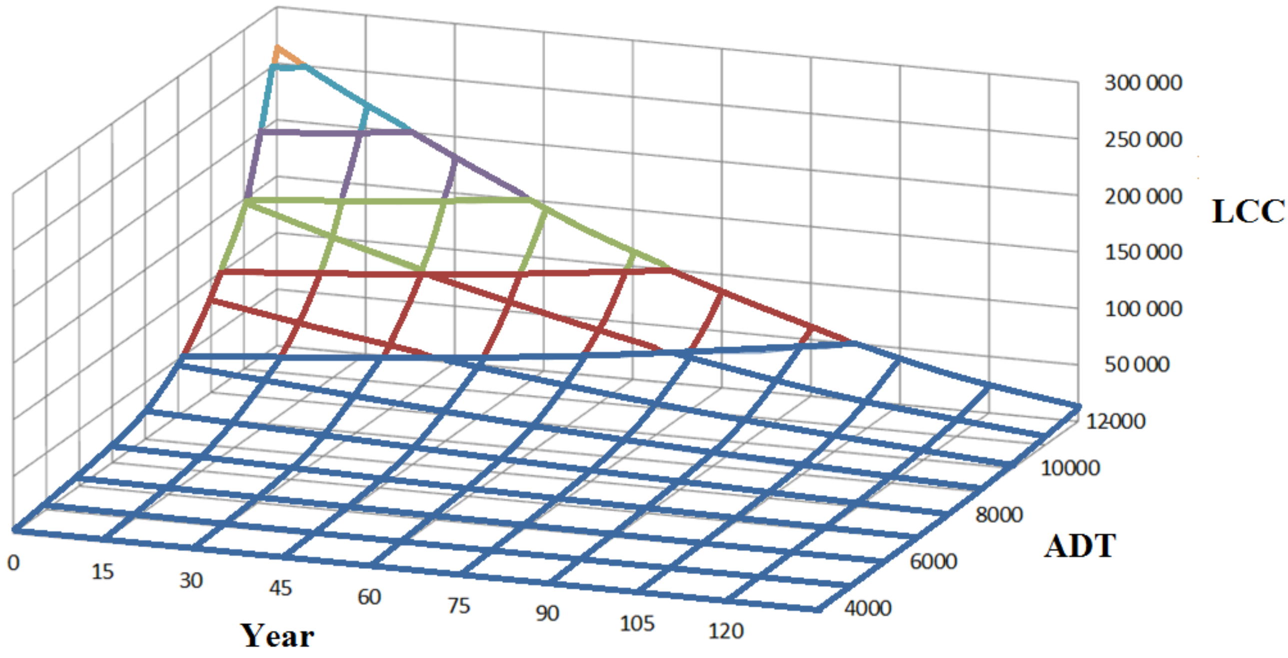

Design of short-span bridges with regard to life cycle costs

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

NIKLAS LARSSON
DAN NILSSON

Department of Civil and Environmental Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011
Master's Thesis 2011:140

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Cover:
Graph showing how the life cycle cost (LCC) varies, depending on at which age of a bridge an activity occurs (age), and the prevailing traffic volume at that time (*ADT*).

Name of the printers / Department of Civil and Environmental Engineering Göteborg, Sweden 2011

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ABSTRACT

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

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

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

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

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

Design av kortspannsbroar med avseende på livscykelkostnader

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SAMMANFATTNING

Syftet med detta projekt var att ta fram en metod för hur livscykelkostnads (LCC) analyser kan användas som beslutsunderlag vid nykonstruktion av broar. Metoden ämnade kunna stödja konstruktören i att ta fram den mest lönsamma detaljlösningen ur ett LCC-perspektiv. Projektets mål var att utföra en jämförelse mellan två olika LCC-fall, där det första skulle motsvara dagens standardutförande och det andra, alternativa detaljlösningar. Jämförelsen grundades på analyser och befintliga erfarenheter gällande vanligt förekommande problem för olika typer av existerande kortspannsbroar.

För att möjliggöra den jämförande LCC-analysen valdes tre, i Sverige vanligt förkommande, kortspannsbroar ut. Samtliga tre brotyper har sina egna karakteristiska problem, vilka också beaktades i den första LCC-analysen, fall 0. Grundat på resultaten från fall 0, föreslogs möjliga förbättringsåtgärder till detaljlösningarna, erkända eller ifrågasatta. Förbättringsåtgärdernas påverkan på LCC:n bedömdes genom att implementera dessa i en andra LCC-analys, fall 1. En jämförelse av resultaten från fall 0 och fall 1 möjliggjorde en identifiering av faktorer, med egenskapen att ha stort inflytande på LCC-resultatet, vilka vidare benämns som känslighetsfaktorer.

Det visade sig, i motsats till förväntningarna, att det inte var detaljlösningarna i sig, utan effekten av att inte implementera dem som hade störst inverkan på LCC:n. De konventionella lösningarna innebär ofta ett behov av framtida underhåll och reparationer. När i tiden dessa åtgärder väntas ske, samt dess påverkan på trafiken, visade sig vara de två faktiska känslighetsfaktorerna för huruvida en detaljlösning kunde anses vara lönsam eller ej. För att styrka resultaten och knyta an till det uttalade syftet, togs ett flödesschema fram parallellt med ett Excel-verktyg. Flödesschemat anger en metod för att på ett systematiskt sätt kunna analysera och jämföra lönsamheten mellan två olika detaljlösningar. Excel-verktyget kompletterar i sin tur flödesschemat genom att utföra de nödvändiga LCC-beräkningarna och presentera grafer där de kritiska värdena, med avseende på känslighetsfaktorerna, kan utläsas.

Denna metod förser konstruktörer med ett utökat beslutsunderlag för valet av den ekonomiskt mest fördelaktiga designen med tillhörande detaljlösningar. Metoden bidrar även till möjligheten att motivera valet av dessa lösningar, även om de initialt kan te sig vara dyrare.

Nyckelord: *LCC, LCC-analys, broar, design, detaljlösningar*

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List of abbreviations

ADT – *Average Daily Traffic*

BaTMan – *Bridge and Tunnel Management*

LCC – *Life Cycle Cost*

MR&R – *Maintenance, rehabilitation and repair*

Preface

This project was carried out during the period September – December 2011 at COWI AB, Göteborg, in collaboration with the Division of Structural Engineering at Chalmers University of Technology, Sweden.

We would like to express our appreciation to all involved in making this master thesis project possible for us, especially; Magnus Bäckström (supervisor at COWI), Björn Engström (supervisor and examiner at Chalmers) and Birit Buhr Jensen (COWI DK/ETSI). Together, all of the above has provided us with their invaluable support and resources throughout the project, for that we are truly grateful.

It was surprising how helpful and engaged the people we came in contact with during the project were. Not the least the bridge managers that were interviewed and the staff at COWI, whom always took time out of their busy schedules to help us out when it was needed.

The overall experience of carrying out the project has been both challenging and inspiring, and we both look forward to starting our carers as civil engineers.

Göteborg, December 2011

Niklas Larsson and Dan Nilsson

Notations

Roman upper case letters

ADT	Average Daily Traffic
ADT_{mod}	Worst hour traffic (5 % of the ADT)
AF	Annuity factor
B_n	Sum of all costs and incomes at age n
C_{delay}	Hourly cost for a delay
C_{driver}	Total driver delay cost
D	D-factor (0.009 in this project)
D_{days}	Duration of MR&R work
K_{yearly}	Yearly cost
$K_{present}$	LCC
L	Service life (design)
LCC	Present value of the life cycle cost
$L_{workzone}$	Size of a workzone

Roman lower case letters

n	Age of which the present value is discounted from
r	Discount rate
t_{wait}	Extra traveling time due to MR&R work on the bridge
v_{norm}	Speed limit during normal conditions
v_{red}	Reduced speed limit trough a workzone

1 Introduction

This chapter will present the background, purpose, aim, scope and method for this master project.

1.1 Background

When it comes to decision-making for infrastructural projects, it often tends to be the design alternative with the lowest investment cost that is adopted when it stands between a number of different possible options. The costs of the projects are often relatively large and in Sweden these costs are often covered by taxpayer money. Therefore it is of paramount public interest that the money spent on new investments also is done as cost effectively as possible.

A well-known fact is that a more expensive product option today, not necessarily will be the most expensive product when summing up all costs over its entire service life. In the year 2009, 74 % of the Swedish government's budget for infrastructure was used for operation, maintenance and repair of the existing infrastructure. In addition, more and more bridges are being built, which will result in an even greater need for maintenance, rehabilitation and repair in the future. These facts tell a story about the potentials and needs to optimise designs for minimised, maintenance, rehabilitation and repair costs. This will in turn open possibilities for an increased budget for new investments, without either increasing or decreasing the available budget.

Forsman (2010) states that the total investments in infrastructure 2009, according to the Swedish Road Administration, were 11.4 billion SEK of which the cost for operation, maintenance and repair was 8.4 billion.

There have been various methods and approaches to already in the planning stage make assessments of future costs for different products or structures. These have become known as Life Cycle Cost methods, and often fall within the scope of the even better known Life Cycle Analysis concept. These methods incorporate a wide range of uncertainties of future costs due to the usually assumed input data. These uncertainties eminently apply when it comes to infrastructural projects, especially bridges that require analysis periods of around 80-120 years. Performing assessments and calculations that include uncertainties are however not unusual when it comes to analysing design solutions, structurally or economically. To address this, various models of varying accuracy have been developed over the years through documentation of research and previous experiences. The approach to, at an early planning stage, assess bridges from an LCC perspective is however relatively new; therefore a great need for research and development in the field is present to achieve greater precision in new and existing models.

The key factors that must be assessed and quantified, concerning bridges, are the financial consequences that early decisions can have on the future needs of maintenance, rehabilitation and repair. These needs, among other things, vary along with the selection of design solutions, workmanship and materials.

An important step in the right direction could be a general database for input data, which is continuously updated with new data and experience from various studies and projects in progress, or already completed. This would pave the way for continuous improvements and increased reliability of the LCC-analysis for future projects, which in turn would result in better investments of the taxpayers' money. According to Forsman (2010), the Swedish Road Administration was carrying out such a project at that moment of writing.

1.2 Purpose

The purpose of the project is to find an approach on how to use LCC-analysis as a decision-making tool in design when planning new bridges. This approach should be focused on decision-making regarding detailing solutions and how to choose the most favourable detailing solution with respect to LCC and sustainability.

1.3 Aim

The project's leading aim is to perform a comparison between two LCC cases, where today's standard and alternative detailing solutions were considered for each case, for different kinds of short-span bridges. The comparison should be carried out by using analyses together with experiences of typical problems associated with selected types of existing bridges.

These analyses should be carried out from an LCC–perspective to represent the actual cost prognosis related to different bridge types and their corresponding detailing solutions.

By using the first LCC-analysis, case 0, where the most commonly accepted detailing and design solutions are to be applied as a basis. From that basis, possible improvements that could be used, recognised or questioned, are to be suggested. These improvements could cost extra time in the planning stage and money in the investment itself. Therefore an assessment of these extra costs should be performed against the actual long term effects, by a second LCC-analysis, case 1. By comparing the results from these two analyses, sensitivity factors, i.e. factors that have great influence on the LCC, should be identified and justified by numerical results, for the different detailing solutions and their corresponding bridge type(s).

In the end recommendations on an LCC methodology for short-span bridges, based on the conclusions drawn from these analyses, are to be formulated to act as an aid for an effective use of LCC-analysis in the early design stage of new bridges.

A secondary aim of the project is to use and evaluate the LCC software WebLCC, which was under development in a Scandinavian project called ETSI, during the time that this thesis project was carried out. The limitations and ambiguities that could be found during the use of WebLCC should continuously be reported back to the ETSI – group along with suggestions for possible improvements.

1.4 Scope

- The approach is to be focused on decision-making with regard to detailing solutions
- The project is limited to analyse three bridge types, one in each of the main structural material, concrete, steel and timber.
- The bridge dimensions are to represent an arbitrary 2 lane short-span bridge
- The bridges themselves are limited to:
  - Bridge application = Road bridge
  - Span width = Short-span ~15-25 m
  - Number of spans = One
  - Width of bridge deck = Equivalent to a 2-lane highway, i.e. ~7 m
- The bridge types are to represent those that are most widely used for the stated limitations and purposes
- The environment that the bridges should be exposed to in the analysis is set to avoid any kind of extreme condition, by choosing the following:
  - Climate zone
    - Southern Sweden
  - Average Daily Traffic
    - Moderately high
  - Location
    - Urban environment
  - Exposure to water
    - No exposure to salt or fresh water
- Swedish conditions should be considered throughout the project
- The LCC-analysis is intended to be applicable for the design stage of the building process

1.5 Method

In order to achieve the stated purpose and aim, the LCC concept is to be used as a start-out point. Initially literature studies are to be carried out in order to acquire the necessary knowledge regarding the LCC concept. Three bridge types are then to be chosen and a compilation of experiences drawn from previously built bridges of the same type is to be formed. As an initial approach, the Bridge and Tunnel Management (BaTMan) database containing operation, maintenance and repair data on Sweden's bridge stock is to be used for the compilation. The significant data acquired from the compilation is then to be analysed with regard to the LCC concept. This analysis is to be performed with the aid of three computer softwares, listed below, which were chosen due to their direct application for the purpose of conducting LCC computations on bridges. The LCC results delivered are then also to be compared to one another to investigate if any discrepancies could be observed and the cause for it.

- *WebLCC* (BroLCC) – A computer software under development during the time when the project was to be carried out
- *Vännen07* – Software developed by the Swedish Road Administration
- *BridgeLCC* – US developed software

An alternative or complementary approach to compiling data from the BaTMan database could be to interview experienced bridge managers on their perception of the different bridge types. This approach would be used as a secondary option, only if the compilation request to the BaTMan database would fail. A drawback of basing a compilation on interviews is that the data would be based on highly subjective opinions and assessments. The compilation would therefore also carry less scientific value.

After the completion of the first LCC-analysis, case 0, considering typical problems concerning detailing solutions associated with each bridge type, possible improvements to these problems are be suggested and evaluated. This evaluation is to be performed by a second LCC-analysis, case 1. This analysis is to be performed by running the data collected through the selected softwares and compile the results into tables where the results can be assessed. The authors' belief is that the improvements will show to be the more favourable solutions once they were viewed upon from an LCC perspective.

Results and conclusions can then finally be drawn and used to develop a method for how these findings could be used to effectively utilise the LCC-analysis in the design stage when planning new bridges.

2 Life Cycle Cost

This chapter describes the general theory concerning the concept of life cycle costs (LCC).

2.1 Fundamentals of LCC

LCC is a concept found as a part of the even better known Life Cycle Analysis (LCA). The LCC is not a new concept at all, it has been used for many years, mainly for cost optimisation of industrialised products/items. Relatively recently, more and more countries and their authorities have begun to recognise the LCC concept as a valid decision-making tool for infrastructural projects.

According to Lyrstedt (2005), LCC is a method or rather an analytical tool of a group called life cycle approaches. It can be defined as "*all costs, both internal and external, that are associated with the life cycle of products and which are directly related to one or more of the actors during a products' life cycle"*.

Today there are three different kinds of LCCs:

1. Business LCC
2. Environmental LCC
3. Societal LCC

What differ between the different kinds of LCCs is mainly how the parameters are set, which in turn depends on the situation and how they are used. This master thesis focuses on the third of the options above, societal LCC. This LCC approach covers all different aspects that concern a bridge. Internal and external costs form more than one perspective, in this context meaning the road users, bridge holders, contractors and authorities.

The main objective of performing an LCC-analysis is to estimate the gross cost related to a certain product over its entire design service life, i.e. the costs for raw materials, processing, manufacturing, inventory costs, shipping, fuel (if applicable), maintenance, repairs and demolition.

This is undertaken by accounting for all activities related to the product or process. These are then broken down into smaller elements, which are assessed one-by-one. This assessment needs the dimensions of time and magnitude in relation to the overall context in order to weigh the elements' costs and effect in relation to one another. These costs are then discounted to a certain point in time, usually the present value, Atterhög (2008). The general LCC equation, shown in Equation (2.1) below, presents how the discounted costs are calculated.

LCC, general equation:

$$LCC = \sum_{n=0}^{L} \frac{B_n}{(1+r)^n} \quad (2.1)$$

Where:

LCC = Present value of the life cycle cost

n = Age of which the present value is discounted from

B_n = Sum of all costs and incomes at age n

r = Discount rate (usually 4 % in Sweden)

L = Service life

2.2 Applications of the LCC concept

The fundamental LCC concept suggests that it can be applied to any kind of product by using different models and methods, with the possibility to control the level of detail that is of interest. This means that the workload can either be decreased or increased on behalf of the accuracy of the analysis.

LCC-analysis has, as mentioned in Section 2.1, mostly been used for industrialised products since a couple of decades back. Relatively recently the construction industry has begun to utilise the benefits of the LCC concept.

So far LCC applications have been limited for use only on a component level in the construction industry. However, most construction projects consist of multiple components that create whole systems, such as buildings or bridges. A component level analysis could easily become far too complex and also be completely misguiding due to the interaction between the many components that needs to be accounted for.

If an approach to work with LCCs on a system level was to be attempted, it would require user-friendly interfaces in order to be accepted for wide use. There is a need to make simplifications and in spite of these simplifications, the analysis must still be able to deliver realistic results. This is the reasoning where the biggest issues lie on whether or not LCC-analysis can be used as a decision-making tool for entire systems.

2.2.1 Basis for the selection of the discount rate

The discount rate, or social discount rate, is one particularly important factor included in Equation (2.1) above. This factor has a great influence on the outcome of the LCC results. It is important to take note on that this discount rate is not the same as the financial discount rate. The social discount rate is used for social investments and is based on time preferences, i.e. "*how fast consumption is growing and how rapidly the benefits are decreasing when consumption is increasing*", Hjort (2008).

The selection of an appropriate discount rate is based on assumptions regarding the benefits future generations will have due to today's consumption. The higher the discount rate is set, the less regard is taken future effects. In Sweden today, the social discount rate is set to 4% and has also been on this level since 1994. Before 1994 the discount rate was actually following the consumption rate, i.e. the reflection on the populations' decision on their own savings. This consumption rate does however not take future generations into account and was therefore concluded to be an unsuitable reference in 1994. The social discount rate was therefore lowered to what is called a risk-free level of 4 %. Looking back even further in time, the Swedish social discount rate was as high as 8 % before 1984. In Table 1.1 below, it can be seen how the social discount rate has changed over the years. Hjort (2008)

Table 1.1 Variations of the discount rate (social) in Sweden during last ~30 years

Year	Rate
2006	4%
2005	4%
2001	4%
1999	4%
1997	4%
1994	4%
1984	5%
Earlier	8%

How this discount rate is chosen varies greatly between different countries. Germany has for instance a social discount rate of 3 %, therefore taking great consideration to future generations. France on the other hand uses 8 %, thus taking little or no consideration to future generations, Sonesson (2011).

An example on how the discount rate can vary depending on what that is being considered is the Swedish policy when discounting carbon dioxide emissions. In this case a discount rate of 2 % is being used. A discount rate of 2 % is relatively low, thus taking great consideration to future generations, which is also in line with today's reasoning regarding environmental sustainability.

2.2.2 Applications of the LCC concept on bridges

A paramount issue when trying to perform LCC-analysis on bridges is that they generally do not generate any income, only benefits in terms of traffic running across. The traffic is limited to road traffic in this project. Traffic benefits are not usually accounted for in today's LCC practice in Sweden, but restrictions on the traffic benefits are charged to the cost estimates, Ronnebrant (1999).

According to Robinsson, Danielsson, Snaith (1998), the benefits of LCC-analysis have developed through time in three different stages:

1. Decisions based on present day investment costs
2. Decisions based on present and future costs for the road manager
3. Decisions based on present and future costs for both road manager and users

When the third stage was introduced, the user costs or traffic costs could be introduced; however there has been a question on how to put a price on traffic costs, i.e. the value lost when there are interruptions of the traffic flow. This can be dependent on how heavily a road or bridge is trafficked. According to Ronnebrant (1999), it is not yet determined exactly how the traffic cost is going to be included, only that it definitely should be included. The United Kingdom has a computer program called QUADRO, which computes the traffic costs. Tests using QUADRO performed by Burley, Rigden (1997) suggest that there is a breakpoint at an Average Daily Traffic (ADT) of 20,000 vehicles. This breakpoint indicates the traffic volume at which disturbance to the traffic becomes a significant factor in the cost estimates. According to Ronnebrant (1999), Sweden has a different philosophy when it comes to traffic costs. When socioeconomic infrastructural investments are considered, traffic costs are not accounted for during certain activities that causes disturbance to the traffic flow. Instead, a comparison of traffic benefits before and after the activity has taken place is carried out. As mentioned above, it could be accepted to neglect these effects of traffic costs at ADT levels below 20,000, but when the ADT exceeds 20,000 the cost estimate becomes underestimated according to the test performed by Burley, Rigden (1997). Whether the QUADRO model is applicable to the Swedish traffic environment is left unanswered, but it is likely to believe that the Swedish roads also have their critical ADT. For the purpose of this project, a moderately high ADT of 6,000 vehicles is assumed. This was believed to have a significant effect on the LCC of the activities, due to their associated traffic costs.

Out of the three computer softwares that were used in this project, WebLCC and BridgeLCC took the traffic costs into account, and that was also one of the reasons for why they were chosen.

According to Trafikverket’s (the Swedish Road Administration’s) “national plan” for infrastructure, the socioeconomic viability shall be the guiding factor for all investment decisions. In other words concerning bridges, the investments are only justified when traffic benefits exceed the expenditures, Ronnebrant (1999).

The socioeconomic viability cannot entirely be based on the initial investment costs. Since infrastructural projects usually have design service lives of about 40-120 years, the maintenance, rehabilitation and repair (MR&R) costs become a significant factor. Especially when these activities result in traffic delays on heavily trafficked roads, due to limited road accessibility, that indirectly costing the society large amounts of money.

Ronnebrant (1999) suggests that custom made LCC models, applicable for all the different stages (planning, design, procurement, construction and operation) in a bridge project should be developed. One type of LCC-analysis cannot be applied to any bridge because bridges are all unique in their own way. It is important to note that LCCs are just models for comparison and a stand-alone analysis is virtually useless. By performing sensitivity analysis, key factors that have big influences on the LCC can be identified and dedicated more analysis time. This can be done by using so-called stochastic values i.e. consider the probability that a certain activity occurs during a prescribed period of time, Ronnebrant (1999).

