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ETSI PROJECT (Stage 2)

Bridge Life Cycle Optimisation

Editor: Lauri Salokangas

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BRIDGE LIFE CYCLE OPTIMISATION

ETSI PROJECT (Stage 2)

Bridge Life Cycle Optimisation

Summary

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Abstract

ETSI Project Stage 2 – Bridge Life Cycle Optimisation was conducted in two years, 2007-2009. It was a continuing work for previous research: *ETSI Project Stage 1*, which was done between 2006-2007. The main task in the second project was to developed suitable tools for the analysis of Life Cycle Costs (LCC). During the research it turned out that nearly equally important topics as costs are the environmental and aesthetic values, when a new bridge is going to be build. Two computer programs were developed. One to do the LCC analysis and the other one for the Life Cycle Assessment (LCA) to estimate the environmental impacts, of a new bridge. Moreover, a simple method for evaluation aesthetical values was developed. The project was an international co-operation of three Nordic countries. From each country; Finland, Norway and Sweden three national Road Administrations and three technical universities acted as participants. The project divided into three subprojects. The results are collected together and published at the end of this report.

Contents of Summary

COLLECTED SUBPROJECT REPORTS

Introduction

This report is a collection of the results of second ETSI Project, ETSI Stage 2 conducted during 2007-2009. It is a continuation to the first ETSI project Stage 1, which was carried out during the years 2006 -2007 [1].

Initially, the idea of ETSI Project arose as early as in the year 2002 by Mr *Juhani Vähäaho*, coordinator of bridge activities at the Finnish Road Administration (FinnRA) and *Aarne Jutila*, Professor of Bridge Engineering at Helsinki University of Technology (TKK).

ETSI originates from the Finnish words "***E****linkaareltaan* ***T****arkoituksenmukainen* ***SI****lta*", which in English could be translated as "*Lifelong Adapted Bridge*" or, more freely, "*Bridge Life Cycle Optimisation*". On the other hand *"ETSI"* is also a Finnish command *"SEARCH"*. So one can easily remember (the Finns at least) the purpose of the project: "*Select an optimal bridge of all alternatives by taking account the costs and impacts to environment during its life time"*.

The main task of ETSI Project Stage II was in the beginning to create an efficient LCC tool for the use of Nordic Road Administrations. During the project it turned out that also the environmental and aesthetical values must be considered similarly as economical values.

Organisation and activities

The project organisation during ETSI Stage 2 has been nearly the same as was in the previous stage. The main financing units were the same three Nordic National Road Administrations as in Stage 1. The project plan was established and agreements were signed between different parties so that the ETSI Project Stage 2 could start from 1st of March 2007. It was originally planned to finish in February 2009, but the closing seminar was later decided to hold on as ship seminar in March 17-18 2009; that is the moment, when the ETSI Project Stage 2 practically ends. So the duration of ETSI Stage 2 was approximately two years.

Besides the three financing administrative units mentioned the following Nordic research institutes and private enterprise were involved in the Project:

- Helsinki University of Technology (TKK)
- Norwegian University of Science and Technology (NTNU)
- Royal Institute of Technology (KTH)
- Extraplan Oy

The persons who strongly influenced to the success of the project and the preparation of the reports are listed in the following:

Seppo Aitta

Hans Bohman

Helge Brattebø

Johanne Hammervold

Eldar Høysæter

Aarne Jutila

Raid Karoumi

Otto Kleppe

Per Larsen

Jan Nygård

Matti Piispanen

Marte Reenaas

Lauri Salokangas

Håkan Sundquist

Marja-Kaarina Söderqvist

Timo Tirkkonen

During the ETSI Stage 2, Helsinki University of Technology acted as Coordinator, similarly as was the case during the Project Stage 1. Project leader changed during the summer 2008. Professor *Jutila,* who had been the project leader also during the previous stage 1, started also as project leader of stage 2 from the beginning of March 2007. He was as at that position till the end of July 2008, when retired from the professorship. Since 1st of August 2008, *Lauri Salokangas* as acting professor has been the project leader of ETSI Stage 2.

As the Chair of the Project Steering Group (PSG) during the Stage 2 has been Mr *Matti Piispanen* from FinnRA, similarly as he was during the ETSI Stage 1. The Project Steering Group had altogether seven meetings during the project duration before the last meeting in the Closing Seminar.

The Project Working Group (PWG), which controlled the progress of the practical work of Subprojects, was gathered nine times during the Project Stage 2. Most of the information, as the Minutes of the PSG or PWG, the progress of each Subproject and coming events etc. was possible to follow from the web pages during the project. The establishing and updating of the Project www-pages have been under control of TKK. Final ETSI reports (both Stage 1 and Stage 2) can be found in PDF-format as well as the developed computer programs can be downloaded from the project's web site [2].

An Intermediate Workshop was organised on 16th of June 2008 at KTH, Stockholm. Altogether 24 participants were attended this workshop. The Closing Seminar was arranged by TKK.

The future research activities for the summary were listed by *Timo Tirkkonen*.

Subproject tasks

ETSI Project Stage 2 consists of three subprojects

- SP1 Life Cycle Costing,
- SP2 Life Cycle Assessment and
- SP3 Aesthetics and Cultural Effects.

Reports of all three Subprojects have been prepared separately, but are collected together and presented in later chapters of this report.

Subproject 1

In the first place, the main task of ETSI Project Stage II was to create an efficient LCC tool for the use of all Nordic road administrations. In SP1 LCC-methodology the comparative cost assessments during the life cycle of a bridge was researched. The LCC report was prepared by *Håkan Sundquist* and *Raid Karoum.i* The costs of a bridge consist of the capital, operational and maintenance costs and the costs of the owners, users and society including the cost of the disposal. The interest rate calculation and the user costs due to delay or accidents are often undervalued. These costs may easily play a leading role, especially if high interest rate values and user costs are used. Web based computer tool WebLCC was developed for LCC -analysis and will be available for public use. It probably still needs some time for testing by Road Administrations, before it can be applied in practical use.

Subproject 2

During the ETSI II project Life Cycle Assessment became practically as important as LCC analysis. In SP2 a systematic way of mapping and evaluation of health, ecological and resource impacts throughout the entire life cycle of a bridge, from resource extraction to final disposal is introduced. *Helge Brattebø, Johanne Hammervold* and *Marte Reenaas* are responsible of the report.

The tasks of SP2 were originally divided into three main categories

- To perform a *state-of-the-art* study regarding environmental effects related to bridges by identification of important environmental factors
- To develop a *method for life cycle evaluation of environmental effects* that is based on the findings in the state-of-the-art study and existing methodology for LCA. The methodology will include identification and choice of a set of relevant indicators for bridges. The choice of indicators will be motivated by the need for sound and relevant indicators for decision-making on technical options for bridges.
- To develop a *practical tool for assessment of environmental effects*. This tool will consist of a database of emission coefficients for relevant material- and energy-flows for bridges, cost-coefficients for relevant emissions, as well as important environmental indicators. In this manner, the database will be a necessary and suitable basis in calculating environmental effects and externality costs of these for bridges. A stand-alone computer program BridgeLCA, based on these principles was developed. The report also includes instructions for program use.

Subproject 3

In SP3 the methods of evaluating aesthetical and cultural effects of bridge design and construction were studied. A Subproject group consisted of four persons: *Seppo Aitta, Hans Bohman, Eldar Høysæter* and *Aarne Jutila* are responsible of this report. A new unique system for evaluating these environmental issues in a systematic way is introduced in the report. To incorporate human requirements as well as cultural and aesthetical requirements into the life cycle analysis is a demanding task. Nevertheless, cultural values and above all aesthetics may be the most decisive factor in the life cycle quality of road structures or bridges over the long term. How to couple aesthetic values into LCC or LCA programs is partly still open.

Future Research

Due to some widening of the project area some special parts of the project could not be carried out as well as originally was planned. These areas need still some further development so that the good operation of the developed tools could be guaranteed for all bridge types and in all conditions in all Nordic countries. Most of these needs were recognized already in Stage 1 of ETSI project [1].

The most important needs for further development are:

Collecting general material based data to a common database

Generally accepted material and structural based data among other things from material costs, needed maintenance and environmental effects should be collected to make the data input for the developed programs easier and more qualified. Due to significant differences in different Nordic countries both in environmental conditions and unit costs the input data have to be collected in every project individually, which is although quite laborious. In LCA tool the material based environmental effects are taken from internationally accepted databases – the need there is to update the data to local level.

Degradation models

Developing degradation models for all kind of bridges and their structural elements in a form which could be used in LCC program is in further development an important task. For at least some structural elements of concrete bridges quite good degradation models already exist. For other materials and other structural elements more research is still needed. Degradation models with bridge condition classing are needed in LCC program to define timings for MR&R actions and further for calculation of maintenance costs.

General testing of programs and developed principles

Until now the developed programs, WebLCC and BridgeLCA, have been tested just with some bridge cases. To get better experience from their real action with all kind of bridge structures and in all kind of bridge conditions more testing work is needed. Already some master level thesis work is going on in Sweden and Norway. Also to test developed principles to take account bridge aesthetics with new real bridge projects is important.

Widening of the research area

After suggested further development and testing work the verified versions of the programs could be published. The tool box could still be widened with some useful additions as

- making of the integrated use of the programs easier.
- possibility to use the tools also better for existing bridges, their maintenance and rebuilding,
- analysis of needed total energy during life cycle,
- new bridge types and materials (now among others stone bridges are missing).

References

[1] TKK-SRT-37 ETSI Project (Stage 1). Bridge Life Cycle Optimisation. Editors: Jutila A. & Sundquist H. Feb 2007. 165 p.

[2] ETSI Home Page: http://www.tkk.fi/Yksikot/Silta/Etsiwww2/

BRIDGE LIFE CYCLE OPTIMISATION

Stage 2

SubProject 1 (SP1)

Life Cycle Cost Methodology and Computer Tool WebLCC

Håkan Sundquist and Raid Karoumi

Royal Institute of Technology (KTH)

Civil and Architectural Engineering
Structural Design and Bridges

KTH Byggvetenskap

Preface

This report is part of a series of reports produced within the joint Nordic project ETSI financed by the Swedish, Norwegian and the Finnish Road Administrations.

This report, the ETSI stage II report is written by Håkan Sundquist. The computer tool WebLCC described in the report is developed by Prof Raid Karoumi and PhD-students Axel Liljencrantz and Ignatio Gonzales.

Stockholm in Mars 2009

Håkan Sundquist

Contents

Main notations

Latin lower case

Symbol	Typical unit	Description
$a_1, a_2, \ldots$	-	Constants
f_A	-	Factor used for calculating the annuity cost
o_D	currency	Operating cost for cars
o_G	currency	Operating cost for transported goods
o_L	currency	Operating cost for the commercial traffic vehicles
p	-	Probability
r	%	General s ymbol us ed f or r ent, w hen no i ndex i s us ed t he symbol stands for calculation rent
r_L	%	Amount of commercial traffic
t	year	Time
v	km/h	Speed
v_r	km/h	Traffic speed during bridge work activity
v_n	km/h	Normal traffic speed at the bridge site
w_L	currency	Hourly time value for commercial traffic
w_D	currency	Hourly time value for drivers

Latin upper case

Symbol	Typical unit	Description
ADT	number/day	Average daily traffic
A	Number/vehicle-km	Accident rate
AC	$, €, SEK, NOK	Annuity cost
C	$, €, SEK, NOK	General symbol for cost
CC	-	Condition class
$K_{H,j}$		Total cost for a bridge failure
L	m	Bridge l ength or l ength af fected b y repair or main-tenance work
LCC		General s ymbol f or l ife c ycle cos t. Different i ndices are used
LCV	% or ‰	Lack of capital value

N		General symbol for number i.e. number of days
N_t		Number of days of road work at time *t*
OCC	-	Overall condition class
T	year	Studied time interval i.e. life-time

Abbreviations

Symbol	**Description**
BMS	Bridge Management System
MR&R	Maintenance, Repair and Rehabilitation

1. Introduction

1.1 Aim and scope for the project

This report presents basis for *L*ife *C*ycle *C*ost (*LCC*) analysis for bridges and description of a computer tool for performing this kind of analysis.

The report is a part of a joint Nordic project "ETSI". This acronym is the Finnish abbreviation for *B*ridge *L*ife *C*ycle *O*ptimisation.

The project is divided into four parts:

- A general compilation of issues regarding bridge life cycle optimisation and three special projects:
  - SP 1 Life Cycle Cost,
  - SP 2 Life Cycle Assessment and
  - SP 3 Bridge Aesthetics and Cultural Effects.

These three special themes is part of the general description of systems for optimisation of bridge design regarding all features of interest for finding the best solution for a bridge at the planning and conceptual design stage.

The project is in time decomposed into two stages ETSI I and ETSI II. The ETSI I project was reported in *Jutila & Sundquist (2007)*.

This report is about Life Cycle Cost methodology as a result of the ETSI II stage.

1.2 Outline

A state-of-the-art report on LCC has, as a part of the ETSI I project, has been published in *Jutila & Sundquist (2007)*. This report contains a literature survey on LCC analysis. For more background information reference is made to Chapter 2 in that report.

This report is the ETSI II report on bridge LCC calculations. The report is divided into two main parts:

- Chapter 2 and Chapter 3 which present a general background and discussion on LCC for bridges and other infrastructures and
- Chapter 4 to Chapter 6 which presents description of a computer tool for LCC analysis of bridges.

2. Bridge management systems

2.1 Introduction

A bridge owner who has typically many thousands of bridges to manage knows that it is a complex task to plan the management and therefore a bridge management system (BMS) is a must for the effective planning and procurement of new bridges and for the maintenance of the existing bridge stock. In *Jutila & Sundquist (2007)* short descriptions are given for the Swedish, Finnish and Norwegian BMS systems. In this section only some information is presented on BMS systems that are of interest for making LCC calculations.

2.2 What is a Bridge Management System?

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

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

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

- Network level system
- Project level system

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

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

The LCC system presented in this report is aiming in discussing and presenting tools for this level, especially for the conceptual stage of the design.

The bridge management system often has a special network level system, typically collecting data on the condition of a large amount of bridges in a stock. This part of the system is meant mainly for high level decision making and economic research. The LCC system discussed in this report is not aiming in presenting tools for this level, but can nevertheless be used for making analysis on standard solutions.

In a BMS user costs are an important issue. For instance, a weak bridge may cause considerable extra expenses for some users as a result of a longer transport route. A narrow old bridge that causes a bottleneck for traffic results in extra expenses to all road users. Normally, the owner costs form a descending curve and the user costs an ascending curve as a function of increasing degradation of a structure. The minimum socio-economic costs, totalling the owner and user costs, would then lie between the extreme ends of high and low condition, as seen in **Figure 3.1**

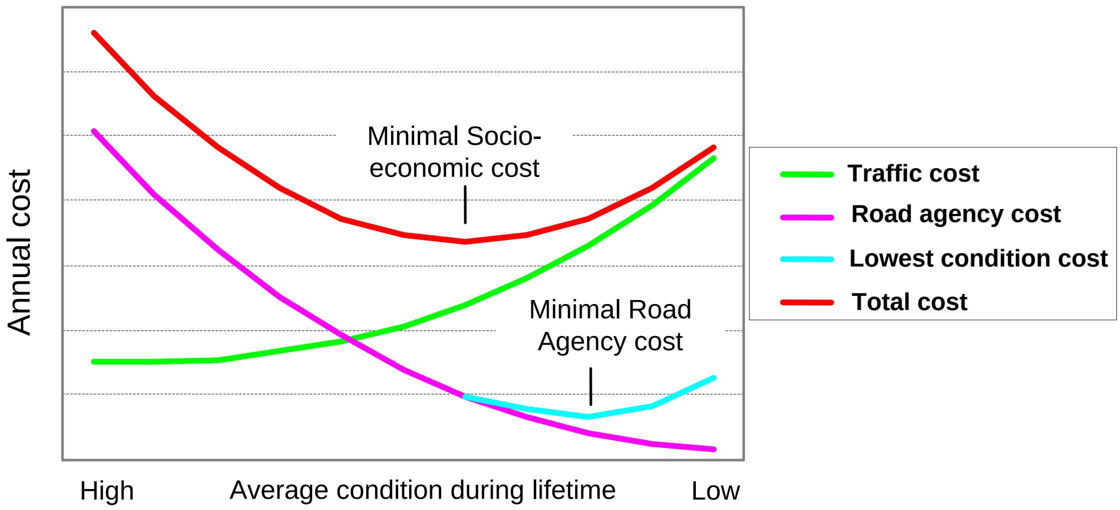

Figure 2.1 *Definition of the optimal condition level of structures from a socio-economic point of view (LT analysis). Redesigned from, Männistö & Feighan (1999).*

A bridge management system is always based on a well-defined data inventory. The data structure of the inventory must be consistent with the system needs. It should allow the input of inspection and condition assessment data and repair data as well as structural data on all levels of structural hierarchy. The LCC system presented in this report is mainly based on the Swedish methodology for defining bridges, but has in certain aspects been generalised and modified to also suit the Finnish and Norwegian BMS systems.

3. Methodology for LCC calculation

3.1 The idea behind Life Cycle Cost analysis

The classical task for the Bridge Engineer was to find a design giving the lowest investment cost for the bridge, taking the functional demands into consideration. **Figure 3.1** shows this process schematically.

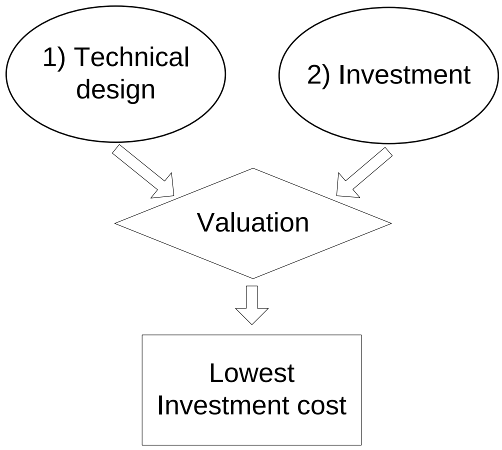

Figure 3.1 *The classical task for the bridge engineer was to find the design giving the lowest investment cost for the bridge.*

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

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

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

1. Functional demands for the bridge. The most important of these demands are the safety, planned life-span and accepted traffic interruptions and user costs.
2. Physical description of the bridge. The structure is usually divided in parts, i.e. according to **Table 4.1** and the different parts are given geometrical measures or weights.
3. Calculation methods for costs. This could be considered to be the LCC basic method including real interest rate calculations with known costs for operation, inspection, maintenance, repair, costs for accidents and demolition. Methods for this are discussed in Sections 3.3 to 3.7.

4. Time for interventions and incidents during the life-time of the bridge.

Point 4 is the most complicated point in an LCC calculation, since it must be based on known future events and behaviour of the bridge. And real knowledge of the future is of course by definition not existing. Tools for this point are though discussed in this chapter in Section 3.8. In *Jutila & Sundquist (2007)* Sections 3.6 and 3.6 a more thorough discussion on this question is presented. In this report it is assumed that the time between different maintenance and repair actions is decided by the user of the system, even if the WebLCC program presented in Chapter 4 has a module for modifying the time for actions depending on climate classes.

3.2 Basic calculation methods for LCC

The different contributions in a complete LCC analysis of a structure could be divided into parts, mainly be cause different bodies in the society will be responsible for the costs occurring as a consequence of constructing or using the structures. There are many reports in this field i.e. *Burley Rigden (1997), Hawk (1998), Siemens et al. (1985), Veshosky Bedleman (1992).* The following presentation follows *Troive (1998), Sundquist Troive (1998a* and *1998b).* In all these reports *LCC* is a general variable describing a cost, usually by using the net present value method calculated to the time of opening the bridge. The different parts of the calculation can be described in **Figure 3.2**.

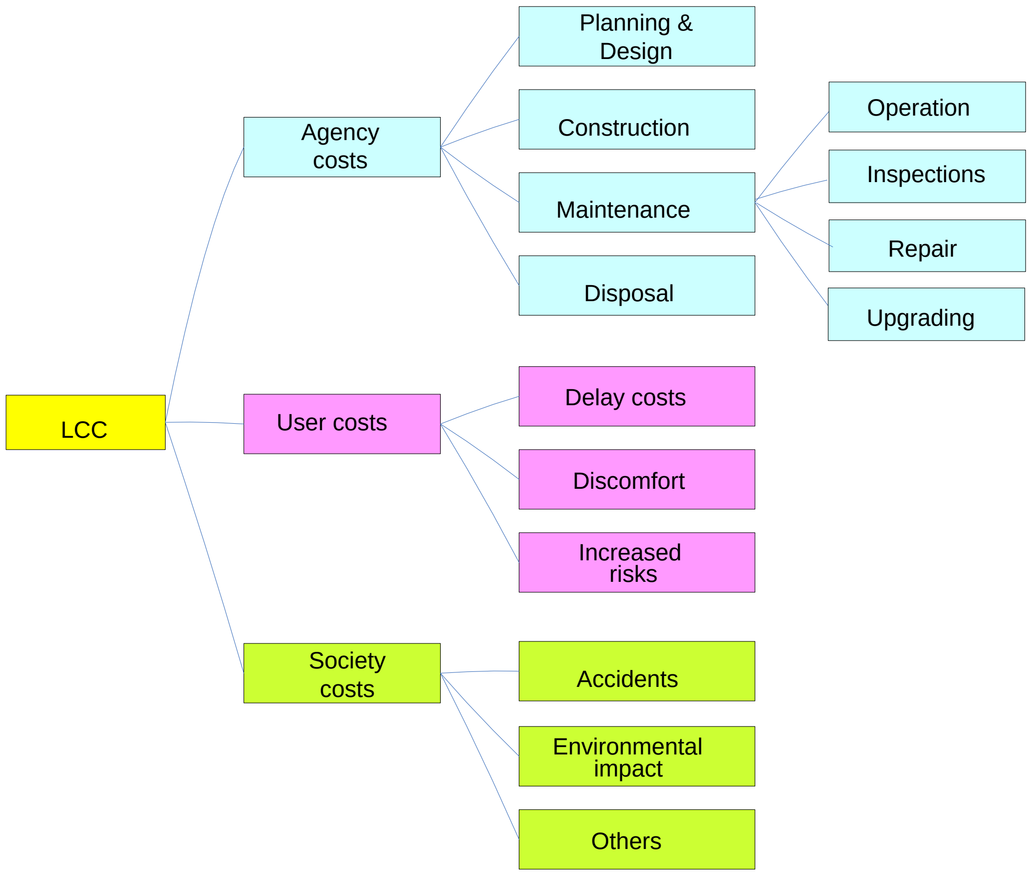

Figure 3.2 *Schematic presentation of the different items in a complete LCC analysis.*

The owner - or in the case of an Agency like a Road or Railway Administration - has the responsibility for investments, operation and MR&R costs. The user is the one who has the benefit of the road system and thus the bridges, but has also has to pay for lost working hours due to traffic interruptions, risks and other problems. The society has to pay for accidents, environmental impacts and if the road network does not function for the welfare of a country. The income for the society of the road and thus the bridge could be called *LCI*, *L*ife *C*ycle *I*ncome.

In a general term the *LCC* should be smaller than the *LCI.* Typically a road system should not built unless *LCI* is 1,5·*LCC*., see Section 3.7.

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

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

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

3.3 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 Eq. (3-1)

$$LCC = LCCA + LSC + LCCC \tag{3-1}$$

Where

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

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

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

The *LSC*, the Life Support Cost, can in turn be divided into two parts according to Eq. (3-2)

$$LSC = CI + CN \tag{3-2}$$

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

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

The investment part of the maintenance, *CI*, could be divided according to eq. (3-3)

$$CI = CI_r + CI_v + CI_d + CI_t \tag{3-3}$$

where

CI_r = spare parts and material,

CI_v = instrument, tools, vehicles that is needed for inspection and maintenance,

CI_d = documentation i.e. drawings and instruction manuals needed for inspection and maintenance and also

CI_t = employment and education of personnel for operation and maintenance.

Usually the *CI* costs for a bridge is small and can often not be coupled to a specific bridge. The Agency cost for Operation could however be referred to this cost, because the cost for operation is probably proportional to the number and complexity of the bridge stock.

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

$$LCC_{\text{agency}} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{3-4}$$

In Eq. (3-4) is

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

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

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

Equation (3-4) is schematically visualised in **Figure 3.3**.

To be able to compare life cycle costs of structures with different service lives, instead of the present value, the annuity costs may be compared. The annuity cost, *AC*, is the inverse of the present value for annual costs and can be calculated using Eq. (3-5)

$$AC = LCC \cdot f_A = LCC \frac{r}{1-(1+r)^{-T}} \tag{3-5}$$

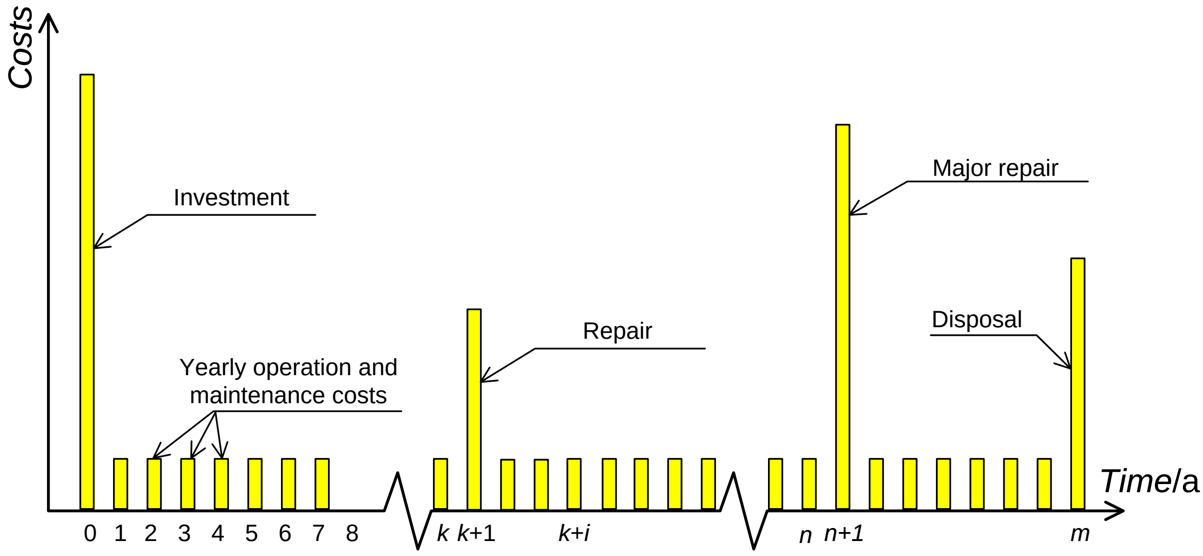

Figure 3.3 *Schematically representation of agency costs for a bridge. The costs in this figure are not recalculated using the present value method.*

In an optimisation context the task, only taking the agency costs into consideration, is to design a bridge to find the lowest LCC cost. This phase of the LCC Optimisation is visualised in **Figure 3.4**.

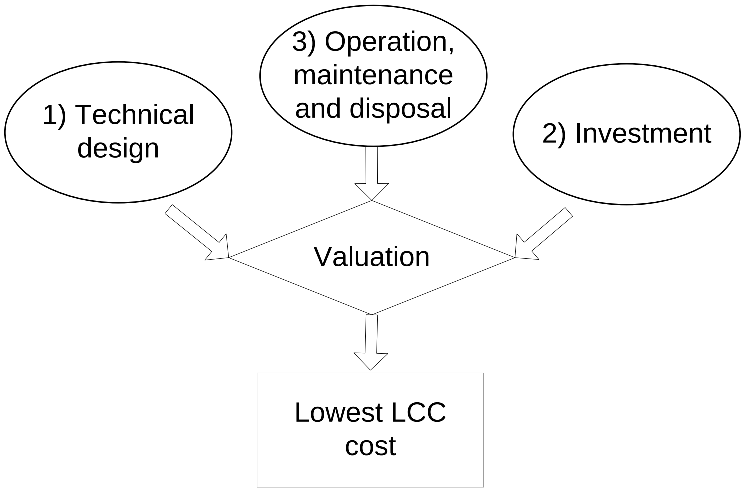

Figure 3.4 *The figure shows schematically the costs taken into consideration in a classic LCC analysis not including society and user costs.*

Eq. (3-4) is usually used to calculate the owners cost for investment, operation, inspection, maintenance, repair and disposal.

The C_t costs at the time of inauguration are usually not too complicated to assume for the necessary above-mentioned steps in the management of a structure. There is a great uncertainty in choosing the *r*-value, but still more uncertain is the calculation of the time intervals between the different maintenance works and repairs.

To be able to assume the time intervals used for calculation, the degradation rate of the different parts of the structure must be known. Every structural engineer knows that this is a very complicated task. According to our knowledge the best information for assuming the time intervals is historical data from actual bridge inspections and repairs. Theoretical degradation models such as using carbonation rates, Fick´s second law or similar approaches seem, at this stage not to feasible. Combination of historical data with Markov-chain methodology seems however to be feasible if enough data is available.

3.4 User costs

User costs are typically costs for drivers, the cars and transported goods on or under the bridge due to delays due to roadwork. Driver delay cost is the cost to the drivers who are delayed by the roadwork. Vehicle operating cost is capital cost for the vehicles, which are delayed by roadwork. Cost for goods is all kinds of costs for delaying the time for delivering the goods in time. Other user costs might be cost of damage to the vehicles and humans due to roadwork not included in the cost for the society. Travel delay costs can be computed using Eq. (3-6)

$$LCC_{\text{user,delay}} = \sum_{t=0}^{T} \left(\frac{L}{v_{\text{r}}} - \frac{L}{v_{\text{n}}} \right) ADT_t \cdot N_t \left(r_{\text{L}} w_{\text{L}} + (1 - r_{\text{L}}) w_{\text{D}} \right) \frac{1}{(1+r)^t} \tag{3-6}$$

In Eq. (3-6)

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

v_{r} is the traffic speed during bridge work activity,

v_{n} is the normal traffic speed,

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

N_{t} is the number of days of road work at time t,

r_{L} is the amount of commercial traffic,

w_{L} is the hourly time value for commercial traffic and

w_{D} the hourly time value for drivers.

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

Vehicle operating costs and costs for transported goods can be calculated using Eq. (3-7)

$$LCC_{\text{user,operating}} = \sum_{t=0}^{T} \left(\frac{L}{v_{\text{r}}} - \frac{L}{v_{\text{n}}} \right) ADT_t \cdot N_t \left(r_{\text{L}} (o_{\text{L}} + o_{\text{G}}) + (1 - r_{\text{L}}) o_{\text{D}} \right) \frac{1}{(1+r)^t} \tag{3-7}$$

In Eq. (3-7) the same parameters are used as in Eq. (3-6) except for

o_{L} which are operating cost for the commercial traffic vehicles,

o_{G} operating cost for transported goods and

o_{D} operating cost for cars.

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

There is usually an accident cost for roadwork for the user not included in the cost for the society. Eq. (3-6) could be used also for this by just adjusting the cost parameter for this case.

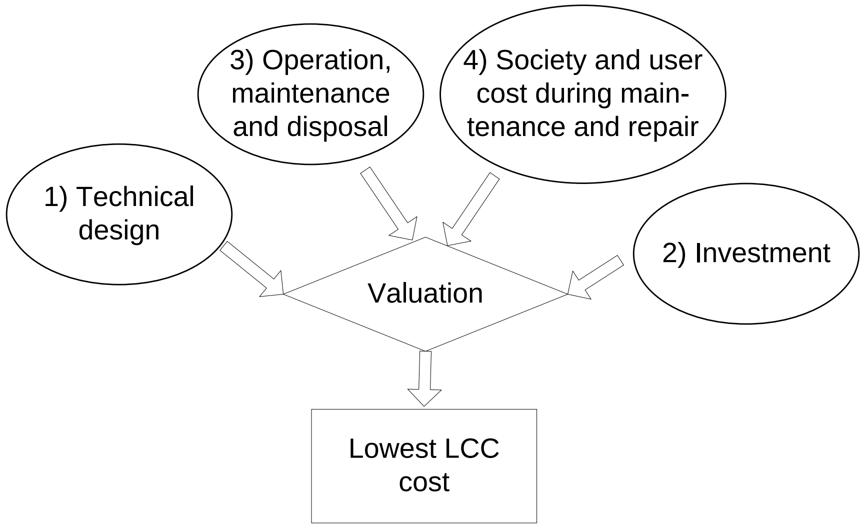

Figure 3.5 *The figure shows schematically the costs taken into consideration in a classic LCC analysis not including society and user costs.*

3.5 Costs for the society

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

Most construction materials consume energy for production and transportation. One way to take this into account is by multiplying all costs for materials for construction and repair with some factor due to energy consumption for manufacturing and transportation. The use of non-renewable materials might be taken into consideration by involving costs for reproducing or reusing materials when the structure is decommissioned. These issues are discussed in the SP2 subproject on Life Cycle Assessment.

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

$$LCC_{\text{society, accident}} = \sum_{t=0}^{T} (A_{\text{r}} - A_{\text{n}}) ADT_t \cdot N_t \cdot C_{\text{acc}} \frac{1}{(1+r)^t} \qquad (3\text{-}8)$$

In Eq. (3-8) A_{n} is the normal accident rate per vehicle-kilometres, A_{r} is the accident rate during roadwork and C_{acc} is the cost for each accident for the society, ADT_t is the average daily traffic, measured in numbers of cars per day at time t and N_t is the number of days of road work at time t. The costs should be calculated to present value and added up for all foreseen maintenance and repair works for the studied time interval T.

As an example the Swedish Road Administration uses a cost of about 2 million $ for deaths and a third of that sum for serious accidents.

3.6 Failure costs

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

$$LCC_{\text{failure}} = \sum_{j=1}^{n} K_{H,j} R_j \frac{1}{(1+r)^j} \tag{3-9}$$

In eq. (3-9), R_j is the probability for a specified failure coupled to $K_{H,j}$. For normal bridges the probability of failure is so small that the failure costs could be omitted in the analysis. The cost for serviceability limit failure is discussed in *Radojičić (1999)*, but actually the methods presented in the present paper are a kind of statistically LCC-method given that the parameters for remedial actions are considered random.

