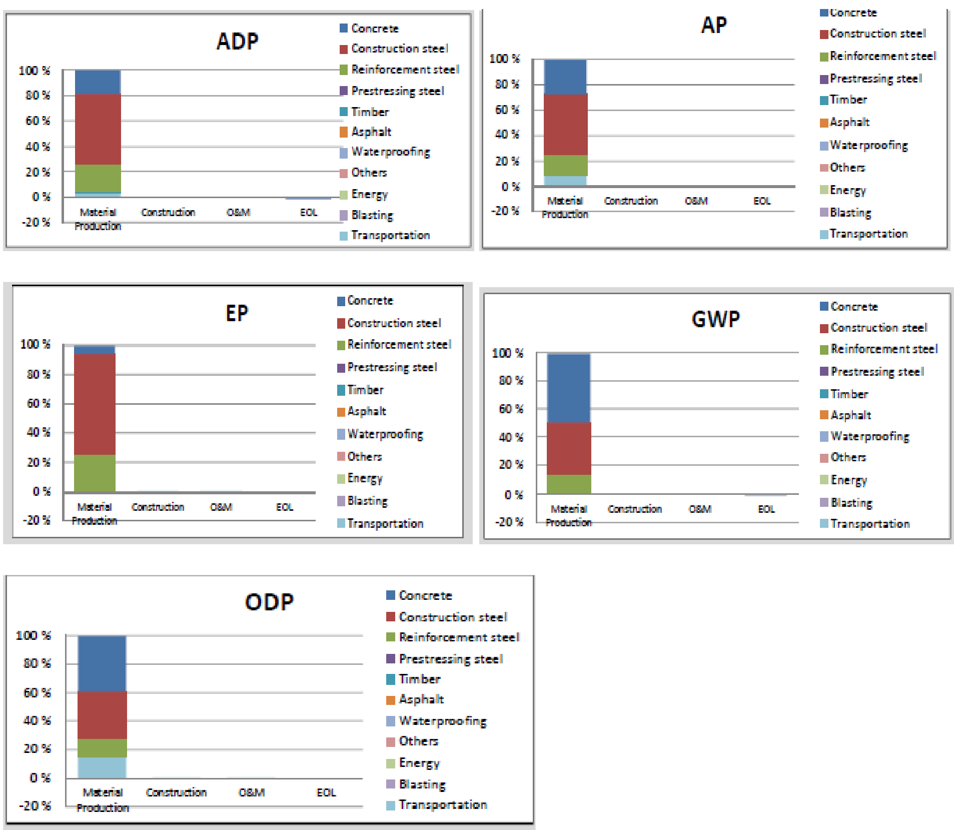


Figure 5. Relative contributions of environmental impacts of bridge parts at construction stage.

4 Conclusions

Considering the LCC and LCA calculations, it is obvious that predicting the inputs for both programs is considerably harder in the design stage. The estimated present value was 1 709 000 € less in the design stage than in the construction stage (*Table 1*). The investment costs were estimated 1 306 000 € and demolition costs 38 000 € more in the design stage than in the construction stage. Maintenance costs were 2 879 000 €, repair costs 2 000 € and traffic costs 192 000 € more in the construction stage. It appears that the hardest to predict are the maintenance costs and the investment. The enormous difference in the maintenance cost can be partly due to the fact that Swedish default values were used in estimating operation and maintenance costs in the construction stage.

The actual costs might be different in Finland. It seems that the investment in estimated very carefully whereas the maintenance, repair and traffic costs are underestimated in the design stage. The investments costs are evaluated more carefully since the price of the bridge is the main point when the bridge is in the design stage. These results show that the LCC tool can provide valuable information in the design stage. By using the tool, the actual cost of a certain design can be evaluated. From *Table 1* it can be seen that the investment costs contribute only half of the actual value of the bridge. This shows that the impact of life-cycle costs is definitely not marginal.

In the design stage the traffic disturbance is almost non-existent compared to the other costs whereas in the construction stage it is 2% of the entire costs (*Table 1*). This is due to the fact that in the design stage calculations the length of the stretch disturbed was 0.472 km when it actually is 1 km. In the construction stage the maintenance costs are almost ten times as much as in the design stage (*Table 1*). The maintenance actions are much easier to predict when there is sufficient data of the bridge equipment and the material amounts. This information is much more detailed in the construction stage than in the design stage. From other parts the cost distribution was fairly similar.

The LCA results in both cases are rather close to one another, the total impacts in the construction stage are a bit higher than in the design stage. The biggest difference is in the GWP impact (*Fig. 3*). Yet again, the construction stage results are higher than the design stage. This is due to the fact that in the construction stage all the parts can be accurately fed to the *BridgeLCA* program. The material amounts are final and no longer estimates and that makes the calculation much more detailed. In the design stage the material amounts which contribute the most to the GWP impact are just estimates and in this case the estimate was little bit off, it being less than the actual amounts.

When considering the contributions of different bridge parts it can be seen that the deviation between parts is much more detailed in the construction stage (*Figs. 4 and 5*). This, again, is the result of more sufficient data. In the construction stage all the smaller parts and details of the bridge are known, whereas in the design stage they are still being considered.

In the design stage construction and substructure are completely negligible while in the construction stage their contribution is not great but noticeable. When it comes to construction impacts, in the design phase it's virtually impossible to know the transportation distances of different materials and that's why the construction's effect is invisible in the impacts. The substructure type might still be under consideration in the design stage so predicting its effects is also hard.

All in all, it seems that the differences between LCC and LCA calculations design and construction stages stem from the lack of sufficient data. It is obvious that the information on materials and costs becomes more detailed when the project is further along. The challenge is to know when one has the sufficient data to perform the calculations so that they will be helpful.