Furthermore, for an LCC model to work properly, it requires reliable input data to process. To be able to distinguish which data and what level of detail are relevant for a bridge, a model needs to be developed first.

A reliable LCC model provides a valuable decision-making tool when trying to build as cost effectively as possible whilst spending tax money. This tool gives the possibility to monitor the financial long and short-term effects caused by early decisions when the possibilities to affect the final costs are the greatest, as illustrated in Figure 2.1 below. Furthermore, when the traffic costs are accounted for, the social benefits are included beyond the costs for MR&R.

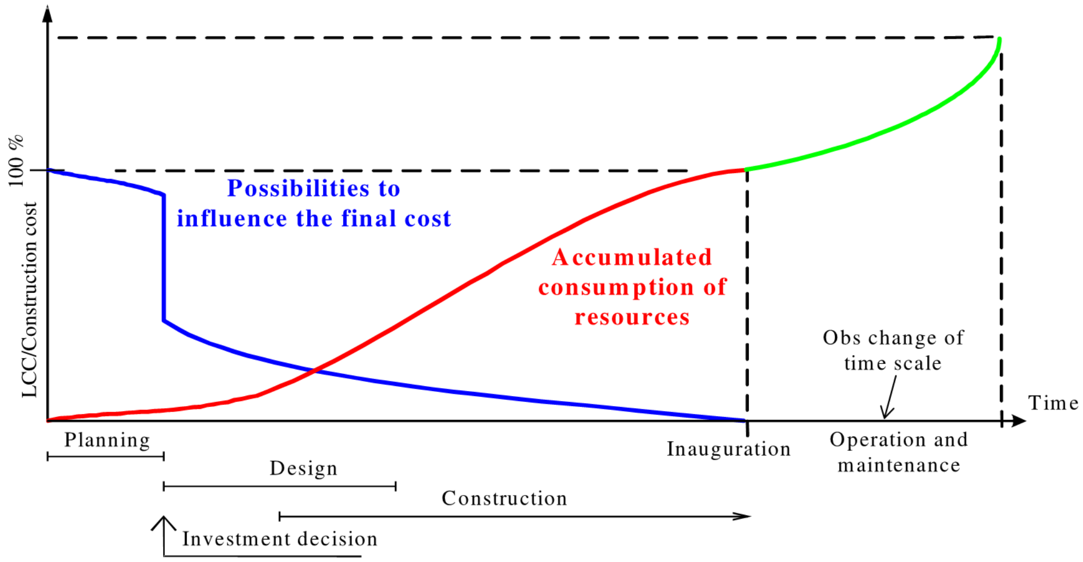

Figure 2.1. How the possibility to influence on the LCC varies during the service life of a bridge according to Safi (2009)

A typical model for an LCC-analysis adapted for bridges is shown in the schematic Figure 2.2 below.

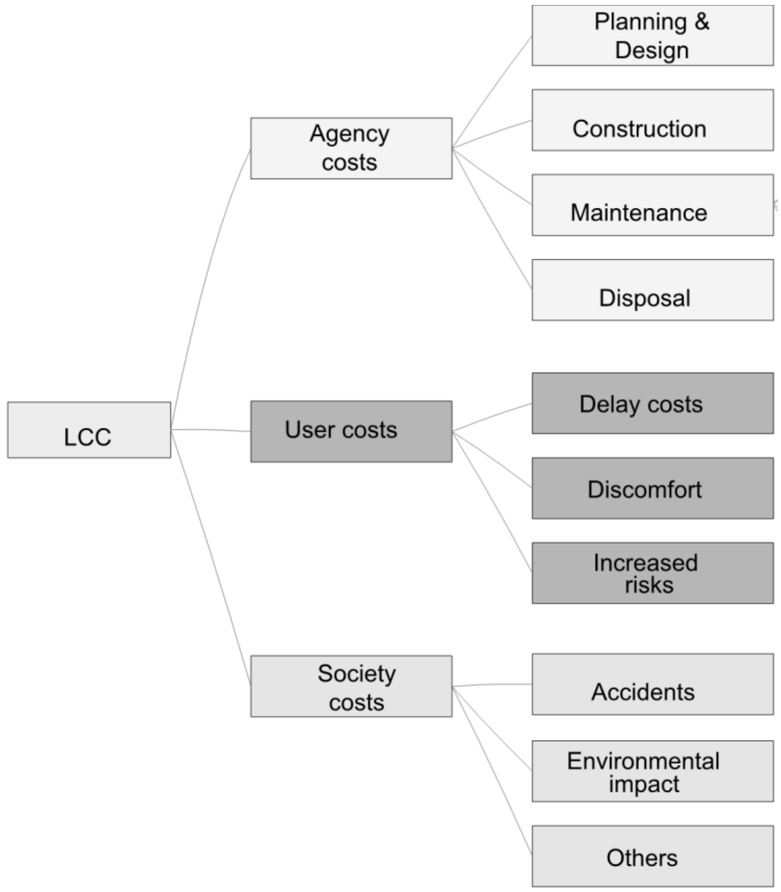

Figure 2.2. Example on how the LCC for a bridge can be distributed over different stakeholders, Salokangas (2009)

2.3 Obstacles and future prospects of LCC for bridges

Regarding the future prospects in the development of LCC application on bridges today, there are a few obstacles listed below that need to be tackled before the usage of LCC-analyses can become common practice when designing new bridges:

1. Agreeing on mutually accepted model(s)
2. Readily accessible and reliable input data for the models to process, i.e. databases
3. Overcome organisational barriers, mainly in the procurement models
4. Agreeing on standard-based MR&R costs

There are several LCC models available today, but they are all regarded to be quite time consuming to use. This is mainly due to the need of gathering all the relevant input data before it can be processed in a model. Some kind of readily accessible source, preferably a database, is therefore needed. As mentioned before, for a model to take shape, there is a need to define what input data that is relevant. Hence, a solution to number 2-4 above, would pave the way for mutually accepted LCC models to be developed, Forsman (2010).

2.3.1 LCC databases

Databases do exist today, but on the contrary to the house construction industry, there are none intended for the purpose of using LCC-analysis. In Sweden however, there has been a database for bridges since 1944, containing documentation of the Swedish bridge stock and the MR&R performed, called SAFEBRO. This database was replaced and digitalised by today's current version 2004, called Bridge and Tunnel Management (BaTMan). BaTMan contains information of more than 27,000 bridges in Sweden. It still lacks an interface to sort out relevant information needed for an LCC-analysis, but the Swedish Road Administration has begun a project to update and arrange the data to be readily accessible for LCC use according to Forsman (2010).

2.3.2 Standard-based maintenance, rehabilitation and repair costs

If databases could be arranged in a manner that would make the retrieval of relevant LCC data fairly easy, the need for standard-based MR&R costs would also become obsolete when the actual costs could be retrieved directly.

2.3.3 Organisational barriers obstructing LCC implementation

Regarding the organisational barriers, the procurement procedure today does not facilitate or motivate the use of LCC-analysis. Two other reasons are that there are no recognised LCC models and the matter of how long the contractors are liable for their projects. If decisions are to be based on a predefined design service life, this service life also needs to be achieved. Today a bridge contractor usually assumes responsibility for a bridge approximately 5-10 years after its production. This is less than a tenth of a normal bridge's design service life. For an LCC-analysis to carry any significance in a procurement stage there is a need to verify and monitor the outcome of what is being agreed upon in the procurement. An extended responsibility to the contractor could be an option to assure that the intended design service life performance is met, since failure to comply would make the contractor liable, Troive (2000a).

Estimating and concretising the performance during a design service life of a bridge also requires consideration of an infinite amount of variables and therefore needs to be simplified with suitable models. Today there is no commonly accepted model of how to deal with the many variables, other than the bridge's durability seen over its design service life. How to tie these issues into the procurements in a way that satisfies all parties involved is a hard challenge.

For this to be realised, new forms of procurements are needed. Troive (2000a), reasons that today's specified requirements of bridges in the procurements should be expressed as functional requirements instead. Examples of the most essential parts of what could be defined as functional requirements for a bridge follows below:

- Safe
- Transfer loads to the base
- Harmonise with the road and surrounding environment
- Cost effective (LCC)
- Sustainable (LCA)

This type of functional procurement is expected to give the contractors more freedom to decide and choose their own designs. As long as they can fulfil the functional requirements (also called: open design solutions), which for example could be to fulfil a certain LCC or design service life. Ang and Wyatt (1999) also suggest that functional based regulations on requirements agree with today's ambitions of a sustainable society in a better way than the current practice, and that was written twelve years ago.

Troive (2000b) also mentions that these types of procurements could facilitate the introduction of "new" structural materials and composites into design, thus giving such materials a more competitive position in today's market. Examples of "new" material could be Fibre reinforced Polymers (FRP) and High Performance Concrete (HPC). The usage of such "new" material also results in incentives for extended Research and Development of new materials, which could result in even more sustainable future structures, Ehlen (1997).

2.4 Summary – Life cycle cost

The LCC concept is not at all a new science, but an approach that can be adapted depending on what it is intended to be used for. The basic idea is to assess what an item's real costs are over its entire design service life, not just the manufacturing cost or as referred to in most parts of this text, the investment cost. Costs that can be expected during the design service life are fundamentally costs for operation, maintenance and repair.

An LCC-analysis is fairly easy to perform when it comes to single items. But when considering large systems such as bridges, the amount of items become almost infinitely large. A simplified model is then needed, but to construct this or these models, the input data of interest needs to be predefined.

When dealing with infrastructural structures i.e. bridges, roads etc. generally never generate any real income. When considering bridges, traffic benefits have to be viewed upon as an income instead. This gives rise to a new important factor to take into consideration, ADT. Then the analysis is basically left with two important cost items, MR&R and traffic costs. Tests performed in the UK showed that there was a critical ADT that gave rise to significant traffic costs when disturbances to the traffic occurred. The cost of MR&R can and must be sub-divided to perform an accurate analysis, but is mainly traced back to the initial design. Therefore, the LCC needs to be divided into three cost-categories; agency (investment), user (benefits) and society (environmental).

In Sweden, infrastructural projects are justified when the benefits exceed the costs; therefore it is paramount to be able to present a reliable basis for this, not only considering the investment stage, but also the design service life perspective. This is the main reason why the LCC perspective becomes of interest. The most important aspects for the LCC-analysis to become a recognised decision-making tool are:

- Widely accepted model(s)
- Reliable input data, and source (database)
- Changes in the way today's procurements are processed

If one or a couple of LCC models would be generally accepted, the selection between the different options in the procurement stage could be based on LCC estimates instead of direct investment costs. This would in turn require the procurement forms to be adapted for LCC-analysis, and perhaps even new forms of contracting. This would all theoretically result in more optimal new bridges in the end. In the report on "Optimal New Bridges", Troive (2000b) argues that to be able to handle the financial aspects, i.e. weighing costs and benefits, there is a need for further development of LCC methods.

One has to bear in mind that the LCC data easily can be manipulated to agree with the user's desired outcome. Thus there is a need to regulate and verify that the analyses are conducted in a proper manner.

However, not all voices praise LCC-analysis. The application on bridges has been questioned because of the bridges' long service lives and the fact that every bridge is unique in its own way. Veshosky (1992) states that without reliable, consistent historical information, on several different bridge types, any type of LCC estimation would be highly speculative. It could also introduce as much uncertainty as it was intended to resolve.

More information on the LCC concept and the calculations methodology can be seen in Section 3.4.

3 Available LCC softwares

This chapter describes the three different LCC softwares that were used in this project, plus the concept behind the hand calculations. Each software is described by a background statement, followed by the softwares' area of application, how they work and what conditions and constraints they are subjected to in their designs.

The process of finding suitable LCC software was conducted through a web research on Trafikverket's, National Institute of Standards and Technology's (NIST), and Elinkaareltaan Tarkoituksenmukainen SIlta's (ETSI) webpages. These locations were where the most suitable LCC softwares for bridges were found. Three different softwares, listed below, were studied further and explained accordingly in this chapter:

- WebLCC/BroLCC (Web-based/downloadable) (2011)
- Bridge LCC v.2.0 (Downloadable) (2003)
- Vännen07 (Comprehensive) (2008)
- Hand-calculation (Verification purposes)

Theses softwares were later used to perform the LCC-analyses on three selected short-span bridge types. Information on these bridge types and the selection procedure is described in Chapter 5.

3.1 WebLCC and BroLCC

This section describes the LCC softwares WebLCC and BroLCC, which were both the same software displayed in two different manners.

3.1.1 Background to WebLCC and BroLCC

The WebLCC software is a web-based version of what originally was an Excel-based toolbox and called BroLCC. "Bro" is the Swedish word for bridge and was developed by A. Liljencrantz at the Royale Institute of Technology (KTH), in Stockholm, Safi (2009).

WebLCC originated in November 2004 when a project was commenced at the Helsinki University of Technology (TKK), Finland, on a request from the Finnish Road Administration. At that time, the Finnish Road Administration had already discussed the LCC matter for bridges since 2002. The project is today known as the ETSI project. ETSI is a Finnish abbreviation, which translates into what can be considered to be the very purpose of the project itself, Bridge Life Cycle Optimisation. Initially the ETSI project was intended to, through a Nordic cooperation, addressing the increased importance of Life Cycle Engineering in future development of bridges. Thus bringing the principals of sustainability into practice in today's bridge engineering, Julita, Salokangas, Rautakorpi, Tirkkonen (2005).

When KTH begun their participation in the ETSI project, the already existing BroLCC was changed from a conventional Excel toolbox into a web-based software. The intention was to make the software accessible from any location, with a restriction that the users needed to have an account and password to use it. There were however no significant functional differences between BroLCC and WebLCC, Julita, Sundquist (2007).

The basic thought of using LCC for bridges is to include every aspect in a bridge from the cradle to the grave. The initial studies of the ETSI project aimed to research and collect the available LCC softwares in 2004, and then present the results the following year. Meanwhile, a research and development agreement had been reached between Sweden, Norway and Finland. Later on, Denmark joined the project too. Following the debriefing on the initial study, the first of the five stages in the scope of the ETSI project begun in 2006, Julita (2007).

The five stages in the scope of the ETSI project are listed below:

1. Tests of the developed LCC and LCA softwares (WebLCC and BridgeLCA)
2. Development of a material database
3. Updating and completion of WebLCC
4. Updating and completion of BridgeLCA
5. Implementation of the new ETSI-system

According to the latest information, stage 1 and 2 are completed, 3 and 4 are still running simultaneously and the 5^{th} stage is expected to start up in the beginning of 2012. The project as a whole is predicted to be completed in April 2012, ETSI (2011).

WebLCC is based on a Matlab and Excel interface, whereas BroLCC is entirely reliant on Excel for computation. The developers claim that both WebLCC and BroLCC can perform LCC calculations for different types of bridge systems, where all costs during the investment, operation and demolition stages are summarised according to the "present value method". The calculations also include indirect third party costs, i.e. costs incurred by delays for the users of the bridge, traffic costs. These delay costs are a function of the duration of a disturbance, causing the delay to the traffic during MR&R activities conducted on a bridge during its design service life.

WebLCC and BroLCC are said to be applicable for both large and small parts of a bridge. The softwares also provide a possibility to compare different design alternatives, both in detail and as a whole.

WebLCC can be accessed by first contacting the responsible staff at KTH for account credentials, then browse the following URL: *"http://webbapp.byv.kth.se:8080/LCC/"*. The same procedure, but without credentials, applies for BroLCC, where the Excel-file can be sent by email instead. This, presumably functional, web-based version had been accessible for some time at the time of this project. Its applications and functions are the same as for BroLCC and will from here on also be referred to as WebLCC, unless otherwise is stated.

3.1.2 Applications of WebLCC and BroLCC

The softwares are designed to handle LCC calculations by the use of "present value" calculations. The softwares are meant to function as a decision-making tool in the early planning stage and as a complement to a life cycle analysis.

3.1.3 Conditions and constraints for WebLCC and BroLCC

The WebLCC can treat both bridges and tunnels, whereas BroLCC only treats bridges. The options of defining input data suggest that road traffic is what the software is designed for, but since the input data regarding the traffic only concerns their cost, train and pedestrian traffic could probably also be considered, as long as an appropriate pricing would be applied.

The geographical region that the analysis is designed for is currently Sweden. The only concern why the software would not be applicable for other countries would be the available climate zones the bridge can be located in. Even though the currency is set to SEK (Swedish krona), that variable can be assumed to be any currency.

The bridge types possible to define in today's version of the softwares are the following eight:

1. Beam
2. Arch & vault
3. Beam frame
4. Frame
5. Culvert
6. Cable-stayed
7. Suspension
8. Other

3.1.4 WebLCC and BroLCC features

A compilation of the softwares' on-screen appearance can be seen in Appendix A.

When using WebLCC, in contrast to BroLCC, an initial task selection can be found in the top border where four items can be considered to be of importance for the user:

- Search project
- Create project
- Delete project
- Help

The meanings of the different tasks are quite obvious. To start a new project, i.e. a new LCC-analysis, a new project needs to be created. Then you give the project a name and if you intend to analyse a tunnel, you specify that by ticking the box for "tunnel".

When a project is created you will be asked to supply the software with input data. The structure of this data is the same for both softwares and is categorised in 5 different categories:

1. General
2. Investment
3. Maintenance
4. Repairs
5. Results (includes sensitivity analysis)

3.1.4.1 General category

The "General" category is where the bridge is structurally described along with its surrounding environment in terms of climate and traffic. Parameters that need to be defined are the following:

- Climate zone (1-7)
- Salt (Degree of road salting; Not, Normal or Heavily salted)
- Investment cost (all costs incurred to the bridge owner before inauguration budgeted, in SEK)
- Demolition cost (%, of investment cost)
- Period (Design analysis period in years, usually 80-120 years)
- Opening year (year of inauguration)
- Calculated to year (Opening year + Period)
- Interest rate (discount rate, 4% in Sweden, see Section 2.2.1 for more information)
- Average Daily Traffic, ADT (average numbers of vehicles crossing per day)
- Traffic growth (%, per year)
- Heavy traffic (%, of ADT)
- Max speed (normal speed limit on the bridge, in km/h)
- Reduced speed (reduced speed during MR&R works on the bridge, in km/h)
- Hourly cost, cars (SEK/h, standard-based in Sweden)
- Hourly cost, lorry (SEK/h, standard-based in Sweden)
- Bridge type (8 types optional)
- Spans (Number of spans)
- Bridge length (in meters)
- Edge beam length (meters, usually the bridge length times 2)
- Bridge width (in meters)
- Bridge area (in m^2)
- Painted area (in m^2)

Weighing of factors of the input data can also be defined in the last part of the "general" tab. These parameters already have pre-set weighing, but can also be selected manually (0.0-1.0) to the following parameters:

  - Climate zone
  - Traffic
  - Road salting
  - Elements exposed to salt
  - Concrete quality
  - Extra covering concrete

An important thing to take note of is that all inputs made in the software need to be saved by pressing the **"update"**-button in the upper part of the field.

3.1.4.2 Investment category

In this category item pricing can be defined, such as formwork (SEK/m^2) and concrete (SEK/m^3) etc. If, for instance, a steel bridge is being analysed, the formwork and concrete sections are set to zero since these cost items do not exist. There are a number of pre-defined investment items that need to be set, but there is also a drop-box available to add additional items such as aesthetical costs, edge beams, cross beams etc.

Depending on which value that is the largest, the estimated investment cost stated in the general tab, or the sum from the breakdown of investment costs in this tab, decides which investment cost that will be used in the further calculations.

3.1.4.3 Maintenance category

The maintenance category is empty in the default mode, so there are no pre-set values in this category. A drop-box below the text "input" allows the user to add a number of predefined maintenance activities (15), and also "other", i.e. if the activity the user is interested in adding is not available on the list.

When the activity is chosen, push the "add new" button. Then the activity needs to be defined in more detail with regard to:

- Price (per unit)
- Quantity (number of units)
- Interval (of occurrence)
    - Fixed
    - Manual (define at which bridge age the activities occur, max five occasions)
- Traffic disturbance
    - Duration (per occasion in days)
    - Distance affected by the disturbance (in km)

The price per occasion consequently becomes the price times the quantity. The total cost will finally be the sum of the number of occasions that occurs during the bridge's service life. In addition, as a function of the input data set for traffic costs from the "general" category, the third party costs due to the maintenance activities are also computed. The sum of these two parameters is then brought along to the final result.

3.1.4.4 Repair category

The same analogy as for the maintenance category is used when the type of repairs and their incurred costs are to be computed. Nine predefined and one "other" option are available for selection for the super and substructure. Besides these, there are also twelve miscellaneous options.

After adding the repair activities, it looks almost just like in the maintenance category, except for the three extra input fields on the right hand side of each activity.

- Exposed to salt (Yes/No)
- Concrete quality (Kxx, according to the old Swedish standard)
- Relative concrete cover thickness

These input data are related back to the weighing factors set in the “general” category and taken into account to the final LCC result.

Below the selected repair activities there is also a link called: “Price List 2009 (Swedish)”. This link takes the user to BaTMan’s price list for activities on bridges, 2009 year’s issue. For more information on BaTMan, see Section 2.3.1. Worth noting is that the more up to date 2011 year’s issue was readily accessible on the BaTMan webpage.

When all desired repair activities have been added and prices, quantities, salt exposures etc. are set, the user can move on to the results category.

3.1.4.5 Results category

The last category is called result. When pressing that button in the lower part of the web browser, the program calls the MatLab/Excel interface and the inputs made by the user are computed into an LCC result.

The results are compiled as follows:

- A table of the original costs from the different categories and a summation of their present values
- Plots of costs, distributed over the bridge service life:
    - Repair costs
    - Maintenance costs
    - Traffic costs
    - Combined graph of: Investment, repair, maintenance, traffic and demolition costs
    - A pie-chart displaying the distribution of all the costs above, excluding the demolition costs
- An option of adding a sensitivity analysis to five of the activities added in the maintenance and repair category is also available below the plots. This is used when exact costs and/or interval of activities are unknown or not available.
    - To acquire the results from the sensitivity analysis, go to the cost and/or interval of variance, and then press result again.
    - The results are presented in a table:
        - Main cost (expected cost)
        - Standard deviation
        - Original cost
        - Change between main- and original costs, expressed as (%)

3.1.5 Summary – WebLCC and BroLCC

The WebLCC is a web-based computer software with its servers located at the KTH in Stockholm. At the time when this project was carried out, a few problems were encountered while using the WebLCC. Since WebLCC was a software yet under development and scheduled to be launched in January 2012, some minor flaws were anticipated. The developers’ objective with WebLCC was that the software would carry out LCC-analyses for different bridges in a way that would make the results useful for decision-making when comparing the LCC of different bridge solutions.