3.7 Comparing cost and benefit

Why a bridge – as a part of a road or railway – is built is of course that the project is considered beneficial for the society. The income for the society of the road and thus the bridge could be called *LCI*, *L*ife *C*ycle *I*ncome, and should of course be greater than the total LCC cost, see the schematically **Figure 3.5**. Calculation of the *LCI* is however not a part of this project.

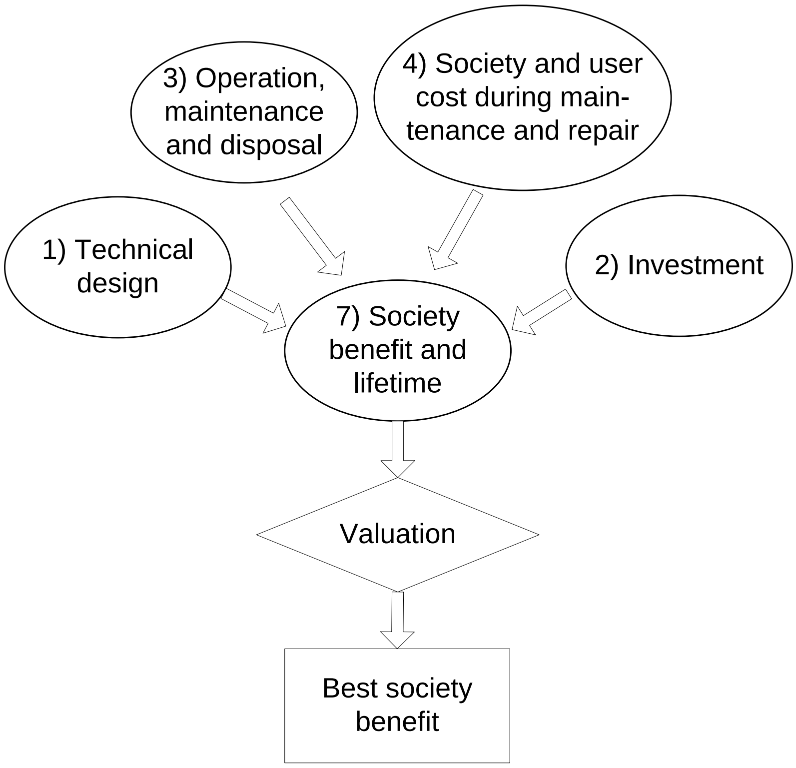

Figure 3.5 *A total cost benefit analysis shall of course also include both the total cost and the benefit for the society.*

3.8 Rent

The most important factor in eq. (3-4) is, except of course the costs, the interest rate *r*. The real interest rate is usually calculated as the difference between the actual discount rate for long loans and the inflation or more exact

$$r = \frac{r_L - r_i}{1 + r_i} \tag{3-10}$$

where

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

r_i is the inflation rate (%).

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

The inflation rate in the society might not be the same as the inflation rate for the construction sector. An investigation presented in *Mattsson (2008)* showed that the inflation in the construction sector in Sweden during the period 1984-2008 was 1 % - 1,5 % higher than the general inflation rate, see also **Figure 3.6**.

This fact shows a decrease in the productivity, but can also be explained by stricter rules for safety measures that must be applied at the construction sites. This is especially true for maintenance and repair work on existing structures along the roads.

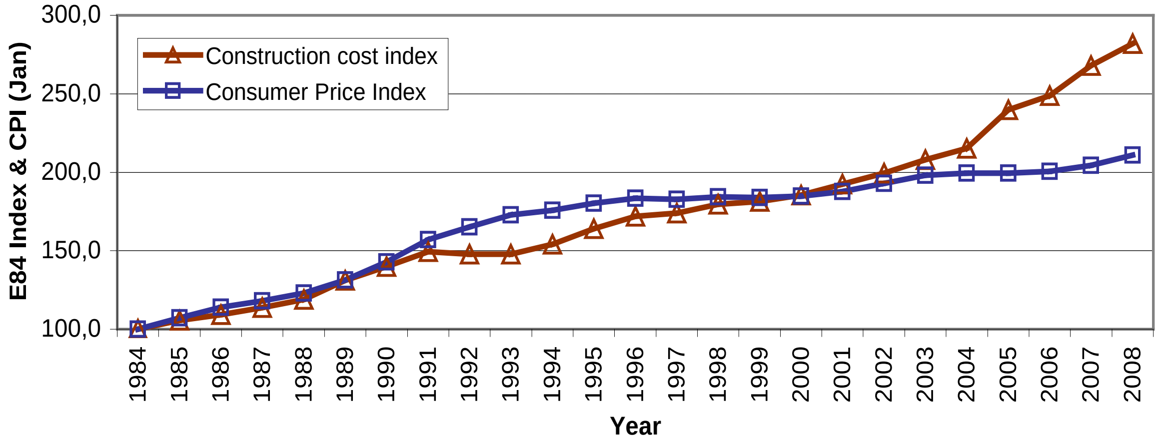

Figure 3.6 *The "inflation rate" in the construction field in Sweden is higher than the general inflation rate in the society.*

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

$$r = \frac{r_L - r_i - r_c}{1 + r_i} \tag{3-11}$$

where r_c is the increase in traffic volume using the structure. If there is a risk for the opposite, a decrease in the usefulness of the structure, this factor should be given a negative sign. This could i.e. be accomplished by building the structure at the wrong place or on a road with decreasing traffic. Taking all factors into account the *r*-value should be called "calculation interest rate" or likewise. Typical values for *r* are in the order from 3 % to 8 %, see *Jutila Sundquist (2007*).

3.9 Time between different MR&R actions

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

Life span

One parameter of great importance is the planned service life span of the bridge. Standards often call for life spans from 40 to 120 years. Standards do not usually define the parameter "life-span" exactly. According to *Mattsson (2008),* which is an interpretation of VBR Standard, the definition of life-span is the lower five percentile of the distribution of the life span. This interpretation means that the life span for 40, 100 and 120 year distribution is as shown in **Figure 3.7**.

In reality very few bridges survives such long lives. Due to the need for road rectifying, road widening, higher prescribed loads and changes in the society the actual service life of a bridge is shorter than the theoretical life span. In Sweden the average time for decommissioning bridges is in the order of 60 to 70 years. However, survival analysis for three common types of bridges in Sweden (concrete slab frame bridge, steel beam and slab bridge and steel culverts in connection with water) shows that they reach the average life span but fell short some 30 % below the minimum life span, see **Figure 3.8.**

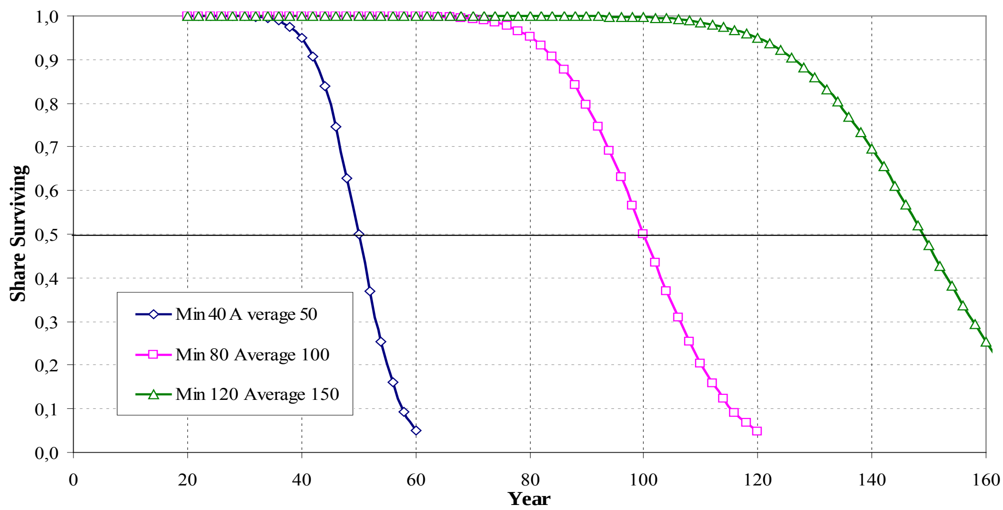

Figure 3.7 *Standards calls for design life span of bridges, but at least in Sweden the design life span is defined as the lower 5 % percentile of a distribution that could be assumed to be normal distributed.*

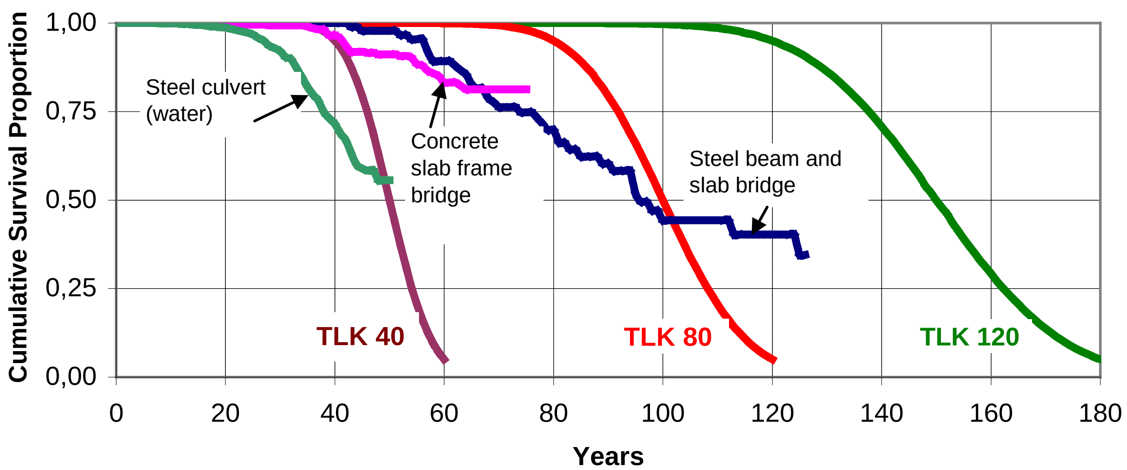

Figure 3.8 *Survival analysis of steel culvert in connection with water, concrete slab frame bridge and steel beam and slab bridge and the technical life spans defined by the SRA.*

There are two ways to describe the real service life of a bridge population. The first is to analyse only the demolished bridges and estimate a service life. This estimated service life will probably be too low for the whole bridge population since only "bad bridges" counts. The second way is to analyse both demolished bridges and existing bridges using survival analysis. This seems to be a better approach since all available data about the bridge population are used.

It may be added that the real life span for modern bridges will be known about 50 to 100 years from now.

Time intervals for inspection and standard maintenance

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

In Sweden all bridges are cleaned every year after the winter season and lightly surveyed. More profound inspections are performed every third or six year. These kinds of measures will of course vary between different countries and different owners. These types of measures will build up a part of the whole life costing for the owner of the bridge.

Inspection intervals in different countries are discussed in *Jutila & Sundquist (2007)*. Definitions of the different types of inspections are different from country to country, so it not possible to directly compare the denomination and the intervals. In the Nordic countries only three main types of inspections are performed. Yearly very superficial inspection and general inspection every 5 to 6 year are performed. Special inspection must also be performed for more complicated cases. This must also be made allowances for in an LCC analysis.

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

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

Degradation models

All the discussed equations in Section 3.3 – Section 3.6 depend on information of lots of parameters, many of which are very uncertain. One very important factor is the time intervals between repair and maintenance work. These intervals for remedial actions are not fixed values as they are affected by the degradation and by considerations of which intervals that are most economical. It is here to mention that bridges usually do not just break down; it is their structural elements that degrade.

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

- One method is to use mechanistic or chemical models like Fick´s second law for diffusion of chlorides, carbonation rates, number of frost cycles and combinations to try to forecast degradation. Such a method is used by *Vesikari (2003)* and *Söderqvist & Vesikari (2003).* This approach is used in combination with the Markov Chain

Method as a tool for analysis and this system is presented and discussed in section 3.8 in this report.

- An other method is to use and evaluate results from field observations, *Racutanu (2000), Mattsson & Sundquist (2007).*
- The up to day most applied method is to use experience from specialists, usually people deeply involved with inspection of bridges.

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

4. Definition of input in WebLCC

4.1 Background

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

4.2 Definition of bridge parts and their measures

To be able to in a consistent way calculate the LCC it is essential that the measures and dimensions of the bridge are inputted. Observe that in the Nordic countries the bridge length also includes the abutments.

Notation for bridge main structures and its elements are presented in **Table 4.1**. see also **Figure 4.1** – **Figure 4.2**.

Table 4.1 *Notations for a typical girder bridge with ordinary bearings and expansion joints.*

Description in English	Explaining figure
Foundation	
Foundation slab (base slab), plinth, pile cap	**Figure 4.1, Figure 4.4**
Excavation, soil	**Figure 4.1**
Excavation, rock	
Pile	
Erosion protection	
Slope and embankment	
Embankment, embankment end, backfill	**Figure 4.1**
Soil reinforcement and slope protection	
Abutments and piers	
All conc rete structures belonging t o t he s ubstructure excl. foundation and including the foundation slabs	**Figure 4.1, Figure 4.3**
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	**Figure 4.3**
Secondary load-bearing truss, wind bracing	
Equipment	
Bearing and hinge	**Figure 4.4**
Edge beam	**Figure 4.3**
Insulation, water proofing	
Surfacing	
Parapet, railing	**Figure 4.2, Figure 4.3**
Expansion joint	
Drainage system, de-watering system	**Figure 4.3**

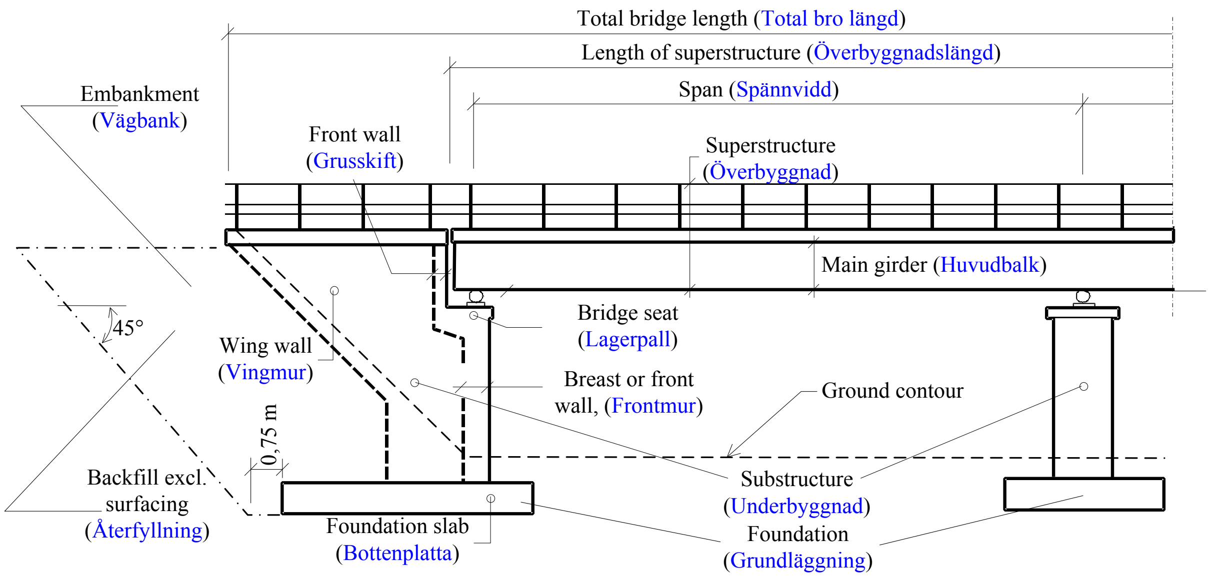

Figure 4.1 *Notations and measures of a typical beam girder bridge with ordinary bearings and expansion joints.*

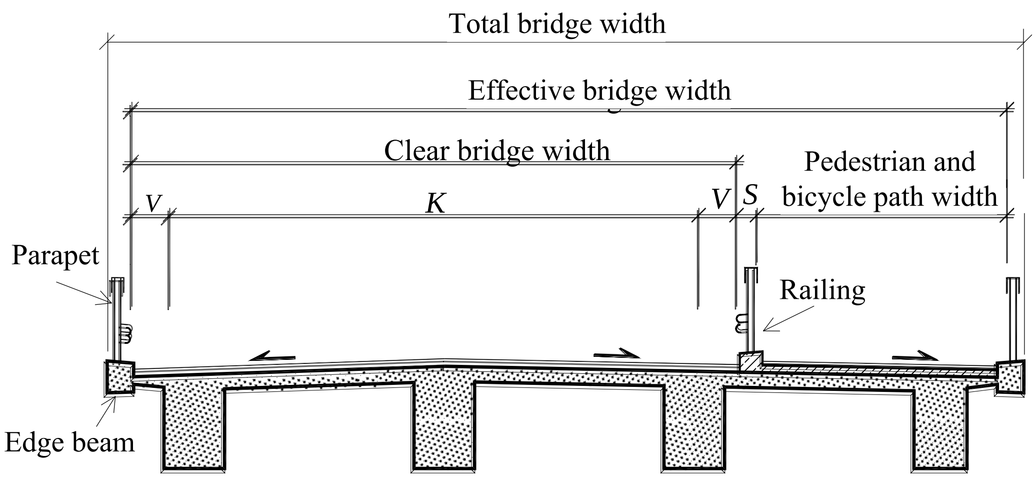

Figure 4.2 *Notations and measures in cross direction of typical beam girder bridge carrying a roadway and a pedestrian and bicycle path.*

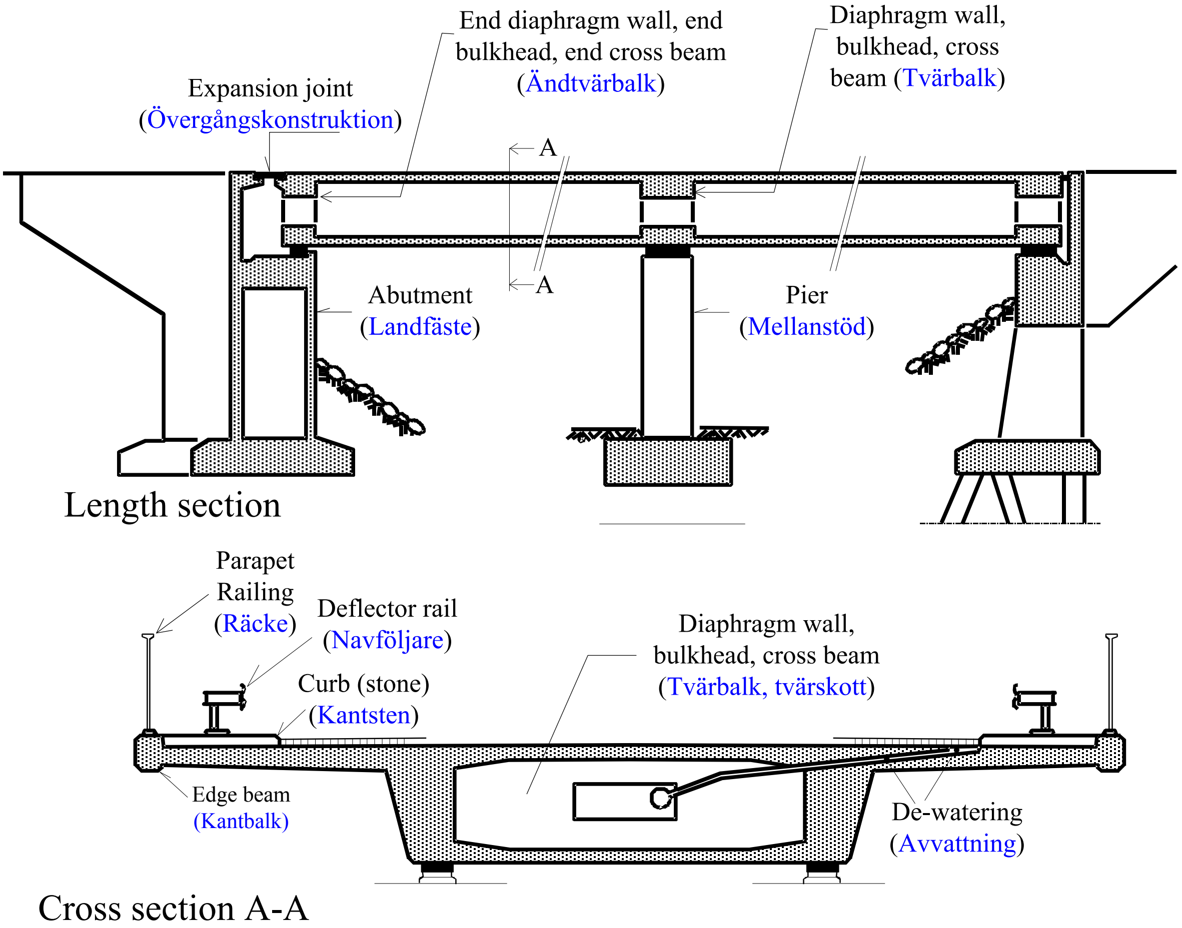

Figure 4.3	*Notations in the longitudinal direction and in the cross direction for a typical box girder bridge with ordinary bearings and expansion joints.*

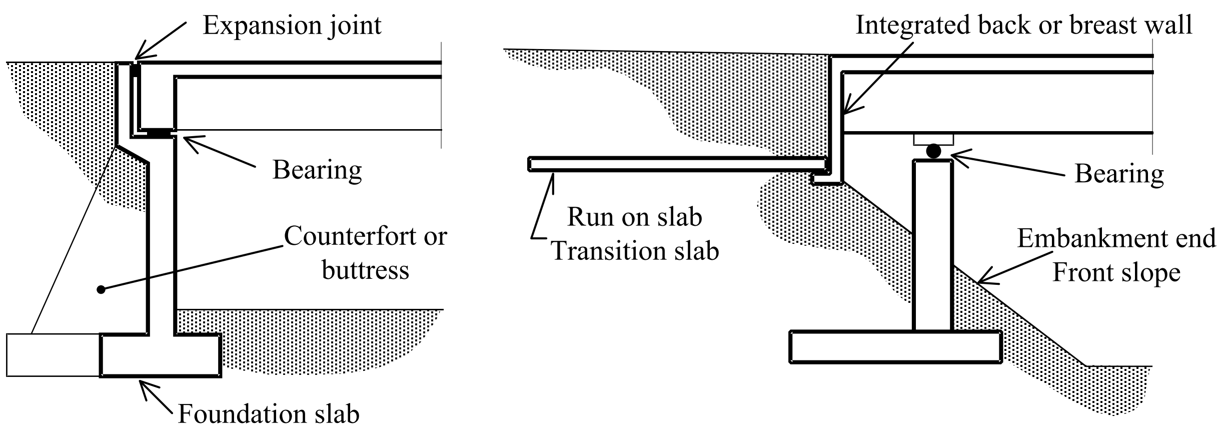

Figure 4.4 *Notations for abutment elements in an ordinary bridge and in an integral bridge with integrated back walls.*

4.3 Definition of material

In **Table 4.2** the materials included in the LCC and LCA systems are defined.

Table 4.2 a) *Materials that should be inputted in the LCC and LCA programs.*

Material	**Unit**	**Quality**	**Description**
Concrete	m^3	C25[1]	Cylinder strength in MPa
Reinforcing steel	ton	500[2]	Yield strength in MPa
Steel for pre-stressing, tendons, cables	ton	1700	Yield strength in MPa
Steel	ton	350[3]	Yield strength in MPa
Sawn Timber	m^3		
Glued laminated timber	m^3		
Impregnated timber	m^3		
Backfill soil	m^3		
Pile	m	Type[4]	Directly coupled to the structural element

The f ollowing i tems o nly us ed i n t he LCA module (in t he LCA o nly s urfacing and insulation in m^2 is given).

Table 4.2 b) *Materials that should be inputted in the LCC and LCA programs.*

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		

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

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

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

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

4.4 Definition of actions

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

- Management
- Operation
- Inspections
- Repair
- Upgrading
- Final demolition

Management is the owners own work for keeping the bridge inventory, the planning and other actions to manage the bridge stock. Usually this work can be assigned as percentage of the actual reconstruction value of the bridges in the bridge stock.

Operation is the *yearly work* to superficially and regularly inspect, clean and to repair small damages of the bridges. The Swedish term is “Drift”. See also **Table 4**.

4.4.1 Inspection actions

Table 4.3 shows typical inspection actions and the intervals

Table 3 *Inspection types and intervals between inspections.*

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

4.5 Operation and repair actions

Maintenance actions could be divided into actions performed as part of the yearly operations and real repair actions needed when some of the structures or elements are severely damaged. Examples of such “Operation actions” are listed in **Table 4.4**, but could usually be calculated as a percentage of the cost to re-build the bridge stock. A typical value could be 0,2 %.

4.5.1 Operation actions

Table 4.4 *Examples of "operation maintenance actions". In the Swedish system this is called "Egenskaper" or "properties".*

Action	Frequency	Aim	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,…	Once a year		
…			

4.5.2 Repair actions

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

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

4.6 Environmental classes

The W ebLCC is fitted with a modul e f or modifying time int ervals f or M R&R a ctions depending on c limate z one, a mount of yearly used de -icing s alt e tc. This r efinement is however not further implemented in the overall project since definition of climate zones etc. has not been agreed in the joint Nordic project.

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5. Using WebLCC

5.1 Introduction to WebLCC and LCC-analysis

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

WebLCC is sufficient general for making LCC analysis even for a small part of a large project. WebLCC also allows for simple and fast way of comparing two different solutions for a bridge or bridge part

5.1.1 Log-in

The address to WebLCC is: http://brolcc.byv.kth.se/etsi. User name and password is inputted on the start page.

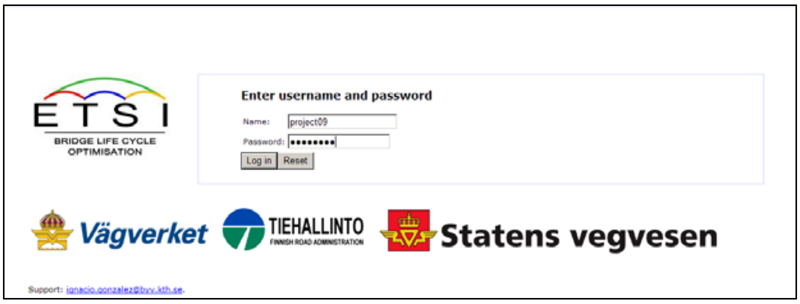


Figure 5.1 *The appearance of the log-in page*

The first page, see **Figure 5.2**, shows the latest projects handled by WebLCC. At the upper right part of the first page the link to the "Help" menu is displayed.

Figure 5.2 *Page 2 shows the current projects handled by WebLCC.*

5.1.2 Help - Overview

The documentation of the WebLCC is build up by a number of pages, see **Figure 5.3** below. On many of the pages in WebLCC there are links to relevant paragraphs in the help text.

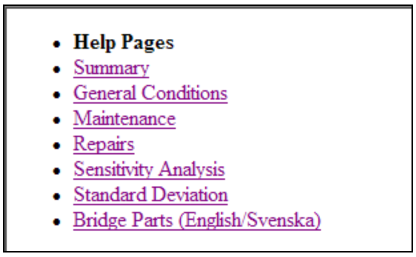


Figure 5.3 *Help Pages Menu.*

5.2 General Conditions

In "General Conditions" general input data regarding the environment and the conceptual design of bridge is entered. The data includes the type, width and length of the bridge (see Chapter 4 or Help Menu "*Bridge Part*)*s*. The *ADT* (Average Daily Traffic), the percentage of heavy trucks, the climate zone, the real interest rate and other factors influencing the LCC calculations must also be defined. It is possible to use WebLCC for making a rough calculation of the investment cost, but it is also possible to calculate the investment separately and input it here in the General Conditions menu. The largest value for investment will be chosen in the calculation.

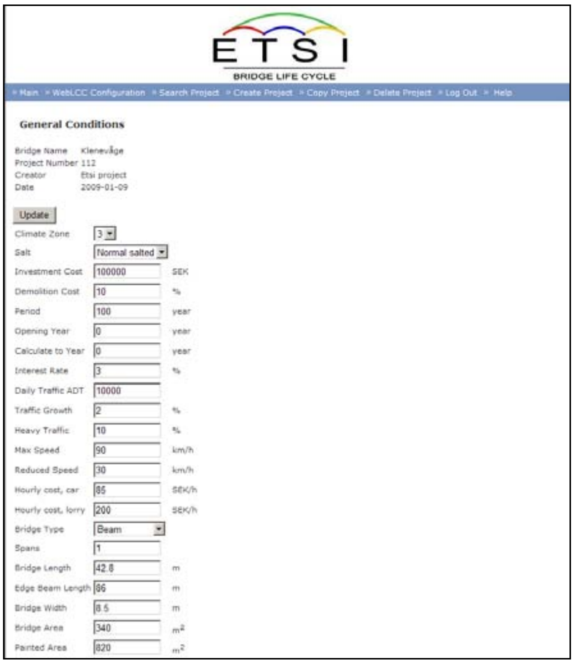


Figure 5.4 *Page 3, General condition menu.*

The second part of *page 3*, is depicted in **Figure 5.5**. This part is for inputting climate factors. Default values are given. **Observe that if there are changes made the button "Update" on the top of this page should be pressed**. The buttons at the bottom of *page 3* is for navigating between the different pages.

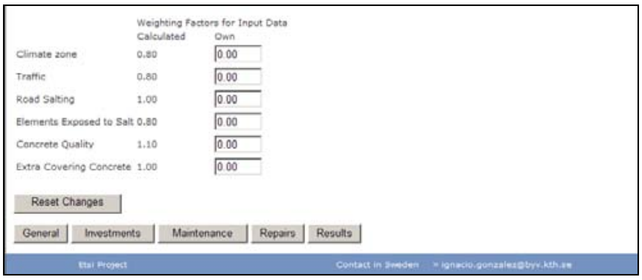
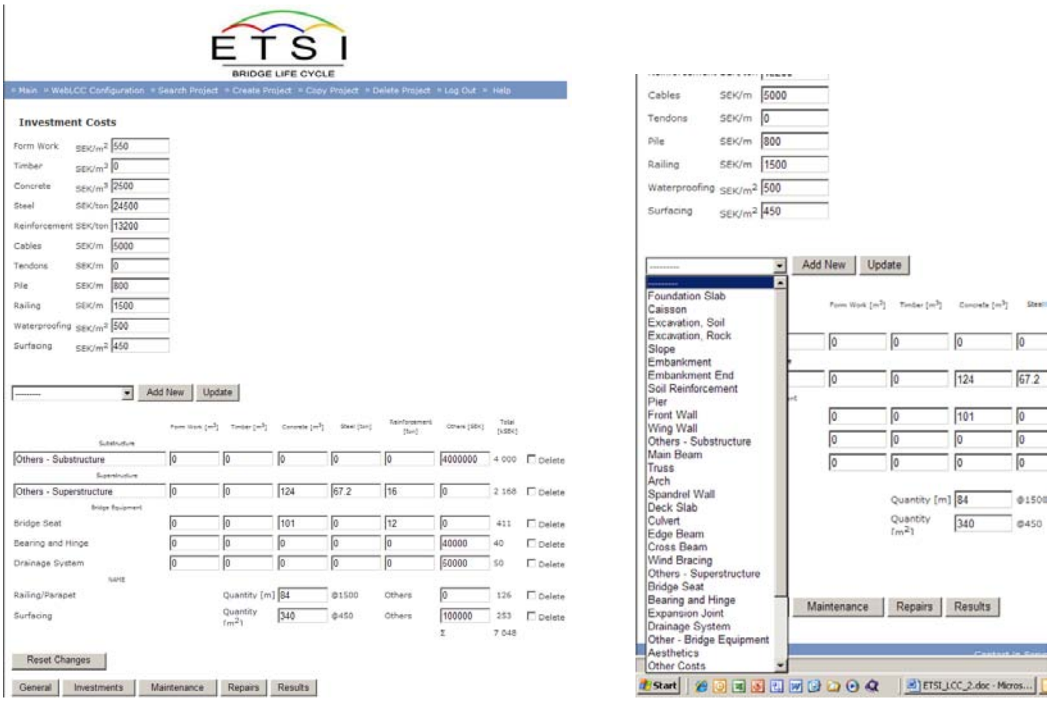


Figure 5.5 Lower part of the General condition menu, defining climate factors.

The next step is the Investments menu, *page 4*.

5.3 Investment

Figure 5.5 a) shows the Investments menu, *page 4*. In this menu unit costs for typical materials are given and on a drop-down menu **Figure 5.5** b). Lots of different bridge parts can be added and also new material costs can be added. This makes the input very flexible. It is of course also possible to delete items. When everything on this page is inputted, the **Update button** should be pressed. **Observe** that the investment cost can be given as a lump sum instead for using this menu! In this case no values should be inputted in the Investment menu.



a) b)

Figure 5.5 *Page 4, the investments menu. A large amount of different bridge parts can be added and modified.*

The next step is the Maintenance menu, *page 5*.

5.4 Maintenance

Figure 5.6 depicts the Maintenance menu. WebLCC lets you specify the operation and maintenance actions that are needed during the life cycle of the bridge.

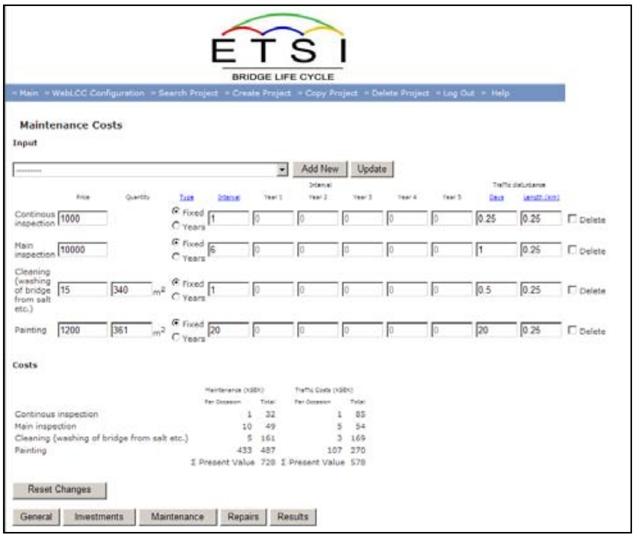


Figure 5.6 *Page 5 in WebLCC is the input and calculation menu for maintenance.*

5.4.1 Overview

The operation and maintenance page is built up by two parts, the input part and the compilation of cost part. The input part, see **Figure 5.7**, presents the repair actions that can be performed and inputted. The user can add or remove repair actions. The compilation of the cost part will show the calculated costs. When everything is defined the Update button should be pressed.