5 Summary

Lövö Bridge is a continuous steel girder bridge with a concrete deck. The Lövö Bridge connects the islands of Lövö and Söljeholmen replacing the Lövö ferry. The two LCC and LCA calculations gave an idea what are the hardest parts to predict when performing the calculations. It goes with out saying that the data early on in a project is often too scarce to estimate accurately the life cycle costs and environmental impacts. Nevertheless, the results especially in LCA calculations were quite close, meaning that the environmental impacts can be calculated fairly accurately in the design stage. The challenge lies in estimating the maintenance and repair actions. The deviations between the two results were clearer in LCC than LCA.

The LCC and LCA are great tools for comparing different options for a bridge. They give valuable information on the life cycle of a bridge which is often ignored.

The minimum investment costs are not always the most economical or the most environmentally friendly solution. Collecting the needed data is a tedious process since you need to collect bits of information from different places. It seems the more detailed the calculations the higher the costs and impacts. The question is what aspects are worth evaluating in the calculations. It is nearly impossible to account for every single part and impact in a bridge hence one has to decide on what to focus.

6 References

[1] ETSI Project (Stage 2), Bridge Life Cycle Optimisation. Ed. Lauri Salokangas TKK-R-BE3- 140 s.

[2] www.ely-keskus.fi/fi/ELYkeskukset/varsinaissuomenely/Tie_ja_siltahankkeet/Documents/Löcön silta asennus esittely_27-8-2010.pdf

[3] www.ramboll.fi/projektit

[4] Tieliikenteen ajokustannusten laskenta. Tiehalinto 2005, 37s.

[5] Siltojen elinkaarikustannukset. Tiehallinto 2009, 27 s.

(Full report is available on ETSI home page: etsi.aalto.fi)

Structural Database and Life Cycle Plan (Abstract)

Riku Kytö

1 Structural Database

1.1 Overview

The purpose of the structural database is to make it easier to determine the environmental and economic impacts of a bridge during its service life. The database helps in life cycle analysis by giving initial information on most important factors regarding the structure itself and its repair. The data in the database concerns mainly rehabilitation actions on different structural parts of a bridge. By using the database as a source of initial information, the designer can estimate and compare different structural options with each other.

The values in the database will likely be updated and also more structures will be added. Considering this, the database has been constructed in a way that it can be easily updated.

1.2 Structure of the Database

The database is an Excel sheet that has pages for each country participating in the ETSI project. In addition, there is a brief info page that includes information about the division to environmental exposure classes and also some information about terms and structural systems mentioned in the database.

Nomenclature		Title	Unit	Year of Action	Maximum delay	Unit cost of repair		Unit duration	Duration	Traffic disturbance (of the repair duration)
ETSI	FIN					€/unit	% of construction cost			
1		**FOUNDATION**								
1.1	4207	Foundation slab								
		1 Patching the surface	m2	100	+25		50%	0,1		
		* underwater, sea		-50				+0,1		
		* underwater, fresh water		-25				+0,1		
1.2	4201.2.1	Excavation, soil								
1.3	4201.2.2	Excavation, rock								
1.4	1320	Pile	m							
1.4.1	1321	Driven piles								
1.4.1.1	1321.1	Concrete piles								
		1 Repair		70	+30		200%	0,05		25%
		* design service life 100 years		+50						
1.4.1.2	1321.2	Steel piles								
		1 Repair		70	+30		200%	0,05		25%
		* design service life 100 years		+50						
1.4.1.3	1321.3	Wooden piles								
		1 Repair		50	+20		100%	0,05		25%
1.4.2	1324	Excavated piles								
1.4.3	1325	Bored piles								
1.4.3.1	1325.1	Bored steel piles								
		1 Repair		70	+30		200%	0,05		25%
		* design service life 100 years		+50						
1.5	2220	Erosion protection		30	+10		25%	0,1		0%

Figure 1. Structure of the Database

The data in these categories varies depending on the structure, material and environmental exposure. All countries have their own data sheet that they can fill in with their significant values. The values may vary in different, but the methodology and procedure stays the same.

1.3 Structural Parts - Repair Methods

The database includes data concerning different parts of a bridge. These structural parts are then divided to different common materials and protections. The relevant data for life cycle analysis is given for these structural parts and materials. The data listed in the database includes: structure, unit, repair interval, maximum delay, unit cost, unit duration and duration of traffic disturbance if it is not the same with the unit duration.

An up to date unit cost needs to be given. The calculations need to be as accurate as possible even though there are a lot of uncertainties in the analysis. The unit costs and their accuracy vary a lot indifferent participating countries. In some cases the cost of the rehabilitation action is given as a percentage of the construction cost. These unit costs are used to determine the agency costs concerning maintenance.

In order to obtain also the indirect costs of rehabilitation, one must estimate the duration of the re pair. For this the database includes unit durations for the rehabilitation actions. If the different rehabilitations are done simultaneously, as often is the case, the designer needs to decide what the combined duration of the "repair package" is.

1.4 Repair Intervals

When dealing with long service lives, as is the case in life cycle analysis, one must estimate the interval after which the structural part must be repaired. The database gives estimates for repair intervals for different structural parts in different exposures. The data concerning structural parts will update when more and more structures are repaired and inspected. This knowledge is supposed to be transferred in to the database. If more than one repair action is done at a time, it is clear that all of the repairs are unlikely to take place at their optimum time. For this, the database gives a maximum delay of the repair. This delay can be used, but the delaying should result in longer and more expensive repair. This can be taken into account with factors that make the duration longer and the price more expensive. The method of doing this is not defined in ETSI project.