A sample bridge was run through the program in order to gain knowledge of its structure and the way it functioned. The software was then experienced as having an easy-to-follow structure. However, the results did not really turn out the way that they were expected to. A feedback to the ETSI project was formulated (seen in Appendix C) where the perceived shortcomings and errors were stated. The turnout was that the WebLCC project was shut down and focus was instead directed on developing its predecessor BroLCC further.

During the initial part of the project WebLCC was believed to be a useful tool when assessing the selected bridges described in Chapter 5. Fortunately BroLCC and WebLCC were basically the same software, which made the necessary switch between these softwares rather easy.

3.2 BridgeLCC

This section describes the US developed LCC software BridgeLCC that was used during this project.

3.2.1 Background to BridgeLCC

The Office of Applied Economics at the National Institute of Standards and Technology (NIST), USA, develops computer softwares. The purpose of these softwares is to provide aids in different areas of the construction industry. One of these areas is bridge construction and BridgeLCC was, much like WebLCC, developed to act as a decision-making tool for bridge designers in the early planning stages, NIST (2011).

The BridgeLCC was developed by M. A. Ehlen and is an LCC software that can compare the costs effectiveness of different compositions of structural materials or structural solutions for bridges, NIST (2011).

BridgeLCC v 2.0 was used in this project and was developed in the early 2000’s, where the last update was launched in September 2003. BridgeLCC is based on the American standard for measuring LCC for buildings and building systems (ASTM E 917), in combination with a cost classification that has been developed at the NIST. The cost classification schemes were introduced to the software to further aid an easy and efficient comparison between different project alternatives, NIST (2011).

This software is free for downloading at the NISTs webpage located at the URL *http://www.nist.gov/el/economics/bridgelcc.cfm*, and can be installed on any computer that has a Windows operating system.

3.2.2 Applications of BridgeLCC

The main purpose of BridgeLCC is to allow for easy comparisons between new structural materials or solutions to more conventional material and solutions for bridge types with regard to LCC. Nevertheless, it can still be used to solely compare different structural materials to each other. BridgeLCC is adapted to be used by engineers and designers with the purpose to analyse the LCC of preliminary bridge designs.

3.2.3 Conditions and constrains for Bridge LCC

The BridgeLCC is primarily designed for comparisons between concrete bridges with different concrete qualities or structural solutions. It works however just as well to compare and analyse two or more non-concrete bridges, such as timber or steel bridges. In fact, it does not even have to be bridges that are being considered, it could also be used to analyse pavements, piers and other civil infrastructures.

Examples of factors that can be analysed in the software are listed below:

- Alternative designs, structural materials, and construction processes
- Effects of different ways to manage traffic diversions
- The way different concrete mixes affects the strength and durability of the concrete in a specific environment
- Effects of repairs and replacements performed on a bridge

NIST (2011)

3.2.4 BridgeLCC features

A compilation of BridgeLCC's on-screen appearance can be found in Appendix A.

To start a BridgeLCC analysis, one of the following options needs to be chosen:

- Start new analysis
- Opening existing analysis

If "Start new analysis" is chosen, a new project is created. This is done in four initial steps. In these steps, properties will be assigned for the number of bridges, up to six alternatives at the same time, that the user wishes to include in the analysis. These steps require the following input data:

- Name of each bridge alternative
- Included components of the bridge(s)
- Dimensions of the bridge deck(s)
- Costs for construction, maintenance and disposal
- Inflation and real discount rate(s)

When the initial steps are completed, the current state of the cost calculations is shown in the "cost summary" window, see Figure 3.1 below. This window forms the platform for the whole program structure. From the "cost summary" window it is possible to assign additional input data along with other costs and activities. These activities can either be in common for all bridges, or unique for one of the bridge types. On the left hand side of the "cost summary" window, a model-tree can be found where 4 main categories are listed as seen below:

1. Data (see Section 3.2.4.1)
2. Tools (see Section 3.2.4.2)
3. Analysis (see Section 3.2.4.3)
4. Results (see Section 3.2.4.4)

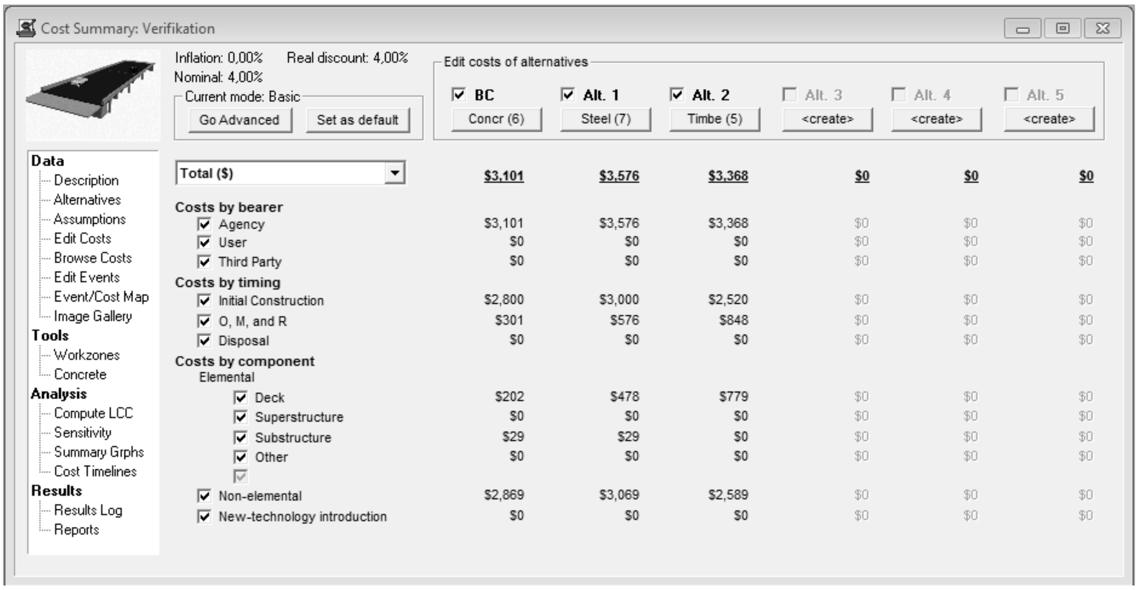

Figure 3.1. View of the Cost Summary window as seen in BridgeLCC. From this window, all settings and function can be chosen. Note the model-tree on the left hand side

3.2.4.1 Data section

In the Data category the user can assign data such as new costs, activities etc. to the bridge(s). The list below shows the “data” subcategories and a brief explanation of the features in each category:

- Description
  - Change the name, date and objective of the project
- Alternatives
  - Summation of properties, how many costs and activities that are assigned to each bridge type
- Assumptions
  - Divided into four tabs:
    - Economic
      - Changing the interest rate or the length of the design service life
    - Workzones
      - Assuming traffic conditions due to different activities. A more detailed description can be seen in Section 3.2.4.2
    - Concrete
      - Possibilities to adjust the concrete mixture
    - Elements
      - Assigning different elements for the bridge’s deck, superstructure, substructure, etc.
- Edit Costs
  - Possibility to create costs and assign them to specific activities
- Browse Costs
  - Summary of the costs assigned to each bridge type

- Edit Event
    - Create new activities, such as replacement of edge beams or painting of steel girders. The activities may be applied to all bridges at once or specific to one or more bridges
- Event/Cost Map
    - Summary of all the costs and the activities in the model-tree.
- Image Gallery
    - Picture/image gallery concerning the project, alternative bridges and results

3.2.4.2 Tools section

This category has two subcategories and is shortly described below:

- Workzones
    - When MR&R is in progress on the bridge and this activity might impact the traffic on and around the bridge, a workzone can be created and assigned to a specific activity or cost. The purpose of adding a workzone is to estimate the financial impact an activity can have on the traffic due to associated delays. These costs are in turn subdivided into the following three parts:
        1. Driver or delay costs – The additional costs to drivers from delays due to activities on the bridge
        2. Vehicle operating costs – The hourly cost for a delayed vehicle
        3. Accident costs – The costs associated with the increased risk of accidents within the bridge's workzone
- Concrete
    - Possibility to adjust the concrete mixture that is intended to be used on the bridge and also compute the design service life of that specific concrete mixture in the prevailing environment

3.2.4.3 Analysis section

LCC calculations are made continuously when new input data are added or changed in the model. The calculations are then collected and presented in graphs and tables. The subcategories to the analysis with a short explanation are shown below:

- **Compute LCC**
    - Updating the calculations if changes have been made to the model
- **Sensitivity**
    - The sensitivity analysis computes uncertainties to selected activities and costs respectively and how these affect the LCC. In the program the sensitivity analysis can be made in two different ways:
        - *Basic method* - In this mode the program performs a "best guess" for the frequency and timing of when different activities might occur. These guesses are made without any possibility for the user to manually insert an uncertainty
        - *Advanced method* - The program will perform the same calculations as the basic method, but this mode considers an uncertainty manually set by the user
    - During the analysis it is also possible for the user to switch between the basic and advanced mode without any loss of data
- **Summary graphs –** Three different graphs are displayed:
    - *LCC by Costs Bearer* – Presents results for each bridge alterative and is divided into:
        - Agency costs
        - User costs
        - Third party costs
    - *LCC by period* – Presents results for each bridge alterative and is divided into:
        - Initial construction
        - MR&R
        - Disposal
    - LCC by project component:
        - Deck
        - Superstructure
        - Substructure
        - Others
        - Non-element
        - New technology
    - **Note!** It is also possible for the user to add categories that the costs can be assigned to

- **Cost timelines -** Two different graphs are shown below in Figure 3.2 representing:

    - Yearly Costs (in Base-Year Dollars)
    - Year Cumulative Costs (in Base-Year Dollars)

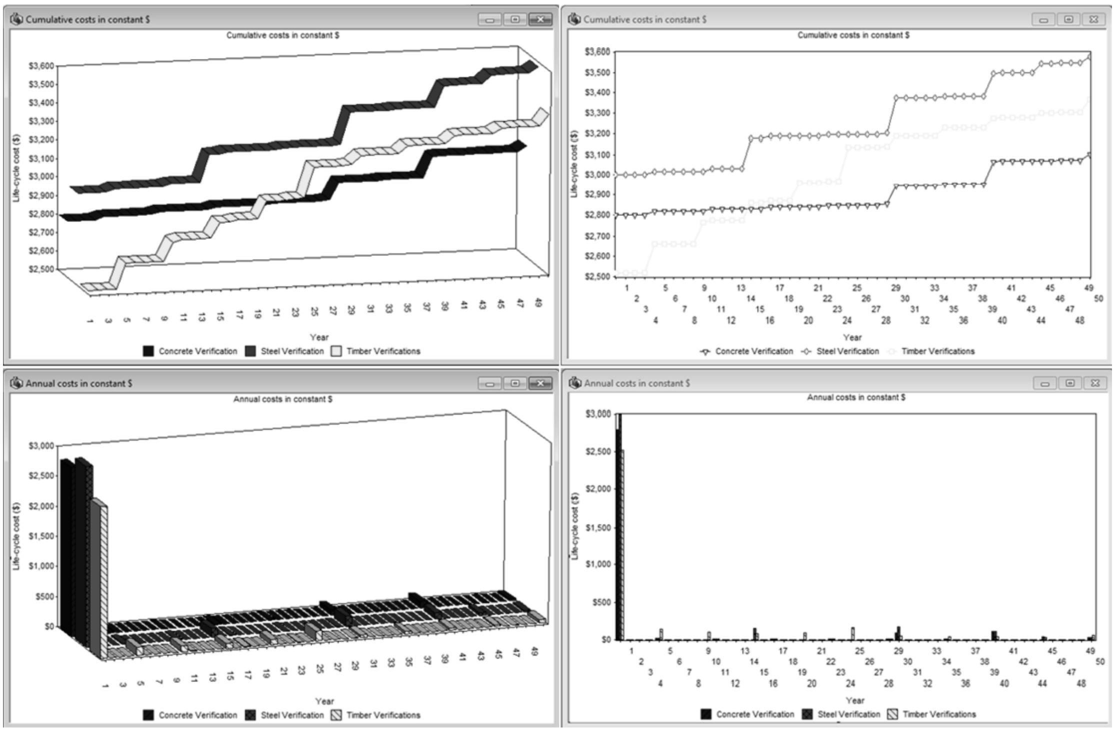

Figure 3.2. Example of result graphs that summarise the cumulative and annual LCC for three "test bridges" in BridgeLCC. The left hand graphs shows the result in 3D, while the right hand graphs shows the same result in a 2D-view

NOTE. More information on BridgeLCC's functions and how to work with it was found during the verification process, see Section 4.3.

3.2.4.4 Results section

In the last main category the results from the analysis are presented. In this category there is also a built in tool that automatically creates a report of the analysis. It is also possible to select which parts of the analysis that should be included and the software will then automatically arrange all selected data into the report.

3.2.5 Summary - BridgeLCC

The BridgeLCC is a software developed to perform LCC-analyses on bridges. It was developed by the National Institute of Standards and Technology, USA, and was last updated in September 2003. The purpose of the software is to, in a user-friendly way, provide an aid for engineers to compare bridges in different materials and/or design solution with regard to LCC. BridgeLCC can provide means for a user to already in the planning stage get an estimation of the costs incurred on a bridge during its entire design service life.

Unlike WebLCC, this software can compare up to six different bridges simultaneously. In addition, different activities and costs can be assigned to one or more of the bridges. The software summaries all the costs and displays them in diagrams and graphs. The costs can also be divided over the different structural parts and stakeholders of the bridge, both in Current-Year and Base-Year values.

3.3 Vännen07

This section describes the Swedish LCC software Vännen07.

3.3.1 Background to Vännen07

Vännen07 was developed in 2008 by the Swedish Road Administration in conjunction with a project called, translated into plain English, “Method/Manual for computation of MR&R costs for large investment projects with an LCC-analysis basis”. Vännen 07 is an Excel toolbox with the purpose to support computation of future MR&R costs. In that sense the Swedish Road Administration considers this approach to incorporate an LCC perspective of the decision-making for new infrastructural projects.

Vännen07 is also designed to be compatible with other softwares created by the Swedish Road Administration, such as the socio-economic toolbox EVA (effect from road analyses) and Kompis06 (used to compute investment costs). EVA is used to perform calculations with standard-based values, whereas Vännen07 as a whole has the ability to handle more object-specific calculations.

The basic idea is that a maintenance plan and available/assumed input data are compiled and run through the software. Then, according to the present value method, the LCC is computed and distributed as a yearly cost in order to better represent the operational costs. This is made according to the annuity method, explained in further detail in Section 3.4.4.1.

When or if Vännen07, Kompis06 and EVA are run together they form what the Swedish Road Administration calls “Polarn”, which is embodied by the elements shown below according to Forsman (2010):

- Mutual
- Investment costs (Kompis06)
- MR&R
    - EVA
    - Vännen07
        - Winter
        - Road
        - Road region
        - Bridge
        - Tunnel
        - ITS (Intelligent Transport Systems)
        - Disturbances
- LCC result

3.3.2 Applications of Vännen07

Vännen07 was developed by the Swedish Road Administration, written in Swedish and consequently adapted for Sweden. It could probably form a good basis to develop similar toolboxes for other countries, but today’s version is probably only suitable for use in Sweden.

Vännen07 is designed to, in the planning stage, handle larger infrastructural projects, meaning large stretches of road passing through tunnels and/or crossing bridges. Therefore the included features are not very detailed, but instead rather comprehensive for an entire project. The software has an emphasis on the road part, which is also the common denominator for all elements included.

3.3.3 Conditions and constraints for Vännen07

As mentioned in Section 3.3.1 above, Vännen07 is an Excel toolbox that was developed for use in Swedish conditions, and should therefore be used with care in other regions. The manual provided by Trafikverket (2008), states that it is intended to be used during the planning stage of projects. The standard-based costs in EVA are initially to be used for first drafts; thereafter they should be supplemented with more accurate data as the project advances.

The toolbox allows the user to define own or use standard-based parameters in eight different tabs seen in the Excel-view. Also see appendix A.

1. Overview
- EVA *(Unnumbered)*
2. Road
3. Road equipment
4. Bridges
5. Tunnels
6. ITS
7. Results

Each tab of these consists of numerous parameters to define. These parameters are arranged in tables with quantities, units and pricing. The various inputs and summations of data are linked to each other in the spreadsheet and summed up to an LCC result. Karlsson (2008) comments that the results given by Vännen07 are only reliable for design life cycles up to 40 years. This might be insufficient when considering bridges. 40 years is approximately only one third of the recommended design service life of a bridge. Karlsson (2008) also lists a number of inherent flaws with Vännen07, essentially related to the standard-based values used for the road and how they are unreliable due to roads being unique depending on which region and type of road that are at hand. In contradiction to what Karlsson (2008) suggested, the Swedish Road Administration claims that if calculation periods exceeding 40 years are needed, the discount rate could be lowered to acquire reliable results.

The result-tab is subdivided into two tables, one grey and one pink. The grey is a basis of accounting of management costs for investment projects, and the pink is dedicated for management purposes. Why the results are subdivided into two different tables is due to that the different stakeholders are interested in the same data, but presented in two different ways.

The estimation of the yearly maintenance costs is meant to show how the yearly cost is distributed for different elements of the road. A discounted amount would not be suitable for this assessment; therefore one column is dedicated to represent the maintenance costs without any discount rate (0%), i.e. no discount of costs in time is performed.

From a Swedish management point of view, investment projects should be characterised by indicators, which can be seen in the pink table in Figure 3.5. These indicators are supposed to supply the mangers with an overview of the financial consequences related to a technical solution. Indicators given in Vännen07 are the following:

- Yearly operational cost
- Distribution of yearly cost between maintenance and repair (%)
- Distribution between the different elements
    a. Road
    b. Bridge
    c. Tunnel
    d. Road equipment
    e. ITS
- Ratio of yearly operational cost and investment cost

Trafikverket (2008)

3.3.4 Vännen07 features

The Excel-file, which is free for download can be found on the Swedish Road Administration's webpage, URL: www.trafikverket.se.

As previously mentioned, the toolbox is built up around eight tabs seen in the lower part of Figure 3.3. A compilation of each tab's appearance can also be found in Appendix A.

Each of the tabs contains tables where input data can be defined, saved and then instantly computed into LCC results in tab 7. Which tabs to use and type of input data that is required depend on the scope of each project. If there for instance are no bridges on the stretch of road to be analysed, that tab can be neglected or set to zero. A brief walkthrough of the different functions and required input data for each tab follows below.

General colour coding for all tabs, which also is displayed (in Swedish) in Figure 3.3 below are:

- Yellow = Operating costs
- Green = Maintenance costs
- Red *flags in cells* = Comments and explanations of cells

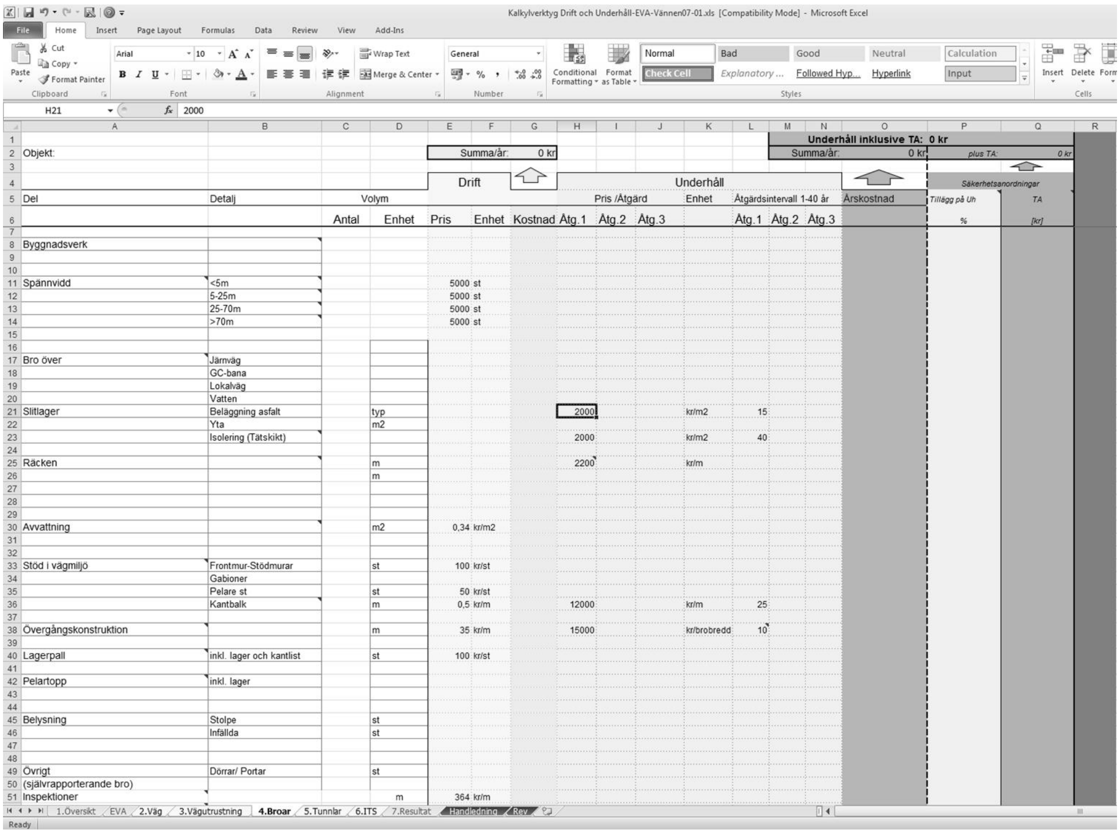

Figure 3.3. Excel view of Vännen07, note the tabs at the bottom (Swedish)

3.3.4.1 The overview tab

In this tab a general description and common input data are defined for a project.

- Discount rate (%), standard-value for Sweden = 4%, Trafikverket (2008)
- Design life cycle (in years)
- Price index (PIX) varies depending on year and has to be looked up. Default setting =1.0

The analysis should be applied on homogenous stretches of 1 km of road, meaning stretches of road with in terms of costs similar conditions with regard to MR&R. The results can then be extrapolated by a factor 5 if the actual homogenous stretch would be 5 km. A bridge with a total length of 500 m consequently results in a homogenous road stretch of 500 m.