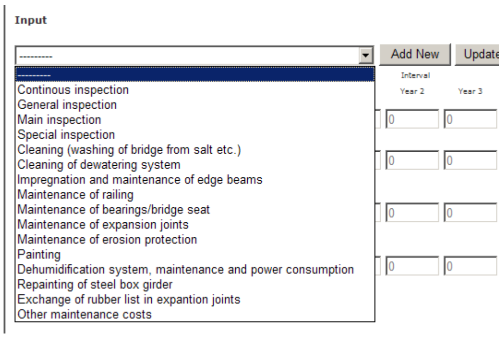


Figure 5.7 *The different operation and maintenance actions that can be inputted. Observe also that it is possible to add more items.*

5.4.2 Interval type

It is possible to define constant intervals between the operation and maintenance actions or to input specific years when the repair actions shall be made.

5.4.3 Traffic disturbance

The cost for traffic disturbances are specified by the number of days and the length of stretch that the maintenance action will affect. The costs are calculated based on the ADT and hourly cost for trucks and private cars, as specified in the “General Conditions” page.

5.5 Repairs

WebLCC gives you the possibility to specify the necessary repairs and the interval between these actions. This is performed on the Repair Costs menu

5.5.1 Overview

The repair page is built up by two parts, the input part and the compilation of cost part. The input part presents the repair actions that can be performed. The user can add or remove repair actions. The compilation of cost part will show the calculated costs.

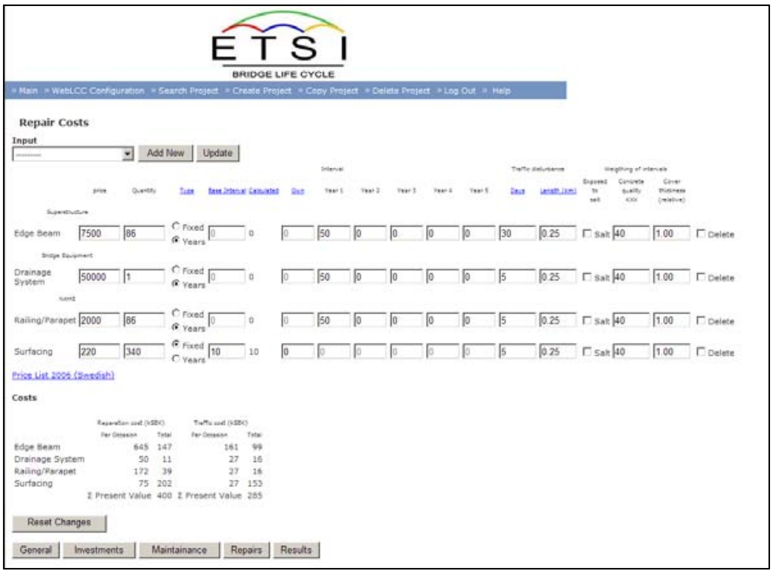


Figure 5.8 *The Repair Costs menu, Page 6 in the WebLCC.*

5.5.2 Type of interval

It is possible to define constant intervals between the repair actions or to input specific years when the repair actions shall be made.

5.5.2.1 Base interval

The Base is defined as a default interval between repair actions. This value is used for calculating the real intervals.

5.5.2.2 Calculated interval

The calculated interval is the base interval multiplied with the modifying factors that will depend on the amount of de-icing salting , thickness of covering sections and other properties.

5.5.2.3 User defined interval

The user can input a chosen value for the repair interval. If a user defined interval is chosen, the value will not be weighted with any of the factors that modify the based interval.

5.5.3 Traffic disturbance

The cost for the traffic disturbance is specified by inputting the length of the stretch that will be affected as well as the number of days this intervention will last.

5.6 Sensitivity Analysis

Sensitivity analysis allows for an estimation of how sensitive the calculations are for variations in certain input parameters. This can be useful when precise costs or time intervals of an activity are not available.

5.6.1 Chose variable

Chose form the list in expanding menu the variables you want to assign uncertainties to and input a value for the standard variation of the cost and/or the interval. The uncertainties are given as percentage of the inputted value, which will be taken to be the expected value.

5.6.2 Results

The results of the sensitivity analysis are shown in a table with the columns as describe bellow:

- Expected Cost: Is the most possible cost, and the average of all costs. It is usually higher than the original cost since a reduction in the intervals increases the costs more than what a corresponding increase on the intervals will increase them, due to interest rate effects.
- Standard deviation: given a measure of the uncertainty of the variable.
- Original cost: with no uncertainties applied to it.
- Difference: between the Expected and Original cost

5.6.3 Standard deviation

The standard deviation can be qualitatively define as a measure of the uncertainty of a parameter or, in other words, how much a certain parameter can be expected to vary from a expected value. For the standard distribution 70 % of all occurrences will vary within one standard deviation and 95 % of all occurrences will vary within two standard deviation of the expected value.

5.7 Result

The result of the calculation can be presented both in a version adapted for the screen and for printing.

Chapter 6 presents an example of calculation and result presentation.

6. Examples

6.1 Introduction

In the ETSI project three different bridges have been studied; Klenevågen Steel Box Girder Bridge (**Figure 6.1** and **Figure 6.2)**, Fretheim Timber Arch Bridge (**Figure 6.3** and **Figure 6.4)** and Hillersvika Concrete Box Girder Bridge (**Figure 6.5** and **Figure 6.6)**. The basic data for these bridges is summarized in **Table 6.1.**

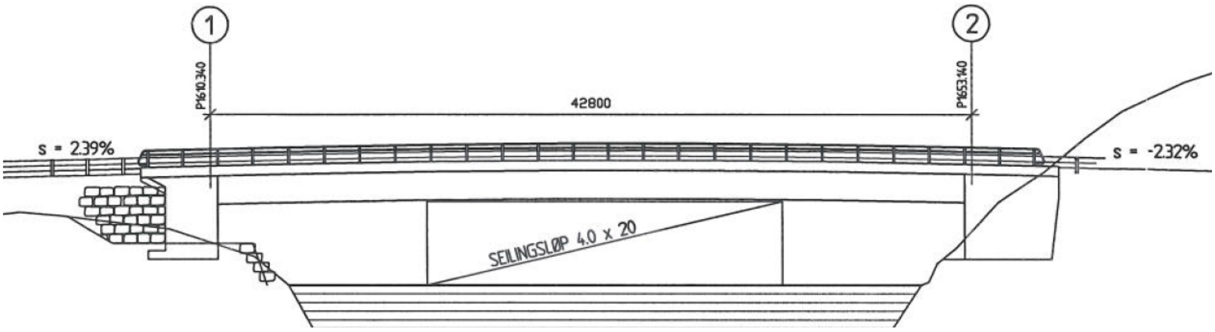


Figure 6.1 *Klenevågen Steel Box Girder Bridge has a bridge span of 42,8 m.*

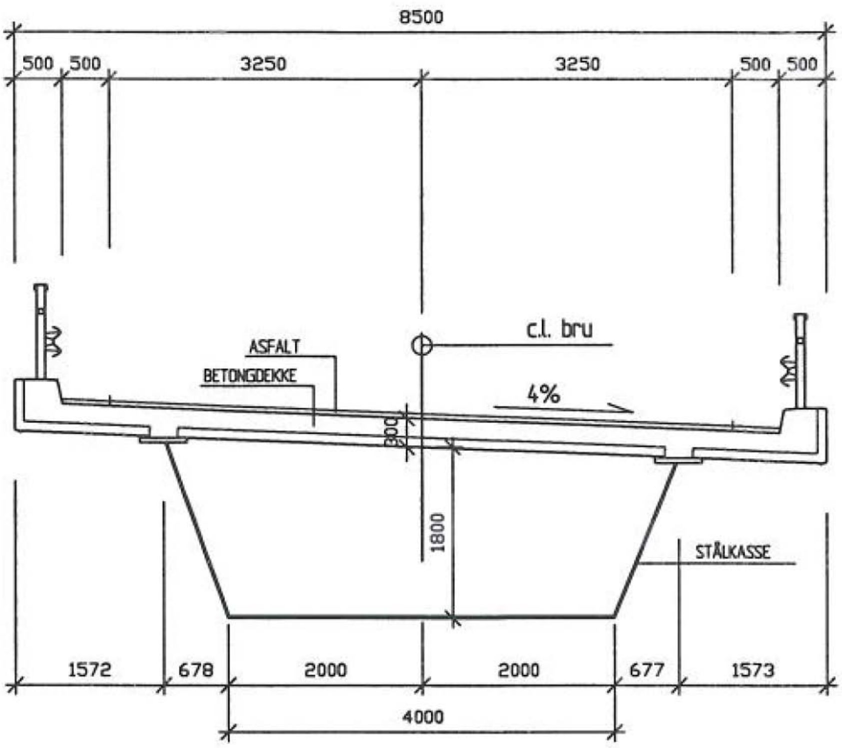


Figure 6.2 *Klenevågen Steel Box Girder Bridge has an effective bridge width of 7,5 m.*

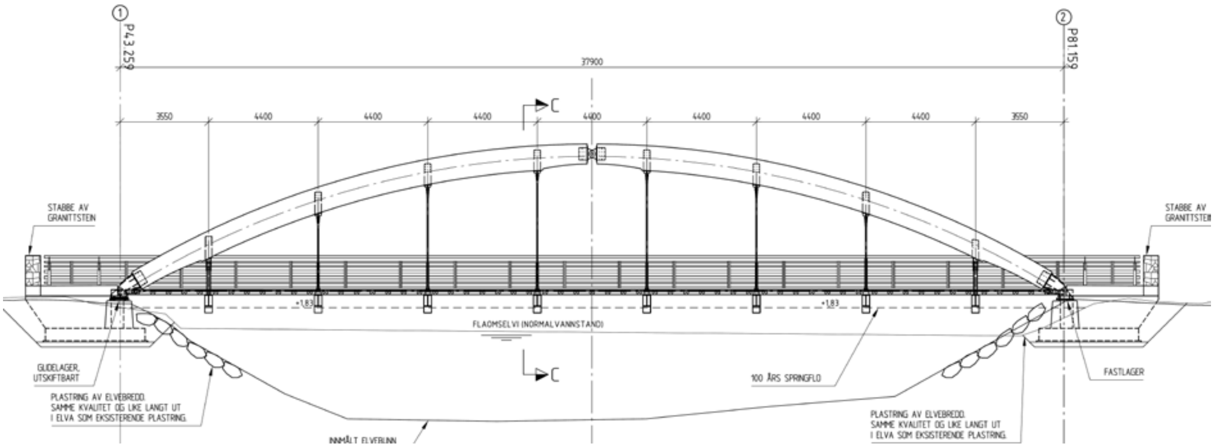


Figure 6.3 *Fretheim Timber Arch Bridge has a bridge span of 37,9 m.*

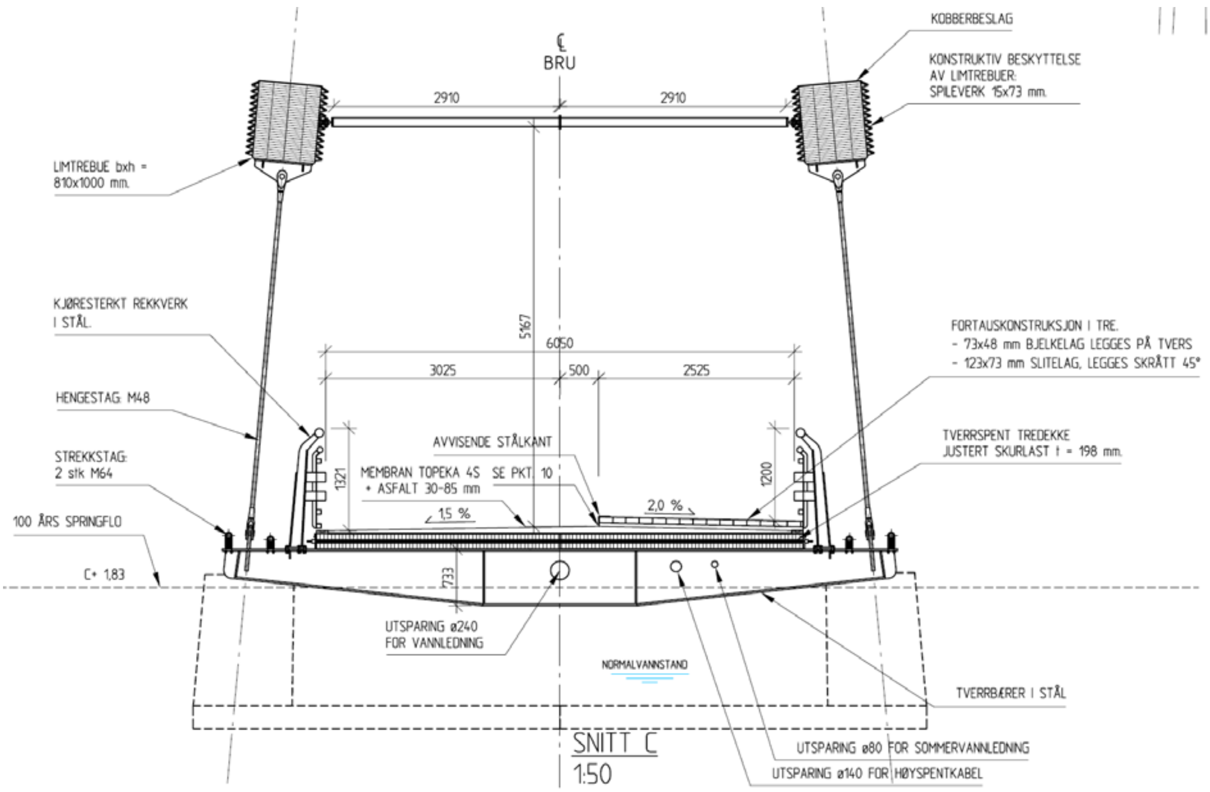


Figure 6.4 *Fretheim Timber Arch Bridge has an effective bridge width of 6,05 m.*

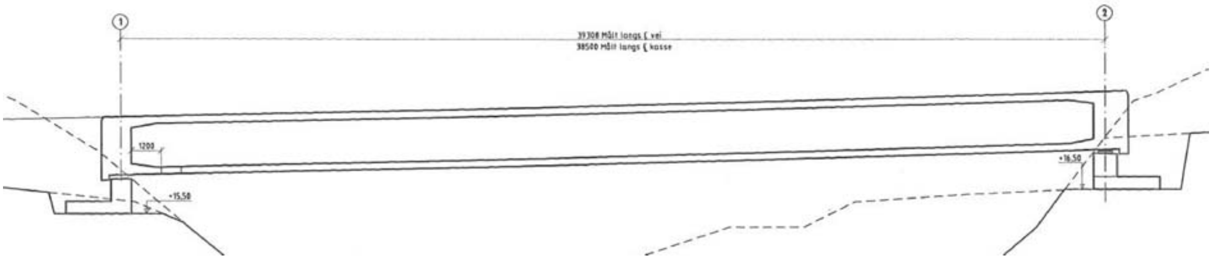


Figure 6.5 *Hillersvika Concrete Box Girder Bridge has a bridge span of 39,3 m.*

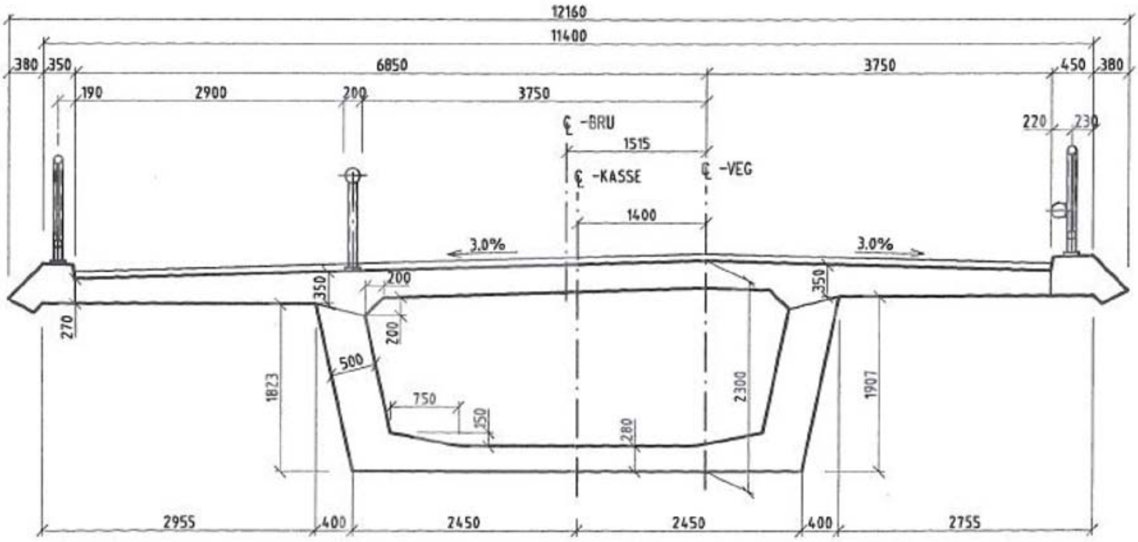


Figure 6.6 *Hillersvika Concrete Box Girder Bridge has an effective bridge width of 10,6 m.*

Table 6.1 *Basic data for the Klenevågen, Fretheim, and Hillersvika bridges.*

	Klenevågen	**Fretheim**	**Hillersvika**
Material in primary load bearing structure	Steel	Timber	Concrete
Year of construction	2001	2006	2000
Construction costs	6,3 MNOK		4,9 MNOK
Construction costs (index 2009)	9,14 MNOK	6,5 MNOK[1]	7,88 MNOK
Bridge span	42,8 m	37,9 m	39,3 m
Length of superstructure (*L*)	44,2 m	38,1 m	40 m
Effective bridge width (*Ebw*)	7,5 m	6,05 m	10,6 m
Bridge deck area (*L·Ebw*)	340 m^2	229 m^2	420 m^2
Total bridge width (*Tbw*)	8,5 m	6,3 m	12,16 m
Bridge area (*L·Tbw*)	376 m^2	240 m^2	486 m^2
Total bridge length (*Tbl*)	51,8 m	45,5 m	48,8 m
Total bridge area (*Tbl·Tbw*)	440 m^2	287 m^2	593 m^2

1 NOK is about 1,25 SEK (Feb 2009). [1]Guessed value.

6.2 Inspection, maintenance and repair intervals

Table 6.2 shows the estimated intervals for inspection, maintenance and repairs for the three bridges. The estimated life span for the bridges is 100 years.

Table 6.2 *Estimated intervals for inspection, maintenance and repair for the Klenevågen, Fretheim, and Hillersvika bridges.*

	Klenevågen	**Fretheim**	**Hillersvika**
Material of primary load bearing structure	Steel	Timber	Concrete
Continuous inspection	1	1	1
Main inspection	5	5	5
Cleaning etc. (properties)	1	1	1
Surfacing (asphalt)	10	10	10
Impregnating edge beam	15	-	15
Painting (steel)	20	15	-
Replacing edge beam	50	-	50
Arch (small repairs)	-	50	-
Replacing railing	50	50	50

6.3 LCC analysis for the three studied bridges

6.3.1 General

In the following analysis the real investment costs for the three bridges have been used, but converting the currencies 1 NOK is converted to 1 SEK, because it has been assumed that level of cost is higher than the level of cost in Sweden. The repair costs have be taken from the Swedish BatMan database for repair costs. These costs don't include establishment, traffic safety precautions and other general costs for the repair campaign. Typically the real repair costs are two to three times higher than the bare repair cost. The user cost is only calculated for the Hillersvika bridge, because it is assumed that this cost is the same for all cases if the *ADT* was the same for all bridges.

6.3.2 Klenevågen bridge

Table 6.3 shows the LCC agency cost for the Klenvågene steel bridge.

Table 6.3 *LCC agency cost for the Klenevågen steel bridge.*

***Life span* /a =**	100			***Calculation rent* /% =**	3			***Deck area* /m² =**		340
	Interval (years)	**Cost**	**Quantity**	**Costs**	**No of times**	**mp**	***NPV*-factor**	**Tot cost**	**%**	**Tot cost/m² bridge deck area**
New construction	-	9 140 000	1	9 140 000	1	-	1	9 140 000	88,3%	26 882
Continuous inspection	1	1 000	1	1 000	99	99	31,55	31 547	0,3%	93
Main inspection	5	10 000	1	10 000	19	95	5,90	58 998	0,6%	174
Cleaning etc. (properties)	1	15	340	5 100	99	99	31,55	160 889	1,6%	473
Surfacing (asphalt)	10	220	340	74 800	9	90	2,70	202 286	2,0%	595
Impregnating edge beam	15	240	86	20 640	6	90	1,67	34 405	0,3%	101
Painting (steel)	20	1 200	361	433 200	4	80	1,12	486 892	4,7%	1 432
Replacing edge beam	50	7 500	86	645 000	1	50	0,23	147 129	1,4%	433
Replacing railing	50	2 000	86	172 000	1	50	0,23	39 234	0,4%	115
Demolishing	100	914 000	1	914 000	1	100	0,05	47 558	0,5%	140
								10 348 938	**100,0%**	**30 438**

6.3.3 LCC analysis of the Fretheim bridge

Table 6.4 shows the agency costs for the Fretheim Timber bridge.

Table 6.4 *LCC agency cost for the Fretheim Timber bridge.*

***Life span* /a =**	100			***Calculation rent* /% =**	3			***Deck area* /m² =**		229
	Interval (years)	**Cost**	**Quantity**	**Costs**	**No of times**	**mp**	**NPV-factor**	**Tot cost**	**%**	**Tot cost/m² bridge deck area**
New construction		6 500 000	1	6 500 000	1	-	1,00	6 500 000	75,2%	28 384
Continuous inspection	1	1 000	1	1 000	99	99	31,55	31 547	0,4%	138
Main inspection	5	10 000	1	10 000	19	95	5,90	58 998	0,7%	258
Cleaning etc (properties)	1	15	229	3 435	99	99	31,55	108 364	1,3%	473
Surfacing (asphalt)	10	220	229	50 380	9	90	2,70	136 245	1,6%	595
Painting (steel)	15	1 500	700	1 050 000	6	90	1,67	1 750 238	20,3%	7 643
Arch (small repairs)	50			100 000	1	50	0,23	22 811	0,3%	100
Replacing railing	50	2 000	75	150 000	1	50	0,23	34 216	0,4%	149
Demolishing	100	650 000	1	650 000	1	100	0,05	33 821	0,4%	148
								8 642 418	**100,0%**	**37 888**

6.3.4 LCC analysis of the Hillersvika bridge

Table 6.5 shows the LCC agency cost for the Hillersvika prestressed concrete box girder bridge and **Table 6.6** shows the WebLCC compilation of costs including the user cost for a case with an *ADT* of 5000 vehicles per day.

Table 6.5 *LCC agency cost for the Hillersvika concrete bridge.*

Life span /a = 100 *Calculation rent /% =* 3 Deck area/m^2 = 420

	Interval (years)	Price	Quantity	Costs	No of times	mp	NPV-factor	Total cost	%	Tot cost/m^2 bridge deck area
New construction		7 880 000	1	7 880 000	1	-	1,00	7 880 000	90,8%	18 762
Continuous inspection	1	1 000	1	1 000	99	99	31,55	31 547	0,4%	75
Main inspection	5	10 000	1	10 000	19	95	5,90	58 998	0,7%	140
Cleaning etc (properties)	1	15	420	6 300	99	99	31,55	198 745	2,3%	473
Surfacing (asphalt)	10	220	420	92 400	9	90	2,70	249 882	2,9%	595
Impregnating edge beam	15	240	80	19 200	6	90	1,67	32 004	0,4%	76
Replacing edge beam	50	7 500	80	600 000	1	50	0,23	136 864	1,6%	326
Replacing railing	50	2 000	100	200 000	1	50	0,23	45 621	0,5%	109
Demolishing	100	788 000	1	788 000	1	100	0,05	41 002	0,5%	98
								8 674 664	**100,0%**	**20 654**

Table 6.5 *Compilation of LCC agency and user costs for the Hillersvika concrete bridge.*

Investment Costs	7 880 kSEK
Maintenance Costs	321 kSEK
Repair Costs	432 kSEK
Traffic Costs	207 kSEK
Demolition Costs	41 kSEK
Σ Present Value	8 882 kSEK

6.4 Concluding discussion

The LCC results presented for these examples are based on information that is not complete and contains many assumptions. The used costs for the repair actions are probably to low because they represent only the actual repair actions and not the total costs for the construction work. The user cost is dependant on the traffic flow, which is unknown for these bridges and the traffic interruptions, depends on the site which also is unknown.

As with all LCC calculations the interest rate is a very important parameter. The value used in these examples is 3 % that could be considered as a low value, but in **Figure 6.7** a comparison for these examples is made showing the effect of different rents.

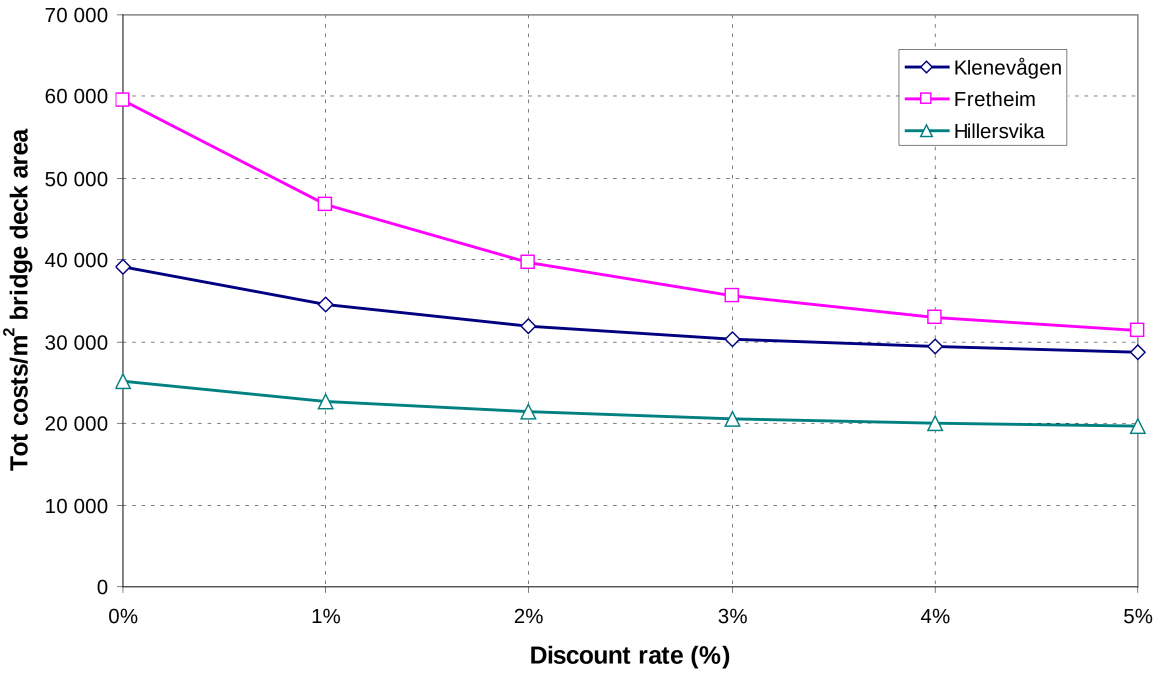


Figure 6.7 *LCC for the three studied bridges for different interest rates.*

7. Literature

This reference list refers mainly to bridge LCC studies. More general references to Bridge management systems, maintenance and management are given in *Jutila & Sundquist (2007).*

Abed-Al-Rahim, I., J. & Johnston, D.,W., (1995) — *Bridge Replacement Cost Analysis Procedures.* In Transportation Research Record No 1490, p.23-31, National Academy Press, Washington D.C.

Al-Subhi, K., M., Johnston D., W & Farid F., (1989). — *Optimizing System Level Bridge Maintenance, Rehabilitation and Replacement Decisions.* Report FHWA/NC/89-001.

Ansell A., Racutanu G., & Sundquist H., (2002) — A Markov approach in estimating the service life of bridge elements in Sweden, *9th International Conference on Durability of Building Materials and Components*, Brisbane, Australia, 2002

Arora (1989) — *Introduction to Optimum Design*, McGraw-Hill, Inc., New York, N.Y., 1989.

ASTM E 917, (1994) — Measuring Life-Cycle Costs of Buildings and Building Systems. American Society for Testing and Materials. 12 p.

Boyes D., S., (1995) — “Policy Traffic Management and Available Options, Bridge Modification”, 23-24 March 1994, Thomas Telford, London, pp 1-11, 1995.

Burley, E., Rigden, S., R., (1997) — The use of life cycle costing in assessing alternative bridge design”, *Proc. Instn Civ. Engrs*, 121, p. 22-27, March, 1997.

Chou, J-S., Wang, L., Chong, W. K, O’Connor, J. T., (2005) — Preliminary Cost Estimates Using Probabilistic Simulation for Highway Bridge Replacement Projects. *Construction Research Congress 2005. American Society of Construction Engineers 2005*, www.ascelibrary.org.

Cohn, Lounis — Optimal Design of Structural Concrete Bridge Systems, *Journal of Structural Engineering*, ASCE, 120(9), pp 2653-2674, 1994.

Collin P., Johansson, B., Pétursson, H., — Samverkansbroar med elementbyggda farbanor, *Stålbyggnadsinstitutet Publ.* 165, Stockholm 1998.

Correialopes M., Jutila A., (1999) — Contracting Procedures, Design and Construction Costs for Bridges in European Countries, *Helsinki University of Technology Publications in Bridge Engineering,* TKK-SRT-25, Helsinki 1999.

COST 345 (2004), — *Procedures Required for Assessing Highway Structures – Joint report of Working Groups 2 and 3: methods used in European States to inspect and assess the condition of highway structures,*

Davis Langdon Management Consulting, — Literature review of life cycle costing (LCC) an life cycle assessment LCA) www.tmb.org.tr/arastirma_yayinlar/LCC_Literature_Review_Report.pdf.

de Brito, J. & Branco, F. (1998)	Computer-Aided Lifecycle Costs Prediction in Concrete Bridges, *Engineering Modelling*, Vol. 11, No. 3-4, pp. 97-106, University of Split/Zagreb, Croatia.
Ehlen, M. A., Marshall, H. E. (1996)	*The Economics of New Technology Materials: A Case Study of FRP Bridge Decking*, U.S. Department of Commerce, NISTIR 5864, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899.
Ehlen, M. A.,	Bridge LCC 2.0 User Manual. Life-Cycle Costing Software for the Preliminary Design of Bridges. NIST GCR 03-853. http://www.bfrl.nist.gov/bridgelcc/UsersManual.pdf.
Frangopol D., M., (1997)	Optimal Performance of Civil Infrastructure Systems, *Proc. Int. Workshops on Optimal Performance of Civil Infrastructure Systems held in Conjunction with the ASCE Technical Committee on Optimal Structural Design Meeting at the Structural Congress XV*, Portland USA, 1997.
Frangopol, D., M., Moses, (1994)	*Reliability-based Structural Optimization, Advances in Design Optimization*, Adeli(ed), Chapman & Hall, London, England, pp 492-570, 1994.
Godart, B. & Vassie, P.,	Bridge Management Systems: Extended Review of Existing Systems and Outline framework for a European System. http://www.trl.co.uk/brime/D13.pdf.
Hawk (1998)	Bridge Life Cycle Cost Analysis, *Developments in Short and Medium Span Bridge Engineering '98, Proc. SMSB V,* Calgary, 13-16 July 1998, s. 1307-1314, Canadian Society for Civil Engineering, Montreal, 1998.
ISO 15686	Buildings and Constructed Assets - Service Life Planning - Part 5: Whole Life Costing.
Jiang, Y. & Sinha, K. 1989	*Bridge Service Life Prediction Model Using the Markov Chain*, Transportation Research Record 1223, Transportation Research Board, National Research Council, Washington D.C, pp 24-30.
Jutila A., & Sundquist H., (2007).	*ETSI PROJECT (STAGE I), Bridge Life Cycle Optimisation*, Helsinki University of Technology Publications in Bridge Engineering, TKK-SRT-37, Espoo 2007.
Karoumi R., Sundquist H., (2001)	Optimala nya broar, delstudie LCC-analyser, TRITA-BKN. Teknisk Rapport 2001:10, Brobyggnad 2001.
Leeming M., B., (1993)	The Application of Life Cycle Costing to Bridges, *Bridge Management 2*, Thomas Telford, London, pp 574-583, 1993.
Lindbladh, L. (1990).	*Bridge Management within the Swedish National Road Administration.* 1st Bridge Management Conference, Guildford, Surrey, UK
Maes, M., Troive, S., (2006)	Risk perception and fear factors in life cycle costing, *IABMAS -06*

Marshall, H., E., (1991)	Economic Methods and Risk Analyses Techniques for Evaluating Building Investments — A Survey, *CIB Report Publication* 136, February, 1991.
Mattsson H-Å., & Sundquist H., (2007)	The Real Service Life of Road Bridges, ICE Bridge Engineering, Vol 169, Issue BE4, 2007, pp. 173-179.
Mattsson H-Å., (2008)	Integrated Bridge Maintenance – Evaluation of a Pilot Project and Future Perspectives, PhD Thesis, TRITA-BKN. Bulletin 95, 2008, ISSN 1103-4270, ISRN KTH/BKN/B—95—SE.
Mohsen, A., Shumin, T., Alfred Y. (1995)	Application of knowledge-based expert systems for rating highway bridges, *Engineering Fracture Mechanics*, Volume 50, Issues 5-6, March-April 1995, Pages 923-934.
NCHRP (2003)	*Bridge Life-Cycle Cost Analysis*, National Cooperative Highway Research Program, Transport Research Board, NCHRP Report 483, Washington D. C., 2003. See also Hawk (2003)
NCHRP report 483:	*Bridge Life-Cycle Cost Analysis*. Part I: P. 16. Part II: P. 9, 32-35 and 54-56.
NCHRP Synthesis 227,	*Collecting and Managing Cost Data for Bridge Management Systems*. P. 5.
Nickerson (1995)	Life-cycle cost analysis for highway bridges, *Proceedings of the 13th Structures Congress,* Part 1 (of 2) Apr 3-5 1995 v1, Boston, MA, USA, pp 676-677, 1995.
OECD (1992)	Bridge management, OECD, Road Transport Research, Paris 1992. ISBN 92-64-13617-7.
PIARC (1996)	Type of Structures Selected for New Bridges, *PIARC Committee on Road Bridges*, World Road Association, 11.06.B, 1996.
Pritchard B., (1992)	*Bridge Design for Economy and Durability*, Thomas Telford, London 1992.
Racutanu, G., (2000)	*The Real Service Life of Swedish Road Bridges – A case study*, Royal Institute of Technology, TRITA-BKN Bulletin 59, ISSN 1103-4270, Stockholm 2000.
Racutanu, G., Sundquist, H., (1999)	Swedish Experiences of Integral Bridges, *IABSE Symposium, Rio 1999.*
Racutanu, G., Troive, S.,	Use of Empirical Database for the Evaluation of Service Life for Bridge Structural Members, *Journal of Computer-Aided Civil and Infrastructure Engineering,* April 1999.
Radojičic´ A., Bailey S., F., Brühwiler E. (2001)	Probabilistic Models of Cost for the Management of Existing Structures, *ASCE, Structural Journal*, 2001.