1.5 Environmental Exposure

When defining the repair intervals of different structures the circumstances, that the structure is in have huge an effect on the performance of the structure. This means that repair intervals vary in different environmental exposures. For certain structures in bridges the amount of traffic can have a direct impact on the performance; e.g. wearing surface or expansion joints.

The structures have been divided into different categories based on what is the critical exposure. These exposures have then been divided into four classes. Based on the structure and the exposure class that the structure is in, one can find the repair interval in the database.

The structural parts have been divided into exposure categories according to the dominant degradation mechanism. The categories are: freeze-thaw cycles and chlorides, climate with sulphur dioxide and chlorides, exposure to rain and weather in general and average daily traffic together with the amount of heavy traffic. The materials and structures that fall into these categories are correspondingly: concrete, steel, timber and equipment and waterproofing. The division to exposure classes and categories is shown in Tables 1 - 4.

Table 1. Description of the used exposure classes with concrete.

Exposure class	Concrete
Easy	little or no chlorides, little freeze thaw cycles
Normal	chlorides (from deicing salt)
Hard	hard chloride exposure, coastal areas (/ heavily salted)
Very hard	very hard chloride exposure, structures in the sea (/ tidal zone)

Table 2. Description of the used exposure classes with steel.

Exposure class	Steel
Easy	Rural climate
Normal	Industrial climate with moderate SO2 and low chloride content
Hard	Industrial and coastal climate with moderate SO2 and chloride content
Very hard	Industrial climate (humid and corroding); high chloride content

Table 3. Description of the used exposure classes with timber.

Exposure class	*Timber*
Easy	Weather protected
Normal	Exposed to weather
Hard	Structures in contact with ground
Very hard	Structures in contact with water

Table 4. Description of the used exposure classes with equipment and waterproofing.

Exposure class	**Equipment and waterproofing**
Easy	ADT < 1000 ; little heavy traffic
Normal	ADT < 3000; more heavy traffic
Hard	ADT < 10000; significant amount of heavy traffic
Very hard	ADT > 10000; lots of heavy traffic

1.6 Using the Database

The database is a source of information for the life cycle analysis. It cannot be used on its own very efficiently. Instead one should use an approved methodology and a calculation sheet designed accordingly. In ETSI project such programs for both LCC and LCA have been developed. Before the actual calculations it is suggested that the service life of the bridge at hand should be carefully considered. Based on the consideration a life cycle plan should be compiled.

This database is used when considering the service life. Times of rehabilitations are decided according to the repair intervals given in the database. The basic procedure of using the database together with life cycle plan is shown in an example in Fig. 2.

Repair action	Unit	Quantity	Unit price [€/unit]	Unit duration [days/unit]		1st Repair year= 20 duration [days]	1st Repair year= 20 price VAT 0%, discount rate 0%	2nd Repair year= 40 duration [days]	2nd Repair year= 40 price VAT 0%, discount rate 0%
ABUTMENTS AND PIERS									
Abutments									
1 Patching the concrete surface	m2	26,7	310	0,2				8,9178	11008,41

Nomenclature ETSI	Nomenclature FIN	Title	Unit	Year of Action	Maximum delay	Unit cost of repair €/unit	Unit cost of repair % of construction cost	Unit duration	Duration	Traffic disturbance (of the repair duration)
3		**ABUTMENTS AND PIERS**								
3.1	**4211**	**Abutments**								
3.1.1	**4211.1**	**Concrete structures in abutments**								
		1 Repairing the concrete surface	m2	35	+10	310		0,2		50%
		* Bridge site class		-3		+20		+0,1		
		* Effect of water and ice				+70		+0,1		
		* Regular concrete: C30/37; w/c=0,45		+0						
		* Exposure: easy		+10						
		* Impregnation								
		**with repeated treatment*		+2						
		* Protective coating								
		**with repeated treatment*		+2						
		* Denser concrete (w/c=0,40)		+10						
		* Exposure: normal		+0						
		* Impregnation								
		**with repeated treatment*		+5						
		* Protective coating								
		**with repeated treatment*		+5						
		* Denser concrete (w/c=0,40)		+10						
		* Stainless steel reinforcement + impregnation (repeated)		+5						
		* HDG-reinforcement + impregnation (repeated)		+10						
		* Stainless steel sheeting		+25						
		* Denser concrete (w/c=0,40) + stainless steel rebar		+10						
		* Exposure: hard		-10						
		* Impregnation								
		**with repeated treatment*		+5						
		* Protective coating								
		**with repeated treatment*		+5						
		* Denser concrete (w/c=0,40)		+5						
		* Stainless steel reinforcement + impregnation (repeated)		+10						
		* HDG-reinforcement + impregnation (repeated)		+8						
		* Stainless steel sheeting		+30						
		* Denser concrete (w/c=0,40) + impregnation		+10						
		* Denser concrete (w/c=0,40) + stainless steel sheeting		+40						
		* Denser concrete (w/c=0,40) + stainless steel rebar		+15						

Figure 2. Using the database as a source of information for the life cycle plan

2 Life Cycle Plan

2.1 Overview

Life cycle plan is the designer's tool to collect the needed data and to determine the needed rehabilitation measures through the service life of the designed bridge. The life cycle plan includes important basic information used in both LCC and LCA calculations. For LCC the important factors are: price, year of action and duration of the repair. In LCA calculations the important factors are: quantities and duration of the repair. Also other data is needed in both analyses.

The designer collects the needed data from the structural database and combines repairs into repair packages that are common in the country or area. The data that is compiled in to the life cycle plan is later inputted into LCC and LCA calculations. In other words, the life cycle plan is used to design and to organise the repairs.