3.3.4.2 The EVA tab

The EVA tab is used when standard-based values are needed, usually in the early stage of a project. According to the Swedish Road Administration, the use of this tab is only valid for preliminary studies; thereafter more object specific data will be required.

Required input data:

- ADT
- Road type (15 different predefined options)
- Yearly increase of ADT (%) optional

When all the data is set, the user needs to press the "Retrieve values and calculate" button. Standard-based calculations on 1 km of road are then performed and relayed to the result tab. The user can make adjustments to the standard-based costs when more detailed information is available. In that case further adjustments are needed in the result tab by dividing the yearly cost of the MR&R by the length of the road stretch, Trafikverket (2008).

3.3.4.3 The road tab

In the Road tab the following input data is required:

- Winter operation class
- Covering/surfaces
    - Drained
    - Noise abatement
    - Concrete
    - Asphalt
    - Gravel, etc.
- Drainage
    - Ducts
    - Manholes, etc.
- Ancillary facilities
    - Buss stands
    - Halting place
    - Parking, etc.

- Roadsides
    - Grass surfaces
    - Slopes, etc.

The requested units are: SEK/pc, SEK/m, and SEK/m^2. In addition there is also a model on the right hand side of the window where different pricings can be computed if input data is missing.

3.3.4.4 The road equipment tab

In this tab component costs and cost per piece are requested. The cost for road signs is a function of the previously set ADT. Similar to the previous tab, there is a model on the right hand side of the window to compute costs if relevant input data is missing.

The requested input data is:

- Central barriers
- Side barriers
- Noise barriers
- Road lightning
- Edge posts
- Wildlife fences

See on-screen views in Appendix A for further information.

3.3.4.5 The bridges tab

This tab allows the user to define a bridge, if that would be a part of the homogenous road stretch. The input data requested is not that detailed but gives an overview of the bridge's overall properties:

- Span
- What the bridge is crossing
- Type of surfacing layer
- Railings
- Drainage
- Supports in the road environment
    - Columns
    - Gabions
    - Edge beams
    - Retaining walls
- Bridge seat
    - Bearings
    - Edge strip
- Column top
    - Bearings
- Lightning
- Inspections
- Foundation
- Architectural

The input units are in: SEK/pc, SEK/m and SEK/m^2.

3.3.4.6 The tunnels tab

This tab addresses tunnel sections on the road stretch and requests the following input data:

- Length of the tunnel
- Tunnel area
- Traffic conditions during maintenance
- Surfacing
- Tunnel cladding
    - Walls
    - Ceiling
- Drainage
- Roadsides, etc.

The units of pricing are the same as in the previous tabs.

3.3.4.7 The ITS tab

This tab treats the costs related to traffic information systems (ITS), where the ITS-equipment is categorised in classes 1-5 with regard to MR&R. Information on how this is performed is found in cell *C6*, Excel spreadsheet. The cost for input data is expressed by pieces, and 8 different types of equipment are possible to define and also shown below:

1. Electronic payment systems (road tolls)
2. Security and rescue
3. Road traffic management
4. Public transport management
5. Driver support systems
6. Traveller support systems
7. Support for monitoring of legislative compliance (speed cameras)
8. Management of freight and vehicle fleets

NOTE. More information on Vännen07's functions and how to work with it was found during the verification process, see Section 4.3.

3.3.4.8 The result tab

Finally there is the result tab where the output data from all previous tabs are relayed and a final LCC result is computed and displayed in two tables. Note that there is an "UPDATE" button on the top border of the window.

LCC results from each section is gathered and displayed in the following table seen in Figure 3.4.

1	Resultat - underlag för redovisning av förvaltningskostnader för investeringsobje				4,0%			Uppdatera	
2	Indikatorer		Investering		Total årskostnad	Drift	Underhåll	Underhåll	
3	Komponentgrupp		Plan+marklösen	Utförande	Drift o underhåll	Årskostnad	Årskostnad	Diskont 0%	Diskont 4%
4			kr	kr	kr/år	kr/år	kr/år	kr/år	kr/år
5	Väg	Vinterdrift			130 000	130 000			
6		Beläggning, (vägkropp)			201 892	650	201 242	227 546	201 242
7		Avvattning			-	-			
8		Sidan om vägen, Övrigt			-	-	-	-	-
9		Summa		20 000 000	331 892	130 650	201 242	227 546	201 242
10	Vägutrustning	Vägmärken			-				
11		Vägräcken			2 217	2 217	-	-	-
12		Vägbelysning			-	-	-	-	-
13		Vägmarkering			59 216	-	59 216	60 000	59 216
14		Rastplatser och sidoanläggningar			-				
15		Bullerskydd			-				
16		Viltstängsel			-				
17		Övrigt			-				
18		Summa			61 433	2 217	59 216	60 000	59 216
19	Bro	Totalt			-				
20					-				
21		Summa			-	-	-	-	-
22	Tunnel	Totalt			-				
23					-				
24		Summa			-	-	-	-	-
25	Väginformatik/ITS	Totalt			-				
26					-				
27		Summa			-	-	-	-	-
28	Övrigt				-				
29									
30	Summa totala kostnader		-	20 000 000	393 325	132 867	260 458	287 546	260 458
31			[kr]	[kr]	[kr/år]	[kr/år]	[kr/år]	[kr/år]	[kr/år]

Figure 3.4 View of the result-tab in Vännen07

The area marked in a dark-grey colour shows the investment costs; these cells can be filled in manually, preferably with output data from Kompis06 that also is available on the Swedish Road Administrations webpage.

In the table shown in Figure 3.5 below, another (pink) table is displayed in the results tab, presenting the indicators mentioned in Section 3.3.3.

Indikatorer

- Förvaltningens årskostnad (kr) *393 325 kr*

- Årskostnadens uppdelning i drift och underhåll (%)

Andel Drift	*33,8%*
Andel Underhåll	*66,2%*

- Årskostnadens fördelning på komponenter väg, bro, tunnel, vägutrustning, väginformatik (%)

Väg	*84,4%*
Bro	*0,0%*
Tunnel	*0,0%*
Vägutrustning	*15,6%*
Väginformatik	*0,0%*

- Förhållandet Förvaltningsårskostnad / Investeringskostnad (%). *2,0%*

- Förhållandet Förvaltningsårskostnad / ÅDT_ap. *0,359 kr/mil/axelpar* 1000 30000

Figure 3.5. Vännen07 view of the indicators intended for management stakeholders

3.3.5 Summary - Vännen07

Compared to the two previous LCC softwares explained (WebLCC/BroLCC and BridgeLCC), Vännen07 is designed in a more general fashion for infrastructural projects, where bridges only represent one of many other elements. A future development might be to import output data from a more bridge-specific program to Vännen07 for more accurate results.

The software can, according to Karlsson (2008), only deliver reliable LCC results over a design life cycle up to 40 years, which might be too short when considering bridges. The question is if any LCC-analysis with a design life cycle of more than 40 years can be seen as reliable? There is a possibility to manually set the design life cycle to more than 40 years. In that case the Swedish Road Administration's recommendation is to adjust the discount rate.

For further studies on Vännen07, see the appended "Manual Vännen07" included in the download package on the Swedish Road Administration's webpage. That document is also the primary source of information for this Section 3.3.

3.4 Hand-calculations

This section presents a general description of the basic calculations that the LCC softwares are based upon.

3.4.1 Background to hand-calculations

Three computer softwares were used in this project to perform the LCC calculations; WebLCC (which was replaced by BroLCC), BridgeLCC and Vännen07. In these softwares different numbers of input data were requested and the softwares would then perform LCC calculations and summarise and present the results. The softwares themselves work like black boxes and the calculation processes are not always easy for the user to follow. Therefore it was necessary to verify the results that the softwares delivered, before starting to use them. This was made by simplified hand-calculation that would provide verification on whether the results from the softwares are reasonable or not.

3.4.2 Applications of hand-calculations

The hand-calculations are based on the present value method, which is said to be the common calculation method used in all softwares. By using the present value method the user is able to in a simple manner get an estimation of costs that may occur in, for instance 50 years into the future and its corresponding value today (present value). Using this method is a good way to compare two products based on all the costs that will occur from one point in time and at different occasions during the whole service life of the products. This provides a reference of the total costs that is easy to refer to.

3.4.3 Conditions and constrains for hand-calculations

Regarding hand-calculations, there are no constrains on how many different factors that can be taken into the account; it is only a matter of how much time the user is willing to put into the analysis. In this project, computer softwares performed the greater part of the calculations and formed the basis of the analyses that followed. Computer softwares have the advantage of performing more and faster calculations than what would have been possible with hand-calculations. The hand-calculations were in this project only used to perform simple verifications of the result integrity of the softwares' output data.

3.4.4 Hand-calculations features

This section describes different features used when performing hand-calculations.

3.4.4.1 Present value calculations

The method for the hand-calculations was first to define the costs that occurred on a bridge at different times during its design service life. The different costs were recalculated according to the present value method and then summed up to a base year cost, see Figure 3.6 below. The present value is calculated according to Equation (3.1), which is explained in Section 2.1:

$$LCC = \sum_{n=0}^{L} \frac{B_n}{(1+r)^n} \tag{3.1}$$

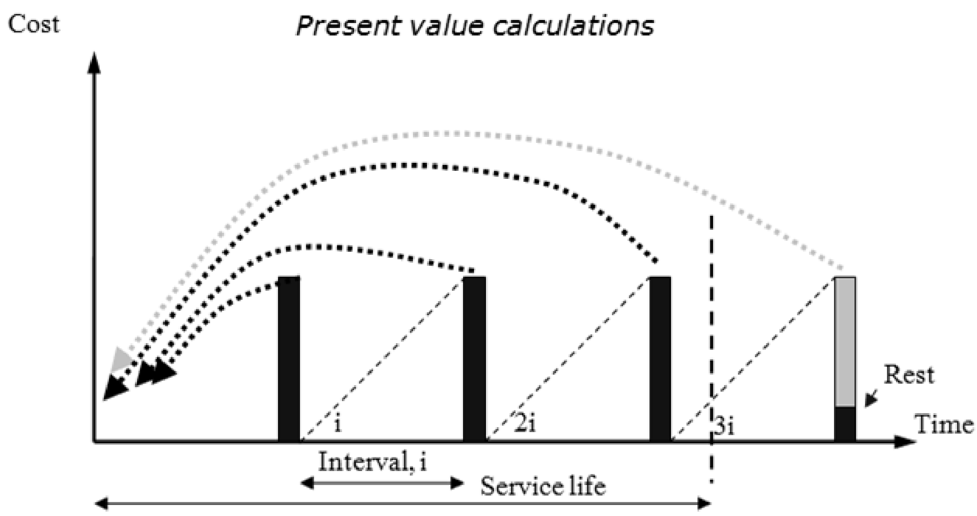

Figure 3.6 Illustration of the basis of present value calculations on periodically reoccurring maintenance activities, Trafikverket (2008)

The resulting present values from the different costs are summarised to get one value for the total cost of a bridge, the LCC. In cases where bridges have different design service lives, it might be more adequate to evaluate what the yearly costs are during the design service life is instead. In that case, the total cost is redistributed to a yearly cost which is equally distributed over the years that the calculation period includes (K_{yearly}). That type of calculation is performed by using the annuity method, defined by Equation (3.2) and (3.3) seen below:

$$K_{yearly} = K_{present} \cdot AF \tag{3.2}$$

Where:

K_{yearly} = Yearly cost

$K_{present}$ = LCC (as stated in Equation (3.1) above)

AF = Annuity factor

$$AF = \frac{r}{1-(1+r)^{-n}} \tag{3.3}$$

Where:

n = Age of which the present value is discounted from

r = Discount rate (usually 4 % in Sweden)

This way to calculate is preferable when it comes to comparisons between projects with different calculation periods. For projects with the same calculation period it works just as well to compare the present value cost (LCC), Trafikverket (2008).

3.4.4.2 Hand-calculations of traffic costs

As mentioned before, the traffic costs can have a significant influence on the LCC for a bridge if the *ADT* exceeds a certain critical value. The effect an activity has to the traffic flow depends on how the traffic is managed with regard to reduced speed, detours, temporary constructions, redirections etc. A simplified method is to focus on the driver delay cost (C_{driver}). This method, which is used in BridgeLCC, is based on the loss of time due to a decreased speed on a defined stretch of road (L/v_{red}-L/v_{norm}) as seen in Equation (3.4) below. In that expression, L is defined as the affected stretch of road (workzone) and v_i the speed (normal or reduced). By multiplying the loss of time with the hourly cost (C_{cost}) for a vehicle, how many vehicles that are affected during a day (*ADT*) and finally how many days this traffic situation prevails (D_{days}), a price can be put on the traffic disturbance caused by an activity. Thereafter, the same procedure as has been shown in Section 3.4.4.1 that is used to acquire a corresponding LCC for the traffic costs can be used. The equation described, which is also used to compute the traffic costs, is shown below in Equation (3.4), Julita (2008).

$$C_{driver} = \left(\frac{L_{workzone}}{v_{red}} - \frac{L_{workzone}}{v_{norm}}\right) * ADT * D_{days} * C_{delay} \tag{3.4}$$

Where:

C_{driver} = Total driver delay cost

$L_{workzone}$ = Size of workzone

v_{red} = Reduced speed limit trough the workzone

v_{norm} = Speed limit during normal conditions

ADT = Average Daily Traffic

D_{days} = Duration of MR&R work

C_{delay} = Hourly cost for delay

3.4.5 Summary – Hand-calculations

In this project hand-calculations were used to perform verifications of the results that were delivered from the three computer softwares; WebLCC/BroLCC, BridgeLCC, and Vännen07. See Chapter 4 for more information on the verification process. The calculations were performed by the use of the present value method. Note that the hand-calculations not were used in the same extent as the computer softwares, but only to verify that the softwares provided reasonable results.

3.5 Summary – Available LCC softwares

In the preliminary project investigation, two suitable bridge-specific and one comprehensive computer software performing LCC calculations were found. These softwares were further investigated with regard to their constraints, areas of applications and how they worked. Later in the project, one of these softwares, WebLCC proved to be unsuitable for further use, but could easily be replaced by its very similar predecessor, BroLCC.

Common for all softwares was that the calculations were performed by the means of the present value method. Since the computations performed by the softwares seldom were transparent, the output data from the softwares also needed to be verified.

The two bridge-specific softwares were more or less related, mostly because the BridgeLCC software inspired the WebLCC designers. However, the layout is far from the same and the way that data is presented and the further possibilities to manage the output data is far more developed in BridgeLCC. It is worth to note that WebLCC software was under development at the time and the uncertainties regarding its reliability and function were unknown. Therefore, parallel to the project, a constant feedback process of our experience from the use of WebLCC was delivered to the ETSI project, developers of the software.

Vännen07 was the more comprehensive software where the road itself was the main emphasis and bridges were more seen as parts of the road. Vännen07 was intended to be used to evaluate what differences simplifications had to the LCC-analysis and if it was possible to improve the output data by using bridge-specific LCC-analyses as a complement to Vännen07, for a better overall LCC result.

The computer softwares were the primary tools for the LCC computations on the selected bridge types, presented in Chapter 5. Further analyses and implementation of alternative detailing solutions with regard to LCC are presented in Chapter 7.

4 Verification of the LCC softwares

This chapter describes the verification process performed on the LCC softwares that are described in Chapter 3.

4.1 Background to verification

The LCC computations were supposed to be conducted and compared with the result from the LCC softwares mentioned in Chapter 3. In order to ensure the reliability of these results, their function had to be verified to the basic LCC method. In this chapter the verification process and the results are described.

4.2 Procedure for the verification

In Section 3.4, the method used to perform hand-calculations is explained. That method forms the basis for all LCC computations, as well as for the softwares mentioned. Therefore a simple check of the output data retrieved from predetermined input data can be compared to hand-calculations.

The hand-calculations were performed in Mathcad, and can be seen in Appendix B, where the basic Equation (3.1), the annuity Equations (3.2) and (3.3) and the traffic costs Equation (3.4) were implemented. Then the following arbitrary input data was inserted for verification purposes, both in the LCC softwares and in MathCad:

- Bridge properties (concrete bridge)
  - Length = 20 m
  - Width = 7 m
  - Area, bridge deck = 140 m^2
- Design service life = 50 years
- Discount rate = 4 %
- Total investment cost = 2.8 MSEK
- MR&R costs:
  - Edge beam replacement = 10,000 SEK/m (every 40^{th} year)
  - Railing replacement = 3,000 SEK/m (every 40^{th} year)
  - Surfaces replacement = 2,000 SEK/m^2 (every 30^{th} year)
  - Bearings replacement = 50,000 SEK/pc (every 50^{th} year)
  - Continuous inspection = 1,000 SEK/m (every 6^{th} year)

Since the softwares deliver different types of LCC results, seen in Chapter 3, different modifications in the verifications were needed.

- WebLCC (and BroLCC) delivers gross, distributed and category-based LCC for:
    - Investment
    - Maintenance
    - Repair
- BridgeLCC delivers gross LCC for:
    - Investment
    - MR&R
    - Demolition
- Vännen07 delivers yearly LCC for:
    - The gross cost from each tab
        - Cost distribution can be found in each tab

The same input data were inserted into the softwares, and the delivered results were compared to the corresponding hand-calculations' result. Correlations between the results were not acquired immediately during the verification. In order to identify possible errors in the softwares or hand-calculations, the problems encountered were broken down into single cost problems, e.g. only analysing the LCC of the edge beam, followed by a trial and error process. Fortunately it was found that the errors observed, actually were due to previously unknown assumptions performed by the computer softwares.

When the WebLCC was to be verified, even though there were doubts of its reliability in the beginning, it came as a surprise when it was found that the software could not be used at all. Basic functions as the relay of data between the different category tabs, and the labelling of results were all out of order. These errors were reported to the ETSI project group and ended up in that the WebLCC software was shut down. The project group led by Sundquist[1] decided to further develop the initial software BroLCC, and launch it as a software available for download instead. As an alternative to use WebLCC, Sundquist provided the BroLCC that was more or less identical to the WebLCC, besides for it being Excel based. Nevertheless, it was successfully verified like the other softwares. The majority of these matters were discussed at the ETSI/Master thesis meeting, held in Stockholm the 27th of October 2011. Minutes of meeting can be seen in Appendix D

In conclusion, the verification process proved to be very valuable in order to get a deeper understanding of how the softwares were built up and which assumptions, not always obvious, that were conducted by the programs. These findings are listed in Section 4.3 below.

A separate Mathcad-file was created for each of the verifications. Each Mathcad-file containing the entire calculations, results, the corresponding software result and the difference of the results can all be seen in Appendix B.

[1] Håkan Sundquist, Royal Institute of Technology. Interviewed 2011-10-27

4.3 Results of the verification

Through the verification process it was found that the softwares did in fact deliver reliable results. However, some minor discrepancies, in the order of 0-3%, were observed in the final results, most likely due to rounding of the results.

During the process it was found that assumptions, some in common for all softwares and some unique, were made. The assumption that were made are listed below:

- If a cost activity is due to take place at a certain age of the bridge (year), the cost is discounted from the year before this certain age
  - This was in common for BridgeLCC and Vännen07
  - BroLCC discounted the cost from the actual age of when the activity occurred
- A rest-value from a reoccurring activity is accounted for at the end of each analysis period in Vännen07, hence presenting a slightly larger LCC compared to conventional present value calculations. Also see Figure 3.6, where the consideration of the rest-value is illustrated
- Discrepancies in the results were found in BridgeLCC and Vännen07, whereas the results from BroLCC correlated exactly, see Appendix B

4.4 Summary – Verification of LCC softwares

The verification of the LCC softwares was concluded to be adequately successful, and it could be reasonable to assume that the output data delivered from the softwares were reliable for further use.

After trying to verify the WebLCC, it was found that the software could not be used. The developers i.e. the ETSI project, decided to shut down the web-based software and further develop the initial stand-alone and Excel-based software BroLCC instead. Because of the almost identical function and layout of these two softwares, it was decided to precede the project with BroLCC instead.

It was noted that the softwares presented the results in different ways, mainly depending on for whom the results were intended. BroLCC and BridgeLCC delivered gross LCCs, whereas Vännen07 delivered the yearly costs, based on the gross LCC by the use of the annuity method. Moreover, Vännen07 also took a rest-value of reoccurring activities into account. That choice results in that Vännen07 sometimes deliver a slightly higher LCC result than the other softwares. If the rest-value should be accounted for or not is not agreed upon depending on who you ask, Trafikverket (2008).

5 Bridges to Analyse

This chapter presents the background and method for the selection of the bridge types that were analysed in this project. The assumed constraints that governed the selection are presented along with general facts about the different bridge types, their structural designs and materials.

5.1 Background to bridges to analyse

For the result from the LCC-analysis to be of interest to as many stakeholders as possible, it was necessary that the analysis reflected a general and relevant case. Bridges like other engineering structures are generally built in three main materials, concrete, timber and steel. These materials were also considered in the choice of bridge types.

As stated in Section 1.3, one aim of this project was to perform LCC-analysis on three different bridge types, one for each of the main materials. The analysis was performed considering today's normal practice regarding typical problems associated with each bridge type (case 0). Thereafter, alternative solutions were suggested to evaluate how these would affect the outcome of the result from a second LCC-analysis (case 1). A comparison of these two analyses allowed for an identification of sensitivity factors, i.e. factors that have great impact on the LCC. These findings were later supposed to form the basis for the results and conclusions drawn from this project.

As mentioned in the scope of the project, Section 1.4, the bridges of interest should be short-span, designated for road traffic, placed in an urban environment and be configured like other widely used structural system for the pre-set conditions. These distinctions narrowed down the number of possible bridge types, but a selection still needed to be made. Section 5.2.1 below describes the selection of the bridge types that were further analysed.

5.2 Selection of bridge types to analyse

The selection of bridge types that was performed is described in the following section.

Regarding the short span, the distinction instantly eliminated a number of bridge types such as:

- Suspension bridges
- Arch bridges
- Cable stayed bridges
- Truss bridges
- Box girder bridges

The selection was more or less narrowed down to the use of slabs, beams or frame structures when short-span bridges were considered.

Regarding the concrete bridge, the option first stood between using a slab, beam or a beam/slab-frame bridge. The beam/slab-frame bridge has a limitation of not being suitable for span longer than approximately 15-20 m, which could have been accepted with regard to the scope. However, the beam bridge can have both longer spans and several supports in comparison to the frame bridges, which better suits the scope and the abundance of the bridge type.