Rautakorpi, H., (1988)	Material Quantity and Cost Estimation for the Design of Highway Bridges, Acta Polytechnica Scandinavia No 90, Helsinki 1988.
Rigde,n S., R., Burley, E., Tajalli, S., M., A., (1995)	Life Cycle Costing and Design of Structures with Particular Reference to Bridges, *Proc. Instn Civ. Engrs Mun. Engr,* 109, pp 284-288, 1995.
RIMES (1999),	Road Infrastructure Maintenance Evaluation Study, Project for EC-DG-VII RTD Programme - Contract No. RO-97-SC 1085/1189, Pavement and Structure Management System, Work Package 3, Network Level Management Model, Final Report 1999. See also: Männistö V., Feighan K. (1999)
Saito, M, Sinha, K.C. and Anderson, V.L (1991).	*Statistical Models for the Estimation of Bridge Replacement Costs*. In Transpn. Res.-A, Vol 25A, No. 6, pp. 339-350, Pergamon Press, UK.
Sarma, K., S., Adeli, H., (1998)	Cost Optimization of Concrete Structures, *Journal of Structural Engineering*, Vol. 124, No. 5, May, 1998.
Shepard (1993)	“Using LCCA For Bridge Managemeant System Applications”, *FHWA Life-Cycle Cost Symposium*, Washington, DC, December, 1993.
Siemes, A., Vrouwenvelder, A., van den Beukel, A., (1985)	Stochastic Modelling of Building Materials Performance in Durability”, *Problems in Service Life Prediction of Building and Construction Materials*, NATO ASI Series E: Applied Science, Number 85, Martinus Nijhoff Publishers, Dordrecht/Boston/ Lancaster, 1985, p. 253-263.
Söderqvist M-K. and Vesikari E., (2003)	“Generic Technical Handbook for a Predictive Life Cycle Management System of Concrete Structures (LMS)”, *Lifecon GIRD-CT-2000-00378 Lifecon Deliverable D1.1*, final report, Dec 2003. 170 p. http://lifecon.vtt.fi/
Söderqvist M-K. and Vesikari E., (2006)	Life Cycle Management Process, In: Sarja A. (Ed.), Predictive and Optimised Life Cycle Management. Buildings and Infrastructure. Taylor & Francis. London and New York 2006. Chapter 5. Ss.530 – 635.
Sundquist H., (1999)	*Optimala nya broar*, Teknisk rapport 1999:8, KTH, Brobyggnad 1999.
Sundquist, H., Hans Åke Mattsson, H-Å., James G., (2004)	Procurement of bridge management based on functional requirements. In *Second International Conference on Bridge Maintenance Safety and Management, IABMAS*, Kyoto, Japan.
Sundquist, H., Karoumi, R, (2003)	Whole life costing and degradation models for bridges, *ILCMI 2003, International workshop on integrated life-cycle management of infrastructures - bridges*, Taipei, Taiwan, 2003.
Sylvest C., Lämsä J., Öderud H., Lindblad L., (1996)	Type of Structures Selected for New Bridges, *PIARC - World Road Association*, 1996.

Troive, S., (1998) *Structural LCC Design of Concrete Bridges*, Royal Institute of Technology, TRITA-BKN. Bulletin 41, ISSN 1103-4270, Stockholm 1998.

Troive, S., (2000) Förstudie till FoU-ramprojekt LCC-modeller (bro), Vägverket 2000.

Veshosky D., Beidlenan C., ”Life-cycle Cost Analysis does not Work for Bridges”. *Civil Engineering (Canada)*, July 1992.

Vesikari E., Statistical Condition Management and Financial Optimisation in Lifetime Management of Structures.” Part 1: “Markov Chain Based Life Cycle Cost (LCC) Analysis”. Part 2: “Reference Structure Models for Prediction of Degradation”, *Lifecon GIRD-CT-2000-00378 Lifecon Deliverable D2.2,* final report, Dec 2003. 113 p. http://lifecon.vtt.fi/

Vesikari E., Söderqvist M-K. (2003) LIFECON LMS Generic Technical Handbook for a Predictive Life Cycle Management System of Concrete Structures. Project for EC-CSG 5th RTD Programme (1998-2002), Contract No. G1RD-CT-2000-00378, *LIFECON, Life Cycle Management of Concrete Infrastructures for improved sustainability*, Deliverable D1.1, Final Report 2003, 170 p.

Vesikari, E. 2002 The Effect of Coatings on the Service Life of Concrete Facades. Proceedings. The 9th International Conference on Durability of Building Materials and Components. Brisbane, Australia, 17–21 March 2002. 10 p

Wonseiwicz T., J., (1988) Life Cycle Cost Analysis: Key Assumptions and Sensitivity of Results, *Transportation Research Record 1191*, Washington 1988.

ETSI

BRIDGE LIFE CYCLE OPTIMISATION

Stage 2

SubProject 2 (SP2)

Environmental Effects - Life Cycle Assessment of Bridges

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Preface

In this section of the report we present result from Sub-Project 2 of the ETSI Bridge Life Cycle Optimisation project, where the focus has been the examination of environmental effects of bridges. This sub-project was started in November 2007, with the Norwegian University of Science and Technology as lead partner in the ETSI project consortium. The sub-project was given the following three main objectives:

1. To perform a *state-of-the-art* study regarding environmental effects related to bridges, aiming at: i) identification of important environmental factors and their causes for various types of bridges/materials, consisting of different components and materials, ii) identification of the most critical factors in design, operation and maintenance of vital importance regarding environmental effects, iii) identification of potential learning from other types of infrastructure transferable to bridges, and iv) clarification of how Life Cycle Assessment (LCA) has been integrated into Life Cycle Costing (LCC) models in earlier studies on built environment structures with long lifetime.

2. To develop a *method for life cycle evaluation of environmental effects* that is based on the findings in the state-of-the-art study and existing methodology for LCA. The methodology will include identification and choice of a set of relevant indicators for bridges. The choice of indicators will be motivated by the need for sound and relevant indicators for decision-making on technical options for bridges.

3. To develop a *practical tool for assessment of environmental effects*. This tool will consist of a database of emission coefficients for relevant material- and energy-flows for bridges, cost-coefficients for relevant emissions, as well as important environmental indicators. In this manner, the database will be a necessary and suitable basis in calculating environmental effects and externality costs of these for bridges.

The work has been carried out pretty much according to the initial intentions, and the most important results are presented in this report. The work has been carried out by the industrial ecology group at the Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology, in close collaboration with our project colleagues at the Norwegian National Road Administration and at the Royal University of Technology (KTH) in Stockholm. At NTNU, most of the work has been carried out by PhD student Johanne Hammervold and research assistant Marte Reenaas, under leadership of Professor Helge Brattebø.

We appreciate very much the challenging work and inspiring collaboration with all other partners of the ETSI project consortium, and particularly we are grateful for all helpful discussion and data input that are provided to us by Otto Kleppe and Jan Nygård from the Norwegian National Road Administration.

Trondheim, Norway, 28th of March 2009

Professor Helge Brattebø
NTNU

Contents

1 Life Cycle Assessment - LCA

Life Cycle Assessment is a methodological framework for estimating and assessing the environmental consequences attributable to the life cycle of a product or a service. The performance of an LCA is explained in short below, based on the framework given in ISO 14041 [1] shown in Figure 1.

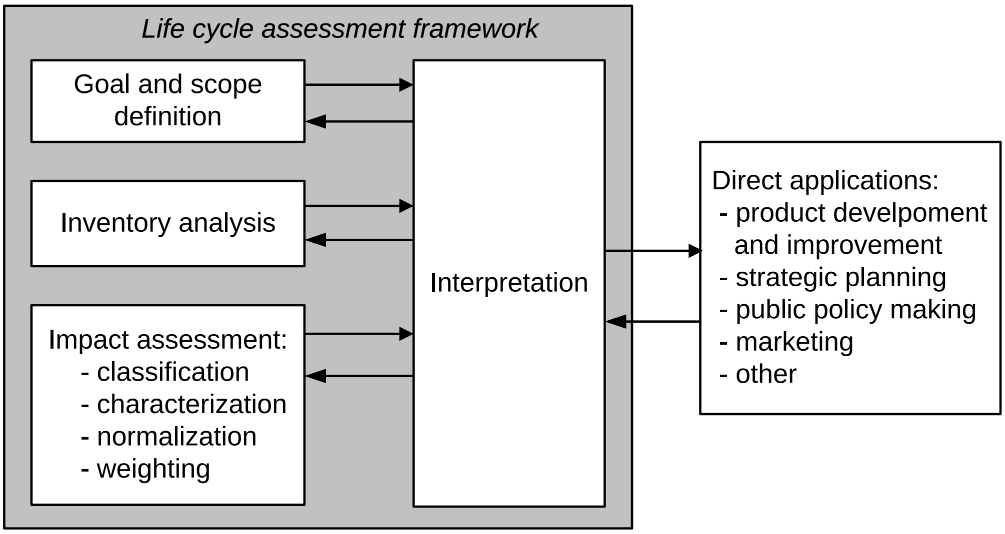


Figure 1: LCA framework according to ISO 14041

1.1 Goal and scope definition

In order to be able to make relevant methodological choices in the subsequent modelling, a specific purpose of the study should be formulated. Examples of purposes can be; revelation of the life cycle process that contributes the most to environmental impacts related to the product(s), possibilities for improvement in the products' life cycle, environmental consequences of changing certain processes in the life cycle in various ways and/or comparison of environmental performance for different product design alternatives.

Deciding the scope of the study implies making choices and assumptions regarding various aspects; choice of which options to model, choice of impact categories to include as well as choice of method for impact assessment (including choice of categorization and weighting factors, and whether to perform weighting or not). System boundaries need to be defined (e.g. what processes to include, what kind of emissions to consider etc). One also has to consider data quality requirements, related to the goal of the study. The functional unit for the system studied must be defined. The functional unit reflects the function or service the product is fulfilling; for instance if one compares various transport modes for commuting, the functional unit should represent transportation of a distinct number of persons over a specified distance and period of time. A relevant functional unit here could for instance be; *Transportation of one person 30 km per day for one year, at a given location*.

Principles for allocation must also be considered. For instance if data for an entire production site is obtained, the inputs and outputs have to be allocated to obtain data for the single process of interest, and how to do this must be clarified. [2]

1.2 Inventory analysis

A process flow chart displaying the different steps in the life cycle of the product in question is constructed, including the production of its most important components. For each process unit (production site, building, truck etc) taking part in the life cycle of the product and the production of its most important components, inputs and outputs are mapped, and environmental stressors (CO_2, PM_{10}, Hg, NH_3 etc.) related to these are accounted. These inventory data must be handled consistently, in order to be able to aggregate them further in the analysis. Obtained data often need to be recalculated to be valid for e.g. one functional unit of the product [2]. Inputs can be raw materials, materials, components, chemicals and energy. Outputs can be products, residual products, energy, waste and emissions to water, soil and air. Inventory data can be obtained from various sources; companies, suppliers and producers, environmental reports, company and/or public statistics, earlier LCA studies, LCA experts, public or computer program specific databases etc [3]. The system boundaries of the study determine what processes and stressors are included. The resulting flow chart and list of emissions throughout the life cycle comprises the systems Life Cycle Inventory (LCI).

1.3 Impact assessment in LCA

Impact assessment is a method to convert the inventory data into more graspable environmentally relevant information, reflecting the potential impacts the emissions and resource uses have on the environment. Impact assessment can be performed in 4 steps; classification, characterization, normalization and weighting. These steps are described in the following paragraphs, and illustrated in Figure *2*.

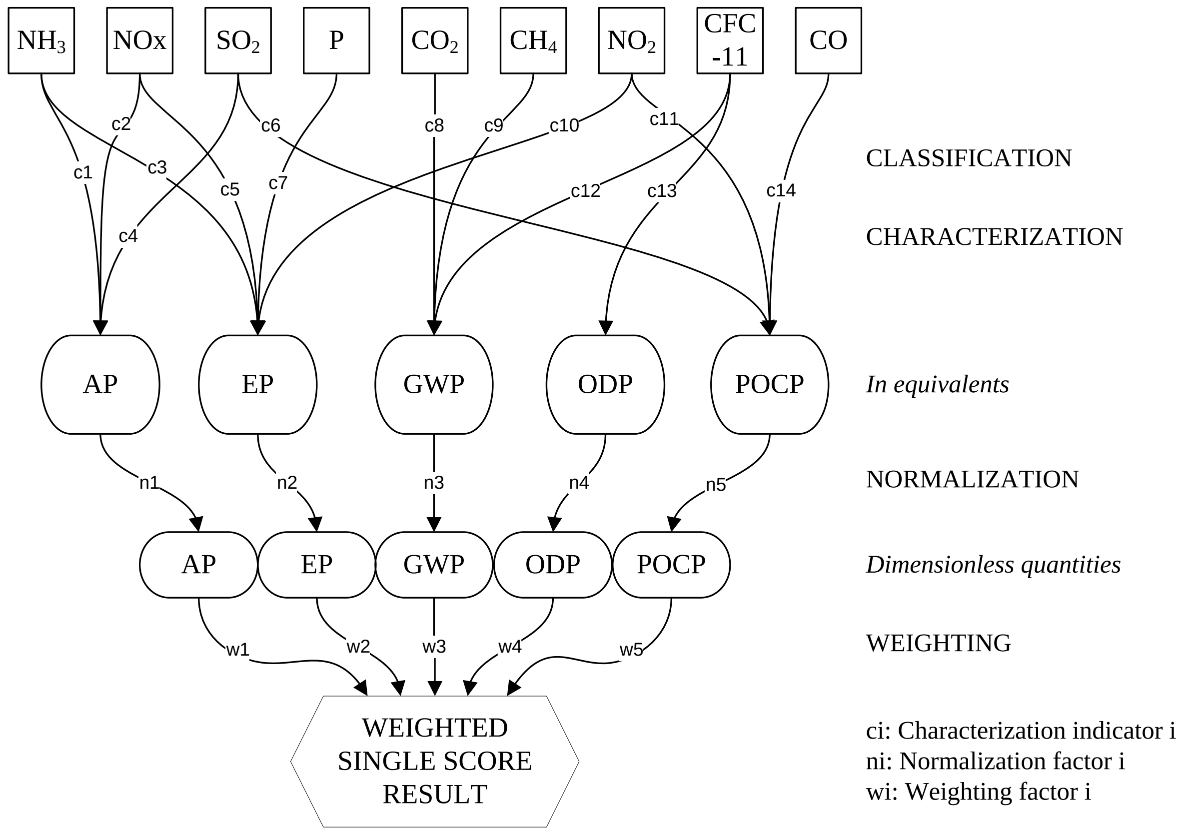


Figure 2: Life cycle impact assessment steps: classification, characterization, normalization and weighting

A selection of emission substances are shown in the upper row. These are classified to one or more of the 5 impact categories: Acidification potential (AP), eutrophication potential (EP) global warming potential (GWP), ozone layer depletion potential (ODP) and photochemical ozone creation potential (POCP) Abiotic depletion potential (ADP) is not included in this figure, as impacts in this category are not caused by emissions, but the use of resources. Each of the emission substance is multiplied with a characterization indicator for each category it is classified into. Total scores for each category are further normalized, and finally the normalized results are weighted into one single total score. The mathematical procedure for the impact assessment is given in equation (0.1) to (0.4) below.

Summarizing each of the environmental stressors caused by all of the input parameters

$$e_{ij} = x_i \cdot f_{ij} \qquad \text{(eq. 1.1)}$$

e_{ij} = emissions of stressor j for total consumption of input parameter i
x_i = consumption of input parameter i
f_{ij} = emission of stressor j per unit input parameter i

Classification and characterization

$$d_k = \sum_{i=1, j=1}^{i=o, j=p} (e_{ij} \cdot c_{jk}) \qquad \text{(eq. 1.2)}$$

d_k = total potential impacts in impact category k, expressed in equivalents
c_{jk} = characterization indicator for stressor j to impact category k

Normalization

$$m_k = d_k \cdot n_k \qquad \text{(eq. 1.3)}$$

m_k = normalized potential impacts for category k
n_k = normalization factor for category k

Weighting

$$v = \sum_{k=1}^{k=q} (m_k \cdot w_k) \qquad \text{(eq. 1.4)}$$

w_k = weighting factor for impact category k
v = total weighted result (sum for all impact categories)

1.3.1 Classification

Each of all the various environmental stressors throughout the life cycle, relative to the functional unit, are summarized and then classified into impact categories, according to which environmental impact(s) the stressors contribute to. Established impact assessment methods cover various impact categories, like for instance global warming, acidification, toxicity etc. In *BridgeLCA*, the CML-IA[1] impact assessment method [4] is applied. This method includes characterization factors for 10 impact categories; Abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP) global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), fresh water ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP) and photochemical ozone creation potential (POCP). However, the 4 toxicity categories are, for the time being, omitted in *BridgeLCA*, due to high uncertainties in the calculation principles of these.

Life cycle assessment is a global tool, calculating burdens throughout the life cycle of a product, material or service. Its strength is that it quantifies all possible environmental burdens; its weakness is low spatial and temporal resolution. It is important to acknowledge that LCA can not predict or measure "actual" impacts or effects, but "potential" impacts. Calculation of environmental impacts, as a result of emission of various substances, is often very complex and difficult to model. LCA results may have limited value in particular two areas: local and/or transient biophysical processes and issues involving biological parameters such as biodiversity, habitat alteration and toxicity. [5, 6]

It is also difficult to include varying spatial and temporal characteristics for processes that occur all over the world, so although the impact from emissions will have significant spatial and temporal variations, concerning climate, population density, fauna etc., LCA in general focuses on a global scale and on steady state, linear-homogeneous modeling. Global, long-lived processes can be modeled with some accuracy through LCA. As processes become more local and more transient the loss of accuracy increases and lose relevance. [5, 6]

There are thousands of chemicals affecting human health and the environment, hundreds of different known mechanisms and many other unknown or incompletely known mechanisms. While toxicologists would not normally combine compounds unless common models of action have been demonstrated, LCA add all toxics into one overall score even if modes of actions are known to be different. [6]

The SETAC2 Second Working Group on Life Cycle Impact Assessment states that the human toxicity and ecotoxicity categories do not yet meet the ISO requirements regarding the natural science background, and recommends further development of these [7].

1.3.2 Characterization

This is a quantitative step, calculating environmental impact per category using characterization indicators. These indicators are based on the physicochemical mechanisms of how different substances contribute to the different impact categories. E.g. Global-warming potential is one of the environmental categories and CO_2 is the equivalent for this category. Methane that is a green house gas which contributes 23 times as much to global warming than CO_2, is multiplied with a factor of 23, and added to the category as CO2-equivalents.

Characterization methods in LCA are based on scientific methods, drawn from environmental chemistry, toxicology, ecology etc for describing environmental impacts. The effects of deposition in geographical areas with different sensitivities to pollutants are disregarded,

[1] Documentation on methodology can be downloaded at: http://www.leidenuniv.nl/cml/ssp/projects/lca2/lca2.html
[2] The Society of Environmental Toxicology and Chemistry (www.setac.org)

meaning that impacts calculated represent the maximum impact; meaning that *potential* impacts are calculated [2].

1.3.3 Normalization

This implies that the characterization results are related to an actual (or predicted) magnitude for each impact category. This magnitude can be total impact for a whole country or region, or it can be on a per person level. For example can impacts to the global warming potential (GWP) category resulting from the LCA of a product, be compared to total impact to GWP for the country where the product is used. The aim of the normalization is to gain a better understanding of the relative magnitude of the environmental impacts caused by the system under study [2].

In *BridgeLCA*, total emissions in Western Europe 1995 are the default normalization factors. These are estimated based on emission data and production data for all or some countries in the region, and interpolation is used to obtain data for the whole region in cases where data are known for only a number of the countries [8]. The normalization factors per category are given in Table 1 below.

1.3.4 Weighting

This is a qualitative or quantitative procedure where the relative importance of an environmental impact category is weighted against all the other. This is done in order to get one single indicator for the overall environmental performance of the product. Weighting can for example be based on political targets, critical emission limits or willingness to pay [3]. Weighting is not always performed in LCA studies, as it implies subjective valuation of environmental issues up against each other, and therefore is a topic of subjective judgment and controversy.

The weighting factors set as default in *BridgeLCA* are developed by a panel consisting of representatives from the U.S. Environmental Protection Agency (US-EPA). These are found in the software *Building for Environmental and Economic Sustainability (BEES®)*[3]. This software allows for LCA studies on buildings and building components. There are also some other suggested weighting factor sets, *Harvard* and *EDIP*, made available for alternative use in the *BridgeLCA* software. The US-EPA weighting factors are given in Table 1.

Table 1: Normalization factors (Western Europe 1995) and US-EPA weighting factors

	ADP	AP	EP	GWP	ODP	POCP
Normalization factor	1.48E+10	2.73E+10	1.25E+10	4.81E+12	8.33E+07	8.26E+09
Weighting factors	5	5	5	16	5	6

The ISO standard *Environmental management – Life cycle assessment – Principles and framework* [1] states that if weighting is performed, it must be transparent to critical review and reporting. The weighting methodology should also be adjusted for spatial and temporal scales of the environmental mechanisms. This is due to the geographical variations in severity within categories.

[3] The BEES 4.0 LCA software, issued by the U.S. BuildingGreen programme, can be found on the URL: http://www.buildinggreen.com/auth/article.cfm?fileName=160619a.xml

In *Development of weighting factors in the context of LCIA* [9], Soares et al present a new methodology for calculating weighting factors. This may be considered for use in *BridgeLCA* in the future, but at present it is not considered appropriate.

1.4 Interpretation

Interpretation is the process of assessing results in order to draw conclusions.

As shown in Figure 1 the performance of an LCA is an iterative process, and the work on one part of the LCA will often lead to adjustments in other parts.

1.5 LCA of bridges – state of the art

A literature survey was performed in the beginning of ETSI Stage 2. This study aimed at identifying important environmental factors for various types of bridges and materials, critical factors in design, operation and maintenance regarding environmental effects, as well as existing methods and tools for environmental assessment of bridges. Since the literature study revealed that there are only few scientific publications available on the topic of environmental effects of bridges, the relevant articles are briefly presented in this section, followed by a conclusion of the findings.

1.5.1 Presentation of previous studies

Below is given a summary presentation of relevant previous studies from literature.

LCA as a basis for environmental comparison of bridge, tunnel and ferry

This study was accomplished by the Norwegian Public Road Authorities in 2000 [10], and compares alternative crossings of a fjord using LCA. The alternatives compared were a concrete bridge, an underwater tunnel, a ferry and driving around the fjord. The systems are compared at a length of 3 200 m, which is the distance between the tunnel openings. Sections within this distance that are not covered by bridge or ferry for these alternatives are covered by road. The traffic in the use phase of the systems is included in the study. The environmental aspects considered were consumption of electricity and fossil fuels, emissions to air of CO_2, NO_x, SO_x, CO, C_xH_y and particulates. The functional unit of the study was *crossing of the fjord for an average annual daily traffic of 3000 units in 25 years*.

The main conclusions of this study is that the tunnel alternative is the far worst regarding electricity use, while the bridge and ferry system score about equal here (it is assumed that roadways and the bridge are not illuminated). The ferry system is the worst regarding fossil fuel use and emissions of CO_2, NO_x, SO_x and particulates. The ferry consumes more fuel than all the cars it transports would have used in total, if they were driving the same distance. The bridge system is the best choice regarding use of fossil energy, emission of CO_2, NO_x and C_xH_y. The tunnel system is the better choice regarding SO_x and particulate emissions.
It is recommended that environmental effects like electricity and fossil fuel use, emissions of CO_2 and NO_x is prioritized in such studies.

Comparison of a prestressed concrete girder bridge and a steel-concrete composite I-girder bridge

A prestressed concrete box girder bridge and a steel-concrete composite I-girder bridge are compared in a study by Gervásio and da Silva [11]. Both life cycle assessment (LCA) and life cycle cost analysis (LCC) methods are applied, representing an integrated methodology for a life-cycle and sustainability analysis. In the LCA, only different grades of steel and concrete inputs to the bridge and the construction phase are included. In the LCC also the use phase is included. The bridges are designed for the same site, with a total construction length of 364.50 m and two twin decks. Piers and foundations are identical for the two bridge alternatives and thereby omitted. In the case of precast concrete, reinforcement steel is not included. It is assumed a lifetime of 50 years for the bridges. The emissions considered are CO_2, SO_2, NO_x, VOC, CO, CH_4 and particulates. These emissions are classified into six categories of environmental impact (global warming, acidification, eutrophication, criteria air pollutants, smog formation and water intake) according to their relative contribution in each category. These categories are normalized using US emissions per capita and year[4]. Weighting is not applied.

Main conclusions are that the composite bridge performs better environmentally in the overall results, but gives higher life cycle costs than the concrete bridge. The most important environmental category is smog formation, accounting for about 70 % of the total impacts. For the categories global warming, water intake and eutrophication, the concrete bridge performs best environmentally.

Comparison of steel and steel-reinforced concrete bridges

Horvath and Hendrickson [12] apply LCA when comparing a steel plate girder bridge and a post-tensioned concrete girder bridge, designed for the same site at a length of 428.2 m and a width of 14.7 m. Material inputs for the two bridges, including all upstream activities for the production of these, are included. For the use phase, only repainting of the steel structure is included. Repainting is assumed each 8^{th} year. The environmental impacts considered are consumption of resources (electricity, various fuels, ores and fertilizers) and selected emissions (TRI chemical emissions, hazardous waste, SO_2, NO_x, methane and VOC).

The main conclusions in this study are that the concrete bridge causes overall lower environmental impacts, but the steel bridge has an advantage in that the steel girder can be reused or recycled. Repainting of the steel is also found to cause significant impacts. The results may assumable be different if more impacts are included. It is recommended that bridges with materials with the lowest environmental impacts should be chosen, if obsolescence is the main problem regarding bridge lifetimes.

Comparison of bridge types and designs

Collings [13] presents two studies where three bridge types and three bridge designs are compared, respectively. The bridge types compared are a concrete cantilever bridge, a concrete cable stay bridge and a steel arch bridge. Relative costs and CO_2 emissions for the material consumptions and the use phase of the bridges are considered.

The main conclusions are that both costs and emissions are highest for the steel arch bridge, actually twice as high as for the concrete cantilever bridge that gives the lowest costs and emissions. Paint, waterproofing and plastics have relatively high values per ton of embodied energy and CO_2 emissions.

[4] Based on a study by the US Environmental Protection Agency (1998)

The bridge designs compared are a profiled girder bridge, a tied arch bridge and a cable-stayed bridge, designed for a longest span of 120 m, and 3 smaller spans (66 m in total) at each end. Three material choices for each design alternative are assessed. The embodied energy and CO_2 emissions from the construction phase and the CO_2 emissions during the lifetime of the bridge are given, assuming a lifetime of 120 years. Maintenance activities included are repainting, bearing replacement, re-surfacing and re-waterproofing. Traffic disruption due to maintenance is also included.

The main conclusions from this study are that concrete bridges have lower embodied energy and CO_2 emissions. More architectural designs like leaning or distortion of elements have larger environmental impact, as they require more materials and more complex construction. Emissions during the use phase are approximately the same for the three material alternatives. The maintenance activity causing most of the emissions in the use phase is resurfacing of the bridge. The traffic disruption due to repair and maintenance are a highly uncertain parameter, as it depends on amount of traffic, proportion of lorries and diversion distance.

Comparison of conventional bridge and minimized girder bridge

Itoh and Kitagawa [14] apply a modified life cycle methodology to evaluate and compare two types of steel bridges; a conventional and a minimized girder bridge. The conventional bridge has seven longitudinal girders and the minimized girder bridge has only three, and thus requires less steel. There is higher requirement for the deck thickness for the minimized girder, as this shall contribute to structural rigidity. The bridges are compared regarding CO_2 emissions and costs. The lifecycle stages included are construction, use and replacement. The use phase includes maintenance cycles for six bridge components (frequency in years); pavement (15), painting (20), expansion joint (20), support (30) and two deck types; prestressed concrete deck (50) for the minimized girder bridge and reinforced concrete deck for the conventional bridge (30). Maintenance activities similar for the two bridge types are omitted. For the demolition, only the use of the demolition machine is included.

The conclusions are that the minimized girder bridge gives lower CO_2 emissions and costs, also when only the maintenance activities are considered. This is mainly because the prestressed concrete deck requires far less maintenance than the reinforced concrete deck.
Effects in variations in lifetime on CO_2 emissions and costs are investigated, from which it is concluded that prolonging the service life of a component is invaluable for both bridges.

Comparison of different bridge deck component alternatives

Keoleian and Kendall [15] compare two types of deck systems; a steel-reinforced concrete deck with conventional steel expansion joints and a steel-reinforced concrete deck with a link slab design using a concrete alternative; engineered cementitious composites (ECC). ECC is fibre reinforced and has a strain capacity 500-600 times higher than normal concrete. It also prevents nearly all corrosion of girders by reducing leakage of corrosive elements usually occurring through worn expansion joints. Corrosion of steel girders is one of the main causes for replacement of deck and superstructure. The study includes material production, construction, use and end-of-life management related to bridge the decks. Initial bridge construction is similar for both studies and therefore omitted. Three reconstruction options are considered; bridge deck replacement, deck resurfacing and repair and maintenance (mainly fixing of cracks and potholes). Traffic disruption during these activities is also included. Various air and water pollutants are considered[5]. The ECC link slab deck is assumed a lifetime twice the lifetime of the deck with conventional joints.

Conclusions made in the analysis are that the ECC deck yields significantly lower environmental impacts, for all pollutants, mainly because of less need for maintenance. For both deck systems, the construction and repair related traffic turn out to be significant for the environmental performance. It is also concluded that prediction of maintenance and repair schedules for each system is critical in evaluating the performance of alternative materials.

1.4.1 Conclusions on state of the art

The presented studies all show that construction materials contribute the most to the life cycle environmental impacts for bridges[6], and all efforts to reduce material usage result in lower environmental impacts; for instance prolonging the lifetime and applying material efficient designs. It is not one obviously preferred material alternative regarding environmental performance of bridges, as amount of material and maintenance required in various designs differ a lot. Generally, concrete contributes to less environmental impact during production compared to steel, but concrete bridges require more material use. Steel is also more easily recycled as it is easier to separate in the end-of-life treatment, resulting in a reduction in the overall environmental impact. Another general recommendation is to use locally produced materials, in order to reduce transport to the production site. It is, however, important to take into account the upstream transport distances (e.g. transport of raw material to material production site), as it is the total transport amount that is of importance.

Maintenance activities cause environmental impacts, but these might also represent an overall gain to the impacts by contributing to prolonging the lifetime of the bridge. Maintenance activities that are pointed to as contributing significantly to environmental impacts are: resurfacing, traffic disruption and materials with high embodied energy (like paint, plastics and waterproofing). Traffic disruption can give large contributions to the life cycle impacts, and it can be complicated to estimate, as it depends on duration of closure, amount of traffic, proportion of lorries and diversion distance. To reduce maintenance and repair requirements it is recommended to minimize joints and bearings, choose material composites that are durable and avoid designs that require total closure of bridge during known maintenance and repair activities.

The findings regarding bridge design are that it is preferable to design for longevity and durability, as this result in overall lower impacts in spite of the higher energy use in production of materials and construction of the bridge. This is because the bridge will have a longer lifetime and also due to higher quality requires less maintenance and repair. As it has been pointed to the fact that bridges are very often demolished and replaced due to obsolescence rather than having faced their end of life, it is important to design bridges that can easily be adjusted to meet future needs, like for instance increased traffic in order to achieve the gains of designing for long lifetimes.

[5] Emissions to air: CO_2, CH_4, CO, PM_{10}, NMHC, NO_X, SO_X.
Emissions to water: BOD, NH_3, PO_4^{3-}, oils, suspended matter and dissolved matter

[6] Except the study comparing bridge, tunnel and ferry where traffic is included and is contributing most of the impacts

2 The *BridgeLCA* environmental assessment tool

BridgeLCA is a tool developed for the assessment of environmental impacts related to bridges. It allows for analyses at various levels of detail, and is thus a flexible tool and suitable for use at all stages in a bridge planning process. Analyses performed with *BridgeLCA* give results in impacts in 6 different environmental areas of concern. These are abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and photochemical oxidation. It also offers a single total score for each bridge analyzed, obtained by applying normalization and weighting factors.