2.2 Contents

The life cycle plan includes information concerning: structural parts and their repair action, unit, quantity, unit price and unit duration. In addition to these there are the actual designed repairs. For these repairs following information should be given: year of repair, total duration and total price. Above mentioned data should be based on the structural database. Quantity, unit price and unit duration are used to determine the corresponding total amounts. In life cycle analysis the duration of the rehabilitation is needed to determine the indirect costs, i.e. user costs because of delayed traffic flow. So actually the duration means the duration of special arrangements because of the repair works. These special arrangements could include at least detour, reduced speed limit and closed lanes.

Maintenance actions, energy consumption and inspections are also listed in the life cycle plan. These must be included in the life cycle analysis. The designer should determine the interval for these actions and their cost. The inspection intervals are country-specific. Energy consumption could be needed if for instance the deck is warmed or the bridge has significant decorative lighting. The annual cost estimate for the energy consumption should be given.

2.3 Filling in the Life Cycle Plan

As stated earlier, the life cycle plan is used together with the structural database and the plan is a tool for organising the repairs. It is possible to design each repair action into its optimum place, but in most cases it is reasonable to combine different repairs.

Combining the repair actions gives the possibility of overlapping the repairs and thus getting shorter overall duration for the repairs. It should be remembered that these repairs must be such that can be done simultaneously in the actual repair site. For combining and for overlapping the repairs designer should use consideration. An example of combining some repairs is given in table 5.

Table 5. Example of combining repairs.

Repair action	Unit	Quantity	Unit Price [€/unit]	Duration [days/unit]	2nd repair duration [days]	year = 40 price [VAT 0% disc.ratio 0%] [€]
EQUIPMENT						
Bearing and hinge						
1 Maintenance	pc	7.0	115.0	0.1		
2 Renewal	pc	7.0	1835.0	0.2	1.4	12845.0
Edge beam						
1 Renewal	m	285.0	150.0		30.0	42750.0
Insulation and waterproofing						
1 Renewal	m2	895.9	19.7	0.0	35.8	17649.2
Surfacing						
1 Renewal of the water surface	m2	895.9	2.3	0.0		
2 Repair	m2	895.9	4.6	0.0	9.0	4121.1
Concrete railing						
1 Repair	m	142.0	110.0	0.0		
2 Renewal	m	142.0	560.0	0.1	7.1	78100.0
Steel railing						
1 Repair	m	140.0	21.2	0.0		
2 Renewal	m	140.0	106.0	0.1	7.0	14840.0
Expansion joint						
1 Repair	m	18.0	143.0	0.1		
2 Renewal	m	18.0	718.0	0.6	12.8	14892.8

Aalto University

A.3 Life Cycle Assessment of Structural parts for Bridge Life Cycle Analysis

Riku Kytö
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Abstract

1 Goal of the study

The study was conducted for the Finnish Transport Agency to be used in ETSI project. The goal of the thesis was to gain information concerning the expected repair intervals of structural parts of a bridge. The idea was to study the structures that are currently used in Finland. These gathered estimates were thought to be added later in to the structural database compiled as a part of ETSI project. This is why the range of structures, materials and protections had to be wide. This way the initial data for life cycle analysis would be as comprehensive as possible at this stage. The values gathered in this study were thought as first estimates that should be updated as data and experiences accumulate.

Initially other goal and aspect of this study was also to get comparable estimates from other ETSI countries. Quickly it became apparent that this sort of comparison would require a lot of work getting accustomed with the ways of the other participating countries. So this comparison was dropped out of the scope of the thesis.

This study concerned new structures and tried to give estimates for those. This way the values could be used for better and more accurate life cycle comparisons of different bridge design proposals. The values were gathered considering Finnish way of designing and building bridges. As in ETSI, also in this study only road bridges were considered. The deteriorating mechanisms nonetheless stay the same. Considering this, the estimates could be used for similar bridge structures build elsewhere as well.

In addition to these, one goal of the thesis was also to test the ETSI tools. Two example life cycle calculations were done with the proposed estimates. For the first the late WebLCC was used. For both the proposed ETSI database and the proposed life cycle plan were used.

Table 1; effect of discount rate on the present value of compared repairs

Repair cost	50 000 €
Discount rate	1,00 %
Option 1 - year of action	20
Option 2 - year of action	30
Present value 1	40 977 €
Present value 2	37 096 €
Difference	3 881 €

2 Research method

Different methods to gather the needed repair intervals exist. One way would have been to study the repair data that exists concerning older structures. This data then would have needed some adjustment so that it could have been used with new structures. But it would be good starting point: at least the new structures should endure longer compared to those older structures and materials in most cases. This method was discarded because of the scope being in researching new structures.

Another method is to model the deterioration with physical models and then trying to create mathematical models based on those physical phenomena. Often deterioration is modeled mathematically using the Markov chain calculations. These were described in the theory part of the thesis, but were not fully implemented in the actual research.

The methods that were used in the study include literature study and Delphi interviews, the main focus being in the Delphi study. Some experiences were found in the studied literature, but mainly the Delphi study was the method used. The idea of Delphi study is that chosen experts are interviewed and when they have answered a summary based on those answers is done. This summary is shown to the experts, if there are deviations from the average answer the expert has a chance to argue and discuss the reasons for this. The goal is that based on this interactivity a consensus is achieved. The interactivity separates the Delphi method from a normal survey.

The Delphi method was chosen because with it a wide range of needed structural solutions, protections and materials could be studied. This method makes it possible to get estimates for wanted subjects quickly. Drawbacks of the method are that the values are estimates. Also the estimates varied a lot in some cases between the different experts. In addition to this it could be seen that most answerers gave their estimates based on the experiences they have had. These experiences resulted in quite conservative estimates in all the categories.