The most common design of beam-type concrete bridges, in Sweden today, was considered to be the back-wall bridges. This design is also possible for steel bridges, but not timber. The timber alternative would have been to design it with freestanding abutments instead of the back-walls solution. The solution with freestanding abutments calls for the necessity of transition zones. The transition zones have been considered a problematic and vulnerable detail on bridges, and should be avoided if possible. Hence, a back-wall concrete bridge was chosen to represent the concrete alternative.

Regarding the steel bridge alternative, it was instantly concluded that short-span “pure” steel bridges are not that common in Sweden at all. However, a number of short-span composite steel bridges can be found in the Swedish bridge stock. The most common way to carry out this design is by fitting two or more steel girders on the supports and then cast a concrete slab onto them. For the same reasons as when concrete was considered, the back-wall type is the most common way to design for this type of bridge. This resulted in that a composite steel bridge was chosen to represent the steel alternative.

Regarding the timber bridge, most of them are, in disagreement with the scope, either pedestrian bridges or found in the northern parts of Sweden. Nevertheless, timber bridges are gaining an increased interest, even in the southern parts of the country, and would therefore still be relevant to include in this project. There are many different ways to design timber bridges, but the most common design for road traffic is an assembly of transversally prestressed glulam beams. These glulam beams could either form a box girder or a slab. The box girder design is usually used for longer spans, whereas the slab is more common and easier to construct. Due to timbers vulnerability to moisture, the back-wall design was not suitable when considering timber bridges. The soil in Sweden is considered to always be 100 % moist, the direct contact of the load carrying back-wall and the moist soil should be avoided, TK Bro (2009). Whether a sealing layer could protect the timber parts in the back-wall or not is considered to be associated with too many inherent uncertainties to be used. Hence, freestanding abutments are the most common solution for timber bridges. In conclusion, a transversally prestressed glulam slab, with freestanding abutments was chosen to represent the timber alternative.

A more detailed description of these design solutions, their advantages and disadvantages are described in Sections 5.2.1-5.2.3 below.

5.2.1 The reinforced concrete beam bridge with back-walls

Today concrete is the most commonly used building material for bridges. In Sweden, 9 out of 10 bridges are built in concrete. Concrete is a well-known and studied material for bridges and is often used when constructing short-span bridges. Reasons for this are its good durability, low costs and long tradition as a bridge building material. Some associated disadvantages are its high self-weight and long constructing time. Nedev, Khan (2011).

The first bridge type that was chosen in this project was the concrete back-wall bridge. This bridge type has been built in Sweden, with good experiences, for the last 20-25 years. The superstructure of the back-wall bridge consists of a slab, resting on beams and two back-walls, one at each end. The back-walls are in direct contact with the soil where the earth pressure from the backfilling is acting at the ends of the back-walls. This allows the back-walls to carry all the horizontal forces exerted on the bridge deck, and therefore no transition zones are required. Horizontal forces exerted on the bridge deck are usually caused by thermal expansions, break and acceleration forces, and these are all transmitted into the soil in the surrounding embankment. Rutgersson (2008).

The substructure usually consists of two or more supports and a base-slab, which is placed close to each back-wall. The bridge spans continuously over the supports, where a bearing separates the bridge from the support, see Figure 5.1. Rutgersson (2008).

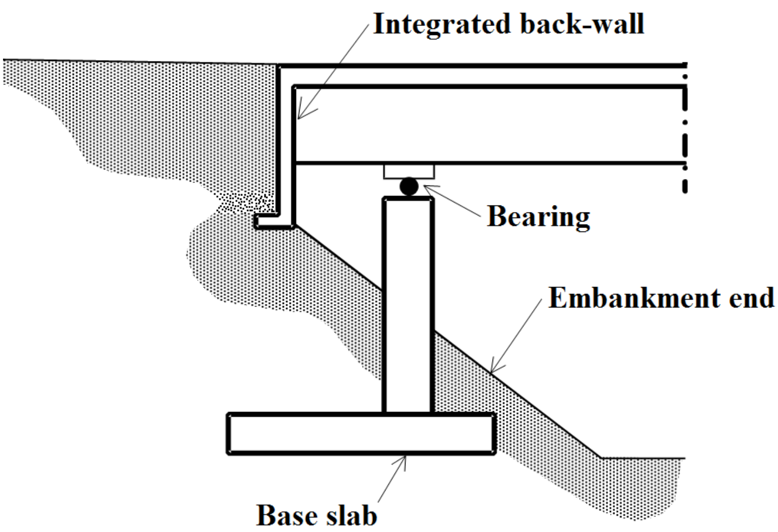

Figure 5.1. Illustration of the back-wall and column of a back-wall bridge, WebLCC (2011)

5.2.2 The composite steel/concrete beam bridge with back-walls

The development of composite steel bridges has been significant for the last 20 years, especially in Sweden. This bridge type is becoming more established on the market and the main reasons are the possibilities to assemble bridges faster and easier, since it is possible to use prefabricated components, e.g. the steel girders and in some cases even the concrete slabs. By using prefabricated elements, the construction time can be cut shorter and also reduce the effects on the surrounding environment and the traffic on the adjoining roads. Stålbyggnadsinstitutet (2011a).

The composite bridge is built up around two load carrying system, consisting of a number of steel girders, which in turn can support the formwork when casting the concrete deck. The second load carrying system is consequently the concrete deck. The interaction between the steel girders and concrete deck is achieved by steel studs, welded onto the top flanges of the girders. The slab is then cast onto the studs as seen in Figure 5.2 below. Stålbyggnadsinstitutet (2011b).

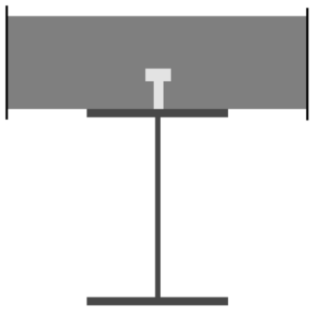

Figure 5.2. Illustration of a steel stud welded to the top flange of a steel girder. When the concrete deck is casted onto the stud and the steel girder, interaction between the steel and the concrete can be achieved

It is also possible to build composite bridges by combining other materials, e.g. timber and concrete. Steel and concrete is however the most commonly used combination.

5.2.3 The transversally prestressed glulam slab bridge

To use timber as the primary load carrying material for road bridges is not as common as for concrete or steel. In Sweden there are a few examples, most of them found in the northern parts of the country.

The main advantages of using timber as a construction material for bridges are its high load carrying capacity in relation to its weight, short construction time, sustainability, and its aesthetically pleasing appearance. Disadvantages that are often mentioned are the durability aspects and its relatively short service life compared to concrete and steel, Nedev, Khan (2011).

Nevertheless timber bridges have a long tradition, especially when it comes to short-spans bridges. New solutions are constantly developed, mostly to improve the durability, and nowadays it is generally assumed that it is possible to build timber bridges with the same durability and design service life as concrete or steel bridges, Martinsons (2011a).

The third and final bridge type that was considered in the project is the transversally prestressed glulam slab with freestanding abutments, illustrated in Figure 5.3 below. The bride deck consists of glulam beams joined together by transversally prestressed steel bars. The timber deck is resting on two independent abutments, one at each end. The abutments are usually are made of concrete and separated from the glulam slab by bearings. The horizontal movements are allowed for by the transition zones, located in the gap between the bridge deck and the abutments. This design solution was considered to be the most common and suitable for short-span timber bridges designated for road traffic.

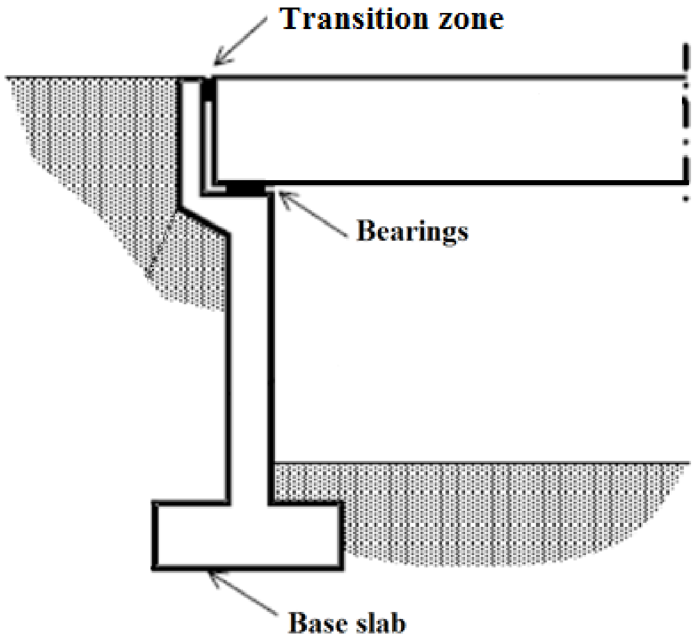

Figure 5.3. How a transversally prestressed glulam slab is fitted to a freestanding abutment, WebLCC (2011)

5.3 External conditions for the bridges

To make it possible to perform as accurate analyses as possible to base the LCC method on, general external conditions needed to be assigned to each bridge type.

In Sweden the majority of the residents live in the southern parts of the country, mainly in urban areas. That naturally results in that the majority of the bridges being built in Sweden also are located within these regions. An exception was made for the timber bridge, where most of the road traffic bridges in contradiction are built in sparsely inhabited north of Sweden.

The bridges that were to be analysed in this project got assigned the same surrounding conditions that would be representative to what the largest possible population of bridges in Sweden would be exposed to. In conclusion, the assigned condition would represent an environment, general to most bridges in the southern parts of Sweden.

- The bridges were to be located in an urban area, at a location with a moderately high ADT
    - The magnitude of costs incurred on the bridge users are usually caused by congestions and delays during MR&R activities on the bridge. This cost is highly dependent on the ADT
- The bridges were not to be located near or in contact with any fresh or sea water
    - Thus omitting the increased rates of deterioration due to erosion and chloride intrusion.
        - This situation would not have reflected the larger population of bridges
- Year of construction
    1. This was important in order to reflect a technical knowledge as current as possible. Preferably, the bridges should have been built as recently as possible
    2. In order to acquire as much information as possible on typical problems and MR&R activities associated with each bridge type, the bridges should have been built as long ago as possible
    - Paragraph 1 and 2 above, are in an obvious disagreement to each other
        - It was assumed that bridges built in the 1990’s would represent today’s technical knowledge fairly well, and that a database of MR&R would have had the time to accumulate

5.4 Summary – Bridges to analyse

This chapter described the three bridge types that were chosen, the selection process and a comprehensive explanation on the three corresponding design solutions. Finally, external conditions were assigned to the bridge types for further use later in the project.

The bridge types that were to be chosen should represent the most common design solutions for short-span road bridges that can be found in Sweden. These bridge types were later to be used in a comparative LCC-analysis, between a case 0, and 1. Where case 0 was representing today’s normal execution and problems associated with them for each bridge type. Case 1 was to represent the same bridge types with alternative design solutions implemented on the problematic details.

It was concluded that the following bridge types would represent the largest, most common stock of short-span road bridges found in Sweden at the time of the project:

- **Reinforced concrete beam bridge with back-walls**
    - Continuous beams and slab without transition zones, and back-walls carrying the horizontal forces by the means of earth pressure acting on the back-walls. This bridge will be referred to as the concrete back-wall bridge in the following chapters
- **Composite steel/concrete beam bridge with back-walls**
    - Concrete slab fitted with back-walls as explained above, where the slab rests on two or more steel girders. This bridge will be referred to as the Composite steel bridge in the following chapters
- **Transversally prestressed glulam slab bridge**
    - Glulam beams joined together by the means of post-tensioned prestressing bars to form a timber slab. The slab rests on freestanding abutments and transition zones are required

A brief explanation followed on the properties, advantages and disadvantages for each bridge type.

Section 5.3 above, described the external conditions that were assigned to the bridge type with regard to:

- **Geographical location**
    - Southern Sweden
- **Surrounding environment**
    - Urban area
    - No fresh or sea water in direct contact with the bridge
- **ADT**
    - Averagely high, according to urban areas in Sweden
- **Year of construction**
    - With regard to technical knowledge (today)
    - With regard to MR&R data (as long ago as possible)
        - With regard to both these points, bridges built in 1990's were to be selected

6 Basis for analysis

This chapter outlines the process used to acquire a compilation of information/data regarding problems and alternative detailing solutions, which was later used as a basis for the analysis following in Chapter 7.

6.1 Background to the analysis

The compilation was one of the key factors in the project since it provided an objective picture of the current state of the bridge types, i.e. which problems which were associated with the particular bridge types. The best way of acquiring this data would be to get an extract from the BaTMan database on a population representing the stock of each bridge type.

From this data, there was a need to sort out location-unique cost situations, i.e. construction errors, extreme environment, poor foundation conditions etc.

After scoping out the relevant data, a compilation could be formed. When the compilation had been finalised and standard costs had been assigned to each cost item, the LCC-analysis could be performed. A following investigation of alternative detailing solutions and possible improvements, with regard to the problems, that could be utilised could then be conducted. After having assigned these new detailing solutions standard costs and running a second LCC-analysis, the results from the two analyses could be compared and evaluated. The sought sensitivity factors could also be identified after this process. Conclusion could then be drawn on where costs, that significantly affect the LCC of all bridges of this kind, were incurred both in time and size and which effect alternative detailing solutions could have.

Unfortunately the record keeping on bridges in Sweden is not always what it should be. Therefore the quality of the records often varies depending on bridge manager and whether it is a bridge owned by the Swedish Road Administration or a local municipality. This uneven level of quality on the information in the bridge records held in BaTMan was one of the first obstacles that Racutanu[2] stressed. Jensen[3], also a participant in the ETSI project, initiated the contact with Racutanu. Racutanu was representing the Swedish Road Administration in the ETSI project with a level of authority to perform precision inquiries from the BaTMan database. For Racutanu to be able to provide this project with the sought information, a specification was needed. This specification was delivered to Racutanu at a meeting at the KTH in Stockholm, on the 27th of October 2011. The specification can be found in Appendix C and the minutes of the meeting in Appendix D.

Racutanu unfortunately announced that the kind of inquiry that was asked for was very complex and would require a far too great effort for him to be able to help out. Even though some problem with the inquiry was expected, efforts to alter the inquiry to make it more manageable turned out to be unsuccessful.

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[2] George Racutanu, Trafikverket. Interviewed 2011-10-27

[3] Birit Buhr Jensen, COWI Copenhagen. Interviewed 2011-10-27

A different approach was then needed in order for the project to proceed. An alternative method to acquire the basis for the analysis was developed in collaboration with the master thesis examiner at Chalmers. The new method had the following consequences to the project:

- Instead of an objective basis for the analysis, the information needed to be taken from interviews with experienced bridge managers

- Basing the compilation on the opinions of bridge managers decreased the scientific credibility of the analysis itself
    - In the sense of developing an approach on how to use LCC-analysis as a decision-making tool in the design stage, the lack of credibility in this particular analysis was considered to be of minor relevance

In response to the changed conditions, the following compilation of the different bridge types' current conditions 2011 was created. The condition was compiled with regard to; MR&R, conducted, planned and observed problems. This compilation was conducted through interviews with experienced bridge managers and designers. The bridge managers that are referred to in the following sections are also listed in Appendix E.

6.2 Typical problems related to concrete back-wall bridges

Back-wall bridges have, as mentioned in Section 5.2.1, the advantage of not having any transition zones. Therefore the design inherently eliminates all problems with the leaking and wearing of joints. Problems and their corresponding standard counter activities are explained below.

6.2.1 Settlements at the back-wall

One typical problem that has presented itself among most back-wall bridges is settlement in the back-wall region. The settlements usually takes place within months after the inauguration and can be up to 20 mm. The magnitude of the settlements is highly affected by the degree and height of compaction of the backfill soil and the length of the bridge deck. This is due to the settlements being induced by the expansion and contraction of the bridge deck due to varying temperatures; this effect increases with an increased length of the bridge deck. When the bridge deck expands, it will exert a pressure on the backfill. When it later contracts, a void is left behind. This void is then filled with the overlaying ground where the road structure rests. This mechanism, illustrated in Figure 6.1 below, creates damages to the asphalt and as a secondary effect, also to the vehicles driving on the bridge. These settlements also generate a discomfort for the drivers, Svensson (2011-10-28).

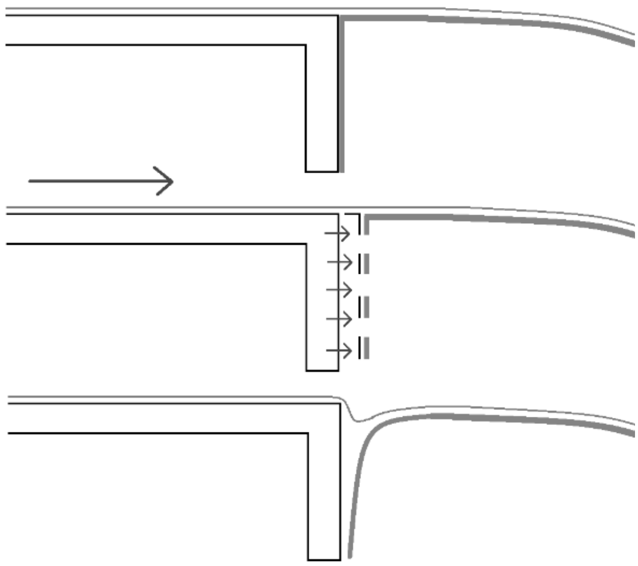


Figure 6.1. Formation of settlements at concrete back-wall bridges

Worth to notice is that in a conventional design, constructed with transition zones that allow the horizontal movements of the bridge deck, this problem does not occur. On the other hand, that design solution has to deal with the problems, mentioned in Section 5.2.1.

Measure to deal with this phenomenon is simply to even out the settlements with an additional layer of asphalt. This activity will most likely have to be repeated with an interval, approximately every 5-10 years during the 50 first years. The measure itself cost money and also generates traffic costs, since it will disturb the traffic at every occurrence. Worst case scenario would be if the dead weight of the asphalt layers themselves increases the settlements even more. That could result in an extensive activity where all the asphalt needs to be removed, replaced with a new backfilling material and the settlement cycle would starts over.

Bäckström (2011-11-14) mentions that if there is a need to repeatedly correct settlements every 10th year, something has not been executed properly. Sandberg (2011-11-09) confirms this, and explains that improper execution of backfills for back-wall bridges are quite common. He suggests that it is due to the fact that bridges are designed by bridge engineers, and backfills by road engineers. The communication between these two fields of expertise fails in too many cases; hence these settlement problems become far worse than necessary.

6.2.2 Thickness of the concrete cover

The time it takes for concrete-aggressive substances such as carbon dioxide and chlorides to reach the reinforcement bars is highly dependent on the thickness of the concrete cover and the density of the concrete. The surrounding environment that the specimen is exposed to and the properties of the specimen itself, i.e. the quality of the concrete, governs the rate of intrusion. When the intrusion has reached the reinforcement bars corrosion can initiate, spall off the concrete and degrade the load carrying capacity. When it comes to concrete it is not a question of if, but rather a matter of when the concrete cover will be consumed.

Insufficient concrete cover is something that can be found in many concrete structures, consequently also back-wall bridges. With an increased knowledge of the intrusion processes and experience of damages on existing structures, the water cement ratio has been regulated and the standard cover thickness has increased from 25-30 mm to 45-50 mm on concrete bridges.

In cases where spalling of concrete is assumed to occur or already have been observed, activities needs to be taken rather quickly. Standard measure is to motor off the consumed concrete, treat the reinforcement bars, and cast a new concrete cover. This solution is however not flawless. The bond between the newly cast concrete and the existing can often be problematic and cracks induced by forces due to restrained deformations often occurs.

If the reinforcement damage would be too far progressed, an alternative could be to retrofit carbon fibre plates on the concrete surface to replace damaged reinforcement. However, verification of the capacity of the carbon fibre plates requires rather complex calculations, Svensson (2011-10-28).

6.2.3 Edge beam problems

Another problematic issue found in almost all concrete bridges is damage to the edge beams. Repair of edge beams has been a costly and time consuming matter for many years. The edge beams are inevitably located in a severely exposed environment next to the roadside. Dirt, water and chlorides are gathered up against its surface, and the rate of deterioration is higher in this region than anywhere else on a bridge.

Cracking can sometimes be found in the edge beam where it runs continuously over supports, mainly in cases where the bridge has more than one span. This mainly occurs due to lack of crack width control in these kinds of edge beams. Since the edge beams usually are cast in-situ along the bridge deck, they also follow the bridge's strain distribution. Over the mid-supports an area of tensile strain is found at the top part of the bridge deck, with the largest tensile strain in the outer fibres. When designing bridges, crack widths can often become the limiting factor with regard to durability. An edge beam, which is most commonly mounted as shown in Figure 6.2 below, is exposed to an even higher tensile strain than the bridge deck. This can cause larger cracks than designed for in the edge beam over the supports, which further increases its rate of deterioration, Darholm (2011-11-09).

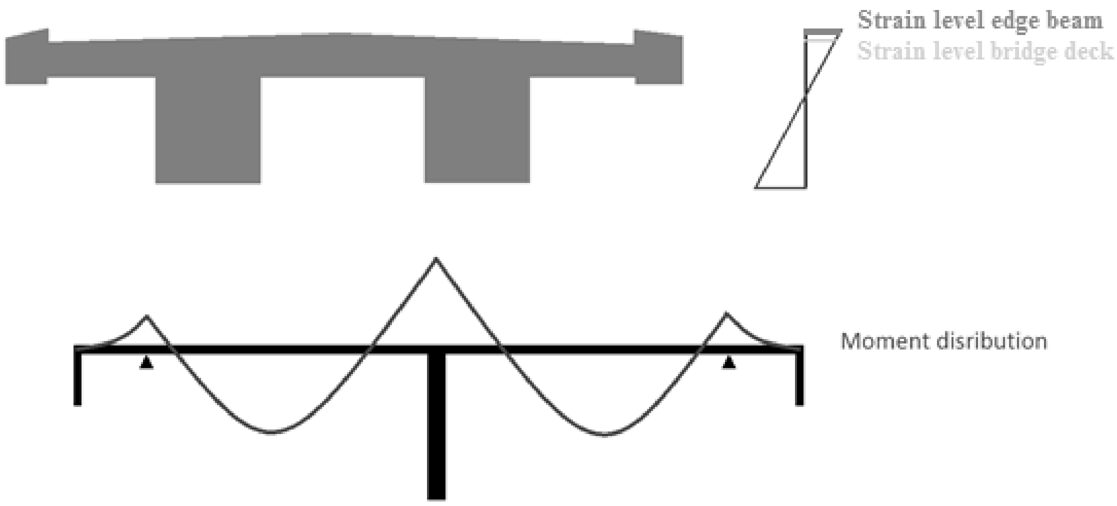


Figure 6.2 Illustration of the moment distribution along a continuous back-wall bridge with one mid support, and how the strain is varying with the height of the bridge's cross section

The deterioration will keep on progressing until the concrete cover is consumed and the entire edge beam needs to be replaced with a new. That replacement usually takes place with an interval of 40 years, and it is a costly activity that also has a significant effect on the traffic crossing the bridge. The new edge beam is usually hard to construct because when the new edge beam is casted onto the existing bridge deck, a restraint situation occurs. This can often lead to unexpected cracking and a yet again higher rate of deterioration. This is a problem that engineers have been struggling with for decades, Darholm (2011-11-09).