BridgeLCA comprises a package of files; the full version *BridgeLCA* and the simplified version *BridgeLCA Simplified*, user manuals for both versions and a documentation report. Both versions of *BridgeLCA* can be used in various stages of a planning process. The simplified version gives environmental impact results based on information entered by the user on bridge types, size parameters and main material choice. The full version calculates environmental impacts based on material, energy and transportation requirements, and it is the user who determines the level of detail of the analysis relative to data availability and amounts of data entered. The system borders applied in the two versions differs. The full version includes the whole life cycle of the bridge, from extraction of raw materials, production of materials and parts, construction of the bridge, the use phase and the end-of-life phase. The simplified version differs by not including the use phase and the end-of-life phase. The system borders are shown in Figure 3.

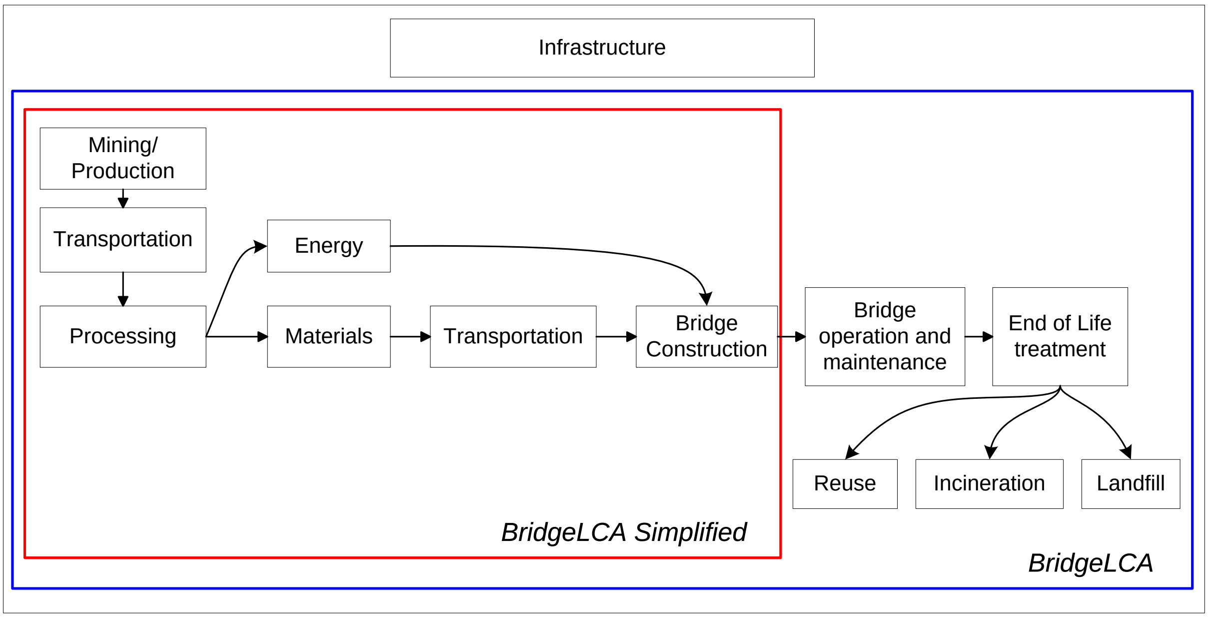


Figure 3: System borders in BridgeLCA and BridgeLCA Simplified

2.1 The full version – *BridgeLCA*

The full version, *BridgeLCA*, is developed with a combination of MATLAB programming and Microsoft Excel. Data used in calculations are read into MATLAB from Microsoft Excel sheets, matrix manipulations and calculations are performed in MATLAB and then results are written to both Microsoft Excel sheets and an html report.

2.1.1 User interface

The user interface of the full version is the Microsoft Excel workbook, through a front page with interactive links to a user manual, a documentation report, and sheets for entering data, background environmental data and some results. There is also a link to *BridgeLCA Simplified*. The front page is shown in Figure 4.

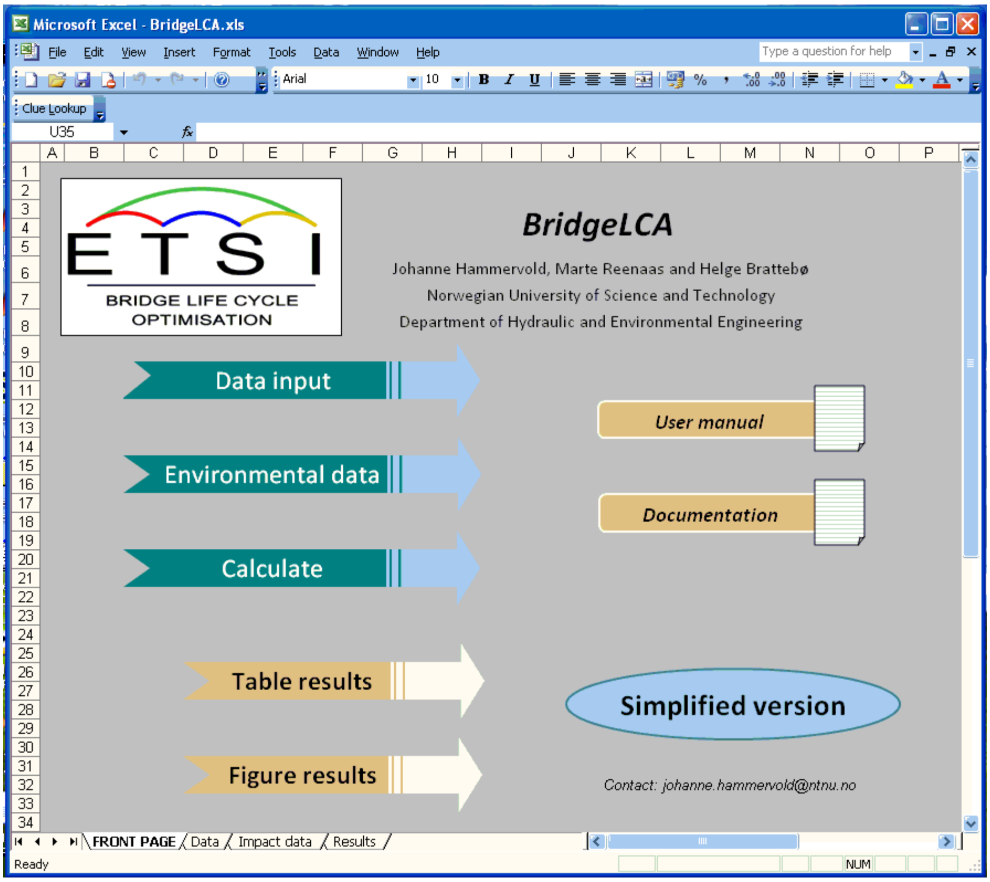


Figure 4: BridgeLCA front page

From the Front page sheet the user can maneuver between the other sheets of the Microsoft Excel document, user manual and documentation, and run the MATLAB program and access the results, i.e. access different elements of the program.

By clicking the blue arrow next to “Data input”, the Data input sheet is opened.

2.1.2 Data input

A section of the Data input sheet is given in Figure 5. Here the user has the opportunity to enter detailed amounts of material, energy and transportation services that the bridge consumes during its lifetime.

Data can be entered for three different bridges or three alternative designs of one bridge in the Data input sheet. In the upper left corner there is a table for entering information about the current project and analysis the user is working on.

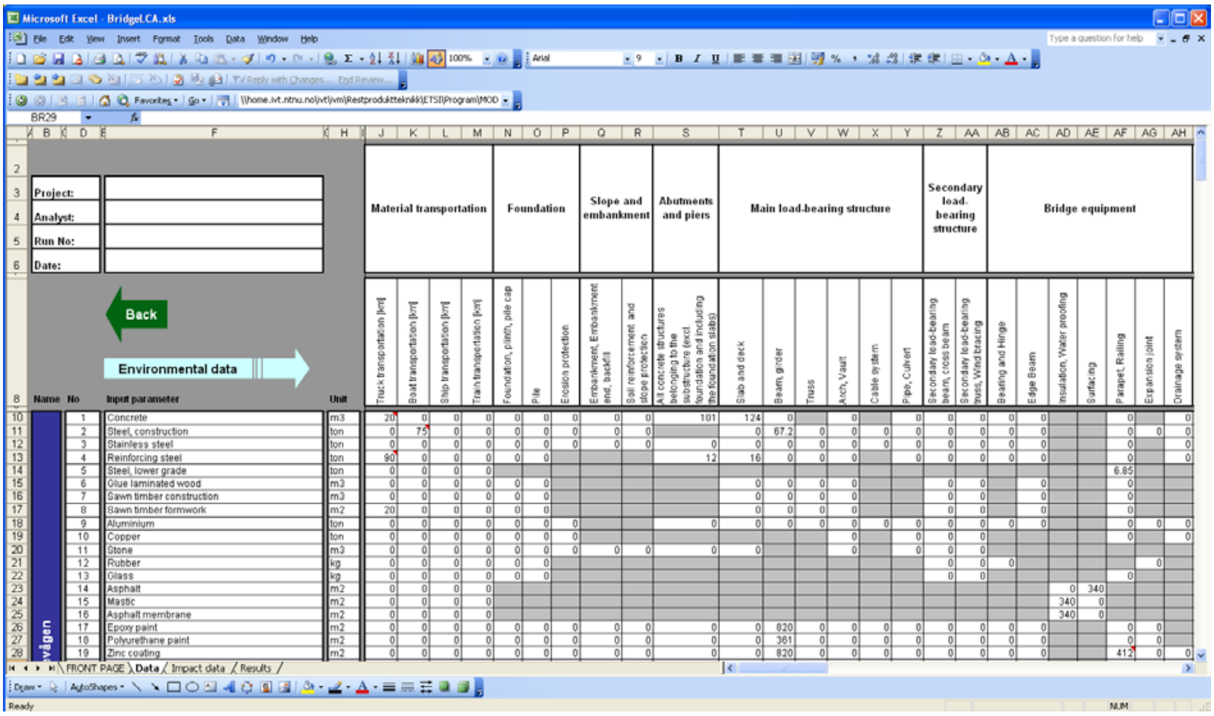


Figure 5: A section of the Data input sheet

The structure of the Data input sheet, divided in horizontal and vertical information, is described in the following.

Horizontally

On top of the main table you will find the different bridge parts and life cycle stages for the bridge listed in two levels of detail;

<u>Material transportation</u> (distances)

- Truck transportation
- Boat transportation
- Ship transportation
- Train transportation

<u>Foundation</u>

- Foundation, plinth, pile cap
- Pile
- Erosion protection

<u>Slope and embankment</u>

- Embankment, embankment end, backfill
- Soil reinforcement and slope protection

<u>Main load-bearing system</u>

- Slab and deck
- Beam, girder
- Truss
- Arch, vault
- Cable system
- Pipe, culvert

<u>Secondary load-bearing system</u>

- Secondary load-bearing beam, cross beam

Secondary load-bearing truss, wind bracing

Bridge equipment

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

Construction

Temporary constructions
Excavation, soil
Excavation, rock
Bridge construction
Transportation of workers
Other activities

Operation, repair and maintenance

Year 1 – 10
Year 11 – 20
…
…
Year 91 – 100

End-of-life management

Demolition
Landscaping
Waste management

Bridge parts and life cycle stages are agreed upon in the ETSI project and a description of these definitions are given in Table 6 in the Appendix.

For each bridge part or life cycle stage you can enter consumption of material and energy in the column underneath.

Vertically

The 1st column (in colors) is for entering the names of the bridges. The 2nd 3rd column of the table lists the number and name of the input parameters. The various input parameters are listed vertically 3 times, as the analysis can be run for 3 bridges (or less) simultaneously. There are 38 input parameters. Inputs 1 - 17 are materials, 18 - 23 painting, coating and impregnation, 24 and 25 are blasting and use of general building machines, 26 - 31 are different modes of transportation and 32 - 39 are different alternatives for end of life treatment for the main materials. Transportation distances for each material used can be given in the 5th – 8th columns next to the materials.

To the right for the main table, densities and layer thicknesses for some materials can be entered. Default values are given, but these can be changed by the user if needed.

Even further to the right, environmental cost for each impact equivalent can be entered. This is for calculating environmental costs of the system in the input sheet. This is done in the columns next to the calculation factors.

2.1.3 Running the calculations

When the bridge data is entered the user can run the *BridgeLCA* MATLAB program easily by clicking the button “calculate” in the front page of the BridgeLCA.xls file. The program will start running and a command window will appear (Figure 6). The user will be asked to save and close the input file; this so that the new input data will be used in the analysis. In the next step the user will be asked to choose input file, the folder with *BridgeLCA* will open automatically and the user can double-click the BridgeLCA.xls file. After these steps the MATLAB program will calculate the environmental performance of the bridges.

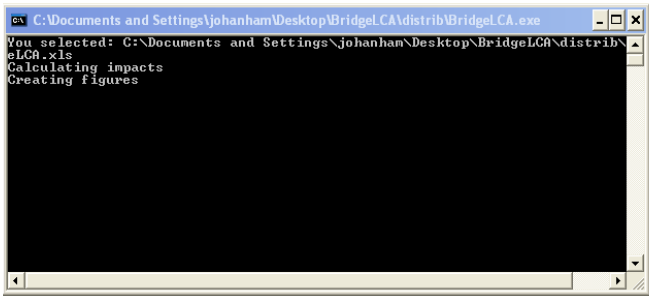
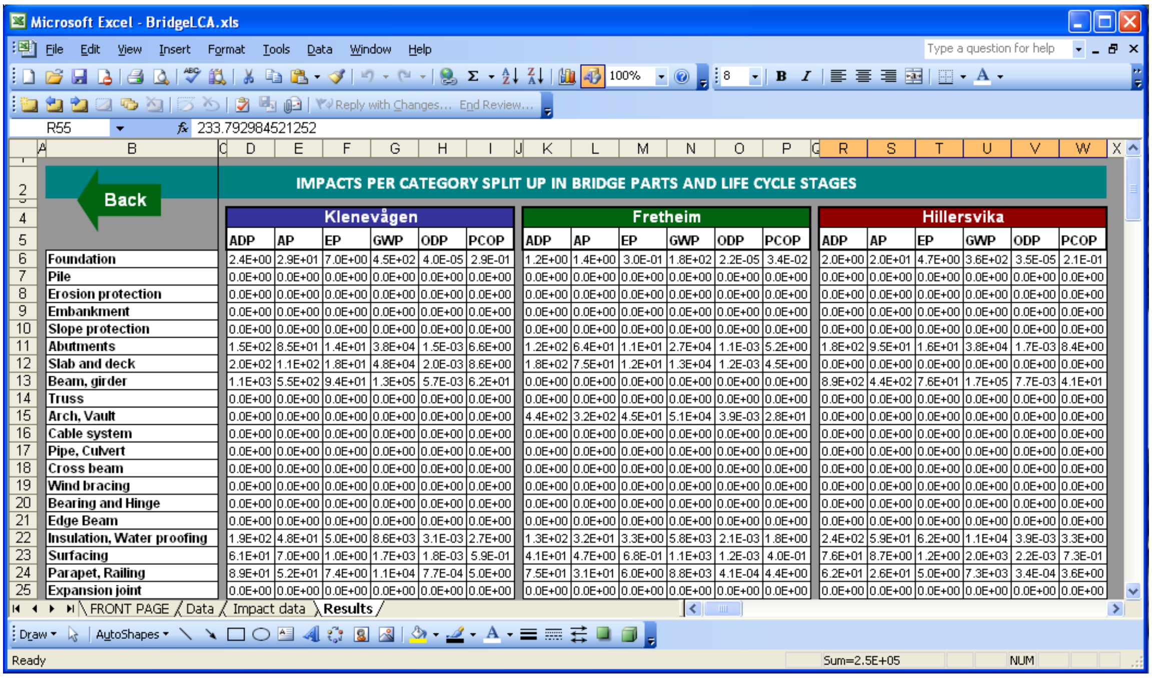


Figure 6: The command window

The environmental impacts are calculated based on the inputs and pre−calculated environmental impacts for all 38 input parameters (further described in following paragraph). The results presented are potential environmental impact for all material and energy demand through the life cycle of the bridges. The LCA results are presented in the Results sheet as tables (Figure 7), and results are also given as figures in an HTML document, both which are accessible from links on the front page. The level of detail in the analysis provides very detailed results. *BridgeLCA* offers results for easy comparison of the bridges analyzed, and also detailed information about what input parameter, what bridge part and what life cycle stage contribute to the various environmental impact categories.



IMPACTS PER CATEGORY SPLIT UP IN BRIDGE PARTS AND LIFE CYCLE STAGES

	Klenevågen						Fretheim						Hillersvika					
	ADP	AP	EP	GWP	ODP	PCOP	ADP	AP	EP	GWP	ODP	PCOP	ADP	AP	EP	GWP	ODP	PCOP
Foundation	2.4E+00	2.9E+01	7.0E+00	4.5E+02	4.0E-05	2.9E-01	1.2E+00	1.4E+00	3.0E-01	1.8E+02	2.2E-05	3.4E-02	2.0E+00	2.0E+01	4.7E+00	3.6E+02	3.5E-05	2.1E-01
Pile	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Erosion protection	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Embankment	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Slope protection	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Abutments	1.5E+02	8.5E+01	1.4E+01	3.8E+04	1.5E-03	6.6E+00	1.2E+02	6.4E+01	1.1E+01	2.7E+04	1.1E-03	5.2E+00	1.8E+02	9.5E+01	1.6E+01	3.8E+04	1.7E-03	8.4E+00
Slab and deck	2.0E+02	1.1E+02	1.8E+01	4.8E+04	2.0E-03	8.6E+00	1.8E+02	7.5E+01	1.2E+01	1.3E+04	1.2E-03	4.5E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Beam, girder	1.1E+03	5.5E+02	9.4E+01	1.3E+05	5.7E-03	6.2E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	8.9E+02	4.4E+02	7.6E+01	1.7E+05	7.7E-03	4.1E+01
Truss	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Arch, Vault	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4.4E+02	3.2E+02	4.5E+01	5.1E+04	3.9E-03	2.8E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Cable system	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Pipe, Culvert	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Cross beam	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Wind bracing	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Bearing and Hinge	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Edge Beam	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Insulation, Water proofing	1.9E+02	4.8E+01	5.0E+00	8.6E+03	3.1E-03	2.7E+00	1.3E+02	3.2E+01	3.3E+00	5.8E+03	2.1E-03	1.8E+00	2.4E+02	5.9E+01	6.2E+00	1.1E+04	3.9E-03	3.3E+00
Surfacing	6.1E+01	7.0E+00	1.0E+00	1.7E+03	1.8E-03	5.9E-01	4.1E+01	4.7E+00	6.8E-01	1.1E+03	1.2E-03	4.0E-01	7.6E+01	8.7E+00	1.2E+00	2.0E+03	2.2E-03	7.3E-01
Parapet, Railing	8.9E+01	5.2E+01	7.4E+00	1.1E+04	7.7E-04	5.0E+00	7.5E+01	3.1E+01	6.0E+00	8.8E+03	4.1E-04	4.4E+00	6.2E+01	2.6E+01	5.0E+00	7.3E+03	3.4E-04	3.6E+00
Expansion joint	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure 7: A section of the Results sheet

After having performed the calculations, a number of figures are produced, with graphs that can be examined for detailed illustration of various aspects of the environmental impacts within the overall bridge system. A selection of these figures is published in the HTML report, which is accessible from the Front page. Two examples of such figures are shown in Figure 8, where the left-hand side part shows bar diagrams for the total aggregated (including weighting) LCA results, and the relative contributions from each of the six environmental impact categories, after an examination of three bridge cases in Norway. The right-hand side of the figure shows the corresponding accumulative environmental impact for each bridge part and life stage of the bridge systems.

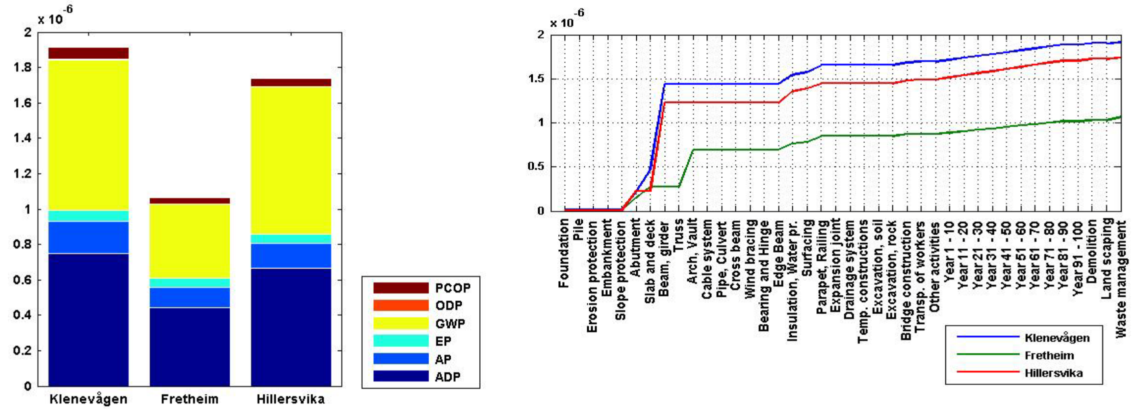


Figure 8: Examples of graphs from the result report

2.1.4 The impact data

For use in the calculation of the potential environmental impacts throughout the bridges' life cycles, emissions in equivalents are obtained for all input parameters, e.g. kg CO_2 equivalents emitted per m^3 of concrete produced. The Impact data sheet (shown in Figure 9) contains these pre-calculated potential environmental impacts for all materials and activities (input parameters) that can be chosen in the Data input sheet. The Impact sheet can be entered by clicking on the environmental data arrow on the Front page. Each input parameter has one vector of equivalents in this sheet. The pre-calculations of impact vectors have been made outside and independent of *BridgeLCA*, by using the LCA software *SimaPro* [16], and the *ecoinvent LCA database* [17]. The environmental data is classified, characterized, normalized and weighted in accordance with the Life Cycle Impact Assessment steps shown in Figure 2. Normalization and weighting are applied for some results only.

The Impact data sheet also contains weighting factors for the different environmental categories. The user can change the weighting vector to fit own wishes, e.g. the importance of different emission categories according to for example governmental national goals.

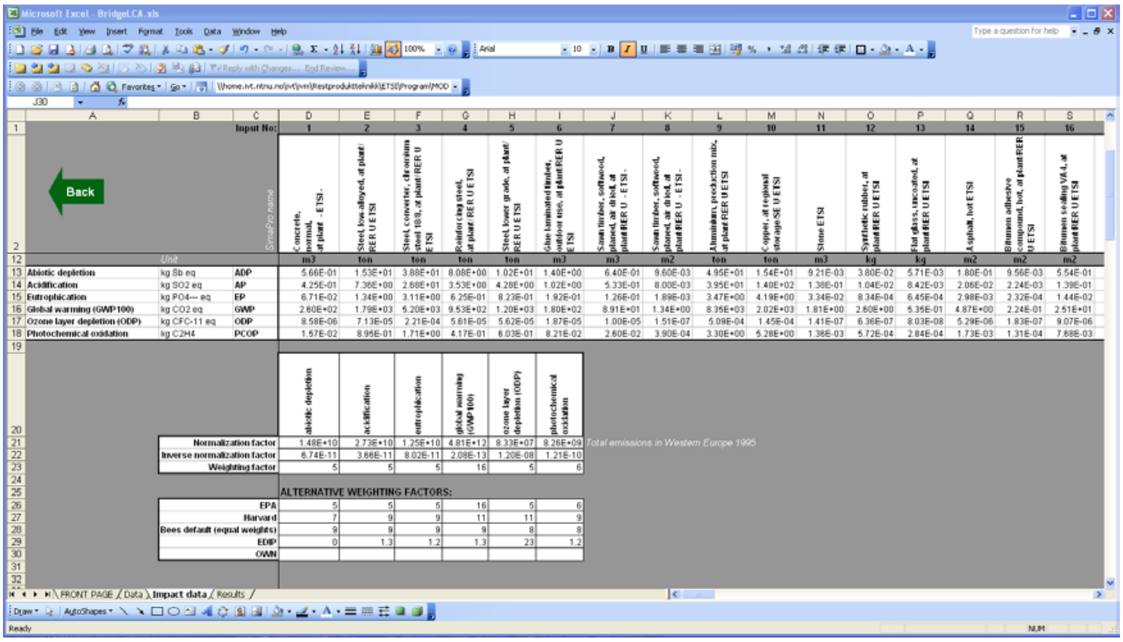


Figure 9: The Impact data sheet

2.2 The simplified version – *BridgeLCA Simplified*

BridgeLCA Simplified is modelled within Microsoft Excel only. This simplified version allows for environmental valuations with poor data availability. Material and energy amounts and flows are calculated based on a few basic inputs mostly known in an early planning stage of a bridge project.

Based on basic information about the bridge, as bridge type, main material in the main load-bearing structure, information about geometry and situation of the bridge, material and energy consumption for construction of the bridge are calculated. The calculations are based on experience on average material use for different bridge designs and situation of bridges by the Norwegian Public Road Administration. The material and energy amounts are of this reason very general, and for the time being rather inaccurate. It is also important to notice that the *BridgeLCA Simplified* model is no full LCA. The model only considers material and energy use for building the bridge. Material end energy use during operation and maintenance as well as end-of-life treatment is not considered.

Based on assumptions and not including the whole life cycle of the bridge the use of *BridgeLCA Simplified* is connected with uncertainty and must be used with care. The results however, will give basic information about the environmental performance of the bridge system. *BridgeLCA Simplified* may be used in an early planning stage of bridge projects, when material amounts are not yet known. In later basic planning, when masses are known or can be assumed at an acceptable level of accuracy, the main program, *BridgeLCA*, should be used.

BridgeLCA Simplified consists of 7 sheets. A front page, a sheet for input, sheets for calculation of material, energy and emission amounts as well as results. From the Front page sheet one can manoeuvre between the other sheets of the Microsoft Excel document, user manual and documentation and get to the full LCA version, *BridgeLCA*.

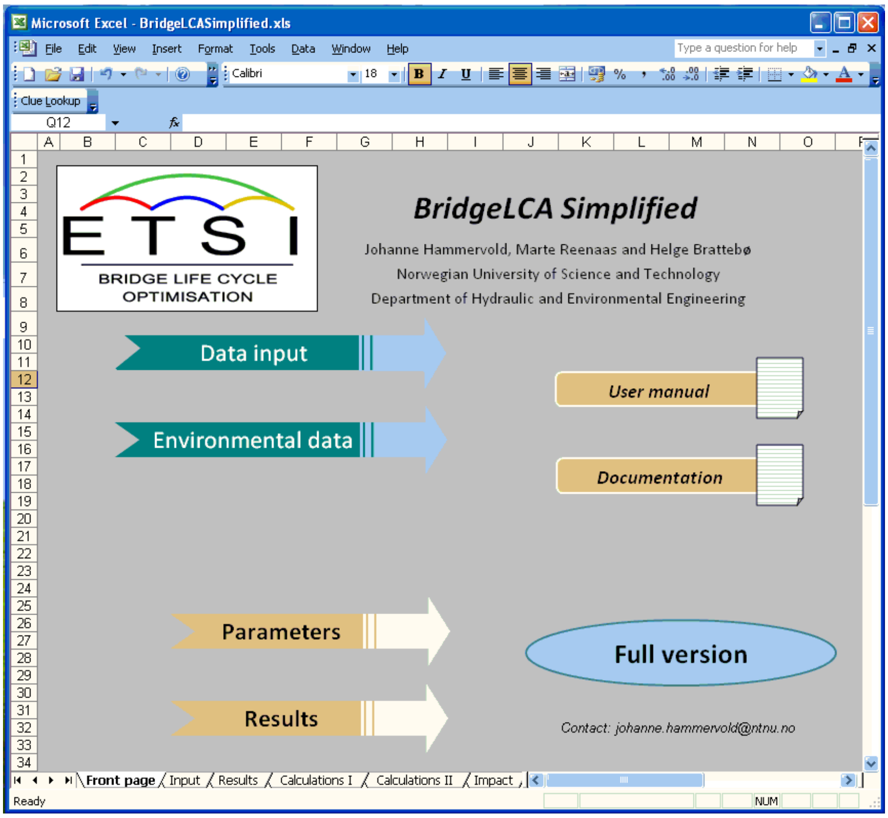


Figure 10: The Front page in BridgeLCA simplified

As for *BridgeLCA*, the input sheet will be opened, by clicking on the “Data input” arrow. Data needed in *BridgeLCA Simplified* is very general data as bridge type, main material, number of spans and some geometrical data for the bridge.

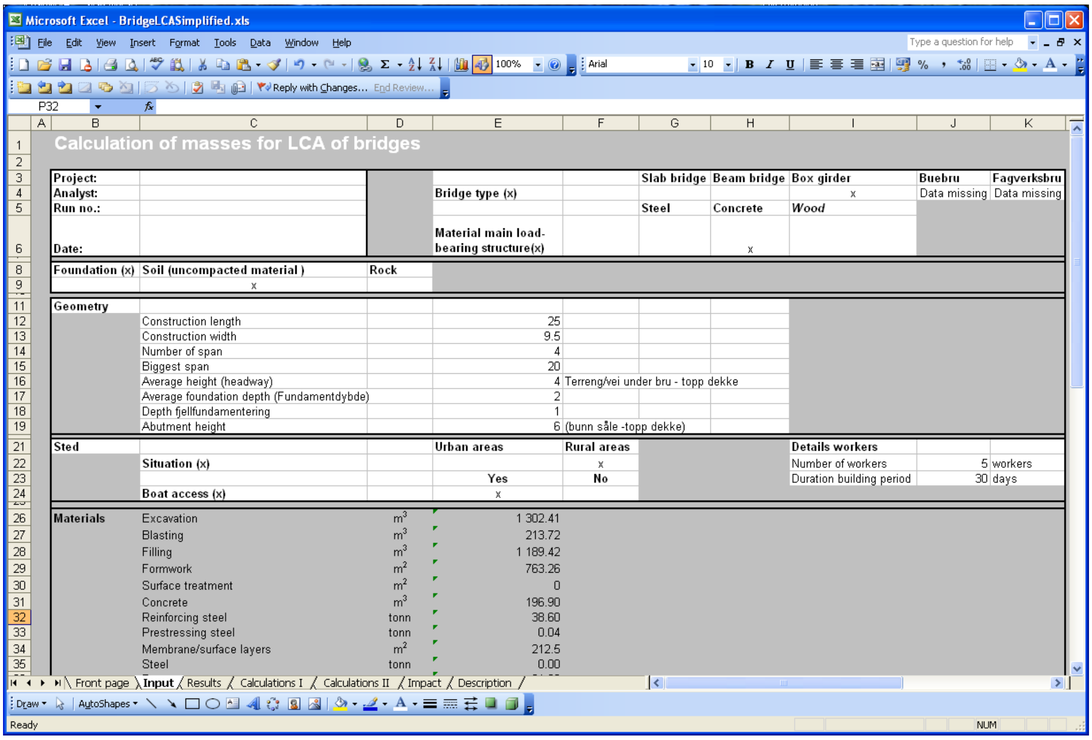


Figure 11: The Input sheet in BridgeLCA Simplified.

To assess the material and energy amounts needed to construct the bridge, calculation factors are needed. These factors can be found in the two sheets “Calculations I” and “Calculations II“. The “Calculations I” sheet contains calculation factors for different densities, fuel and material use as well as environmental costs. The user may change all the calculation parameters. The “Calculations II” sheet contains calculations of material amounts, blasting, excavation and filling needed to build different bridges. This calculation factors are based on the experience in the Norwegian public road administration and may also be changed by the user. The two calculation sheets are shown below.

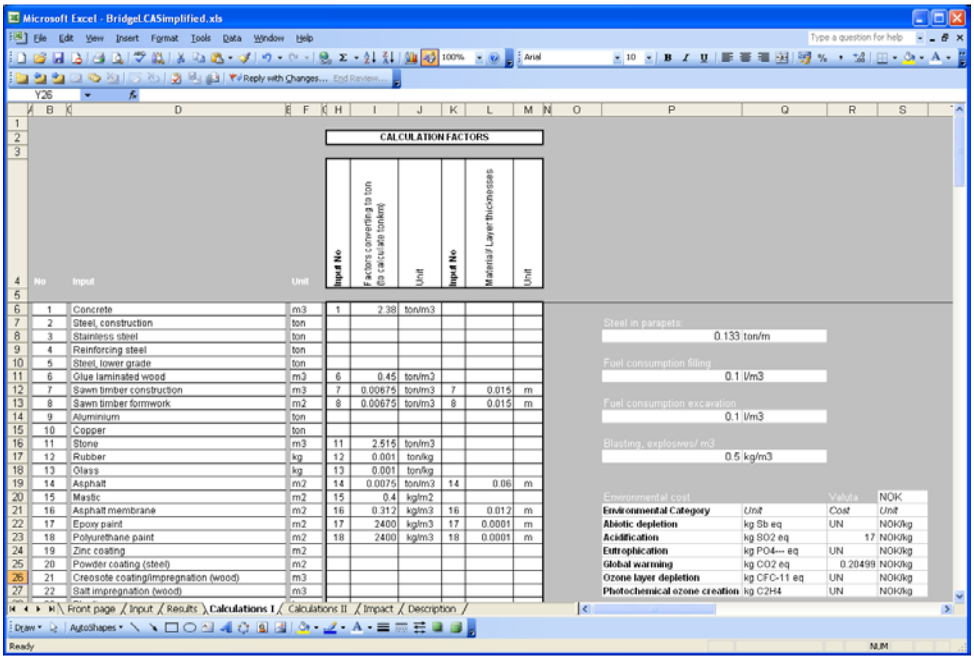


Figure 12: The Calculations I sheet

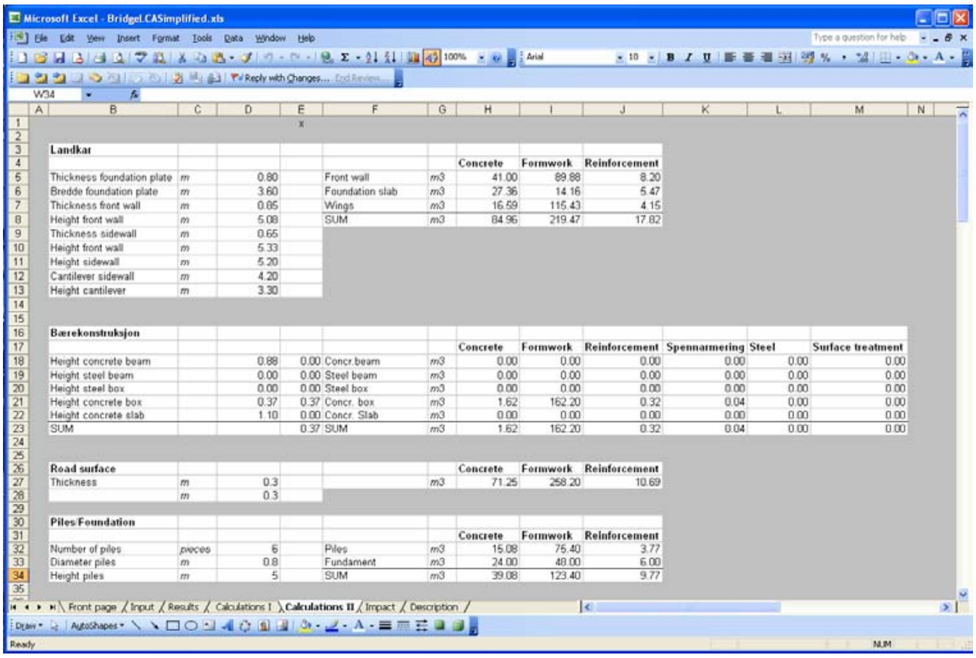


Figure 13: The Calculations II sheet

Based on the inputs and pre-calculated environmental impacts for different material use and activities, the potential environmental impacts for the bridge are calculated. The pre-calculated potential environmental impacts are presented in the “Impact” sheet. The potential impact is calculated for all materials and energy use from the input sheet, using the software *SimaPro* [16] and the *ecoinvent LCA database* [17]. In the pre-calculations emissions are being divided into emission categories, calculated to equivalents for each category and summed up to a total for each category. For instance, the global-warming potential (GWP) is one of the environmental impact categories, and CO_2 is the equivalent indicator for this category. Methane is a green house gas with 23 times more powerful global warming potential than CO_2, hence methane is calculated to CO_2 equivalents and multiplied with a factor of 23, and then added to this category.