The experts meant to answer the interview were selected so that the most important interest groups: design, maintenance, owner, material researchers and manufacturers etc. The full scale of Delphi method couldn't be used in the thesis with proper discussion between all the experts. The study was conducted via mail or email. Based on the answers a summary was sent to experts and some commented and presented their views regarding the average values in different exposures.

The structures that were considered in the study were: concrete structures in general, edge beams, steel structures (girders and trusses), wood structures, expansion joints, bearings, surface structure with waterproofing. The study regarded the repairs of these structures in different exposure classes.

3 Results

Concrete structures

Most of the alternatives considered in the study were of concrete with different protections and reinforcement:

- denser concrete
- shell (concrete element or stainless steel)
- different rebars (stainless steel, epoxy coated, hdg-rebar)
- different coating (impregnation and protective coating)
- combinations of these

These were chosen since they're the most common now and could be used in the near future.

In the interview, two different repair actions were considered: repair by concreting and renewal (mainly regarding edge beams). The main degradation mechanism leading to these repair actions was considered to be freeze-thaw (intensified by chlorides). Because of this, the main way to lengthen the repair interval is to apply better quality (frost resistant and low permeability) concrete.

The effect of some of the alternatives can be seen in *Figure 1* and *Figure 2*. These values are taken as averages from the interview. The standard deviation varied between different concrete alternatives. First difference could be seen with the type of the answerer: bridge inspectors had generally lower estimates compared to e.g. researchers. Another difference was observed between already used alternatives and the uncommon alternatives; newer and unused alternatives had stronger deviation. The deviation can be seen in the Annex 1.

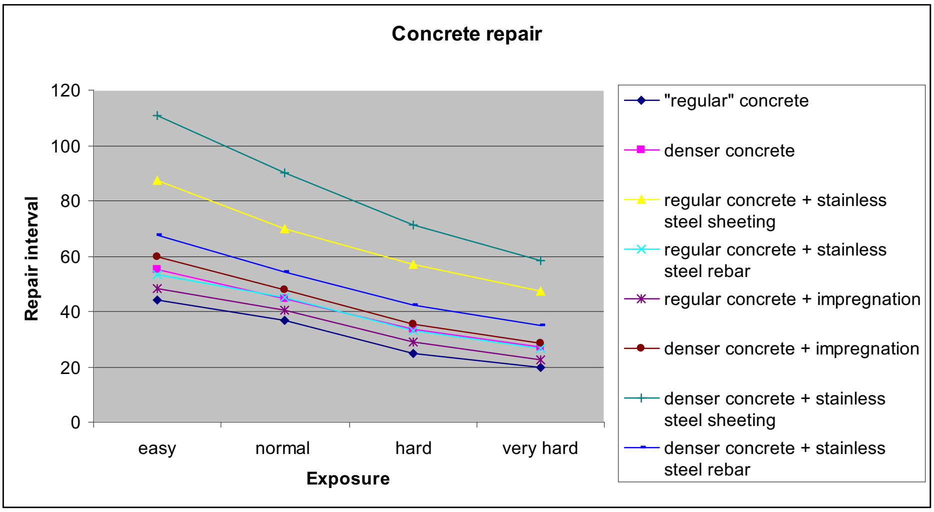

Figure 1; Concrete repair intervals for some alternatives

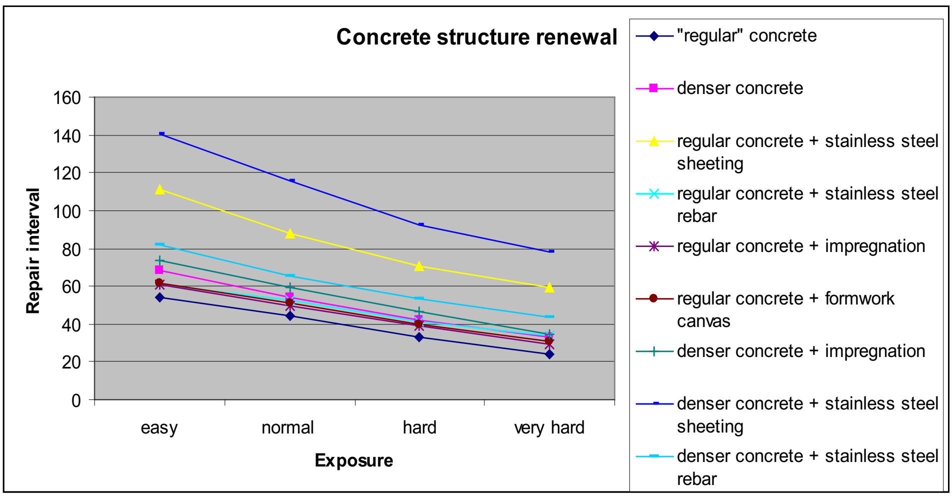

Figure 2; Concrete structure renewal for some alternatives

Steel structures

Steel structures were also considered. The estimates were asked regarding different protection methods and also different steel types. These include:

- 5-layer painting system (EPZn(R)EPPUR 310/5-FeSa2½)
- 3-layer painting system (not specified, but comparable with 5-layer painting system)

- duplex-system (thermal spraying and painting)
- weathering steel
- stainless steel

The standard deviation in these estimates was lower and the participants' estimates were closer to each other than with the concrete estimates. This was probably because the answers to these were mainly acquired from experts with similar background. Also some of the alternatives were quite familiar and already used or at least close to currently used structures. There were no big surprises among the given estimates.

Again two repairs were considered: patching the paint (*Figure 3*) and repainting (*Figure 4*). The renewal interval of weathering steel and stainless steel were considered in the same table with repainting.