With regard to concrete cover and quality, today's execution of edge beams is said to have a design service life of approximately 80 years, according to Thunstedt (2011-11-09). However, the veracity of that statement is yet to be verified.

6.2.4 Occurrence of potholes

A commonly used cross-section for the different surface layers on concrete bridge decks is shown below in Figure 6.3. From the bottom and up, a carpet of waterproofing is glued directly onto the concrete bridge deck. On top of the waterproofing a layer of polymer modified casting asphalt (PGJA) is fitted and the top layer consists of regular asphalt. The top layer is worn down when the bridge is in use, both by the traffic driving on the bridge and radiation from the sun that will heat the surface and dry it out. These matters all cause problems to the surface layer and eventually results in that the surfacing needs to be replaced with an approximate interval of 30-40 years.

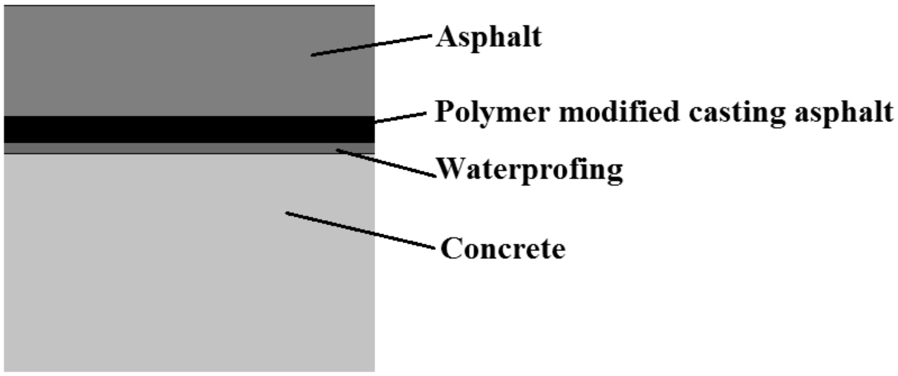


Figure 6.3. Typical cross-section of the surfacing on a concrete bridge deck

Another problem that can be traced back to the surfacing takes place in the interface between the waterproofing layer and the concrete. In some cases, air or water bubbles can form underneath the waterproofing. Why these bubbles are formed is presently unknown, but Larsson (2011-11-03) has two possible theories. The first is that the bubbles are formed in the concrete during construction. When the waterproofing is glued to the concrete, air can easily be trapped underneath the carpet. The other theory is based on relative thickness of the concrete slab. If the slab is "too" thick, the moisture that is being dried out when the concrete is hardening tries to escape in two directions. Even though one side is supposed to be completely impervious, the water escaping upwards gets trapped below the waterproofing carpet, see Figure 6.4 below.

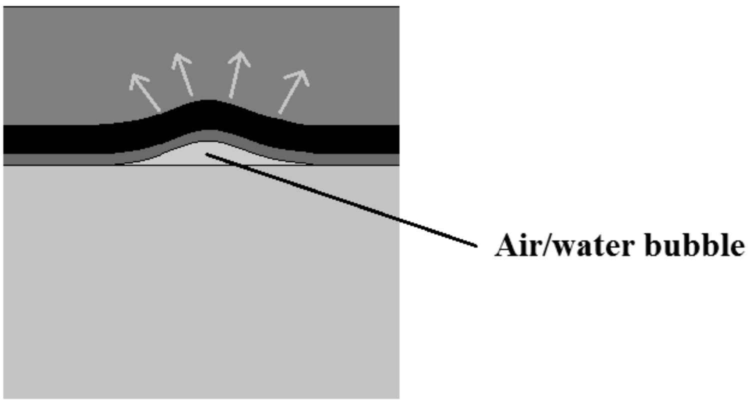


Figure 6.4. Trapped air/water-bubble causing stresses in the surfacing

When vehicles drives on the bridge and over the bubble, induced stresses might cause the bubble to explode and cause potholes to the surfacing on the road.

When or if these potholes will occur is very hard to estimate, since the reason to why the bubbles are formed is not known yet. When these damages are observed, the standard approach is simply to fill the holes with new surfacing, Larsson (2011-11-03).

6.2.5 Drainage problems

The drainage system on bridges with concrete decks is usually divided into two parts, surface and foundational water drainage. The surface water is the water flowing on the bridge's surface, in the direction of the bridge deck's inclination. The foundational water on the other hand, is the water that is transported through the porous asphalt layers and then travels on top of the waterproofing layer, see Figure 6.5 below. The run-off water is in both cases collected in pipes and then removed from the bridge, either by gutters or by just letting it fall off the bridge. The foundational water is removed in relatively thin pipes; consequently coarser pipes are used for the surface water.

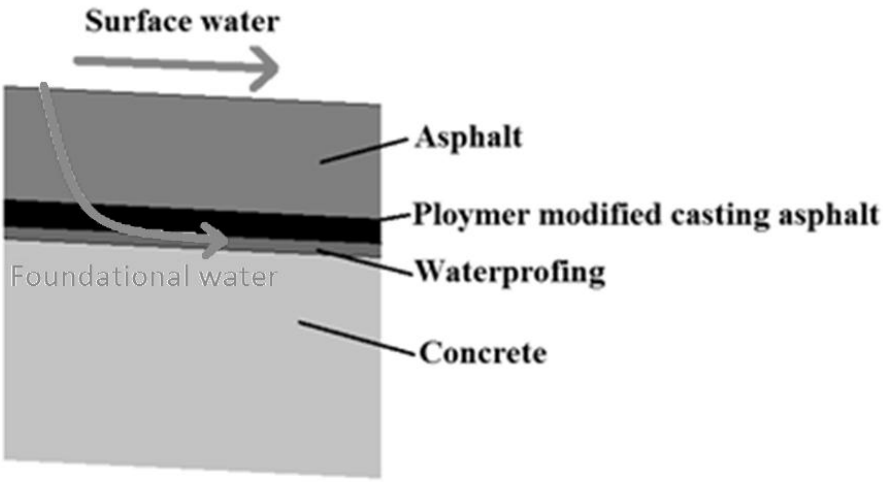


Figure 6.5. The differences between surface water and foundational water on bridge decks with concrete slabs

The surface water itself will seldom cause any significant damage to the bridge, besides eventual erosion of the cones as explained in Section 6.2.7. The foundational water on the other hand can cause problem if the inclination of the bridge deck would be insufficient, or the plastic funnels leading the water into the pipes are cracked or not completely tight. Gatherings of contaminated water containing chlorides and toxins can become stagnated and penetrate the concrete, resulting in damages.

If the bridge deck's inclination would be insufficient, it is usually both hard and expensive to remedy afterwards. It is therefore of big importance that this issue is taken into consideration during the design, and that the execution on the construction site is carried out in a careful and correct manner, Larsson (2011-11-03).

Measures to cope with these problems can be to replace the cracked and damaged pipes, or in the worst case, remove the whole surface layer and replace the waterproofing.

An optional approach to avoid the cracked pipes, which is also used as standard today, is to provide aluminium or stainless steel pipes instead. These two materials are much more durable, resistant to cracking, and will also have a longer service life than plastic pipes.

Another approach is to avoid casting the pipes directly into the concrete. This can be performed by first casting the concrete slab and then drill holes for the pipes to be retrofitted in. This approach results in a relatively small extra investment cost, but is expected to pay off when it will become both easier and cheaper to repair or replace the pipes, if necessary, Uvhage (2011-11-03).

6.2.6 Problems with bearings

There are many different types of bearings depending on which situation that prevail. When considering short-span bridges, the option usually stands between sliding steel or deformable rubber bearings, according to Sandberg (2011-11-09).

The deformable rubber bearing is the less expensive option in the investment stage, but is limited by the magnitude of movement of bridge deck. The rubber bearing cannot cope with movements that are too large. The magnitude of movements usually increases with an increasing bridge length. Rubber bearings are expected to have a service life of approximately 30 years before a replacement is needed. The replacement procedure is however relatively easy, which might motivate their use.

The sliding steel bearings are more expensive than the rubber bearing in the investment stage, but can on the other hand cope with much larger movements. With regard to durability, the sliding bearings are expected to have a service life that exceeds the design service life of the bridge itself.

6.2.7 Occurrence of cone erosion

According to Bäckström (2011-11-14), another common problem for these bridge types is erosion of the cones. This erosion takes place when storm water is drained from the bridge deck, and in the end runs off at the bridge’s ends. This water will naturally flow downwards along the cones, causing them to erode.

When the cone erodes, the stability of the slope will decrease. The material in the cone carries the road and the backfill that stabilises the back-walls. Measures taken when cone erosion has occurred are to refill and compact new masses onto the cone(s).

6.3 Typical problems related to the composite steel bridge

Short-span steel composite bridges with concrete decks are usually designed as back-wall bridges. Therefore the issues that were addressed regarding settlements, Section 6.2.1, and edge beams, Section 6.2.3, also apply for this bridge type. Other problems that have presented themselves on composite steel bridges and the associated counter-measures follow below.

6.3.1 Corrosion of steel details

As for the concrete bridge mentioned above, the steel is deteriorated by the initiation of corrosion. When considering concrete structures, the steel is protected from the surrounding environment by a protective concrete cover. Steel bridges on the other hand are comparatively unprotected against corrosion. Preventive measures are of course taken to delay, or in best case completely avoid, any initiation of corrosion. These preventive measures are essentially carried out by applying a protective coating, epoxy, on the exposed members and parts.

In the original maintenance plan, a scheduled repainting of the steel members should be considered with a time interval of approximately around 25 years, if no indications show that this activity would need to be carried out earlier. The procedure is basically to remove the corroded steel, usually by means of sandblasting, and then apply a new layer of protective coating. This activity needs to be repeated continuously during a bridge's service life, Svensson (2011-10-28).

6.3.1.1 Points of corrosion initiation

In old structures, corrosion could often be found in the interface between the concrete and the steel in composite steel bridges. This was because the entire upper flange was not treated with protective coating, according to Thunstedt (2011-11-09). This was however noted, and measures were taken to improve the detailing. Nowadays the upper flange is always treated as a whole and the corrosion issues in these regions have vanished.

One particularly sensitive item according to Sandberg (2011-11-09) is corrosion in the gaps between the units in bolted connections, e.g. where the transversal beams meet the longitudinal girders. Relative movements between the different parts in the connection, during the service state, leads to that the protective coating wares down in local regions within the connections. As soon as the steel is exposed, initiation of corrosion can take place and needs to be treated.

According to Darholm (2011-11-09), local corrosion of the steel can also be caused by vandalism, see Section 6.3.1.2, and when assembling prefabricated elements. Designers usually prefer to use as many prefabricated elements as possible when designing composite steel bridges. This is one of the main advantages of the bridge type, allowing for faster erection time of the bridge at the construction site. The prefabricated steel members are usually delivered with an applied layer of protective coating. Hardened protective paint has the property of being very brittle. This property in combination with the assembly on the construction site can cause problems when the members are joined together, usually by bolts. When the bolts are fitted along with the washers and then tightened, cracks in the paint-layers can easily develop around the bolts due to compressive forces. The steel then becomes unprotected and initiation of corrosion can take place in this region.

This is usually taken care of, if observed, by covering the damaged regions with a new layer of protective paint.

6.3.1.2 Occurrence of vandalism

Another reason for local initiation of corrosion can be due to unexpected damages to the bridge. Sadly, initiation caused by vandalism is fairly common. This type of vandalism is mainly due to people throwing hard and sharp objects, usually rocks, against the flanges and webs of the bridge girders. The layers of protective painting are, as mentioned in Section 6.3.1.1, very brittle and can locally break off when rocks hit it. This damage also needs to be treated, but the procedure is more costly, since all, usually five, layers of paint needs to be reapplied. This also leaves a mottled appearance on the girders that can be perceived as aesthetically unappealing, Sandberg (2011-11-09).

6.3.2 Durability of epoxy

Two decades ago, it was standard procedure to treat corroded areas with the toxic, but also very durable lead-paint, called red-lead paint. For environmental reasons, Swedish Road Administration banned the use of all kinds of lead-paint back in the 1980's. Instead, common practice today is to use epoxies. Like red-lead paint, epoxies, along with other agents during its application, are still toxic and allergenic, but do not possess the same durable properties.

The problem with the epoxy is its toxicity and the poor durability, sometimes as short as 6 months can pass before the treatment needs to be repeated, Svensson (2011-10-28).

6.3.3 Edge beam problems

See Section 6.2.3.

6.3.4 Occurrence of potholes

See Section 6.2.4.

6.3.5 Drainage problems

The drainage problems are basically the same for composite steel bridges as they are for the concrete back-wall bridges, se Section 6.2.5. There is however one aspect that differs between these two bridge types. That is that it matters more where and how the foundational run-off water is diverted from the bridge. This is because the steel girders are located directly underneath the bridge deck. These girders are sensitive to water containing chlorides, which usually is the case for the run-off water.

According to Darholm (2011-11-09), these run-off spots are often found in surprisingly inappropriate locations, allowing the foundational water to run off straight onto the underlying steel girders as see in Figure 6.6 below.

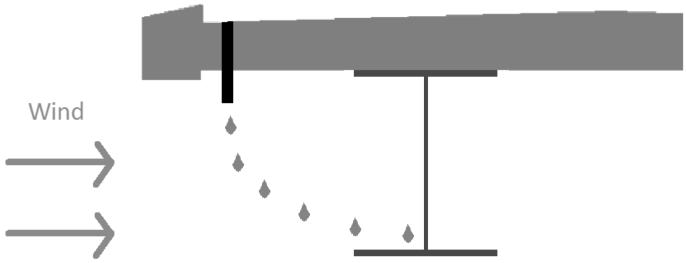


Figure 6.6 Example of an inappropriate location of the run-off spot for a foundational drainage system. The contaminated water, which can cause damage, is allowed to blow straight onto the steel girders

Darholm (2011-11-09) suggested quite simple and inexpensive solutions to this issue. The pipe could be bent away from the steel girders, or just extended in a way that prevents the water to blow onto the girders. Examples of the two solutions could be performed are shown in Figure 6.7 below.

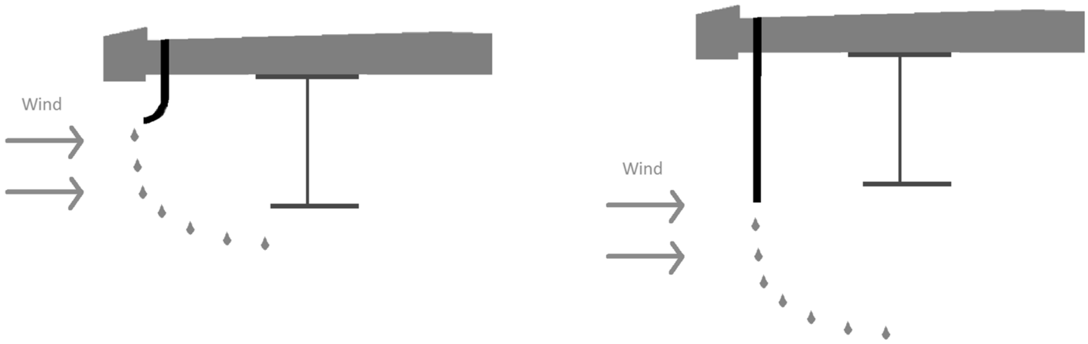


Figure 6.7 Example of two different solutions for the foundational drainage system to avoid that contaminated water blows onto the steel girders

6.3.6 Problems with bearings

See Section 6.2.6.

6.3.7 Occurrence of cone erosion

See Section 6.2.7.

6.4 Typical problems related to transversally prestressed glulam slab bridges

Unlike the other two bridge types that were considered in this project, timber bridges of the same kind is not commonly fitted with back-walls. This is due to the timber's poor durability properties when it comes in contact with moisture. Therefore, a design solution with freestanding abutments is used for almost all short-span timber bridges. The soil in Sweden is always considered to be 100% damp, therefore it would be unsuitable to fit a timber back-wall to a bridge. Using freestanding abutments makes it necessary to incorporate transition zones on the other hand. That results in a new vulnerable and moving part of the bridge that is constantly exposed to the surrounding environment.

Another issue, related to what was mentioned above, is the importance of moisture protection. Exposing timber to excessive levels of moisture can cause mould, fungus and rot. These agents degrade the load carrying capacity of the timber and often cause a need for replacement of the infested parts. Therefore, bridge managers prefer to take measures before any damage even has initiated. That is done by continuous inspections where the moisture quotient in the timber is measured. Below, in Section 6.4.1, follows a further description of this problem and other common problems associated with transversally prestressed glulam slab bridges.

6.4.1 Moisture problems in the timber

As previously mentioned, moisture can become a significant problem if the timber would not be properly protected. Engineers are aware of this fact and consequently design their bridges with regard to it. Nevertheless, moisture damage is a large problem when it comes to timber bridges. Sandberg (2011-11-09) speculates that the reason for why moisture is a problem for timber bridges, even though designers and contractors are aware of it, is due to a general lack of knowledge. This applies to the handling of timber in all the different stages before a finished bridge structure is in place and in careful detailing.

The most difficult task can often be to find the damaged parts. This is because the areas where moisture damage usually takes place are where the moisture cannot dry out properly. That means that the areas are fairly confined and sometimes completely inaccessible for inspection. A common example is the end-timber at the freestanding abutments. Destructive testing is sometimes the only way to get an accurate idea of the moist conditions in the timber. Since destructive testing by itself can give rise to new problems, it is not performed if there are no clear indications that a problem might be present.

If moisture damage would be observed visually, it is usually fairly easy to correct. The unwanted agents are removed; the timber is cleaned and then allowed to dry out. If there is a risk that the timber will be exposed to an excess of moisture again, preventive measures are taken, e.g. protective painting etc.

If there is any suspicion that an excess of moisture can be present somewhere where it cannot be visually confirmed, an assessment of whether a destructive testing should be executed or not needs to be carried out. Jacobsson (2011-11-14).

6.4.2 Need for re-tensioning of prestressing bars

Post-tensioned prestressing bars are what provide integrity of the glulam slab. These bars are tensioned by the use of a jack and then fixated by nuts. Each nut is separated from the glulam beams by two washers, one steel and one aluminium, that in turn are placed on a piece of hardwood, see Figure 6.8 below.

After the inauguration it is common that these prestressing bars need to be re-tensioned. This can be because of two reasons; either the timber has got moist and lost some of its stiffness thus allowing the bar anchorage to settle into the timber, or the timber settles due to creep under the applied compression. Bridge managers' opinions go apart on how often re-tensioning of bars in general needs to be performed. Racutanu argues that it has to be done several times per year, whilst Svensson (2011-10-28) disagrees and suggests that it is only during the first year after inauguration that this activity might be relevant. Jacobsson (2011-11-14) informs that it is usually only done within 20 years after the inauguration, as it is stated in the Swedish bridge building code, Vägverket (2009). Judging from the mechanism causing the need for re-tensioning, the need should be varying depending on the surrounding environment and the applied compressive stress on the timber. Nevertheless, it is an activity that needs to be carried out, and an assessment will be necessary in order to perform the LCC-analysis.

A secondary problem, caused by the tensile forces in the prestressing bars, is that the aluminium washers sometimes crack. This phenomenon is shown in Figure 6.8 below. Svensson (2011-10-28) suggests that it can be caused by the hardwood being too soft and bends, leading to local stresses in the washer that eventually causes it to crack. Jacobsson (2011-11-14) on the other hand reasons that it is due to design errors or that the primary beams has been exposed to moisture and therefore shows a decreased stiffness, thus allowing the hardwood plate to settle into the beam. A design error could be if the fibres of the hardwood plate were to be orientated perpendicular to the compression force, the stiffness of the plate would then be significantly reduced, compared to if they were to be orientated parallel to the applied force. Another option could be to use thicker washers or replace the hardwood plate with a steel plate.

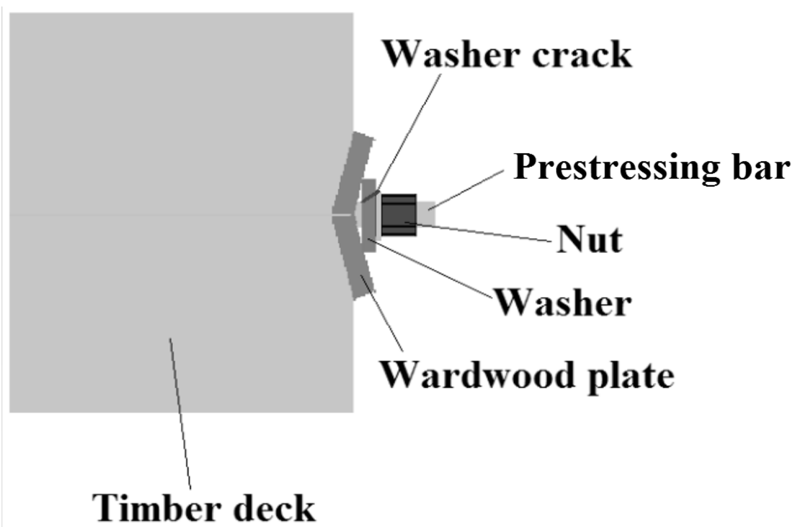


Figure 6.8 Example of the cracking mechanism of the washer plate in a prestressing bar anchorage

6.4.3 Sealing problems

As mentioned in Section 6.4.1, timber can be very sensitive to moisture, both when it comes to durability properties that are described below in Section 6.4.5, and strength properties. Therefore it is paramount to ensure that the timber structural members are not exposed to any excessive moisture. This is prevented by providing exposed members and parts with protective painting and/or sealing that drains away the water, also see Section 6.4.4 below on protective panels.