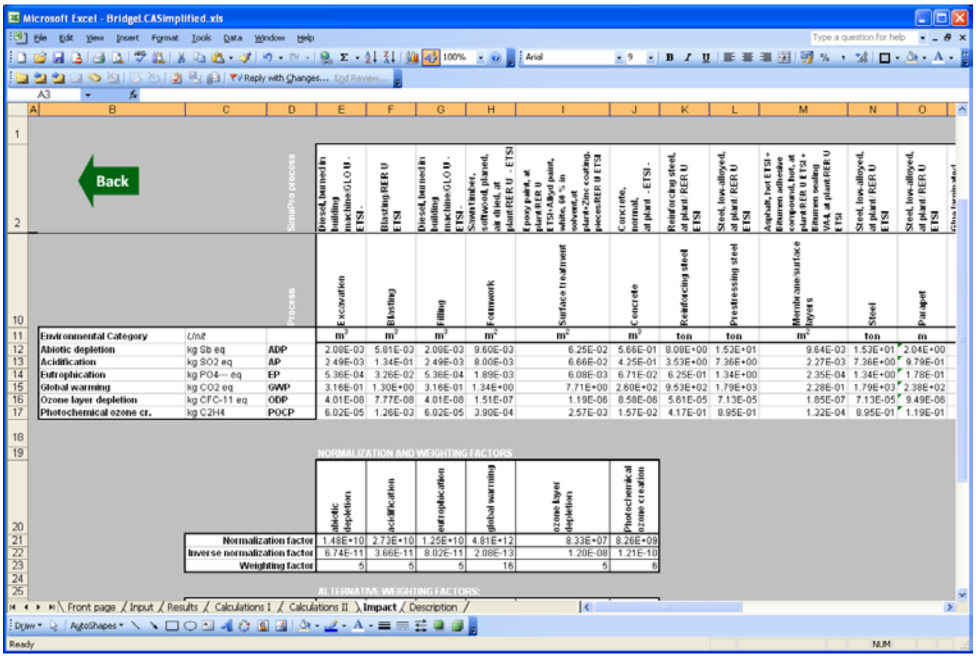


Figure 14: The Impact sheet

Based on the inputs in the “Input” sheet and potential impact in the “Impact” sheet, potential environmental damage throughout the bridge life cycle is calculated. The LCA results are presented in the “Results” sheet as tables and graphs. The results presented are potential environmental impacts for all material and energy demand from cradle to construction, both absolute and weighted results.

The LCA results from *BridgeLCA Simplified* are, because of uncertainty in both material amounts and the fact that only material and energy use in the construction phase of the bridge is included, inaccurate and the results must be handled with care. If material amounts are known the full LCA tool *BridgeLCA* should be used.

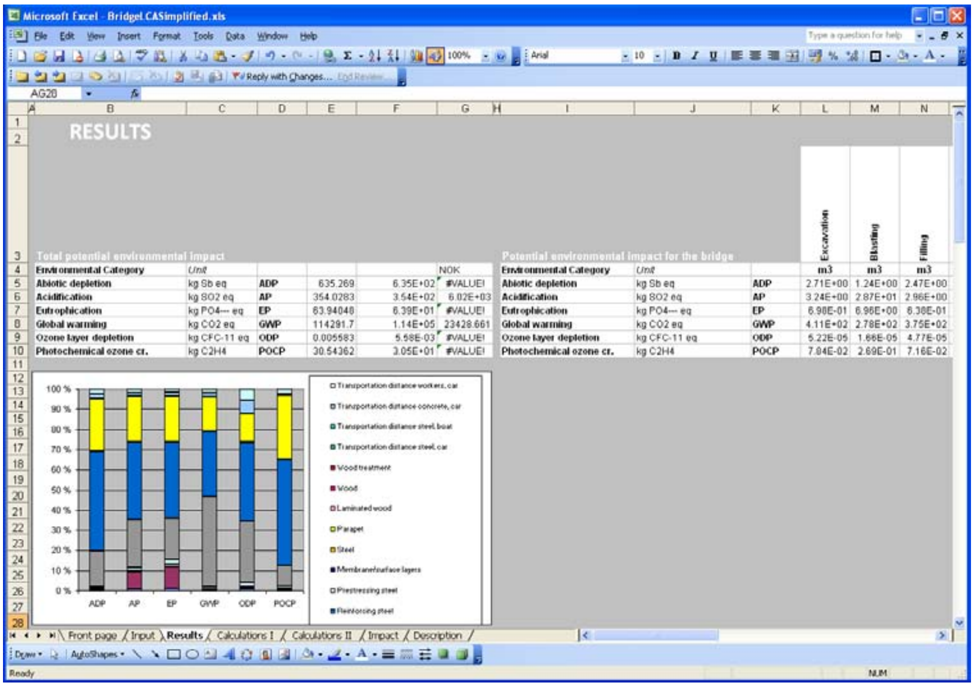


Figure 15: The result sheet

3 Case study on three bridges

BridgeLCA was developed through the use of three case bridges; one steel bridge, one concrete bridge and one wooden bridge. The bridges are already built bridges in Norway, and are thus not planned for the same location. They differ in size and are not directly comparable. The concrete bridge, Hillersvika, has longer construction length and width, and thus requires the most materials. The steel bridge, Klenevågen, is the shortest bridge. An overview of the bridges and key parameters for these are given in Table 2.

Table 2: Key parameters for the case bridges

	Klenevågen	**Fretheim**	**Hillersvika**
Type	Steel box girder	Wooden arch	Concrete box girder
Span length	42.8 m	37.9 m	39.3 m
Construction length	44.2 m	45.4 m	51.9 m
Effective bridge width	7.5 m	6.1 m	10.6 m
Construction width	8.5 m	8.7 m	12.2 m
Headway	4.1 m	-	7 m
Traffic lanes	2	1	2
Pavement	0	1	1

The bridges are analyzed throughout an assumed lifetime of 100 years, covering the manufacturing phase (including upstream processes), the construction phase, the use phase and the end-of-life phase, in line with the system borders given in Figure 3. A description of each bridge and life cycle phase is given below.

Details on material requirements, transport distances, inspection frequencies etc are given in Table 7 to Table 10 in the Appendix.

3.1 Klenevågen Bridge

Figure 16: Construction of Klenevågen Bridge

Manufacturing phase

Klenevågen is a steel box girder bridge on Rv570 outside Bergen, Norway, dimensioned for two traffic lanes. The abutments and the deck consist of 225 m^3 concrete and 28 tons reinforcement steel. The steel box girder consists of 67.2 tons of construction steel which is blast cleaned, galvanized and painted with epoxy and polyurethane paint. The parapets consist of 6.85 tons of galvanized steel. The deck of 340 m^2 is surfaced with three layers; mastic, membrane and asphalt covering according to cover type A3-4 described in *Bridge Decks* [18]. Figure 16 shows the mounting of the steel box for Klenevågen Bridge.

Construction phase

The construction phase of Klenevågen Bridge includes preparation of the foundation; blasting and mass movement, concreting of the abutments including use of wooden formwork, mounting of the steel box, consumption of diesel in building equipment and transport of materials, parts and workers. The duration of the construction is assumed 2 months.

Use phase

In the use phase operation, repair and maintenance activities are included. Only routine repair actions are included, as repairs due to accidents or other unforeseen events cannot be included in a sensible way. MOTIV, a cost model for operation, repair and maintenance for bridges and ferry quays used by the Norwegian Public Roads Administration, is used as basis for assumptions regarding operation, repair and maintenance activities and frequencies.
The steel box is assumed repainted with polyurethane paint every 20^{th} year, using the same amount of paint as originally. 10 % of the steel in the parapets are replaced during the lifetime of the bridge (average number for all bridges); this is assumed to happen in year 50-60 [19].

End-of-life phase

End treatment of the main materials only is considered. All steel is assumed recycled in Bergen (90 km transport) and all concrete is assumed re-used locally (10 km transport assumed) as filling material. The assumption on 100 % recycling/re-use is based on increasingly strict requirements towards the construction sector on waste treatment.

3.2 Fretheim Bridge

Figure 17: Fretheim Bridge (DBC-bygg)

Manufacturing phase

Fretheim wooden bridge in Flåm, Western Norway consists of one wide traffic lane and one pavement. It was originally planned for 2 traffic lanes, but the planned pedestrian bridge alongside is not yet accomplished. The abutments consist of 67 m^3 concrete and 10 tons reinforcement. The deck contains 56.4 m^3 creosote impregnated construction wood, 0.5 m^3 concrete and 1.34 tons construction steel. The arch contains 59.3 m^3 salt impregnated glue laminated wood, 20.54 tons construction steel and 654 kg copper. The glue laminated arches is treated with mordant of oil. The construction steel in the arches and girders hanging from the arches are treated with zinc and powder coating. However, this was given as tons of steel treated, and coatings amounts were therefore difficult to estimate and thus omitted. The parapets are made of 7.32 tons of steel. The 229 m^2 deck is surfaced with two layers; membrane and asphalt covering. It is assumed that the wearing course is renewed every 10^{th} year throughout the lifetime of the bridge, which is common for bridges with average traffic load [20].

Construction phase

The construction phase of Fretheim Bridge includes preparation of the foundation (mass movement), concreting of the abutments including use of wooden formwork, mounting of the bridge, consumption of diesel in building equipment and transport of materials, parts and workers. The duration of the construction is assumed 2 months.

Use phase

Operation activities like inspections, cleaning and underwater clearing are the same for Fretheim as for Klenevågen.

The steel cables hanging from the wooden arch require inspection every 25^{th} year. The wood surfaces painted with mordant of oil need repainting every 15^{th} year, assumed the same amount of paint as initially. 10 % of the steel in the parapets are replaced during the lifetime of the bridge (average number for all bridges); this is assumed to happen in year 50-60 [19].

End-of-life phase

All steel is assumed recycled in Bergen (160 km transport) and all the concrete is assumed to be re-used locally 10 km transport assumed). Untreated wood is assumed incinerated in a municipal incinerator in the area (20 km transport assumed) while impregnated wood is assumed incinerated in Bergen (160 km transport).

3.3 Hillersvika Bridge

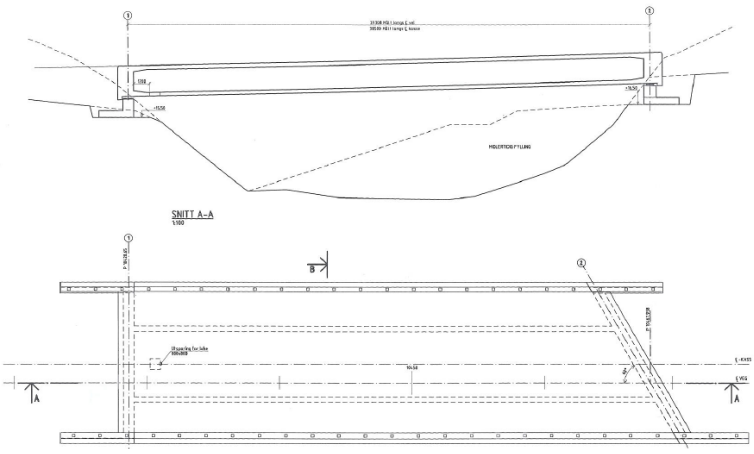


Figure 18: Hillersvika, superstructure, construction drawing

Manufacturing phase

Hillersvika is a concrete box girder bridge situated at E39 in Stord, Western Norway. The construction drawing of the superstructure of the bridge is given in. The abutments contain 83 m^3 concrete and 17 tons reinforcement steel. The box girder is made of 330 m^3 concrete and 86.4 tons reinforcement steel and the parapet is made of 6.05 tons galvanized steel. The deck of 420 m^2 is surfaced with three layers; mastic, membrane and asphalt covering according to cover type A3-4 described in *Bridge Decks* [18].

Construction phase

The construction phase of Hillersvika Bridge includes preparation of the foundation; blasting and mass movement, concreting of the abutments and the concrete box including use of wooden formwork, consumption of diesel in building equipment and transport of materials, parts and workers. The duration of the construction is assumed 3 months.

Use phase

Operation activities like inspections, cleaning and underwater clearing are the same for Hillersvika as for Klenevågen and Fretheim.

No surface treatments are performed during the lifetime of the concrete bridge. 10 % of the steel in the parapets are replaced during the lifetime of the bridge (average number for all bridges); this is assumed to happen in year 50-60 [19].

End-of-life phase

All steel is assumed recycled in Bergen (80 km transport) and all the concrete is assumed to be re-used locally (10 km transport assumed).

3.4 Results from the LCA analyses of case studies

The resulting environmental impact potentials throughout the lifetime of the three bridges are calculated and processed in *BridgeLCA*, i.e. the full LCA software. The results are discussed and shown graphically and in tables in the following. It is emphasized to keep in mind that the three bridges are *not directly comparable*, as they differ quite a lot in size. The consequences of this are discussed in section 3.4.5.

3.4.1 Total weighted results

Total weighted results, given in Figure 19, show that Klenevågen (steel box girder bridge) causes the highest impacts, closely followed by Hillersvika (concrete girder bridge). Fretheim (wooden arch bridge) causes roughly half the impacts as Klenevågen. The most important categories in total weighted results are Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP) for all three bridges. Acidification Potential (AP) is also a relatively important category, while Ozone Depletion Potential (ODP) is negligible in these results. Subsequent graphs will show what input parameters contribute the most to the three important impact categories for these three bridges, and also what bridge part and life cycle stage contributes to the impacts.

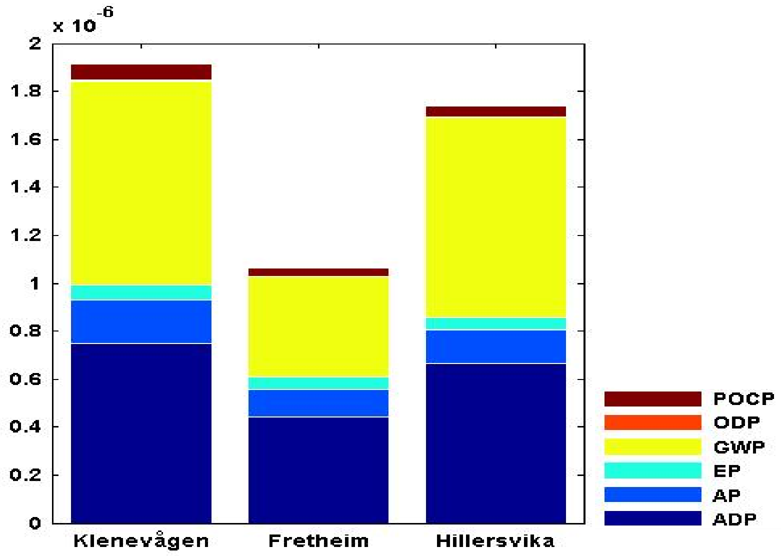
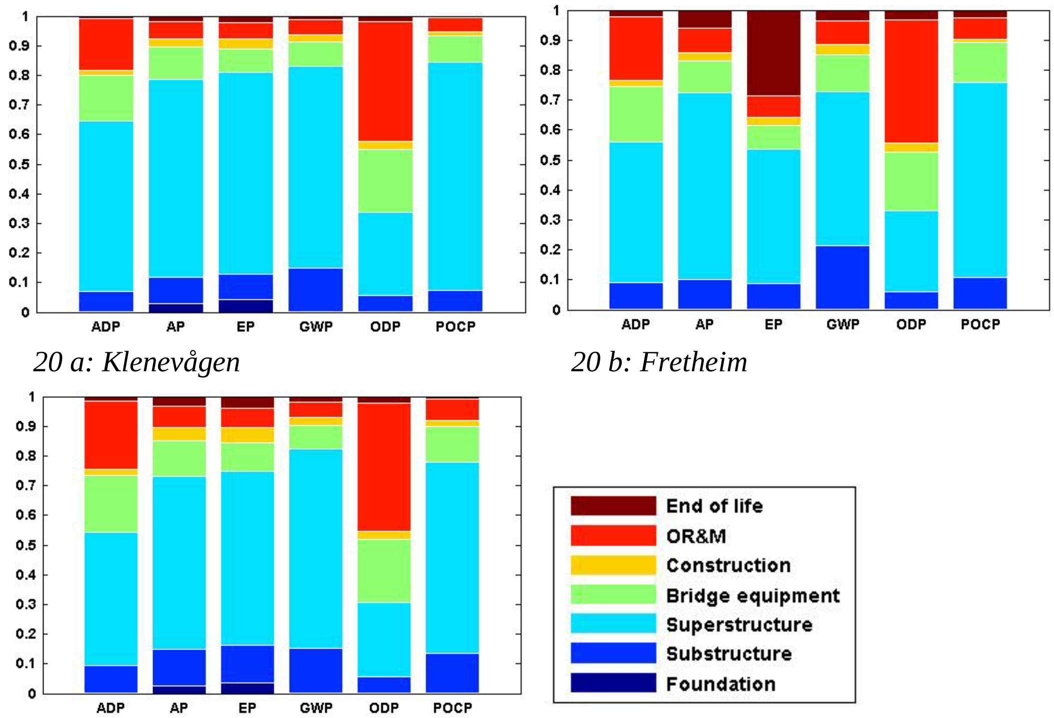


Figure 19: Total weighted results

3.4.2 Impacts related to bridge parts and life cycle stages

The impacts caused by material and energy consumptions related to various bridge parts and phases in the life cycle of the bridges are shown in the Figure 20 below. The results in absolute values are given in Table 11, Table 12 and Table 13 in the Appendix, and as totals per bridge and impact category in Table 3 below.

For all the bridges, the superstructure (which includes the main and secondary load-bearing systems) contributes the most to all impact categories. Except in the Ozone Depletion Potential category, but as seen in Figure 19 this category is insignificant in the results. The superstructure consumes the main share of material inputs to the bridges, and hence causes the largest shares of impacts. The substructure also contributes to the impacts in all categories. This is mostly due to consumption of concrete and reinforcement in the abutments.



20 a: Klenevågen

20 b: Fretheim

20 c: Hillersvika

Figure 20 a, b, c: Relative contributions from aggregated bridge parts and life cycle stages to impacts in each category

Table 3: Total results per bridge and category

	ADP	AP	EP	GWP	ODP	POCP
Unit	*kg Sb eq*	*kg SO_2 eq*	*kg PO_4 eq*	*kg CO_2 eq*	*kg CFC-11 eq*	*kg C_2H_4 eq*
Klenevågen	2.2E+03	9.8E+02	1.7E+02	2.6E+05	2.7E-02	9.2E+01
Fretheim	1.3E+03	6.4E+02	1.3E+02	1.3E+05	1.9E-02	4.9E+01
Hillersvika	2.0E+03	7.7E+02	1.3E+02	2.5E+05	3.0E-02	6.4E+01

In the category Abiotic Depletion Potential bridge equipment and the use phase (OR&M) also contribute substantial shares of the impacts. This is mainly caused by the surfacing of the bridges. The original surfacing is part of the bridge equipment, and re-asphalting is performed each 10^{th} year throughout the lifetime. Asphalt, asphalt membrane and mastic are all bitumen products, which consume raw oil in production which again causes the impacts to the ADP category.

For the wooden bridge, Fretheim, there are larger impacts occurring in the end-of-life phase than is the case for the steel and concrete bridges. This is caused by incineration of the glue laminated wood and the creosote impregnated wood used in the bridge deck. This is especially important for the Eutrophication Potential category. Impacts here are related to process specific burdens for the incinerator, and apply to both incineration of treated and untreated wood.

For all three bridges, the construction phase causes a small share of the impacts to all categories. The construction phase includes use of formwork and building machines and transport of workers and materials. The results show that these factors are of less importance in this analysis.

3.4.3 Impacts related to input parameters

The following figures show impacts related to each of the input parameter for the three bridges. Figures for the three categories Abiotic Depletion Potential, Acidification Potential and Global Warming Potential are included, as these were found to be most important.

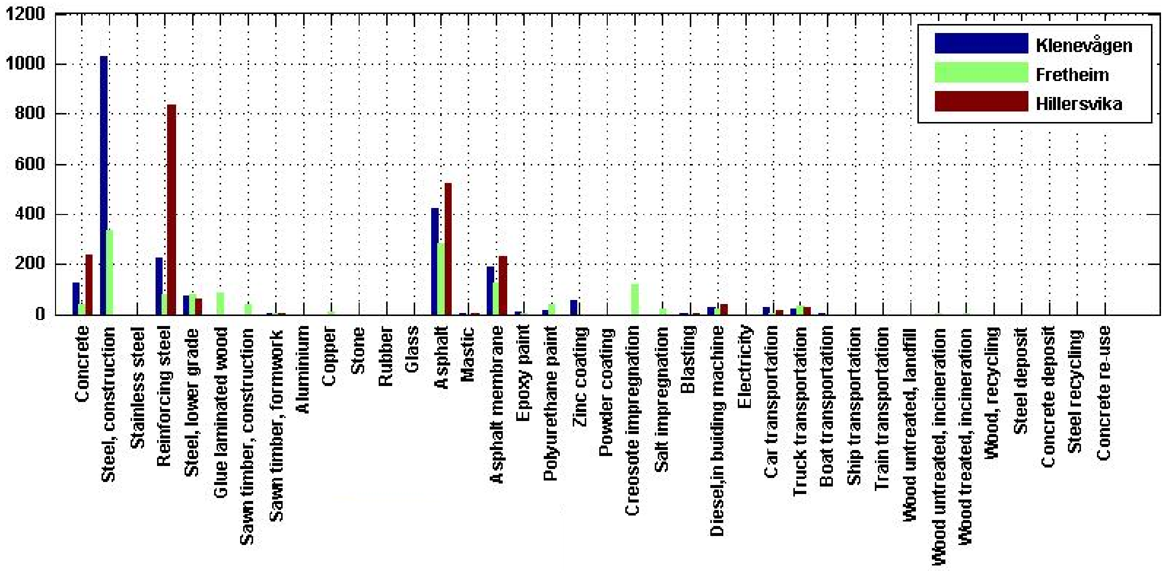


Figure 21: Abiotic Depletion Potential [kg Sb-equivalents]

For the ADP category, the most contributing inputs are steel, reinforcement, asphalt, asphalt membrane, creosote impregnation and concrete. The asphalt membrane causes relatively large impacts considering the small quantities used. For instance, covering of 1 m^2 with asphalt membrane (0.012 m layer thickness) represents 3 times higher impact in ADP than covering of the same area with asphalt (0.05 m layer thickness). This is due to a much higher share of bitumen in the production of asphalt membrane (0.723 kg per kg membrane versus 0.056 kg per kg asphalt). Bitumen is in turn produced from crude oil, representing impacts to ADP.

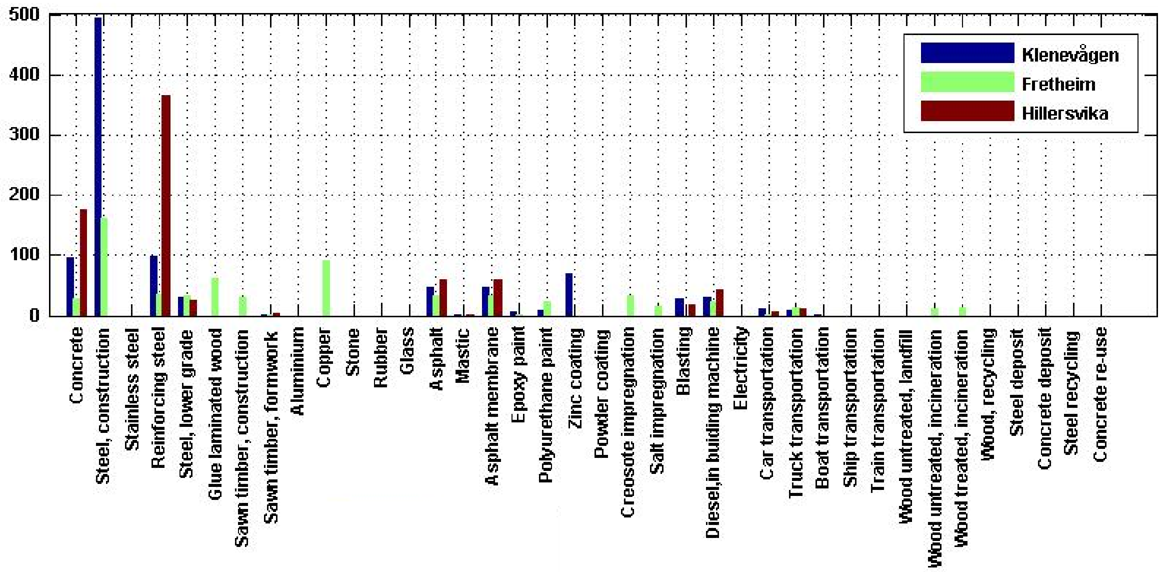


Figure 22: Acidification Potential [kg SO_2-equivalents]

Concrete and steel contributes a lot also to the AP category, but other inputs contribute relatively much considering there small amounts of material consumption. Copper, zinc coating, salt impregnation, blasting and use of building machine (diesel) are inputs which contribute to high impacts in this category relative to the amounts used.

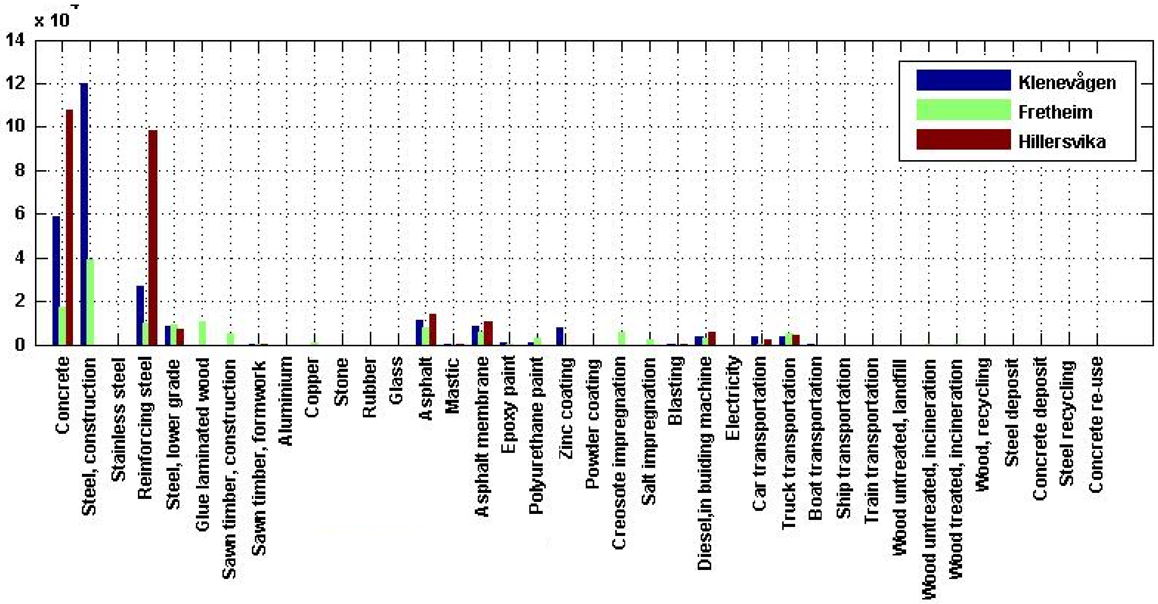


Figure 23: Global Warming Potential [10^4 kg CO_2-equivalents]

In the GWP category, the inputs used in large quanta are contributing to the most of the impacts. The impacts related to concrete use are relatively higher in this category, compared to steel, than what is the case for the other categories. This is because concrete production is quite CO_2 intensive, as the production causes CO_2 emissions both through energy consumption and chemical reaction in cement clinker production.
Inputs used in smaller quanta are of less importance in the GWP category.

3.4.4 Sensitivity analysis

A sensitivity analysis has been performed on this study, to identify magnitudes of potential errors or different methodological choices.

Input parameters and environmental data

The input parameters were manipulated each at a time in order to identify the magnitude of effect potential errors related to each input parameter can have on the overall results. For each input parameter, the impact data is increased by 10 % (in all impact categories simultaneously). For each of the input parameter, the resulting change in total score is compared to the original overall score. The results are shown graphically in Figure 24.

It is clear that none of the 10 % changes in the input parameters affect the overall results more than 5 %. Further one can see that the main materials (used in largest quantities) for each bridge alter the results the most, as one would expect. The numeric results are given in Table 14 in the Appendix.

From this sensitivity analysis it can be concluded that minor errors, less than 5-10 % in environmental data or amounts of input parameters (e.g. material quantities, transport distances) will not affect the overall results significantly, regarding the input parameters that originally do not contribute much to the total impacts. The main contributing materials are concrete, construction steel, reinforcement steel, steel lower grade (e.g. in parapets), glue laminated wood (relevant for wooden bridges only) and the surfacing materials asphalt and asphalt membrane. It is thus important that these materials are treated with a higher degree of accuracy.

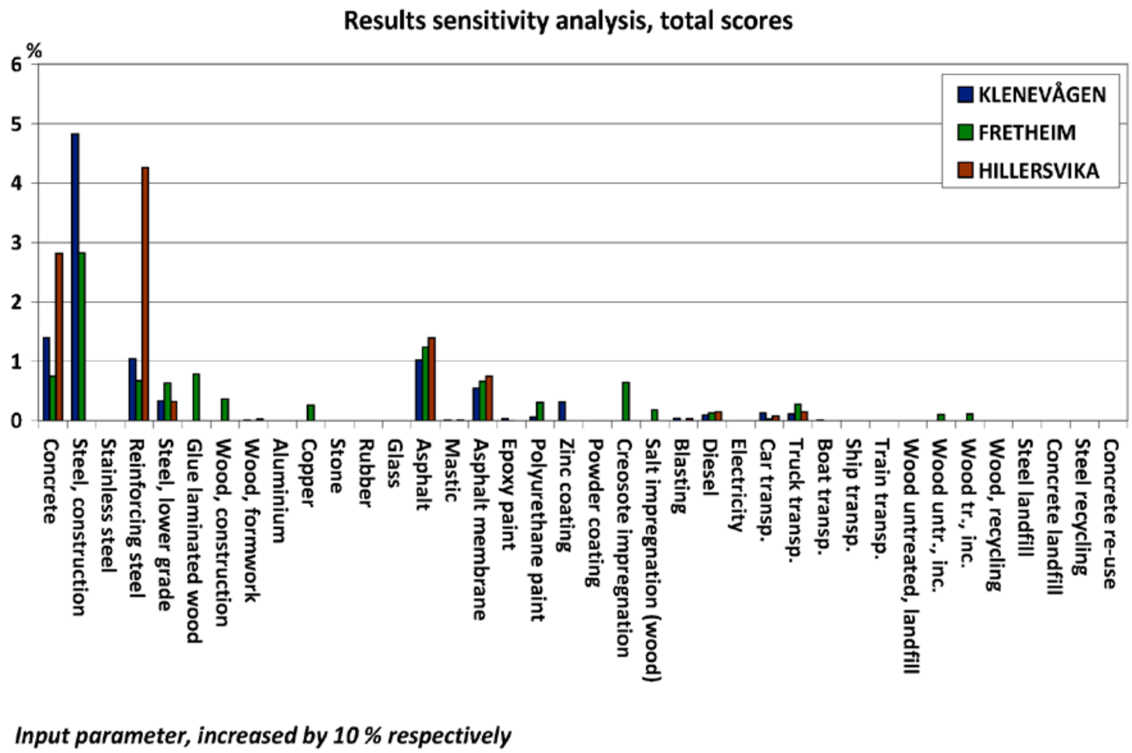


Figure 24: Results from sensitivity analysis, weighted results

Comparison of the weighting methods

To illustrate the potential effect of different weighting methods for the overall results, an analysis with four different weighting methods were performed. These weighting methods are given in *BridgeLCA* and are; the US-EPA, Harvard, BEES and EDIP methods. The weighting factors of these are given in Table 4 below.