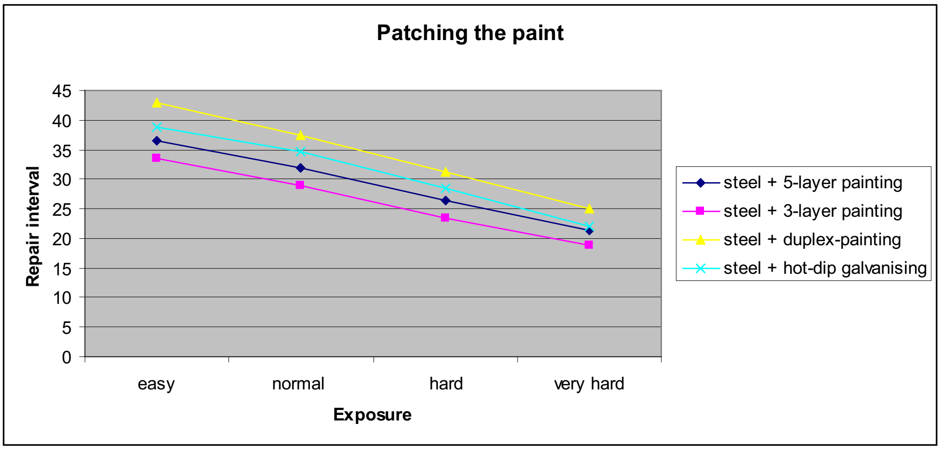

Figure 3; Patching the paint

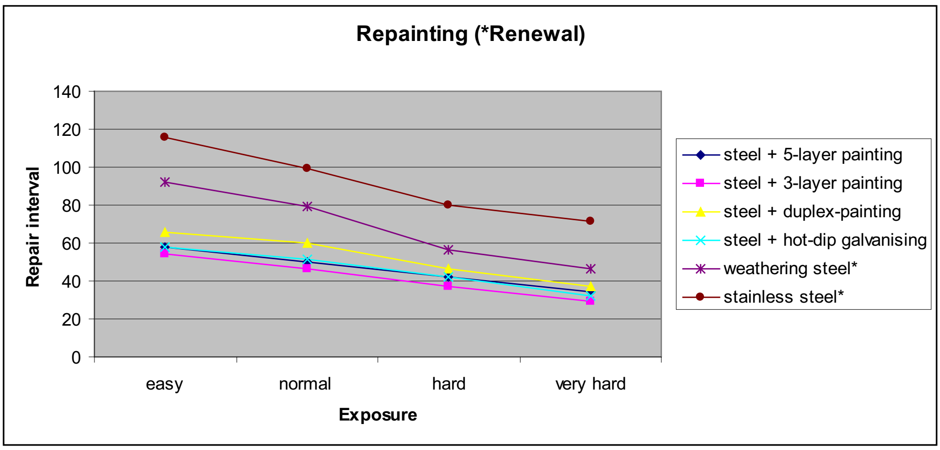

*Figure 4; Repainting (*Renewal)*

Wood structures

The biggest change in the use of wood as bridge material is the prohibition of creosote impregnation in the near future. This will be replaced with less harmful salt impregnation. The structures considered in the interview were:

- creosote impregnated glue-laminated members (currently used)
- salt impregnated glue-laminated members (in the near future)
- structurally protected salt impregnated members
- normal wooden bridge deck
- stress laminated wood deck

Two actions were considered also regarding wood structures: repair and renewal. In Finland wooden bridge structures are normally designed to last 50 years. Considering this, the estimates were quite close, at least with the load-bearing structures (glue-laminated wood with impregnation).

The three protection types (creosote, salt and salt plus structural protection) were all quite close to each other (*Figure 5* and *Figure 6*). Structural protection with salt impregnation was considered the most durable and the least durable of these three was the salt impregnation by itself.