Continuous inspections should be performed on timber bridges to assure that no moisture damage is present. If the sealing is deemed to be insufficient anywhere, the surface needs to be retreated. However, as it is in most cases when something needs to be corrected, it never turn out as good as it would have been if it was carried out correctly the first time. Bond problems are usually the main issue when protective coatings are re-applied, Svensson (2011-10-28).

Jacobsson (2011-11-14) stresses the importance of that the seals are performed correctly and the consequences it might have if not. For instance, if the sealing layer is not tight around the edge-strip, shown in Figure 6.9, moisture can penetrate the load carrying members. This can in turn lead to the formation of rot, loss of stiffness, settlements of anchors etc. In the event of rot formation, the entire slab would have to be dissembled and the infested members need to be replaced. This activity would be very expensive and last for approximately one week, while the traffic would have to be rerouted, causing even more societal costs.

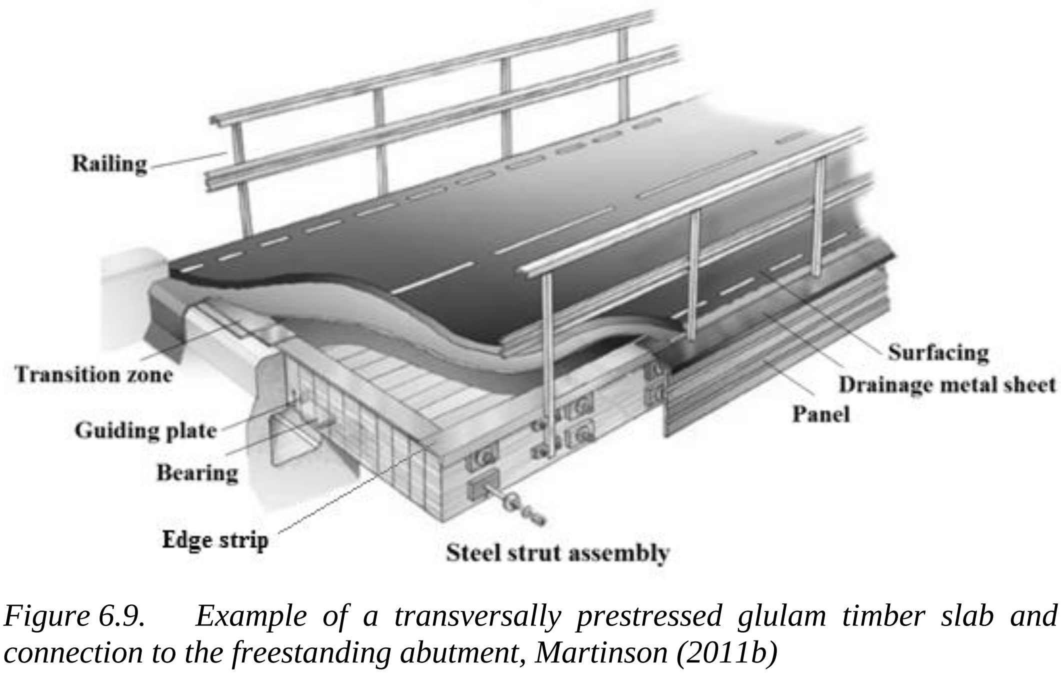


Figure 6.9. Example of a transversally prestressed glulam timber slab and the connection to the freestanding abutment, Martinson (2011b)

6.4.4 Problems with the protecting panels

Another way to protect the timber against moisture is to fit the edges of the bridge deck with protective panels, seen in Figure 6.9 above. These panels protect the timber against direct contact with water.

These panels can be treated in two different ways, either by pressure impregnation or protective painting. The main difference between these two treatments is their corresponding durability. According to Jacobsson (2011-11-14), an impregnated protective panel has a design service life of approximately 30-40 years, whereas a panel fitted with protective paint needs to be repainted every 8^{th} year.

Jacobsson (2011-11-14) does not mention this issue as a particular problem, but definitely as a part of the process of decision-making regarding the durability and maintenance costs of these kinds of bridge types. Why protective painting would be preferred to pressure impregnation was suggested to be of aesthetical reasons. Svensson (2011-10-28) explains the reason why the aesthetical painting is not applied on the pressure impregnated timber. It is due to the poor bond condition and that if aesthetical painting still would be considered, its application would have to be delayed for at least two years.

6.4.5 Issues regarding the durability of timber

The design service life of timber bridges in Sweden is generally assumed to be approximately 80 years, i.e. shorter than concrete and steel bridges that can be designed for as long as 120 years. In other Scandinavian countries, such as Norway and Finland, timber bridges are assumed to last at least as long as bridges constructed in the other materials. This is mainly because the usage of the preservative, and highly toxic, substance Creosote is allowed. Why Sweden do not allow Creosote is due to the relatively strict environmental policies, resulting in that less effective, but more environmentally friendly impregnations are used instead, Jacobsson (2011-11-14).

Having a shorter service life of a bridge directly influences its LCC, since the costs of the investment and the activities are spread over a shorter time period.

Degradation due to poor impregnation substances is one of the bigger problems when it comes to timber bridges in general. As long as no new more durable and environmentally friendly preservatives are accepted, this problem will remain unchanged, Jacobsson (2011-11-14).

6.5 Summary – Basis for analysis

The compilation of typical problems associated with each of the three bridge types was one of the key factors in this project. It was supposed to provide an objective picture of the current state of the selected bridge types. The intent was to acquire the compilation through an extract from the BaTMan database, containing a representative population for each of the three bridge types.

Unfortunately this approach was unsuccessful when the Swedish Road Administration was not able to provide the sought information. The alternative solution was to compile the corresponding data from a number of interviews with experienced bridge managers instead. This approach would not carry the same scientific credibility compared to the first approach. That was due to the fact that the input data would be based on a few, however experienced persons', subjective opinions. Concerning the main purpose of the project however, this setback was considered to be irrelevant.

The compilation showed that settlements in the back-wall regions were a reoccurring problem for back-wall bridges. Problems in common for both the concrete and steel bridge were also the issues with the edge beams and foundational drainage. The steel bridge showed to mainly having problems with regard to corrosion that differed from the ones mentioned for the concrete bridge. This fact had of course a lot to do with the fact that both bridge decks are made out of concrete and designed with back-walls.

Most of the problems associated with timber bridges were related to moisture. Another issue was that the bridge deck for the timber bridge, unlike the concrete and composite steel bridges, was supported on freestanding abutments. This resulted in the presence of transition zones, which allows horizontal movements of the bridge deck.

A lot of useful information of the three different bridge types was gathered during the interviews and compiled in this chapter. The next chapter will describe the comparative LCC-analysis, including suggestions for improvements to some of the problems mentioned in this chapter.

7 Comparative Life Cycle Cost Analysis

This chapter describes the comparative LCC-analysis performed on the basis of the previous chapters 1 to 6.

7.1 Outline for the comparative LCC-analysis

When the bridge types were set, the LCC softwares had been chosen and verified, all the necessary tools to perform the analyses were accounted for.

The analysis was structured according to the following 6 steps:

1. A general description of the analysis process, as the described in Section 7.1

2. LCC-analysis, case 0, was performed on each bridge type, based on the compilation that is described in Chapter 6
    a. An explanation of the procedure for case 0
    b. The bridge types were set into a mutual context
        i. Selection of arbitrary assumptions to be applied on each bridge type with regard to:
            1. General dimensions
            2. Traffic conditions
            3. Costs, time-interval and duration for activities
    c. Presentation of relevant results in table-form

3. Suggestions of improvements to avoid, preferably decrease MR&R induced LCC for each bridge type were described
    a. Evaluation of advantages and disadvantages with each improvement
    b. Assessment of effects due to their implementation

4. LCC-analysis, case 1, was performed on each bridge type, based on the inclusion of the suggested improvements
    a. An explanation of the procedure for case 1
    b. Alteration of the bridge context
        i. Selection of new arbitrary assumptions with regard to
            1. Costs, time-interval and duration for activities
            2. Other conditions that remained the same as in case 0
    c. Iteration
        i. Were the improvement(s) was accepted or rejected
            1. Explanation and motivation
    d. Presentation of relevant results in table-form

5. Identification of sensitivity factors
    a. Evaluation of case 0 and case 1
        i. Reflections
        ii. Conclusions

6. Summarisation of the analysis
    a. Conclusions

The expectation of this analysis was that the suggested improvements would prove to be favourable with regard to the LCC. Weather this assumption was true or not was left to be discovered, and is presented in this chapter.

7.2 LCC-analysis for case 0

This section describes the first of the two LCC-analysis, case 0. The problems presented in Chapter 6 are put into a context, thus representing the experience-based current state of the selected bridge types.

7.2.1 Procedure of the LCC-analysis for case 0

When the experiences of the bridge types had been collected, as described in Chapter 6, a general idea of the most common problems for each bridge type had formed. The next step was to evaluate which of these problems that could be relevant for the analysis.

The aim of the project states that: "*By using the first LCC-analysis, case 0, where the most commonly accepted detailing and design solutions were to be applied as a basis, possible improvements that could be used, recognised or questioned, was suggested and implemented in a second LCC-analysis, case 1*". Therefore it was decided that it was only relevant to further investigate the problems that incurred significant MR&R costs, and that a better alternative design solution existed to. As a consequence, the following problems, brought up in Chapter 6, were sorted out as being irrelevant:

- **The back-wall bridge**
    - Conventional or increased concrete cover (Section 6.2.3)
        - Insignificant cost difference if extra was to be added in case 1
    - Occurrence of potholes (Section 6.2.4)
        - No known solutions
    - Drainage problems (Section 6.2.5)
        - Already solved
- **The composite steel bridge**
    - Paint damages due to vandalism (Section 6.3.1.2)
        - Unreasonable to assess the occurrence
    - The poor durability properties of epoxy (Section 6.3.2)
        - No known solutions
    - Occurrence of potholes (Section 6.2.4)
        - No known solutions
    - Drainage problems (Section 6.2.5)
        - Already solved or insignificant cost difference
- **The transversally prestressed glulam slab bridge**
    - Need for Re-tensioning of steel bars (Section 6.4.2)
        - Washer cracks
            - Insignificant cost differences
    - Poor durability properties of timber (Section 6.4.5)
        - No known solution

Furthermore, it was necessary to assign a cost to each MR&R activity. There are however no exact values available; hence assumptions needed to be performed. Not only the costs are of importance when considering an activity, but also when, how long an activity lasts, its disturbance to the traffic flow and how often it has to be performed. These issues are all explained in further detail in Section 7.2.2.3, below.

When all input data was set, it was a matter of inserting the data into the already verified computer softwares:

- BroLCC
- BridgeLCC
- Vännen07

This was the first time "full scale" analyses were carried out by the use of the softwares in the master thesis project and some difficulties in managing the softwares did occur.

- **BroLCC**, which was the "new" software, showed to be the easiest software to work with, exempting a few minor errors that were reported back to the ETSI group.
- **BridgeLCC**, which initially looked like the most promising software, showed to be prone of crashing and sometimes scaled up the input data by a factor of 1000, for no apparent reason at all. This was dealt with by a careful verification of the input data before accepting the output data.
- **Vännen07**, the comprehensive LCC software, had as previously mentioned traffic as a factor for MR&R planning, but was noted to **not consider traffic costs** as a consequence of MR&R work. This was considered to be a significant drawback of Vännen07, since indications on the importance of traffic costs induced by MR&R work had shown to be emphasised during the LCC background studies. Nevertheless, data was still run through the software keeping the shortcoming in mind.

When the data was run through the three softwares, another issue presented itself. The kind of output data that was of interest for the comparative analysis needed to be defined, which could be presented in three principal ways:

1. As a gross total LCC, including the cost for all activities over the design service life
2. Individual LCC for each activity
    - Distinguish which part of each individual activity's LCC that belonged to traffic costs, and the actual activity
3. Yearly LCC cost, as described in 1 and 2

Since the comparative analysis is aimed to form the basis for an LCC method to be used by designers in the initial design stage, yearly costs were considered to be superfluous. Instead, it was decided that the data would be presented according to both 1 and 2, to cover as many eventualities of the results as possible and to avoid having to go back and re-do any analysis if information would be missing.

The next Section 7.2.2 describes the assumptions that needed to be made before the first LCC-analysis, case 0, could be carried out.

7.2.2 Assumptions for case 0

This section describes the assumptions that needed to be performed before being able to run the first LCC-analysis, considering the common problems associated with the different bridge types.

7.2.2.1 General assumptions for case 0

The purpose of performing the LCC-analysis, case 0, was to have a reference case to which the effects on LCC of implementing improvements in case 1 could be compared. The improvements were to be applied to the problems associated with each bridge type. It was therefore unnecessary to account for any other costs, than the actual costs related to the problems. All other costs would remain unchanged in both case 0 and 1.

The bridge dimensions were chosen to be the same for all three selected bridge types in order to represent an arbitrary short-span bridge. Some type-specific data needed to be assigned to the bridges as shown below:

- **Dimensions in common**
  - Number of spans = 1
  - Bridge deck length = 20 m
  - Bridge deck width = 7 m
  - Design service life = 80 years

- **Composite bridge**
  - Height of steel girders = 1 m
  - Length of girders = 20 m (as the bridge deck)
  - Number of transversal ties = 5
  - Area of steel girders = 120 m^2 (6 m^2/m_{bridge})

- **Transversally prestressed glulam slab**
  - Height of protective panel = 1 m
  - Length of protective panel = 20 m (as the bridge deck)
  - Area of protective panels = 40 m^2

7.2.2.2 Assumptions regarding the traffic conditions for case 0

The traffic costs are, as mentioned in Section 3.4.4.2, calculated with the following general Equation (7.1), Julita (2008):

$$C_{driver} = \left(\frac{L_{workzone}}{v_{red}} - \frac{L_{workzone}}{v_{norm}}\right) * ADT * D_{days} * C_{delay} \quad (7.1)$$

The term v_{red} represents the reduced speed while an activity is performed, thus delaying the traffic. In this case an activity would be performed on a bridge, where $L_{workzone}$ represents the affected stretch of road and the fraction of $L_{workzone}$ and v_{red} give the time it takes to get from one point to another. The difference in time given by the reduced speed represents the delay.

The input data requested in BroLCC and BridgeLCC (Vännen07 does not account for traffic costs) is the normal speed and the reduced speed. The normal speed is not that difficult to estimate or just assume, but the reduced speed on the other hand calls for a number of assumptions to be made.

The activities performed on a bridge can have three general effects on the traffic:

1. No effect, activity does not affect the traffic flow
2. One lane closed, the bridge capacity is decreased by 50 %
3. Both lanes closed, the traffic needs to be diverted

The delay caused by case 2 above cannot be derived from which speed a vehicle can travels across the bridge in. Since there is just one lane open for traffic, there will be an additional delay for allowing the traffic going in the opposite direction to pass. Hence, the decreased speed can be computed by the time it will take to cross the affected stretch of the road, **and** the extra delay caused by waiting. This delay could easily be estimated by the use of the computer software called CapCal (2011). CapCal assumes that 5 % of the total ADT represents ADT_{mod}, i.e. the traffic going in one direction during the worse hour of a day. The size of the workzone and the reduced speed was inserted into CapCal, which delivered an estimate of the waiting time according to Frid[4].

When considering case 3, another situation arises. Now the vehicles can be assumed to travel at a constant speed without any waiting times, but on a detour instead. The speed and the length of the detour will result in time spent driving around the affected area. This time can then be assigned to the effective distance the vehicles have travelled, i.e. the length of the workzone, resulting in a significantly lower v_{red}.

Consistently with Section 7.2.2.1 above, arbitrary values were initially set to the different variables and assigned to each bridge type according to the three different traffic situations stated above.

- Normal speed (v_{norm}) = 70 km/h
- Reduced speed ($v_{red\ actual}$) = 50 km/h
- Size of workzone ($L_{workzone}$) = 50 m
  - Bridge deck length + 15 m, on each side
- Waiting time (t_{wait}) = 12 s
  - Output data from CapCal
- Length of detour = 7 km
- ADT = 6,000 vehicles/day
  - 10 % heavy vehicles (standard-value), Racutanu[5]
  - Cost per private vehicle (C_{cost1}) = 140 SEK/h
  - Cost per heavy (commercial) vehicle (C_{cost2}) = 320 SEK/h

A weighing of C_{cost1} and C_{cost2} was implemented to BroLCC, where the two costs could not be defined separately.

- Weighed vehicle cost (C_{cost}) = 158 SEK/h

[4] Erik Frid, COWI Göteborg. Interviewed 2011-11-15
[5] George Racutanu, Trafikverket. Interviewed 2011-10-27

These input data, recomputed to the reduced effective speeds to be inserted into the general equation, are shown in Appendix F. An illustration of traffic situation 2 and 3 is shown in Figure 7.1 below.

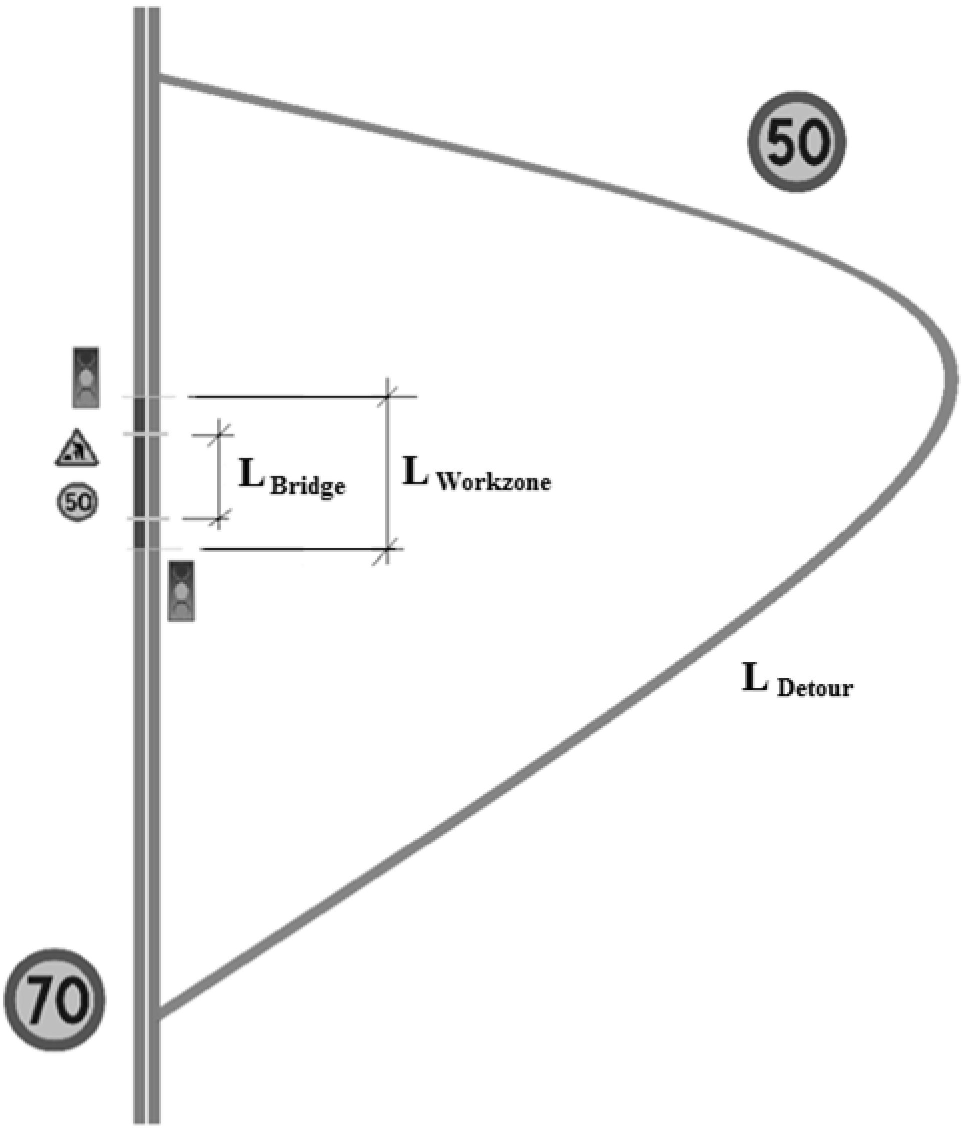


Figure 7.1 Illustration of the workzone (traffic situation 2) and a suggested detour around a bridge (traffic situation 3) during MR&R work

The effective reduced speeds calculated in Appendix F, resulted in the following speeds:

- Traffic situation: 2
  - 11.25 km/h
- Traffic situation: 3
  - 0.36 km/h

These were all the assumptions that needed to be made with regard to traffic conditions in order to proceed with the LCC-analysis.

7.2.2.3 Assumptions regarding costs, time-intervals and duration of the activities for case 0

As mentioned in Section 7.2.1, each activity needed to be assigned a cost. Since bridges most often have unique properties, there is no exact value that can be used, especially not when the particular bridges in question do not exist. Instead, standard-values needed to be assumed.

To acquire these standard-values, information on costs were available in the BaTMan pricelist, BaTMan (2011). However, prices for all the activities needed to cope with the problems stated in Chapter 6 were not listed in the pricelist. Nevertheless, numerical values were needed to run the LCC-analysis.

The approach was to once again contact the bridge managers that were interviewed as a basis for Chapter 6, this time to perform reasonable estimations of the costs for the activities that were not listed in the BaTMan pricelist.

After covering the cost issues, reasonable assumptions needed to be made on how often these activities would take place and finally the duration of each activity, where the latter primarily was used to calculate the associated traffic costs. Since these matters are closely connected to each unique bridge, arbitrary assumptions were necessary regarding all the activities.

References to the assumptions mentioned above, and the adopted numerical values for the problems stated in Chapter 6 can be found in Table 7.1 below.

In the cases where the information was inconclusive, not available or easily figured out, the values were arbitrarily assumed as follows:

- **Edge beam**
    - The edge beams are assumed to be running along the entire bridge deck on both sides, i.e. 40 m
    - Replacement of edge beam
        - Replaced at an interval of 60 years
            - Experience has presented a need for replacement at an interval of 40 years. Today's edge beam execution has however improved, and designers claim a new replacement interval of ~80 years in the future. Hence, 60 years was considered to be a reasonable compromise
- **Cone erosion**
    - 3 m^3 of filling was assumed to be needed for repairs on both sides of each cone. Hence, a gross volume of 12 m^3
- **Steel girders**
    - A girder area of 6 m^2/m of bridge was assumed, totally 120 m^2
- **Gap corrosion**
    - An total area of 10 m^2 was assumed to need treatment
- **Protective panel**
    - Painting-area was assumed to be 40 m^2
- **End-timber**
    - Damage was assumed to occur at a bridge age of 50 years
    - When damaged, 3 glulam beams would need to be replaced
- **Bearings**
    - The bridge types were assumed to have two bearings on each side, 4 in total

The compilation of the assumed costs used in the LCC-analysis for case 0 is shown in Table 7.1 below.