Table 4: Weighting factors

	ADP	AP	EP	GWP	ODP	POCP
US-EPA	5	5	5	16	5	6
Harvard	7	9	9	11	11	9
BEES default	9	9	9	9	8	8
EDIP	0	1.3	1.2	1.3	23	1.2

The BEES default weighting factors assign the six environmental impact categories quite equally weights. The Harvard weighting factors weight Abiotic Depletion Potential lowest and Global Warming Potential and Ozone Depletion Potential highest, however, the differences are not big. The US-EPA weighting factors are quite similar for all categories, besides Global Warming Potential, which is given a weight 3 times higher than the other categories. The EDIP weighting factors assign no weight to Abiotic Depletion Potential, and Ozone depletion potential is given a weight about 18 times higher than the remaining four categories.

Despite these variations between the weighting factor sets, the different weighting does not give substantially different total results for the bridges in our case study. The different weighting methods give some differences in scale of the total results, but when comparing the ratio between the bridges for the different weighted total results, this differs by a few percents only. This is shown in
Figure *25*.

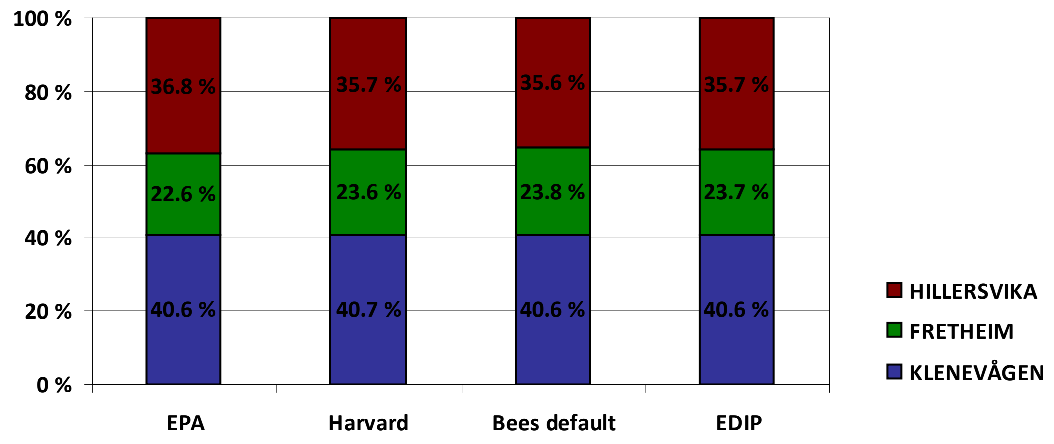


Figure 25: Comparison of weighting methods, relative values

This shows that choice of weighting method is not a critical aspect when using *BridgeLCA*; rather, normalization factors are much more important. However, this observation need not be valid for all analyses performed in *BridgeLCA*. For instance, the EDIP weighting set would give substantially different results if there were any significant impacts to the Ozone Depletion Potential category for a given bridge. It should be emphasized that weighting does influence results and should thus be used carefully. Preferably, bridge owners, such as the national road authorities, should agree on how to make use of weighting factors as a result of dialogue with the national environmental authorities.

A sensitivity analysis regarding normalization factors has not been performed, but it can be a high variation in normalization factor sets depending on chosen methodology for normalization. As actual regional emissions are the most established method for normalization, the method applied in *BridgeLCA* is considered sufficient. It could, however, be a better idea, for the future, to implement emission data for Scandinavia and implement these as normalization factors, rather than the emission data for Western Europe that are used in this present version of *BridgeLCA*.

3.4.5 Discussion of the results

To obtain more comparable results, the total results per category are divided by total surface area. The surface areas of the bridges are; Klenevågen 340 m^2, Fretheim 229 m^2 and Hillersvika 420 m^2. Figure 26 below shows a comparison of the results per m^2, the absolute results are given in Table 5.

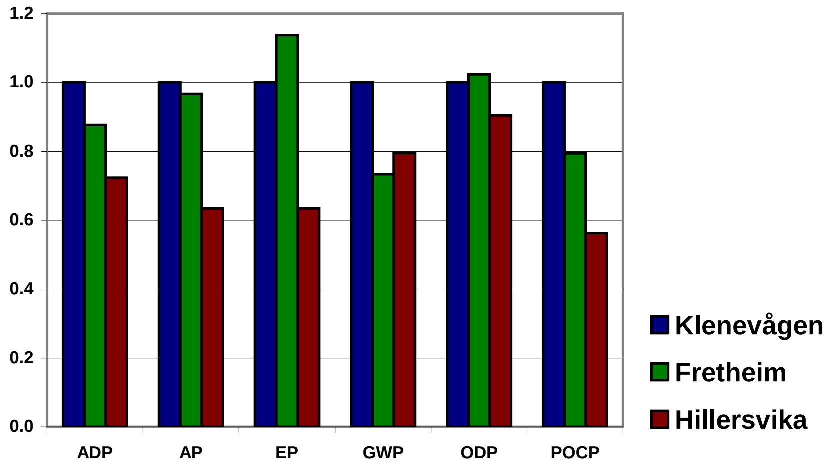


Figure 26: Relative impacts for each category, per m2 surface area of bridge

In the graph all results are shown relative to Klenevågen steel box girder bridge for each impact category. These results differ quite much from the total results for the whole bridges. The steel bridge, Klenevågen, still performs poorest, except in the categories EP and ODP (categories that are not very important in the overall results seen in Figure 19). The concrete box girder bridge, Hillersvika, is causing the least impacts in all categories, except from GWP.

The impacts per m^2 surface area for the bridges are given in Table 5 below.

Table 5: Impacts for each category, per m^2 surface area of bridge

	ADP	AP	EP	GWP	ODP	POCP
Unit	*kg Sb eq / m^2*	*kg SO_2 eq / m^2*	*kg PO_4 eq / m^2*	*kg CO_2 eq / m^2*	*kg CFC-11 eq / m^2*	*kg C_2H_4 eq / m^2*
Klenevågen	6.5E+00	2.9E+00	4.9E-01	7.5E+02	8.0E-05	2.7E-01
Fretheim	5.7E+00	2.8E+00	5.5E-01	5.5E+02	8.2E-05	2.1E-01
Hillersvika	4.7E+00	1.8E+00	3.1E-01	6.0E+02	7.3E-05	1.5E-01

It is important to keep in mind that a comparison per m^2 will neither give directly comparable results. The material and energy consumptions, and also transport services and operation, repair and maintenance activities will not vary linearly relative to bridge size. One example is the abutments; the size of these will not change if bridge length is changed, but it will change if the width of the bridge is changed. The main load-bearing systems and their consumption of materials will differ with bridge length and width, but only to a certain degree, and definitely not linearly.

Important mechanisms in the use-phase of the bridges were omitted from the study, like creosote leakage from the deck in Fretheim bridge, weathering of paint and concrete and emissions of paint in repainting of steel. The most critical of these are the creosote leakage, which induces emissions of several toxic substances, mostly poly-aromatic hydrocarbons (PAHs) harmful to humans (carcinogenic) and the remaining environment. This definitely favours the wooden bridge, but it is unknown to what degree. The current version of *BridgeLCA* would not include impacts caused by these substances even if creosote leakage was included, as the toxicity categories are kept outside the analysis. This is a weakness of the present version of the software, due to the fact that toxicity issues are still associated with high levels of uncertainty as part of LCA studies, and this must be kept in mind when analysing bridges containing creosote impregnated wood.

4 Appendix

4.1 ETSI definitions for a bridge system

Below are given the detailed definitions for a bridge system that are made use of in the ETSI project, and hence, which are also made use of in the *BridgeLCA* tools.

Table 6: Notion for bridge main structures and its elements

Element Code	Bridge structures and elements
	Foundation
110	Foundation slab (base slab), plinth, pile cap
158	Excavation, soil
159	Excavation, rock
160	Pile
193	Erosion protection
	Slope and embankment
220	Embankment, embankment end, backfill
260	Soil reinforcement and slope protection
	Abutments and piers
310	All concrete structures belonging to the substructure excl. foundation and including the foundation slabs
	Main load-bearing structure
610	Slab / deck
630	Beam, girder
650	Truss
660	Arch, vault
690	Cable system
697	Pipe, culvert
	Secondary load-bearing sstructures
710	Secondary load-bearing beam, cross beam
750	Secondary load-bearing truss, wind bracing
	Equipment
510	Bearing and hinge
	Edge beam
	Insulation, water proofing
	Surfacing
	Parapet, railing
	Expansion joint
	Drainage system

4.2 Background data for the case bridges

Table 7: Background data for the manufacturing phase

Manufacturing phase	Unit	Klenevågen	Fretheim	Hillersvika
Concrete	m^3	225	67.5	413
Reinforcement steel	ton	28	10	103.4
Construction steel	ton	67.2	21.88	-
Steel, lower grade	ton	6.85	7.32	6.05
Glue laminated wood	m^3	-	59.3	-
Sawn timber, construction	m^3	-	56.4	-
Wooden formwork	m^2	130	45	400
Copper	ton	0	0.654	0
Asphalt	m^2	340	229	420
Asphalt membrane	m^2	340	229	420
Mastic	m^2	340	-	420

Table 8: Background data for the construction phase

Construction phase	Unit	Klenevågen	Fretheim	Hillersvika
Transport, concrete	km	20 (truck)	20 (truck)	0.5 (truck)
Transport, reinforcement	km	90 (truck)	160 (truck)	130 (truck)
Transport, constr. steel	km	75 (boat)	160 (truck)	-
Transport, glue lam. wood	km	-	280 (truck)	-
Transport, constr. wood	km	-	50 (truck)	-
Diesel, building machine	l	610	426	890
Blasting	kg	102	0	67.5
Travel distance, workers	km	30	2.5	10
Construction period	months	2	2	3

Table 9: Background data for the use phase

Use phase	Unit	Klenevågen	Fretheim	Hillersvika
General inspection	$Year^{-1}$	1	1	1
Main inspection	$Year^{-1}$	5	5	5
Flushing	$Year^{-1}$	2	2	2
Clearing below water	$Year^{-1}$	10	10	10
Repainting, steel	$Year^{-1}$	20	-	-
Repainting, wood	$Year^{-1}$	-	15	-
Re-asphalting	$Year^{-1}$	10	10	10
Repair of parapets	$Year^{-1}$	50	50	50

Table 10: Background data for the end-of-life phase

End-of-life phase	Unit	Klenevågen	Fretheim	Hillersvika
Diesel, building machine	l	500	340	700
Concrete	treatment	Re-used	Re-used	Re-used
Steel	treatment	Recycled	Recycled	Recycled
Wood	treatment	-	Incinerated	-

4.3 Assumptions made in the case study

Below are listed the assumptions made for general input parameters in the case study.

- Explosives: 0.5 kg explosives per m^3 of mass [10]
- Mass moved: 0.1 litre diesel per m^3 of mass moved [10]
- Wooden formwork: A third of the required amount is included, to account for re-use
- Transportation of workers [personkm] = No of workers * travel distance * No of workdays
- Transport of materials [tonkm] = Tons of material * transport distance
- Surfacing: The most common surfacing for bridge decks in Norway consists of 3 layers; mastic, membrane and asphalt. This type is named A3-4 is and is described in *Bridge Decks* [18].
- Asphalt: Thickness of 0.05 m assumed (common for bridges with an average traffic load) and density of 2.4 tons per m^3 [20]
- Laying of asphalt: consumption of 0.16 litres of diesel per ton asphalt [10]
- Re-asphalting: laying of 65 % of original amount [10]every 10^{th} year [20]
- Inspections: included by transport of personnel
- Operation and repair actions: included by transport of personnel, use of materials and energy required for each activity
- Copper: density 8.960 ton/m^3

4.4 Selected results from case study

Table 11: Relative impacts, Klenevågen

	ADP	AP	EP	GWP	ODP	POCP
	kg Sb eq	kg SO_2 eq	kg PO_4 eq	kg CO_2 eq	kg CFC-11 eq	kg C_2H_4 eq
Foundation	2.4E+00	2.9E+01	7.0E+00	4.5E+02	4.0E-05	2.9E-01
Substructure	1.5E+02	8.5E+01	1.4E+01	3.8E+04	1.5E-03	6.6E+00
Superstructure	1.3E+03	6.6E+02	1.1E+02	1.7E+05	7.7E-03	7.1E+01
Bridge equip.	3.4E+02	1.1E+02	1.3E+01	2.1E+04	5.7E-03	8.2E+00
Construction	3.8E+01	2.7E+01	5.4E+00	5.9E+03	8.1E-04	1.2E+00
OR&M	3.9E+02	5.7E+01	9.2E+00	1.3E+04	1.1E-02	4.5E+00
End-of-life	2.2E+01	1.7E+01	3.6E+00	3.4E+03	4.7E-04	4.5E-01
TOTAL	**2.2E+03**	**9.8E+02**	**1.7E+02**	**2.6E+05**	**2.7E-02**	**9.2E+01**

Table 12: Relative impacts, Fretheim

	ADP	AP	EP	GWP	ODP	POCP
	kg Sb eq	kg SO_2 eq	kg PO_4 eq	kg CO_2 eq	kg CFC-11 eq	kg C_2H_4 eq
Foundation	1.2E+00	1.4E+00	3.0E-01	1.8E+02	2.2E-05	3.4E-02
Substructure	1.2E+02	6.4E+01	1.1E+01	2.7E+04	1.1E-03	5.2E+00
Superstructure	6.1E+02	4.0E+02	5.7E+01	6.5E+04	5.0E-03	3.2E+01
Bridge equip.	2.4E+02	6.8E+01	1.0E+01	1.6E+04	3.7E-03	6.6E+00
Construction	2.6E+01	1.7E+01	3.5E+00	4.0E+03	5.7E-04	5.4E-01
OR&M	2.8E+02	5.2E+01	9.3E+00	1.0E+04	7.8E-03	3.5E+00
End-of-life	2.8E+01	3.8E+01	3.6E+01	4.4E+03	5.9E-04	1.3E+00
TOTAL	**1.3E+03**	**6.4E+02**	**1.3E+02**	**1.3E+05**	**1.9E-02**	**4.9E+01**

Table 13: Relative impacts, Hillersvika

	ADP	AP	EP	GWP	ODP	POCP
	kg Sb eq	kg SO_2 eq	kg PO_4 eq	kg CO_2 eq	kg CFC-11 eq	kg C_2H_4 eq
Foundation	2.0E+00	2.0E+01	4.7E+00	3.6E+02	3.5E-05	2.1E-01
Substructure	1.8E+02	9.5E+01	1.6E+01	3.8E+04	1.7E-03	8.4E+00
Superstructure	8.9E+02	4.4E+02	7.6E+01	1.7E+05	7.7E-03	4.1E+01
Bridge equip.	3.7E+02	9.4E+01	1.2E+01	2.0E+04	6.4E-03	7.7E+00
Construction	4.2E+01	3.3E+01	6.8E+00	6.5E+03	8.8E-04	1.3E+00
OR&M	4.5E+02	5.7E+01	8.5E+00	1.3E+04	1.3E-02	4.6E+00
End-of-life	2.9E+01	2.4E+01	4.9E+00	4.6E+03	6.3E-04	6.1E-01
TOTAL	**2.0E+03**	**7.7E+02**	**1.3E+02**	**2.5E+05**	**3.0E-02**	**6.4E+01**

4.5 Results from sensitivity analysis

Table 14: Numeric results from sensitivity analysis.

	Klenevågen steel box girder bridge						Fretheim wooden arch bridge						Hillersvika concrete box girder bridge					
	ADP	AP	EP	GWP	ODP	PCOP	ADP	AP	EP	GWP	ODP	PCOP	ADP	AP	EP	GWP	ODP	PCOP
Concrete	0.6	1.0	0.9	2.3	0.7	0.4	0.3	0.5	0.4	1.4	0.3	0.2	1.2	2.3	2.2	4.3	1.2	1.0
Steel, construction	4.7	5.1	5.5	4.7	1.8	6.6	2.6	2.6	2.3	3.1	0.8	4.0	0.0	0.0	0.0	0.0	0.0	0.0
Stainless steel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reinforcing steel	1.0	1.0	1.1	1.1	0.6	1.3	0.6	0.6	0.5	0.8	0.3	0.9	4.3	4.9	5.1	4.0	1.9	6.8
Steel, lower grade	0.3	0.3	0.4	0.3	0.1	0.5	0.6	0.5	0.5	0.7	0.2	0.9	0.3	0.4	0.4	0.3	0.1	0.6
Glue laminated wood	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.0	0.9	0.9	0.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0
Wood, construction	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.5	0.6	0.4	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Wood, formwork	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Aluminium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Copper	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.5	0.2	0.1	0.1	0.7	0.0	0.0	0.0	0.0	0.0	0.0
Stone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rubber	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Glass	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Asphalt	1.9	0.5	0.4	0.4	4.5	0.4	2.2	0.5	0.4	0.6	4.4	0.6	2.7	0.8	0.7	0.6	5.0	0.8
Mastic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Asphalt membrane	0.9	0.5	0.3	0.3	1.1	0.3	1.0	0.5	0.3	0.5	1.1	0.4	1.2	0.8	0.5	0.4	1.3	0.5
Epoxy paint	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Polyurethane paint	0.1	0.1	0.1	0.0	0.1	0.0	0.3	0.4	0.4	0.3	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Zinc coating	0.2	0.7	0.3	0.3	0.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Powder coating	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Creosote impregnation	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.5	0.2	0.4	0.2	0.4	0.0	0.0	0.0	0.0	0.0	0.0
Salt impregnation	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.2	0.2	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Blasting	0.0	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.0	0.0	0.0
Diesel	0.1	0.2	0.2	0.1	0.1	0.0	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.3	0.4	0.1	0.1	0.1
Electricity	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Car transportation	0.1	0.1	0.1	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Truck transportation	0.1	0.1	0.1	0.1	0.2	0.0	0.2	0.2	0.2	0.4	0.4	0.1	0.1	0.1	0.2	0.2	0.2	0.1
Boat transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ship transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Train transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wood untreated, landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wood untr., incineration	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.3	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Wood tr., incineration	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.4	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Wood, recycling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Steel landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Concrete landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Steel recycling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Concrete re-use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Remark: Change of results higher than 1 % is highlighted

References

1. ISO, *Environmental management - Life cycle assessment - Principles and framework*. 2006.
2. Baumann, H.a.T., A-M., ed. *The Hitch Hiker's Guide to LCA*. Studentlitteratur. 2004.
3. Rydh, J., M. Lindahl, and J. Thingstrøm, eds. *Livscykelanalys*. 2002, Studentlitteratur AB.
4. CML. *University of Leiden, Institute of Environmental Sciences*. 2001 [cited 2007 14.12.2007]; Available from: www.leidenuniv.nl.
5. Heijungs, R.R., *Three Strategies to Overcome the Limitations of Life-Cycle Assessment.* Journal of industrial ecology, 2004. **8**(3): p. 19.

6. Owens, J.W., *Life-Cycle Assessment: Constraints on Moving from Inventory, to Impact Assessment.* Journal of industrial ecology, 1997. **1**(1): p. 37.
7. de Haes, H., et al., *Best available practice regarding impact categories and category indicators in life cycle impact assessment.* The International Journal of Life Cycle Assessment, 1999b. **4**(3): p. 167-174.
8. Huijbregts, M.A.J., et al., *Normalisation figures for environmental life-cycle assessment: The Netherlands (1997/1998), Western Europe (1995) and the world (1990 and 1995).* Journal of Cleaner Production, 2003. **11**(7): p. 737-748.
9. Soares, S.R., L. Toffoletto, and L. Deschênes, *Development of weighting factors in the context of LCIA.* Journal of Cleaner Production, 2006. **14**(6-7): p. 649-660.
10. Veritas, D.N., *Miljøsammenligning av bro, tunnel og ferje. Livsløpsanalyse som grunnlag for sammenligning av alternative fjordløsninger*, in *Bruavdelingen*, B. Otto Kleppe, Editor. 2000, Statens Vegvesen, Vegdirektoratet.
11. Gervásio, H. and L.S. da Silva, *Comparative life-cycle analysis of steel-concrete composite bridges.* Structure and Infrastructure Engineering, 2008. **4**(4): p. 251 - 269.
12. Horvath, A. and C. Hendrickson, *Steel versus steel-reinforced concrete bridges: Environmental assessment.* Journal of Infrastructure Systems, 1998. **4**(3): p. 111-117.
13. Collings, D., *An environmental comparison of bridge forms.* Bridge Engineering, 2006. **159**(4): p. 6.
14. Itoh, Y. and T. Kitagawa, *Using CO2 emission quantities in bridge lifecycle analysis.* Engineering Structures, 2003. **25**(5): p. 565-577.
15. Keoleian, G.A., et al., *Life cycle modeling of concrete bridge design: Comparison of engineered cementitious composite link slabs and conventional steel expansion joints.* Journal of Infrastructure Systems, 2005. **11**(1): p. 51-60.
16. PRéConsultants, *SimaPro 7.1.5.* 2008.
17. Ecoinvent, *Ecoinvent Database v2.01*. 2008, Swiss Centre For Life Cycle Inventories.
18. Bruavdelingen, *Bridge Decks - Waterproofing and Wearing Course*, in *Vegvesenets håndbokserie*. 1997, Statens Vegvesen NO.
19. Stensvold, B., *MOTIV Kostnadsmodell for drift og vedlikehold av bruer og ferjekaier*. 2003, The Norwegian Public Roads Administration.
20. Støland, E., *Personal communication*. 2009, Vegdekke.

ETSI

BRIDGE LIFE CYCLE OPTIMISATION

Stage 2

SubProject 3 (SP3)

Bridge Aesthetics and Cultural Effects

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TIEHALLINTO
FINNISH ROAD ADMINISTRATION

Vägverket

Statens vegvesen

Extraplan Oy

Preface

The *ETSI II Project* consists of three subprojects. *Subproject number 3 (SP 3)* deals with "*Bridge Aesthetics and Cultural Effects*". According to the general *Project Plan* of the *Project* it "should list the essential principles for bridge design and construction".

For *SP 3* a *Project Group* consisting of four persons was nominated:

Dipl. Eng. *Seppo Aitta* from the *Finnish Road Administration*
Civ. Eng. *Hans Bohman* from the *Swedish Road Administration*
Civ. Arch. *Eldar Høysæter* from the *Norwegian Road Administration*
Dr Tech. *Aarne Jutila* from *Insinööritoimisto Extraplan Oy*.

The work was started in *May 2008* and completed in *February 2009*. During that time three *Project Group* meetings were arranged in Helsinki and one in Stockholm. Two of the *Project Group* members attended all four meetings and two attended three meetings. Between the meetings material related to the subject was gathered and individually studied and text for this *Report* was prepared.

The outcome of the work is presented in this report.

Contents

1. Introduction

1.1 Background

Location of a bridge, cultural values of the surroundings, landscape and the viewpoints of local people have influence on the goals that are set to a bridge in the beginning of a project. One of the main aims of bridge projects is to preserve the harmony of the scenery. The assessment of bridge projects according to specified rules is important when deciding on planning, construction, maintenance and financing.

1.2 Objective of *SP 3*

The aim of *SP 3* is to relate aesthetical, environmental and cultural values with the other important aspects of bridge design and construction, *i.e.*, functionality, economics and techniques. When doing so, they can be taken into consideration and made suitable to the computer program developed in the *ETSI II Project*.

1.3 Practice in the Nordic countries

The practice used in the different Nordic countries for defining the goals for cultural and aesthetic values of bridges varies.

In Finland the so-called *classification of bridge sites* is used. This system was developed by the *Finnish Road Administration* (*Finnra*). It considers the value of the scenery. A publication "*Siltapaikkaluokitusohje*" (*Guide for Grading a Bridge Site*) already exists (in Finnish) [4].

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.

Grading of bridge site *Mossala* in Houtskär, Finland, offers a practical example of the grading system created in Finland. Four different items were evaluated and the corresponding bridge classes were determined corresponding each item. Bases for the evaluation were also listed for each case. Consequently the final bridge site class could be determined. The process is described in *Table 1*.

Table 1. *The process used in the evaluation of the Mossala bridge site in Houtskär, Finland.*

Evaluated item	Class	Arguments
Location of the bridge site	II	The bridge site is located between two inhabited islands. There is settlement on both shores and due to that the daily traffic is considerable. Furthermore, the road leading to the ferry is part of the archipelago ring road that is kept open for tourists in summer time. The bridge will replace the present ferry.
Value of the landscape	I	*Björkö* and *Mossala* villages with there storehouses on shore are considered as a valuable landscape even on countrywide level. The bridge site is part of this valuable cultural landscape.
Cultural value of the bridge site	II	Important environment considering the history of the area. In the vicinity there is the *Lills-Kills croft* that is protected by the support of the building protection law.
Aesthetical demands of the bridge	II	The bridge is part of valuable landscape. The bridge may not be a too dominating element but shall be suited to the nearby surrounding.
Overall evaluation of the bridge site class	I-II	Especially demanding or demanding bridge site.

The relative shares of bridges in the different classes suggested in the "*Siltapaikkaluokitusohje*" (*Guide for Grading a Bridge Site*) are given in *Table 2*. Consequently, the additional costs compared to the cheapest possible solution are given in the same table.

Table 2. *Shares of bridges and the corresponding additional relative costs in percentage in the different classes according to "Siltapaikkaluokitusohje" (Guide for Grading a Bridge Site).*

Item	**Bridge Site Class**			
	I	II	III	IV
Number of Bridges	1…2	5…15	65…75	15…25
Additional cost allowed	0…30	0…20	0…10	0

In Norway the *Norwegian Road Administration* (*Statens vegvesen*, *NRA*) has no general method or system for choosing the bridge design system. The process that takes place may differ from case to case and is strongly connected to the people involved in the process.

The key to understand the mechanism in Norway is to identify the builder (prospective owner). Principally there are three kinds of bridge owners: *NRA*, the county authorities and the local authorities (municipality). Trunk roads and main roads are owned and maintained by *NRA*. County roads are owned by the counties. Counties have no own road administration, but they handle the practical work for the *NRA*.

The public road administration consists of five regions: North, Mid, West, South and East, and a central unit called *Norwegian Public Roads Administration* (*Vegdirektoratet*). "*Vegdirektøren*" is the leader of the organization in a region. As far as bridges are concerned, the know-how differs from region to region. Regions West and Mid have a group of competent bridge engineers who are designing even complex bridges. All regions have qualified bridge engineers.

Norway has 19 counties and more than 400 local authorities.

The leaders of the regions handle all contracts related to ***trunk and main roads*** and the money comes directly from central authorities. Ranking of priorities is done by *Stortinget* (the *Norwegian Parliament*) as stated in a national plan of transportation. The regions have freedom to handle the different projects as far as the outlines of the scope are not exceeded.

When the total project cost exceeds a certain limit, then the contracts have to be approved by *Vegdirektoratet*, but this approval mainly is associated with contracts. All bridge projects on trunk and main roads are subjected to a technical approval (Teknisk delgodkjenning, Teknisk godkjenning) led by the bridge section in *Vegdirektoratet*. The terms make demands even to bridge design and aesthetic quality, but in practice it is very rare in a project that this process interferes with the fundamental ideas.

Despite formalities the region leader has a certain freedom to emphasize aesthetics. It's even possible to arrange competitions that are normally advertised as engineering competitions. The main reason for this are the formalities connected to the term "*architect competition*". Normally it is said that it has to be an engineering consulting company who is responsible for the proposal. The engineers, however, have to involve aesthetic competent members in the team. In some cases the term architect is used. In other cases it is not specified.

To help the region leader, *Vegdirektoratet* has written a guide "*Utforming av bruer*" (*Shaping of bridges*) [5]. This guide is based on examples. There is no central coordination of the design processes, but concerning long-span and complex bridges the regions in most cases cooperate with the central authorities.

On ***county roads*** the county administration is the builder and project owner. County administration has no own road administration to handle the projects, so the region leader does the work on behalf of the county administration. The leader of the region has to bring all controversial questions with some financial aspects to the bridge owner. Besides that project finance is often more complex. Budget overrun is much harder to cope with.

The priorities are tough and are often done mainly from a cost aspect's point of view. Only when great cost savings are prospected there might be a wish for controversial design. Aesthetics is very seldom the driving force in the design process.

On ***municipal bridges*** the local authorities run the whole process. Usually they have even less money than the *Central Administration*, but in some cases it can be different. Since the 1990's there are a handful examples of architect competitions mainly related to pedestrian bridges. In urban municipalities the architects have a more dominating position. That means that the administrations are used to use architect competitions as an important element in urban development.

Bridges are often seen more or less as sculptures and icons which the citizens may relate with the soul of the city. This atmosphere and the will to identify the town and its values with an icon may motivate for bold and spectacular solutions. Some projects have exceeded all cost estimates but still it has been possible to fulfil them with success.

In Sweden at the *Swedish Road Administration* (*SRA*) there is no common procedure for evaluating the aesthetical part of bridges today. The frequency of bridge design competitions is low, less than one competition in a year.

When a bridge design competition is arranged, special rules are established just for that particular case. The responsibility of the decision, whether a competition is arranged or not, lies at the Region in question. This concerns bigger and more spectacular bridges. For the smaller ones, architects are today engaged in almost every project, but not in the form of architectural competitions, more directly the project leader engages an architect of his/her choice.

There is a development project called the "KUL-strategy" started in 2007. Its objective is to describe the aesthetical demands for different road and bridge projects. There should also be a developed system for evaluating the different proposals in road/bridge aesthetics in the procurement process.

As an example on, how we handle aesthetics, we can look at the current (2009) bridge over the *Motala Bay* in the Middle of Sweden. In order to get a nice and beautiful bridge, a bridge design competition was arranged. Seven architectural firms were invited to participate. Nine different proposals were sent in to the Swedish National Road Administration. The proposals on, how to design the bridge, should contain a lot of documents describing the bridge from a lot of different aspects as:

A Descriptions

General description of the proposal.
Design concept.

Technical description.

Description of the construction process.

Description on how to inspect and maintain the bridge.

LCA-analysis.

B Design calculations

Rough statical and dynamical analyses of bridge.

A lot of other important factors that affect the bridge, as for instance wind, stability, vibration, stiffness, etc.

Rough estimated cost calculations, design included, subdivided into: foundation, substructure, superstructure, and special details.

LCC-calculation.

C Drawings

Plan.

Elevation.

Special elevations in a smaller scale 1:100.

Type sections.

Important details.

D Perspective/Photomontage/Model

Photomontage of the bridge on four delivered pictures.

Model in scale 1:500.

In evaluation of the different proposals, the following factors should be taken into consideration:

- Aesthetics 30%: design, balance, dynamics, uniformity, and details. The bridge and the landscape. The bridge and the near surroundings. The experience of the road users.

- Bridge technique 30%: the technical relevance of the bridge structure, aspects on maintainability, inspectability, durability fulfilment of technical norms and demands, technical standards and safety, flexibility, constructional aspects.

- Economics 20 %: construction cost, LCC, calculation ability aspects.

- Environment 20%: materials in an LCA-perspective, noise, the bridge and the nature, destruction aspects.

- Traffic safety.

1.4 Practice in the Minnesota Department of Transportation

Minnesota Department of Transportation has developed aesthetic guidelines for bridge design and flow charts for the aesthetic design process [1]. Three levels, A, B and C, are used.

Level A is used for projects of major aesthetic importance. Characteristics of bridges in this category are highly visible bridges, bridge projects that generate substantial citizen interest, bridges located in environmentally sensitive and historic locations, and bridges that are historic themselves. Aesthetics may be a significant factor in determining the structure type for Level A projects.

The aesthetic design flow chart for Level A is presented in *Fig. 1*.

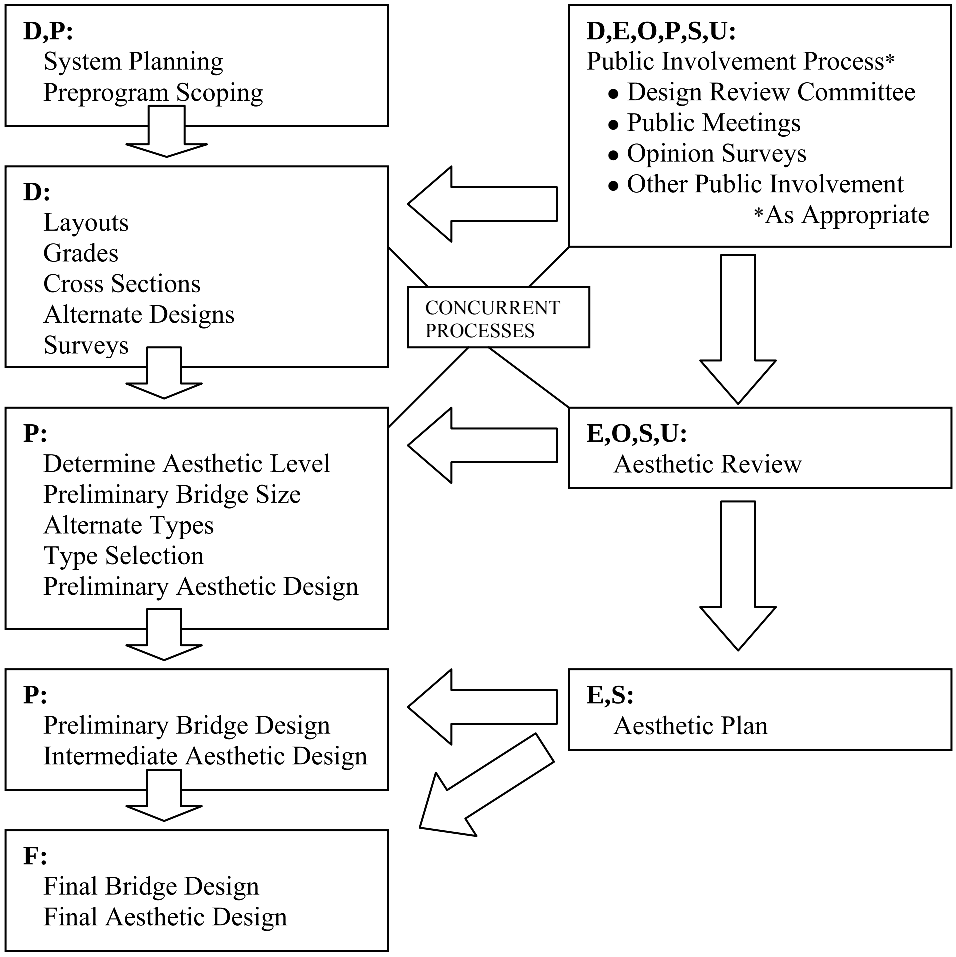

Fig. 1. *Aesthetic design flow chart for Level A in the Minnesota Department of Transportation's aesthetic design process. The key letters have the following meaning: D - district preliminary design, final design, maintenance and construction, E - environmental services, F - bridge design final, P - bridge design preliminary, S - site development, U - public, O - other agencies (State Historical Preservation Office, Dept. of Natural Resources, local government units, etc.).*[1]

Level B is used for bridges where moderate aesthetic treatment is appropriate, but not to the extent that it controls the design. This level includes grade separations over higher volume roads, and bridges near recreation areas, parks, or recreational waterways. Corridor bridges (generally when three or more new bridges are built in close proximity) would be included in this level.