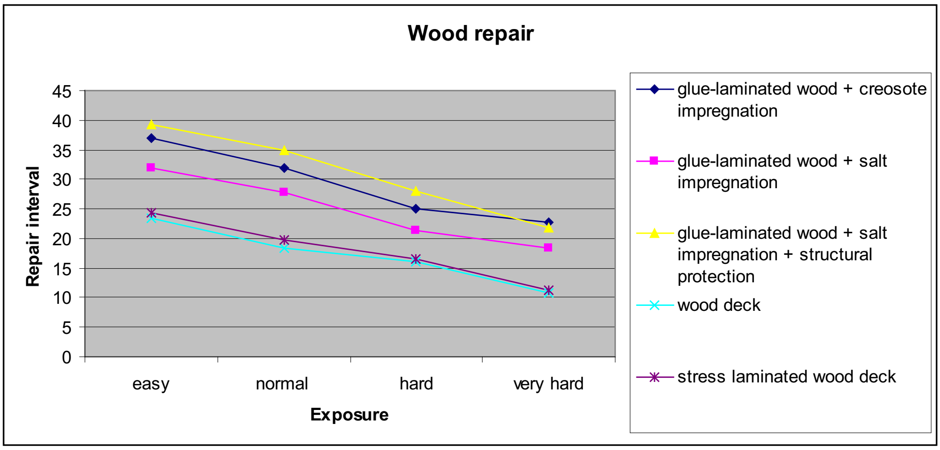

Figure 5; the repair of wooden member

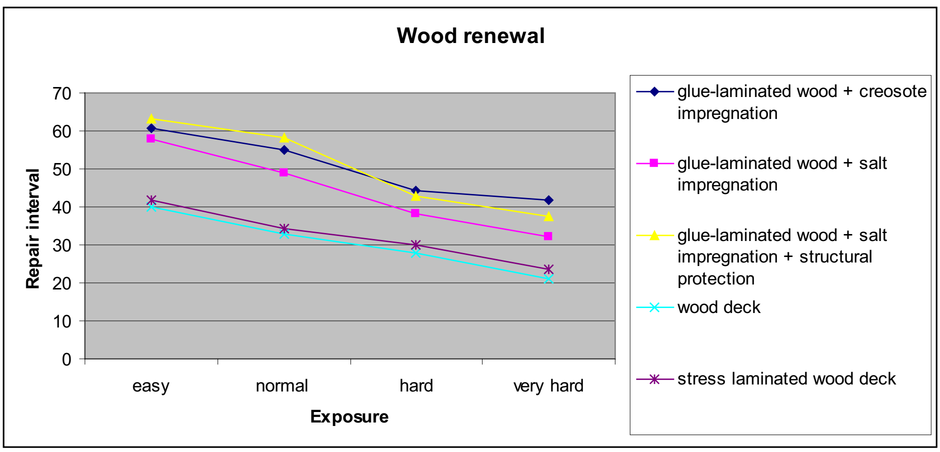

Figure 6; Renewal of wooden member

Equipment and waterproofing

Different currently used equipments were considered in the interview. These include different types of bearings and expansion joints.

- elastomeric bearings
- pot bearings
- steel bearings
- flexible plug expansion joint
- expansion joint

With waterproofing four different options were considered. One of these was an alternative where no waterproofing was applied. The others were:

- sheet membrane
- liquid applied membrane
- mastic

The estimates for these were quite close to each other, probably because the options in the interview were all already widely used (except non-waterproofed deck). Biggest deviation was observed with the maintenance of elastomeric bearings.

With bearings, the renewal interval was 32–55 year (regarding the exposure). Steel bearings were estimated to be the most durable. Renewal intervals of the expansion joints were a bit shorter: 22–45 years (regarding the exposure), flexible plug expansion joint being slightly less durable (*Figure 7* and *Figure 8*).

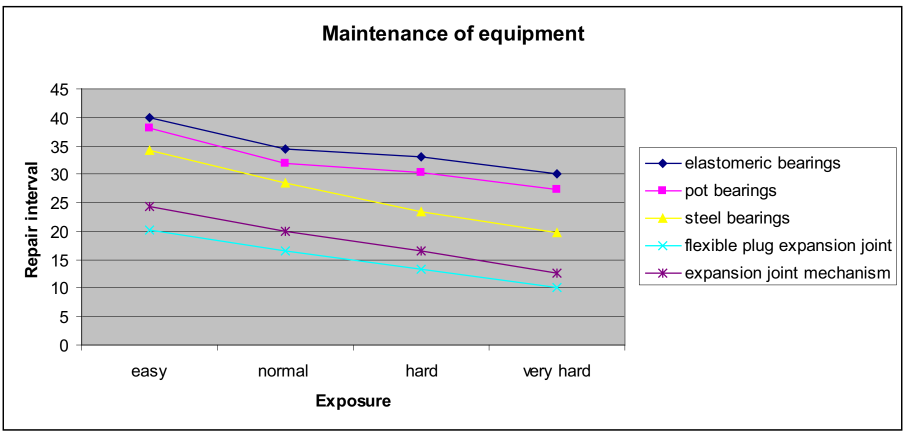

Figure 7; Maintenance of equipment (bearings and expansion joints)

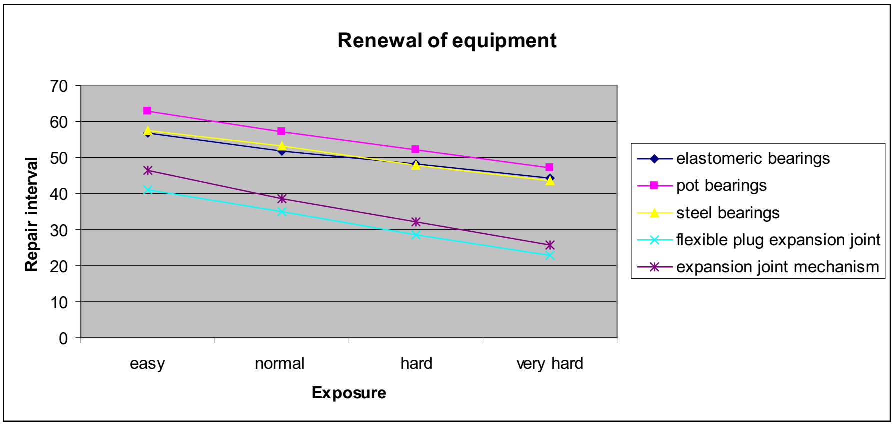

Figure 8; Renewal of equipment (bearings and expansion joints)

With waterproofing (*Figure 9*) it could be seen that the sheet membrane and the liquid applied membrane were considered the most durable (sheet membrane slightly better). Mastic was less durable compared to the two membrane systems. As expected, the option with no waterproofing was considerably less durable than the others.