The aesthetic design flow chart for Level B is presented in *Fig. 2*.

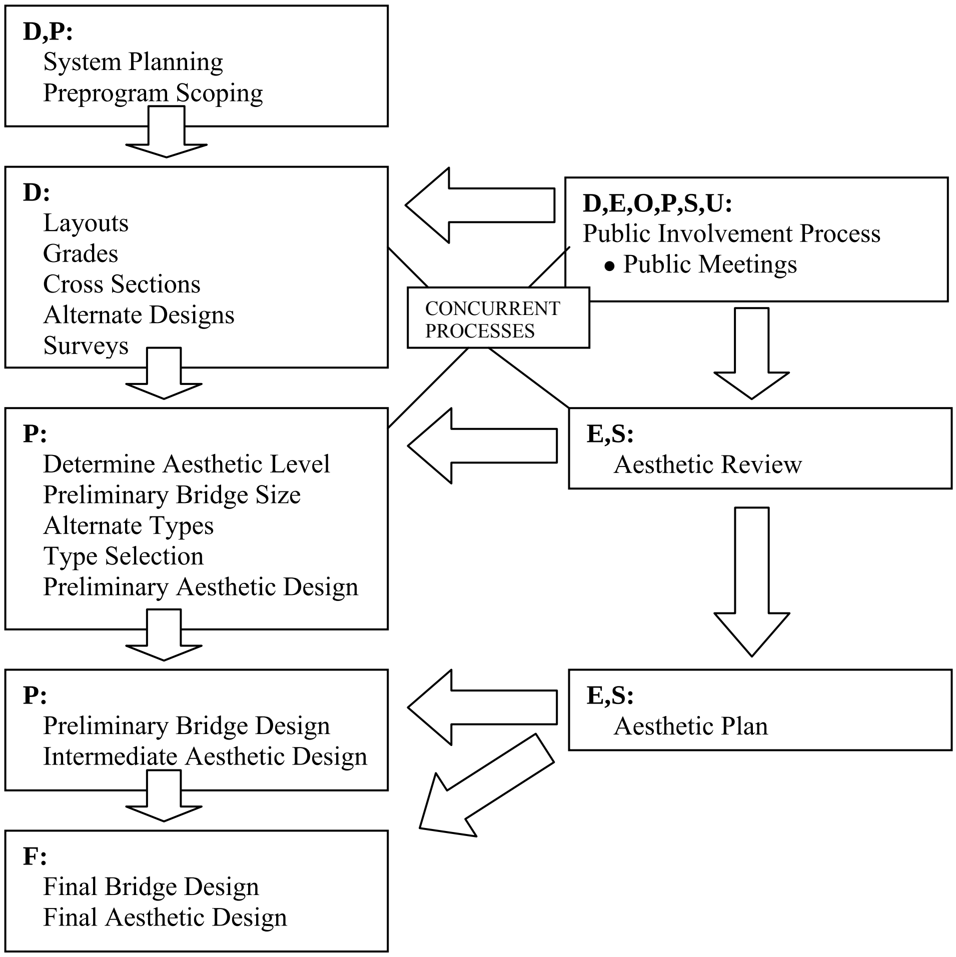

Fig. 2. *Aesthetic design flow chart for Level B in the Minnesota Department of Transportation's aesthetic design process. The key letters have the following meaning: D - district preliminary design, final design, maintenance and construction, E - environmental services, F - bridge design final, P - bridge design preliminary, S - site development, U - public, O - other agencies (State Historical Preservation Office, Dept. of Natural Resources, local government units, etc.).*[1]

Level C is used for the smallest and most routine of bridges where minor aesthetic treatment is appropriate. This level includes low visibility bridges, bridges over non-recreational waterways, bridges over railroads, or overpasses of low-volume roads. Corridor bridges would not be included in this level.

The aesthetic design flow chart for Level C is presented in *Fig. 3*.

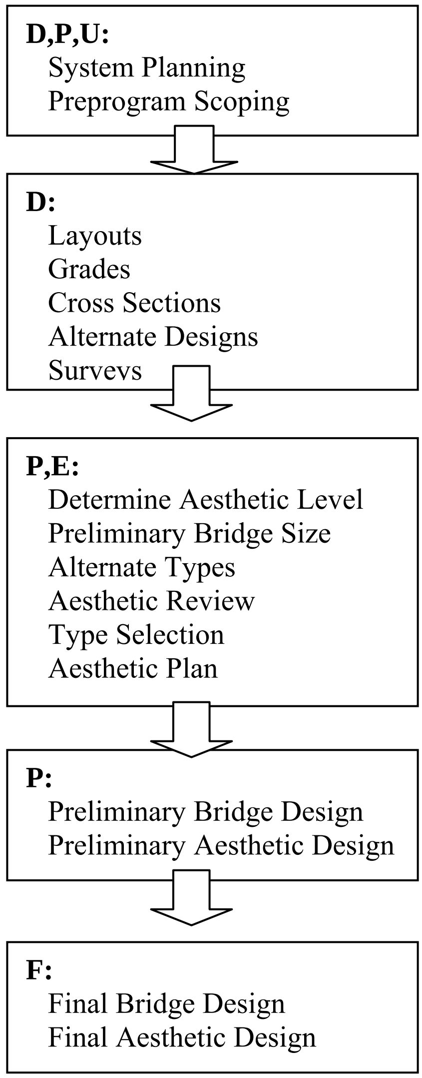

Fig. 3. *Aesthetic design flow chart for Level C in the Minnesota Department of Transportation's aesthetic design process. The key letters have the following meaning: D - district preliminary design, final design, maintenance and construction, E - environmental services, F - bridge design final, P - bridge design preliminary, S - site development, U - public*. [1]

Finally, in the Aesthetic Guidelines for Bridge Design of the Minnesota Department of Transportation a functional group participation table is presented (*Table 3*).

In the Minnesota system no information is given about, how aesthetics and economics are related.

***Table 3**. Functional Group Participation Table in the Minnesota Department of Transportation's aesthetic design process. The key letters have the following meaning: C - bridge construction, D - district preliminary & final design, E - environmental services, F - bridge design final, P - bridge design preliminary, S - site development, T - traffic, U - public. Prim. denotes primary participation. Sec. denotes secondary participation.* [1]

	Aesthetic Factors	**Aesthetic level**					
		A		**B**		**C**	
		Prim.	**Sec.**	**Prim.**	**Sec.**	**Prim.**	**Sec.**
Principle	Superstructure Type and Shape	DEPS	U	PS	DE	P	D
	Superstructure Depth-Span Ratio	P	DEFSU	P	EFS	P	F
	Vertical and Horizontal Geometry	D	EPSU	D	P	D	P
	Pier Placement	DP	EFSU	P	DEFS	P	DF
	Pier Shape	PS	CDEFU	PS	CEF	FP	C
	Abutment Placement	DP	EFSU	P	DEFS	P	DF
	Abutment Shape	FS	DEPU	FS	EP	FP	
	Bridge/Site Integration	DEPS	U	PS	DE	P	D
Secondary	Embellishments	PSOU	CDEF	PS	CEF	FP	C
	Railing Details	FPSOU	E	FPS	E	FP	
	Surface Colours and Textures	FSOU	EP	FS	EP	FP	S
	Lighting	STOU	EF	ST	EF	T	F

1.5 Issues to be considered

Ranking of bridges and bridge design proposals is a difficult task. Especially difficult it is, if we have to make aesthetical and cultural values of bridges measurable with other values like cost or global warming. At the first sight the easiest way seems to be to establish some kind of jury to evaluate different proposal. Of course the judgment of the jury would be based on individual opinions without an exact scale of measuring. However, an open question still remains: how to convert the judgement to money that seems to be the only common value available when comparing different things. It is generally acknowledged, that such a jury in the case of bridge construction should consist of experts with right education, profession and position, e.g. owners, bridge engineers and architects. In some cases even ordinary people of the local community could be represented.

For the decision making and base of the work of the jury some guiding principals have to be set up. The main issue to be clearly stated is, where to put weight when comparing different alternatives. This is even more important, if the bridge has special dignity.

In the decision making the following issues at least should be considered:

- How is the bridge merged in its surroundings (dominating contra not visible).

- Additional costs due to aesthetics compared to that, how many observers do see the bridge and from which distance, angle and speed.
- How is extra decoration related to the function of the bridge.
- Colour. No problem with steel that can be repainted, if not stainless or Corten steel. In concrete structures, mixtures giving certain spectrum can be used. How to evaluate that.
- Design of railings considering maintenance and repare. The same with bearings etc.
- Lighting.
- Maintenance possibilities and costs generally.

2. Structure of the evaluation system

The system developed in *SP 3* is based on the idea that points given to different things according to a given scheme and the opinion of the evaluators. The *number n of things* to be considered can be freely chosen and each thing can have different *weight* w_i of importance. For the evaluation, numerical values or *points* p_i on a chosen scale are given to each thing that one wants to be considered. For each *thing i* the scale can be different, but essential is, that the *extreme values* p_{imin} and p_{imax} are related to each other so that always

$$p_{i\min} = -p_{i\max} \tag{1}$$

For evaluating the effect of aesthetical and cultural aspects, a *reduction coefficient* k_{rel} calculated by equation

$$k_{rel} = 1 - a\frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_i p_{i\max}} \tag{2}$$

is used. Here *a* is another non-dimensional *scaling factor* by which the effect of these aspects can be regulated. Finally, the *reduced relative cost* C_{rel} of a design or a bridge, where aesthetical and cultural aspects are taken into account, is then obtained by equation

$$C_{rel} = k_{rel} C_{LCC} \tag{3}$$

Here C_{LCC} is the *lifecycle cost* obtained by cost calculation considering the construction, repair, maintenance and demolishing costs of the bridge from its whole lifetime. Consequently, the final *overall cost* of the bridge is

$$C = C_{rel} + C_{LCA} \tag{4}$$

where C_{LCA} is the corresponding *environmental impact cost*.

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

3. Proposal for numerical values

3.1 Numerical values for points p_i and scaling factor a

The scale for *points* p_i and the corresponding individual values should be chosen so that an evaluator has enough possibilities to distinguish the different designs or bridges, but at the same time not too many categories to keep the evaluation process simple. That is why it is proposed that

a) the scale for each item is the same,
b) the scale varies from -2 to +2, and that
c) only five categories with even steps are used.

When so, the extreme values p_{imax} have a constant value p_{max} = 2 and the categories are as presented in *Table 4*.

Table 4. *Proposed categories expressed by corresponding points p_i and their verbal explanation.*

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

For the non-dimensional *scaling factor a* numerical value ***a* = 0,2** is recommended. That means that in the extreme cases the reduction coefficient k_{rel} varies between 0,8 and 1,2. This may be reasonable, because consequently an excellent design or bridge may be 50 % more expensive than a poor solution and could still be chosen.

With the values mentioned above *Eq. (2)* takes a reduced form

$$k_{rel} = 1 - a\frac{\sum_{i=1}^{n} w_i p_i}{p_{\max}\sum_{i=1}^{n} w_i} = 1 - 0{,}2\frac{\sum_{i=1}^{n} w_i p_i}{2\sum_{i=1}^{n} w_i} = 1 - 0{,}1\frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_i} \qquad (2a)$$

To demonstrate the system above, let us take a simple artificial example. Let us assume that we have only two things to consider: aesthetics and culture. Let the former one have weight w_1 = 2 and the latter one weight w_2 = 1. Let us further assume that our bridge was given 2 points for its aesthetical values, *i.e.*, p_1 = 2, and 1 point for cultural values, *i.e.*, p_2 = 1. Thus the reduction coefficient k_{rel} takes the value

$$k_{rel} = 1 - 0,2 * \frac{2*2+1*1}{2*(2+1)} = 1 - 0,2 * \frac{5}{6} = 0,83$$

which means that the value of aesthetics and culture in this particular case is 1-0,83 = 0,17 = 17 % of the cost of an ordinary solution, *i.e.*, very good.

3.2 Recommended values for *points* p_i and *weights* w_i in different circumstances

For the LCC computer program to be developed some kind of initial or medium values for *points* p_i in different circumstances are needed. The user is then supposed to change these values to more suitable ones in each particular case, if needed. The same applies to *weights* w_i.

The numerical values recommended here are dependant on the bridge site classes determined in publication "*Siltapaikkaluokitusohje*" (*Guide for Grading the Bridge Site*) mentioned above. According to that publication, there are four different bridge site classes as follows:

Class I	The bridge site is most demanding considering the landscape or city view.
Class II	The bridge site is demanding considering the landscape or city view.
Class III	The bridge site is conspicuous considering the landscape or city view.
Class IV	The bridge site is ordinary considering the landscape or 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. This kinds of bridge sites usually do not require any special environmental or aesthetical consideration or design.

In this *Report* the same four classes as above are used, but the terminology is changed:

Class I is defined as “*demanding*”.
Class II is defined as “*remarkable*”.
Class III is defined as “*ordinary*”.
Class IV has no name, but it includes the rest of the bridge sites.

That means that *Class IV* is the lowest one and does not require any special aesthetical attention. That is why bridges located at *Class IV* building sites always get the value $p_i = 1$.

This is in fully agreement with the proposal of the "*Siltapaikkaluokitusohje*" of *Finnra*, where no additional cost is allocated to bridges belonging to *Class IV* (*Table 2*).

An example is given in *Table 5*.

Table 5. *Values of points p_i and weights w_i in different bridge sites. Preliminary recommendation.*

Item	**Class I**		**Class II**		**Class III**	
	p_i	w_i	p_i	w_i	p_i	w_i
Integration between the bridge and the site		6		4		2
Horizontal and vertical geometry		3		2		1
Superstructure		(9)		(7)		(4)
- harmony of spans		2		2		1
- type and shape		4		3		2
- simplicity, slenderness and transparency		3		2		1
Abutments		(4)		(3)		(3)
- placement		2		1		1
- shape		1		1		1
- visible size		1		1		1
Columns, piers and pylons		(4)		(3)		(2)
- placement		1		1		1
- shape		3		2		1
Railings		2		2		1
Embellishments, surface colours and textures		2		2		1
Lighting		2		2		1
Σ		(32)		(25)		(15)

4. Example of practical application and testing of the evaluation System

As a practical application, the *Motala Bay Bridge* mentioned above is used. It also serves for testing of the evaluation system developed.

The *Motala Bay Bridge* is located in a small town called *Motala*. The town was founded in 1822 and has 30 000 inhabitants. It is situated in the western part of *Östergötland* by the *Göta Canal* outlet into Sweden's second largest lake, *Lake Vättern*, right between *Stockholm* and *Gothenburg*. The bridge - still in design phase in early 2009 - crosses the *Motala Bay* and will be about 600 meters long. The map of the building site is shown in *Fig. 4*.

Fig 4. Map of the *Motala Bay Bridge* area [3].

For the *Motala Bay Bridge* an aesthetical design competition was arranged. It resulted in nine different bridge proposals. Three of them were chosen to serve the test evaluation carried out below.

Proposal Nr. 1 is a continuous steel-concrete composite box girder bridge with inclined struts supporting the side cantilevers and inclined V-shape legs made from steel around the main span that is 156 meters long. The side spans are 72 and 123 meters on one side and 123, 72 and 42 meters on the other, altogether six spans. The sum of spans is 588 meters and the total length 610 meters (*Figs. 5* and *6*).

On both sides of the bridge there is a pedestrian and cycling lane slightly below the road level. The cross-section is symmetric with respect to the center line of the bridge and constant throughout the bridge. The steel box part of the superstructure is supported by the sub-structure. Longitudinally the bridge is symmetric with respect to the waterway, but outside that area it is not. Due to the modest structural depth, 4 meters, the height of the bridge remains relatively small reducing the maximum slope to 35 o/oo. Vertical clearance under the bridge is 22,5 meters on a length of 40 meters. Embankments are not steeper than 1:2. Indirect lighting and spotlights

on the inclined legs will be provided. The traffic density on the bridge will be about 6300 vehicles per day.

Fig. 5. Side view of the bridge according to *Proposal Nr. 1*. [2]

Fig. 6. Perspective view of the bridge according to *Proposal Nr. 1*. [2]

Proposal Nr. 2 is a continuous steel-concrete composite box girder bridge with a long arch span, 191 meters, in the middle. The bridge consists of nine spans: 40+3x48+191+3x48+40 = 559 meters. The arch is made from steel. The width of the bridge is 23 meters. The height of the bridge is 25,5 meters and vertical clearance in the main span is 22,5 meters on a length of 40 meters. The arch is curved in horizontal plane just as the girder, too. There is a pedestrian and cycling lane on one side of the deck (*Figs. 7*, *8*, *9* and *10*). The traffic density on the bridge will be about 6300 vehicles per day. The design life length of the bridge is planned to be 120 years.

Fig. 7. Side view of the bridge according to *Proposal Nr. 2.* [2]

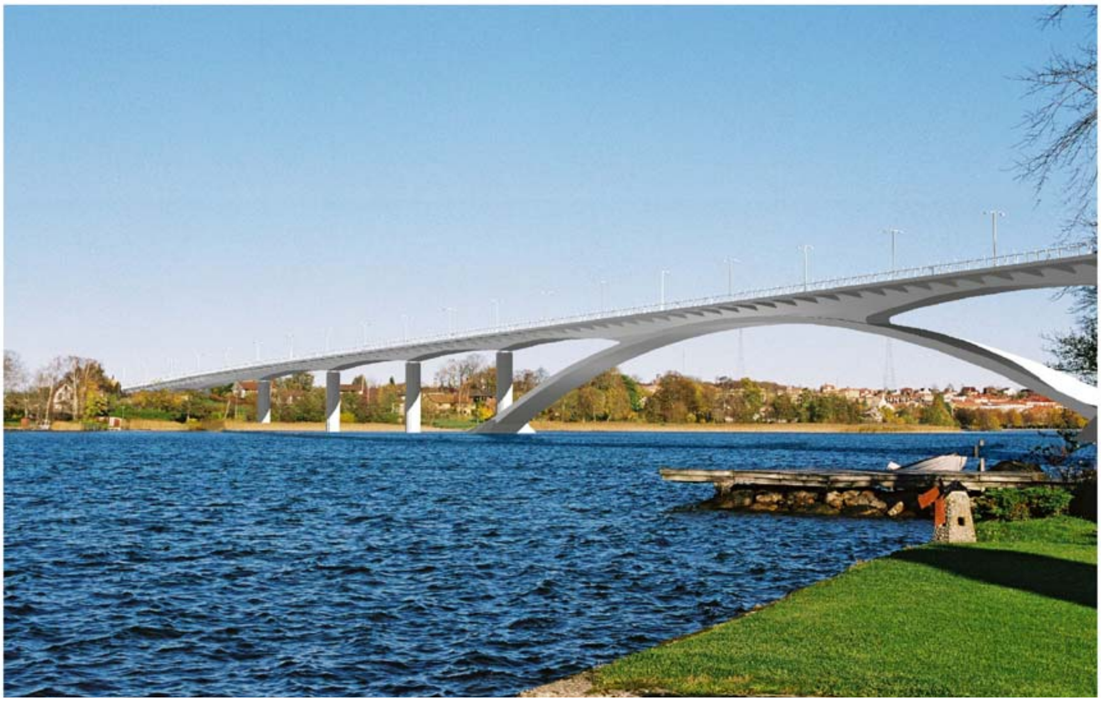

Fig.8. Perspective view of the bridge according to *Proposal Nr. 2*. [2]

Fig. 9. Perspective view of the bridge according to *Proposal Nr. 2*. [2]

10

Fig. 10. Perspective view of the approaching span according to *Proposal Nr. 2*. [2]

Proposal Nr. 3 is a continuous prestressed concrete box girder bridge whose 6 out of 13 spans are supported by cables. So the bridge actually is a combined box girder and cable-stayed bridge. Its spans are 36+2x54+60+4x72+60+3x54+42 = 756 meters. The total width of the deck is 24,7 meters. In the cable-supported spans there are four and in the other spans 5 boxes side by side. The deck is unsymmetrical with respect to the center line of the bridge and to the cable planes that are located in the middle of the bridge. There is a pedestrian and bicycle lane only on one side of the bridge. The five pylons supporting the stay-cables form a monolithic structure with the superstructure without any joints. At the other piers, however, and at the abutments the superstructure is supported by bearings. The design life length of the bridge is planned to be 120 years. Photomontage views of the bridge are shown in *Figs. 11*, *12* and *13*.

Fig.11. Side view of the bridge according to *Proposal Nr. 3*. [2]

Fig.12. Perspective view of the bridge according to *Proposal Nr. 3*. [2]

Fig. 13. Perspective view of the approaching span according to *Proposal Nr. 3*. [2]

The three different proposals presented above where used as a base for **testing the evaluation method** developed in this report. The testing procedure was carried out so that each of the four evaluators studied the documents available and then individually tried to evaluate first the bridge site and then the proposals themselves. Finally the outcome was compared and discussed.

Evaluation of a bridge site should be based on maps and documents available and on site visits. In the present case, however, a site visit was not possible. Additionally the documents available were not very covering in this respect and that made the bridge site evaluation difficult. The only documents available were the map of the region (*Fig. 4*) and the photomontage views of the different proposals. After a short discussion, however, it was not difficult for the evaluators unanimously to agree that the bridge site class in this case is *Class II* ("*remarkable*"). That fixed the weights accordingly (*Table 5*).

The more difficult part, to define points for the different items in each of the three cases, followed. The scale was agreed to be the one proposed in this report, *i.e.*, $p_{max} = 2$. Consequently, value 0,2 for the *scaling factor a* was accepted. The item list was slightly reduced, because there was not enough information to judge such things like railings, embellishments etc. and lighting. So, finally, only ten items were evaluated, namely

- integration between the bridge and the site,
- horizontal and vertical geometry,
- superstructure, *i.e.*, harmony of spans, type and shape and simplicity, slenderness and transparency,
- abutments, *i.e.*, placement, shape and visible size and
- columns, piers and pylons, *i.e.*, placement and shape.

Consequently, according to *Table 5 Class II*

$$\sum_i w_i = \sum_{i=1}^{10} w_i = 4+2+2+3+2+1+1+1+1+2 = 19. \qquad (5)$$

The complete results of the evaluation are presented in a compact mathematical form below. The *reduction coefficient* k_{rel} is of main concern. In this particular case, due to *Eq. (2a)*,

$$k_{rel} = 1 - 0{,}1 \frac{\sum_{i=1}^{10} w_i p_i}{19}. \qquad (6)$$

To cover all evaluation cases, a matrix presentation is used. Thus,

$$\{k_{rel}\} = 1 - \frac{0{,}1}{19} (p_i)^T \{w_i\}, \qquad (7)$$

where $\{k_{rel}\}$ is the final *reduction coefficient vector*, dimensions 1x7, (p_i) is the *evaluation result matrix*, dimensions 6x10, and $\{w_i\}$ is the *weight vector*, which in this case has the value

$$\{w_i\}^T = \{4 \quad 2 \quad 2 \quad 3 \quad 2 \quad 1 \quad 1 \quad 1 \quad 1 \quad 2\}. \qquad (8)$$

In the case of ***Proposal Nr. 1*** the evaluation result matrix $\{p_i\}$ takes the form

$$(p_i) = \begin{pmatrix} 1 & 2 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0{,}75 & 1 \\ 1{,}5 & 2 & 2 & 2 & 1{,}875 & 2 \\ 1{,}5 & 2 & 1 & 2 & 1{,}625 & 1{,}75 \\ 1{,}5 & 2 & 1 & 2 & 1{,}625 & 1{,}75 \\ 1{,}5 & 1 & 0 & -1 & 0{,}375 & 0{,}5 \\ 1{,}5 & 0 & 0 & 2 & 0{,}875 & 0{,}75 \\ 1{,}5 & 1 & 0 & 2 & 1{,}125 & 1{,}25 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 2 & 2 & 0 & 1{,}25 & 1{,}5 \end{pmatrix}. \qquad (9)$$

In matrix (9) the first column represents the points which the first evaluator gave to the ten different items. The points are listed in the same order as in *Table 5*, or in the list just above *Eq. (5)*. Similarly, the second column consists of the points given by the second evaluator, and so on until the fourth column, which is related to the fourth evaluator. The values in the fifth column are simply the average values of the four previous ones on the same row. The sixth column is similar to the fifth one, but in this case the extreme values on the row are neglected. In this particular case it means the same as the median value.

When the operation shown by Eq. (7) is carried out using the numerical values presented in *Eqs. (8)* and *(9)*, the final result

$$\{k_{rel}\}^T = \{0{,}87 \quad 0{,}84 \quad 0{,}89 \quad 0{,}91 \quad 0{,}88 \quad 0{,}87\} \tag{10}$$

in the case of ***Proposal Nr. 1*** is obtained.

In the case of ***Proposal Nr. 2*** the evaluation result matrix $\{p_i\}$ takes the form

$$(p_i) = \begin{pmatrix} 1 & 1 & 1 & 2 & 1{,}25 & 1 \\ 1 & 1 & 1 & 2 & 1{,}25 & 1 \\ 2 & 1 & 2 & 2 & 1{,}75 & 2 \\ 2 & 1 & 0 & 2 & 1{,}25 & 1{,}5 \\ 2 & 1 & 1 & 1 & 1{,}25 & 1 \\ 1{,}5 & 1 & 0 & 0 & 0{,}625 & 0{,}5 \\ 1{,}5 & 1 & 0 & 1 & 0{,}875 & 1 \\ 1{,}5 & 1 & 0 & 0 & 0{,}625 & 0{,}5 \\ 1{,}5 & 1 & 1 & -1 & 0{,}625 & 1 \\ 1{,}5 & 1 & 1 & 0 & 0{,}875 & 1 \end{pmatrix}. \tag{11}$$

Consequently, in the case of ***Proposal Nr. 2***

$$\{k_{rel}\}^T = \{0{,}85 \quad 0{,}90 \quad 0{,}92 \quad 0{,}87 \quad 0{,}88 \quad 0{,}89\}. \tag{12}$$

Finally, in the case of ***Proposal Nr. 3*** the evaluation result matrix $\{p_i\}$ takes the form

$$(p_i) = \begin{pmatrix} 1 & 0 & 1 & 1 & 0{,}75 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 2 & 2 & 1{,}25 & 1{,}5 \\ 1 & 0 & 1 & 2 & 1 & 1 \\ 1 & -1 & 1 & 2 & 0{,}75 & 1 \\ 1{,}5 & 0 & 0 & 2 & 0{,}875 & 0{,}75 \\ 1{,}5 & 0 & 0 & 0 & 0{,}375 & 0 \\ 1{,}5 & 0 & 0 & 2 & 0{,}875 & 0{,}75 \\ 1{,}5 & 0 & 1 & 2 & 1{,}125 & 1{,}25 \\ 1{,}5 & 1 & 2 & 2 & 1{,}625 & 1{,}75 \end{pmatrix}. \tag{13}$$

Consequently, in the case of ***Proposal Nr. 3***

$$\{k_{rel}\}^T = \{0{,}88 \quad 0{,}99 \quad 0{,}89 \quad 0{,}84 \quad 0{,}90 \quad 0{,}89\}. \tag{14}$$

The test carried out shows that the evaluation method developed is easy to use and mathematically simple. The judgments of the four evaluators were in most cases surprisingly similar. Although some differences appeared in some details, they were greatly balanced out in the final result. The smallest differences are in the cases of *Proposal Nr. 1* and *Proposal Nr. 2*, where the *reduction coefficient* k_{rel} according to *Eqs. (10)* and *(12)* varies between 0,84 and 0,91, and 0,85 and 0,92, respectively. In the case of *Proposal Nr. 3* the variation according to *Eq. (14)* is bigger, from 0,84 to 0,99, but even in this case every evaluator comes to the conclusion that the aesthetical and cultural values of the proposal are positive. Based on these results *Proposal Nr. 1* seems to be slightly superior to *Proposal Nr. 2* and *Proposal Nr. 3* occupies the last position in this evaluation.

Better than to compare the judgements of individual evaluators might be to compare the average or median values. According to *Eqs. (10)*, *(12)* and *(14)* the variation between the different proposals is extremely small, from 0,88 to 0,90 in the average values and from 0,87 to 0,89 in the median values. Maybe the average and median values give more objective result, when there are several evaluators, as it was the case in the test evaluation carried out. The final order between the three proposals, however, is still the same: *Proposal Nr. 1* is slightly superior to *Proposal Nr. 2* and *Proposal Nr. 3* occupies the last position.

5. Practical use of the method developed

The method developed in this Report is a unique system that enables to incorporate aesthetical, environmental and cultural values to bridge design or construction projects and to make them comparable with construction and lifecycle costs. The method can be used beneficially in the following cases:

- Evaluation of aesthetical, environmental and cultural values with 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.
- Rewarding - or punishing - of those involved when an aesthetically better - or worse - result is achieved than expected.

The method can as easily be used by an individual as by a jury or group of evaluators. Due to its simple mathematical formulation it can also be easily incorporated in a LCC computer program to become part of it.

Practical use of the method is simple. At the first stage one has to consider the bridge site and determine, which class the bridge site belongs to. Here *Finnra's* "*Siltapaikkaluokitusohje*" or the instructions given in Chapter 3.2 of this *Report* can be utilized. It is worth of noticing, however, that the terminology used in this *Report* slightly differs from that used in *Finnra's* report.

The second stage is to agree about the items that will be evaluated and to determine weight to each item. This should be done before the evaluation process begins. The weights should be considered as "*fixed values*" and may not be changed during the evaluation process. One is totally free to choose any items and their number is by no means restricted. Too detailed items, however, may cause difficulties to the evaluator. A good practice might be that items and their weights are determined by the bridge owner in advance. When so, there could be a standard list with standard weights that then can easily be altered to meet the requirements of the project in question. Such a standard list could be stored in a computer in such a form that it can easily be altered or "*zero weight*" can be given to those items that are left outside consideration. The total number of items needs to be altered correspondingly.

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 aesthetical values compared to costs. The value 0,2 recommended in this *Report* sounds reasonable, because in extreme cases it restricts the effect of aesthetics up to ±20 %, but of course also any other value between 0 and 1 is possible. Even this value should be determined by the bridge owner.

The third and final stage includes the evaluation itself, *i.e.*, the determining of *points* p_i. Before that, however, the scale to be used has to be determined. In this report a fixed scale with $p_{max} = -p_{min} = 2$ is recommended, but the system allows again any scale. With steps equal to 1 recommended here one has to decide between five different values, *i.e.* -2, -1, 0, 1 and 2, when only integer values are allowed. That scale should be dense enough to obtain distinction between different categories but scare enough to keep the evaluation simple. But here again any numbers, integer or decimal ones, are possible.

When the evaluator has decided on *points* p_i, it is a simple mathematical task to calculate the final values of interest, *i.e.* the *reduction coefficient* k_{rel} and the *reduced relative cost* C_{rel} by using *Eqs. (2)* and *(3)*.

6. Conclusions and recommendations for practice and future research

In this *Report* the practice to consider aesthetical, environmental and cultural values in bridge design and construction in Finland, Norway and Sweden, respectively, is described. The methods used are different, but in each country these values are taken into account in one way or another. In Finland the system is most sophisticated because of a publication called "*Siltapaikkaluokitusohje*" (*Guide for Grading a Bridge Site*) [4] produced by the *Finnish Road Administration*, but this publication is restricted to concern only bridge sites. It is used as base of this *Report*. To guide bridge design in Norway, the *Norwegian Road Administration* has also produced a publication called "*Utforming av bruer*" (*Shaping of Bridges*) [5]. In Sweden the situation is somewhat different. Aesthetical issues in bridge design and construction are more individually solved by case to case. What is said above is related to road administrations only. There are also other bodies in these countries that are engaged with bridge aesthetics, for instance universities and private enterprises.

For comparison, a U. S. system from Minnesota is also introduced in this *Report*, but it has not been applied further.

The main part of the *Report* is devoted to developing and introducing of a unique new system for evaluating aesthetical and cultural aspects in bridge design and construction in a systematic way. The method is based on *weights* and *points* given to different items. From their product a *reduction coefficient* is derived that makes it possible to relate aesthetical values to real cost values.

Numerical values for *weights* and *points* are suggested. The system is mathematically compact but simple and very flexible to individual variations. It was numerically tested by a test group using three real bridge design proposals. The result was clear and promising considering further applications.

Finally, it can be concluded that the method developed is ready for practical use. It can be utilized in many different ways in bridge design and construction. It can also be easily programmed to a computer or incorporated in a computer program calculating for instance lifecycle costs of a bridge. What is really needed in the future, however, is to study and develop a comprehensive list of items that need to be considered and to give them appropriate weights valid for different bridge site classes. In this *Report* only a short preliminary list is presented (*Table 5*).

References

[1] Aesthetic Guidelines for Bridge Design. Minnesota Department of Transportation. Office of Bridges and Structures. March 1995. 116 p. P. 3-7…3-11.

[2] Bridge Design Competition arranged by the Swedish Road Administration.

[3] http://maps.google.fi/maps?f=d&ie=UTF8&hl=fi.

[4] Siltapaikkaluokitusohje (Guide for grading the Bridge Site). Luonnos 2.8.2007. Tiehallinto - Vägförvaltningen. Helsinki 2007. 53 p. In Finnish.

[5] Utforming av bruer (Shaping of Bridges). Statens vägvesen. Nr. 164. Oslo 1992. 201 p. In Norwegian.

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