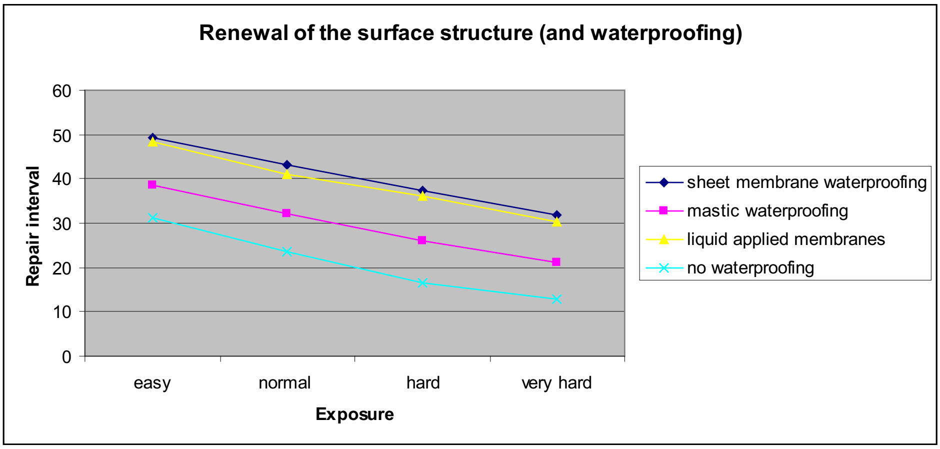

Figure 9; Renewal of the surface structure (and waterproofing)

4 Implementation and conclusions

The values and effect of exposure were implemented in to the ETSI database as base information. These estimates are probably rather conservative and they need to be updated later. The values presented as a result of this thesis make comparison of these structures possible and they will also make it easier to make similar comparisons with different designers.

It was also a part of this study to implement and test these values on example bridges. Two bridges were analyzed. Both examples emphasized that the repairs do have an effect on the outcome of the analysis. Biggest impact to the outcome of the LCC calculations seems to be with the discount rate, user costs i.e. delayed traffic and number of rehabilitations. Based on this it would be important to make the traffic arrangements during the repair as effective as possible. Another thing to do would be to achieve one renovation service life for bridge structures. This would reduce the life cycle costs greatly. It would also provide a chance to reassess the need of the bridge in the mid of its designed service life.

5 Reference

Riku Kytö.(2011). *Service life assessment of structural parts for bridge life cycle analysis.* (Ms Sc. Theasis).. Aalto Yliopisto, Department of Civil and Structural Engineering. Espoo, May 2011
Full Thesis available in ETSI home page.

A.4 Life Cycle Cost calculations of concrete bridge deck surface structures

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Abstract

In this study, the life cycle costs of different concrete bridge deck surface structures are analysed and compared. The essential data for the life cycle cost calculations is the investment cost together with a realistically predicted rehabilitation point in time and cost. The driver delay costs are also often a major consideration in the final result. The driver delay costs can be affected by selecting the most appropriate rehabilitation times and practices.

The study is part of the third phase of the Nordic ETSI Project. It consists of a study of literature about international bridge deck surface structures, interviews with Finnish experts, and a questionnaire compiled for Swedish, Norwegian and Danish bridge engineers. The study describes the functions of bridge surface structures, the most common surface structures in Nordic countries - known as deterioration mechanisms, and also used rehabilitation methods. The essential data for the life cycle cost calculation is taken from a p arallel study that describes the most suitable rehabilitation times, and from previous Finnish Transport Agency research.

The life of new and already rehabilitated bridge deck surface structures depend on the surface structure materials and connection details, such as waterproofness, deterioration sensibility, compliance to construction regulations, and level of quality control. The analysed pavements are asphalt concrete, stone mastic asphalt, hot rolled asphalt and concrete wearing coarse. The waterproofing methods in the comparison are sheet membrane, mastic and liquid applied waterproofing.

The example bridge in the life cycle cost analysis was selected because it does not represent the worst nor easiest rehabilitation site from the point of view of traffic arrangements. The volume of daily traffic on a lane was set at 500, 2 000, 5 000, and 10 000 vehicles in the deck surface structure comparisons. The results show that driver delays dominate the life cycle costs with large traffic volumes. In these cases, resistance to rutting in the wearing course of the surface is proven to be an important factor.

The most effective waterproofing methods from the life cycle cost point of view are sheet membrane and liquid applied waterproofing methods because this means lowest cost in reparation during the lifetime of the bridge. The degradation levels of isolation-free, concrete course bridge decks is not as well-known as other waterproofing systems, thus two scenarios have been analysed for the small volumes of traffic on these bridges.

A5. Design of short-span bridges with regard to life cycle costs

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design
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Abstract

The purpose of this project was to find an approach on how to use life cycle cost (LCC) analysis as a decision-making tool in design when planning new bridges. This approach was intended to help the designer to choose the most favourable detailing solutions with respect to LCC. The leading aim of the project was to perform a comparison between two LCC cases, where standard and alternative detailing solutions were considered for each case. The comparison was carried out by the use of analyses and experiences of typical problems associated with existing short-span bridges.

To perform the intended comparative LCC-analysis, three, in Sweden commonly reoccurring short-span bridge types, were selected. All three bridge types suffer from their own typical problems. These problems were implemented in the first, case 0, LCC-analysis. By using case 0 as a reference, suggestions for possible improvements that could be made, recognised or questioned, were performed. The improvements effect on the LCC was assessed by a second LCC-analysis, case 1. By comparing the results from these two analyses, factors that have great influence on the LCC, sensitivity factors, could be identified.

As it turned out, it was not the specific detailing solutions themselves that were favourable or not, but the effect of not implementing them that was the decisive factor. The conventional solutions often require future needs of maintenance and repair. When in time such activities would occur and their impact on the traffic were found to be the two actual sensitivity factors to whether a design solution could be justified or not. In order to utilise these results to achieve the stated purpose, a flow chart diagram was developed parallel to an Excel toolbox. The flow chart presents a systematic method on how to analyse and compare the profitability of two different detailing solutions. The Excel toolbox complements the flow chart by performing the necessary LCC calculations and presents clear graphs, where critical values can be derived with regard to the sensitivity factors.

This method can provide designers with an extended basis for choosing the most viable long term design decisions and the ability to financially motivate their implementation, even if the detailing solution initially appear to be the more expensive option.

Key words: *LCC, LCC-analysis, bridges, detailing, design*

Co-operation of Nordic countries

NordFoU

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