Table 7.1 Presentation of the assumed costs (SEK), time-intervals and duration of activities performed on the selected bridge types, case 0

Reinforced concrete beam bridge with back-walls (case 0)										
Activity	Cost for activity	Interval [years]	Duration [days]	Traffic disturbance	Closed lanes			Source		
					0	1	2	Cost	Interval	Duration
Replace edge beam	10 500 SEK/m	60	28	yes		X		BaTMan	SA	DG
Bearings (rubber)	7 500 SEK/pc	35	1	yes			X	JS	JS	DG
Cone erosion	1 300 SEK/m^3	25	-	no	X			BaTMan	TS, MB	-
Settlement repairs	40 000 SEK	10	1	yes		X		JS	JS	DG

Composite steel/concrete beam bridge with back-walls (case 0)										
Activity	Cost for activity	Interval [years]	Duration [days]	Traffic disturbance	Closed lanes			Source		
					0	1	2	Cost	Interval	Duration
Replacement of edge beam	10 500 SEK/m	60	28	yes		X		BaTMan	SA	DG
Bearings (rubber)	7 500 SEK/pc	35	1	yes			X	JS	JS	DG
Cone erosion	1 300 SEK/m^3	25	-	no	X			BaTMan	TS, MB	-
Settlement repairs	40 000 SEK	10	1	yes		X		JS	JS	DG
Painting of girders	3 000 SEK/m^2	25	-	no	X			DG	JS	-
Gap corrosion	2 500 SEK/gap	35	-	no	X			MB	JS	-

Transversally prestressed glulam slab bridge (case 0)										
Activity	Cost for activity	Interval [years]	Duration [days]	Traffic disturbance	Closed lanes			Source		
					0	1	2	Cost	Interval	Duration
Bearings (rubber)	7 500 SEK/pc	35	1	yes			X	JS	JS	DG
Painting of panel	90 SEK/m^2	8	-	no	X			PJ	PJ	-
Damaged end timber	25 000 SEK/beam	50	14	yes			X	SA	SA	PJ

7.2.3 LCC results case 0

The output data from the first analysis, case 0, run through the softwares is presented in Table 7.2 below.

Table 7.2 Presentation of the LCC output data (SEK), case 0, from the three softwares for each selected bridge type

Reinforced concrete beam bridge with back-walls (case 0)									
Activity	BroLCC			BridgeLCC			Vännen07		
	MR&R-costs	Traffic	Tot. LCC	MR&R-costs	Traffic	Tot. LCC	MR&R-costs	Traffic	Tot. LCC
Edge beam replacement	39 925	7 610	**47 535**	41 522	7 914	**49 436**	41 182	-	**41 182**
Bearings (rubber)	9 529	41 392	**50 921**	9 910	44 290	**54 200**	10 834	-	**10 834**
Cone erosion	8 870	-	**8 870**	9 225	-	**9 225**	12 149	-	**12 149**
Settlement repairs	79 677	5 695	**85 372**	82 865	5 923	**88 788**	82 865	-	**82 865**
Sum			**192 698**			**201 649**			**147 030**

Composite steel/concrete beam bridge with back-walls (case 0)									
Activity	BroLCC			BridgeLCC			Vännen07		
	MR&R-costs	Traffic	Tot. LCC	MR&R-costs	Traffic	Tot. LCC	MR&R-costs	Traffic	Tot. LCC
Edge beam replacement	39 925	7 610	**47 535**	41 522	7 914	**49 436**	41 182	-	**41 182**
Bearings (rubber)	9 529	41 392	**50 921**	9 910	44 290	**54 200**	10 834	-	**10 834**
Cone erosion	8 870	-	**8 870**	9 225	-	**9 225**	12 149	-	**12 149**
Settlement repairs	79 677	5 695	**85 372**	82 865	5 923	**88 788**	82 865	-	**82 865**
Steel girder (painting)	204 701	-	**204 701**	212 889	-	**212 889**	280 121	-	**280 121**
Gap corrosion	7 941	-	**7 941**	8 259	-	**8 259**	9 686	-	**9 686**
Sum			**405 340**			**422 797**			**436 837**

Transversally prestressed glulam slab bridge (case 0)									
Activity	BroLCC			BridgeLCC			Vännen07		
	MR&R-costs	Traffic	Tot. LCC	MR&R-costs	Traffic	Tot. LCC	MR&R-costs	Traffic	Tot. LCC
Bearings (rubber)	9 529	41 392	**50 921**	9 910	44 290	**54 200**	10 834	-	**10 834**
Painted panel	9 344	-	**9 344**	9 555	-	**9 555**	9 717	-	**9 717**
Damaged end timber	10 553	277 408	**287 961**	10 976	274 688	**285 664**	11 455	-	**11 455**
Sum			**348 226**			349 419			**32 006**

In the table above it can be seen that the individual and gross LCC correlate fairly good between the different softwares. The slight difference in the results between BroLCC and BridgeLCC was traced back to the fact mentioned in Section 4.3. The activities in BridgeLCC were discounted from the year **before** it took place, whilst BroLCC discounted it from the actual age of the bridge. This indicates that the point in time (bridge age) from which an activity is discounted could have a significant effect on the LCC. The rest-value that Vännen07, unlike the other softwares, took into consideration distinguished itself markedly when looking at the "steel girder painting". Furthermore, as mentioned in Section 7.2.2.2, Vännen07 does not take any traffic costs into account, thus creating the large difference between the "Tot. LCC" for Vännen07 and the other two softwares.

Fortunately, the performed distinction of the costs for MR&R and traffic could easily explain the large difference in gross LCC cost of the transversally prestressed glulam slab compared to the other bridge types. A large portion of the gross LCC cost, ~300'000 SEK, was accumulated solely due to traffic costs. This gave a first indication of the previously stated importance that the traffic costs could have and that special care should be taken when considering it.

These LCC results were not of much further use without having anything to compare them to. One could argue that the bridge types could be compared to each other. That would however be misleading, since all the costs have not been included, only the costs for action which have a corresponding alternative solution. The next Section 7.3 describes the suggested improvements with regard to the problems that the LCC-analysis, case 0, were computed for.

7.3 Alternative detailing solutions

This section describes the alternative solutions that were suggested to improve the conventional solutions and to avoid or minimise the problems described in Chapter 3.

7.3.1 Alternative detailing solutions for concrete back-wall bridges

A description of the improvements that were suggested for the concrete back-wall bridge is found below.

7.3.1.1 Managing the back-wall settlements with link plates

One of the main problems associated with Back-wall concrete bridges is the settlements that usually occur in the back-wall region. These settlements cause discomforts for the drivers crossing the settlement-regions and increased wearing of both the vehicles and the road surface. Also see Section 6.2.1.

One effective way to reduce the effects of this problem could be to fit the structural system with a concrete link plate during construction. The main purpose of the link plate is to reduce the effective depth of the soil layer where these settlements take place. This allows the settlements to even out, provided that the length of the link plate is adequate. The optimal length of such link plates has shown to be about 5 m according to Sandberg (2011-11-09). In a case of longer plates, the plate would be too heavy and further add to the initial problem. Shorter plates would not achieve the desired function to even out the settlements. See Figure 7.2 below for an illustration of a proper link plate function.

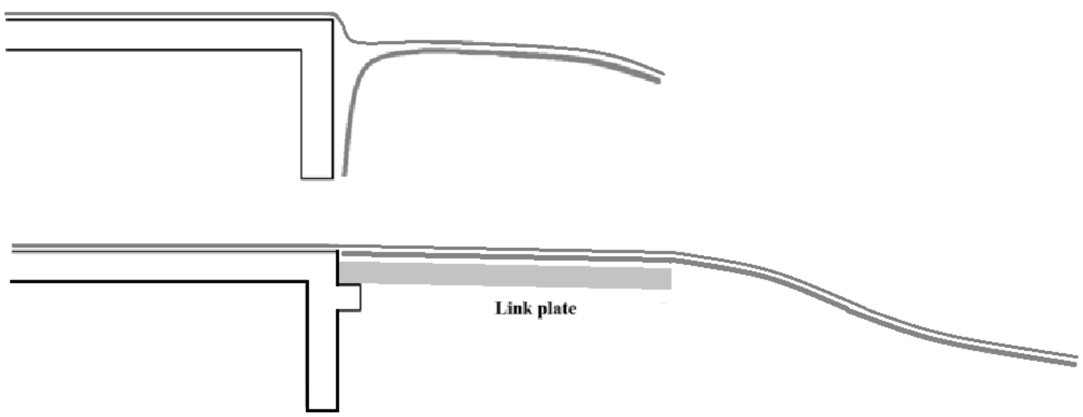


Figure 7.2. Illustration of how the settlements differ for a back-wall bridge, with and without a link plate

The payback time for the extra cost of installing a link plate is about the same as the cost of evening out the settlements with a layer of asphalt approximately three times, according to Sandberg (2011-11-09). It would probably be reached within ~25-30 years after the inauguration of the bridge. As mentioned above, a link plate would not eliminate the settlements, but decreases them significantly. As a result, an activity to remedy the settlements with asphalt is still expected to be needed, but not before a bridge age of 50 years.

To construct and utilise link plates is a relatively inexpensive way to minimise the settlements in regions where they are expected to be a problem. In some cases when it is hard to predict if there will be a problem or not, Sörling (2011-11-08) suggests that the back-walls should be provided with a corbel, which allows for a link plate to be installed after construction, if needed. If settlement problems would occur, there is a possibility to delve away the top part of the embankment and install a link plate afterwards.

7.3.1.2 Managing the edge beam

To avoid the need to replace edge beams, one solution could be to use stainless steel instead of conventional reinforcing steel. This solution would however result in a higher investment cost for the bridge, but since stainless reinforcing steel is unaffected by the deteriorates that breaks down the conventional reinforcing steel, its durability is assumed to be at least as long as the design service live of the bridge itself. By using stainless reinforcing steel, the advanced, expensive and traffic-disrupting procedure to replace the edge beams is virtually eliminated on the account of a larger investment cost.

Another solution could be to use prefabricated edge beams provided with conventional reinforcement. By using prefabricated edge beam elements the time and complexity of a replacement would be significantly reduced, which in turn also minimises the traffic disruptions.

This type of solution and the way the prefabricated edge beam elements are fixed to the concrete deck by bolts has a favourable effect with respect to the tensile cracks that can take place in edge beams over interior supports, see Section 6.2.3. This is due to the fact that prefabricated edge beam become more or less independent of the bridge deck and experience less strain. Prefabricated edge beams are common in Germany where they have been used successfully on a number of bridges. In Sweden however, less successful tests have been performed in northern Halland, Darholm (2011-11-09).

7.3.1.3 Prevention of cone erosion

Two different solutions are suggested to prevent the occurrence of cone erosion, see Section 6.2.7 for further information regarding this problem.

The first solution could be to extend the edge beams at all four ends away from the cones. This would prevent the surface water from the bridge to be drained off down the cones, but instead drain off on the road embankment further away from the cone. Road embankments are, unlike cones, designed to drain away surface water according to Bäckström (2011-11-14).

An alternative solution could be to form grooves in the asphalt that collects the surface water and diverts it to an enhanced groove that runs down the cone, Bäckström (2011-11-14).

7.3.2 Alternative detailing solutions for composite steel bridges

A description of the improvements that were suggested for composite steel bridges is presented in this section.

7.3.2.1 Pre-emptive washing and maintenance painting

One of the more expensive activities needed on steel bridges, and also composite steel/concrete bridges, is the re-appliance of the corrosion protective painting of the bridge's steel members. This activity usually needs to be carried out at an interval of around 25 years.

A way to reduce the costs for this activity could be to extend the time-interval between the repaints. One way that might increase the time-interval between the repaints would, according to Skoglund (2011-11-08), be to clean the bridge approximately once a year. This measure would generate a relatively small cost per cleaning occasion, assuming that small damages are discovered and treated during continuous inspections. This measure could probably postpone the expensive repainting by approximately 5-10 years.

7.3.2.2 Welded connections for transversal stiffeners

Another common problem with steel bridges is corrosion initiated in small joints, also see Section 6.3.1.1. When considering composite steel/concrete bridges, the bolted connections between the transversal stiffeners and the primary girders are typical examples. An easy method to avoid this problem, which is caused by small relative movements, is to use welded connections instead of bolted. Welded connections are stiffer, tighter and do not allow for any relative movements to take place in the connections. It also provides a gap and crevice-free detail, which also could have caused corrosion problems. These types of welded connections are more expensive than the bolted alternative, but have the advantage of eliminating this type of corrosion. It is important to keep in mind that adding welds to a bridge, most likely gives rise to other issues such as fatigue damages instead, Sandberg (2011-11-09).

7.3.2.3 Prevention of vandalism

One unnecessary and often expensive problem when it comes to steel bridges is the need for maintenance painting caused by vandalism.

A way to reduce this kind of problem could be to secure loose objects in the vicinity of the cones, e.g. by fitting a net over such objects or replace smaller rocks with bigger, or just pave the ground, Sandberg (2011-11-09).

7.3.3 Alternative detailing solutions for transversally prestressed glulam slab bridges

A description of the improvements that were suggested for transversally prestressed glulam slabs is presented in this section.

7.3.3.1 Installation of moisture indicators

As mentioned in Section 6.4.1, the end timber on transversally prestressed glulam slabs is usually inaccessible for visual inspections. The alternative is to perform destructive testing, which preferably is avoided.

One easy and inexpensive possibility to monitor the moisture quotient, thus reducing the risk of getting moisture related damages to end timber, would be to install moisture indicators during construction. By installing moisture indicators it becomes relatively easy to monitor the moisture quotient and to take preventive measures before the moisture quotient would cause any damage, Jacobsson (2011-11-14).

7.3.3.2 Managing the protective panels

As mentioned in Section 6.4.4, protective panels can be performed in two different ways. One way is the use of regular timber, which needs re-application of protective painting at an interval of 8 years, or by using pressure impregnated timber, which do not require any application of protective painting.

Both methods are relatively common, and it is usually due to aesthetical reasons one would prefer regular timber panels, Jacobsson (2011-11-14). For analysis purposes the impregnated panel was considered to be an improvement compared to solutions with a regular panel.

7.4 LCC-analysis for case 1

This section describes the second LCC-analysis, case 1, where the suggested improvements were implemented into the same scenario as the previous, case 0, above. This analysis had the purpose of simulating an alternative way to design a new bridge.

7.4.1 Procedure for the LCC-analysis for case 1

The second LCC-analysis, case 1, was in contrast to case 0 not directly applied to the collected data that is described in Chapter 6, but considering suggested improved detailing solutions to avoid or minimise such problems instead. The LCCs of these improved solutions could then be used for comparison with the results from case 0.

The suggestions for improvements are covered in Section 7.3,**Error! Reference source not found.** above, and not unlike the procedure for LCC case 0, a few of the possible improvements needed to be left out. This concerned the following:

- **Back-wall concrete bridges**
  - Prefabricated edge beam
    - Decided to be left out on the account of the solution with stainless reinforcing steel and due to the general lack of knowledge
  - Grooves in the embankment
    - Decided to be left out on the account of extended edge beams
- **Composite steel bridge**
  - Prevention of vandalism
    - Not included in case 0 and would cause an insignificant cost difference if used

Unlike case 0, the costs of all improvements, excluding the link plate, are considered to be investment costs. Therefore, the majority of the improvements do not generate any MR&R or traffic costs and the issue of assessing when in time the MR&R activities will occur vanishes in those cases. Nevertheless, these investment costs need to be assigned realistic numerical values in relation to case 0. How and why these and other assumptions were performed is explained below in Section 7.4.2.

The procedure was then basically the same as in case 0, with the difference that other values were inserted into the softwares instead.

7.4.2 Assumptions for case 1

This section describes the assumptions that needed to be made in order to run the second LCC-analysis, case 1, considering the implementation of the suggested improvements.

7.4.2.1 General assumptions for case 1

At this stage the first LCC-analysis, case 0, had already been performed and was supposed to be compared to this, case 1, analysis. Since it was decided in case 0 that it was only necessary to account for the costs related to the stated problems, the same principal was used in this second analysis.

Since this analysis was based on case 0, it was decided that only the **extra** costs, i.e. the cost difference between the conventional solution and the improved solution would be considered for all improvements, thus using the costs for case 0 as zero reference values for the analysis.

The bridge dimensions and analysis period were the same for case 1 as for case 0.

7.4.2.2 Assumptions regarding the traffic conditions for case 1

The traffic situations stated in case 0 remained unchanged for case 1. See Section 7.2.2.2 for more information.

7.4.2.3 Assumptions regarding costs, time-intervals and duration of the activities for case 1

To be able to use the new improvements in the softwares, new costs, time-intervals and durations of activities needed to be assumed. These improvements were not as easy to find standard-values for in the BaTMan pricelist, as it was for case 0. In fact, no prices for the improvements could be found in the BaTMan pricelist. The approach to solve this issue was the same as for case 0, to contact the bridge managers and experienced personal at COWI for reasonable estimations of probable costs for the suggested activities.

There were also cases where the information needed to be assumed single-handedly. This was applied for the following:

- **Edge beam**
    - Stainless reinforcing steel
        - The cost was assumed from considering an arbitrary edge beam and then calculating its price with regard to the steel volume. By then replacing the conventional steel with stainless steel, a cost could be assumed according to the calculations shown in Appendix F
    - Extension
        - A distance of 2 m was assumed to be sufficient to avoid the effects of cone erosion
- **Moisture indicators**
    - 2,000 SEK in total, for the instalment of indicators, covering all end-timber was assumed to be on the safe side
- **Welds**
    - The improved connection was assumed to a new cost of 5,000 SEK/connection
        - Five transversal beams were assumed, where each beam required two connections. That resulting in total10 connections and a total cost of 50,000 SEK for the welds

The assumed costs used in the LCC-analysis for case 1 are shown in Table 7.3 below.

Table 7.3 Presentation of the assumed costs (SEK), time-intervals and duration of activities performed on the selected bridge types (case 1)

Reinforced concrete beam bridge with back-walls (case 1)										
Activity	Cost for activity	Interval	Duration	Traffic	Closed lanes			Source		
		[years]	[days]	disturbance	0	1	2	Cost	Interval	Duration
Stainless steel reinforcement	1 500 SEK/m	∞	-	no	X			SA	JS	-
Bearings (sliding)	22 500 SEK/pc	∞	-	no	X			JS	JS	-
Extended edge beam	6 000 SEK/m	∞	-	no	X			MB	MB	-
Link plate	40 000 SEK	50	1	yes		X		JS	JS	DG

Composite steel/concrete beam bridge with back-walls (case 1)										
Activity	Cost for activity	Interval	Duration	Traffic	Closed lanes			Source		
		[years]	[days]	disturbance	0	1	2	Cost	Interval	Duration
Stainless steel reinforcement	1 500 SEK/m	∞	-	no	X			SA	JS	-
Bearings (sliding)	22 500 SEK/pc	∞	-	no	X			JS	JS	-
Extended edge beam	6 000 SEK/m	∞	-	no	X			MB	MB	-
Link plate	40 000 SEK	50	1	yes		X		JS	JS	DG
Painting of girders	3 000 SEK/m^2	25	-	no	X			DG	JS	-
Pre-emptive washing	2 500 SEK	1	-	no	X			DG	SA	-
Welded connections	2 500 SEK/gap	35	-	no	X			MB	JS	-

Transversally prestressed glulam slab bridge (case 1)										
Activity	Cost for activity	Interval	Duration	Traffic	Closed lanes			Source		
		[years]	[days]	disturbance	0	1	2	Cost	Interval	Duration
Bearings (sliding)	22 500 SEK/pc	∞	-	no	X			JS	JS	-
Impregnated panels	10 SEK/m^2	40	-	no	X			SA	PJ	-
Moisture indicators	2 000 SEK	∞	-	no	X			SA	SA	-

7.4.3 LCC results case 1

The output data the softwares delivered for the second analysis, case 1, is shown below in Table 7.4.

Table 7.4 LCC output data (SEK) for case 1, from the three softwares, for each selected bridge type

Reinforced concrete beam bridge with back-walls (case 1)									
Activity	BroLCC			BridgeLCC			Vännen07		
	MR&R-costs	Traffic	**Tot. LCC**	MR&R-costs	Traffic	**Tot. LCC**	MR&R-costs	Traffic	**Tot. LCC**
Stainless steel reinforcement	60 000	-	**60 000**	60 000	-	**60 000**	60 000	-	**60 000**
Bearings (sliding)	90 000	-	**90 000**	90 000	-	**90 000**	90 000	-	**90 000**
Extended edge beam	48 000	-	**48 000**	48 000	-	**48 000**	48 000	-	**48 000**
Link plate	105 629	402	**106 031**	105 854	418	**106 272**	106 098	-	**106 098**
Sum			**304 031**			**304 272**			**304 098**

Composite steel/concrete beam bridge with back-walls (case 1)									
Activity	BroLCC			BridgeLCC			Vännen07		
	MR&R-costs	Traffic	**Tot. LCC**	MR&R-costs	Traffic	**Tot. LCC**	MR&R-costs	Traffic	**Tot. LCC**
Stainless steel reinforcement	60 000	-	**60 000**	60 000	-	**60 000**	60 000	-	**60 000**
Bearings (sliding)	90 000	-	**90 000**	90 000	-	**90 000**	90 000	-	**90 000**
Extended edge beam	48 000	-	**48 000**	48 000	-	**48 000**	48 000	-	**48 000**
Link plate	105 629	402	**106 031**	105 854	418	**106 272**	106 098	-	**106 098**
Pre-emptive washing	171 257	-	**171 257**	168 667	-	**168 667**	178 711	-	**178 711**
Welded connections	50 000	-	**50 000**	50 000	-	**50 000**	50 000	-	**50 000**
Sum			**375 288**			**372 939**			**382 809**

Transversally prestressed glulam slab bridge (case 1)									
Activity	BroLCC			BridgeLCC			Vännen07		
	MR&R-costs	Traffic	**Tot. LCC**	MR&R-costs	Traffic	**Tot. LCC**	MR&R-costs	Traffic	**Tot. LCC**
Bearings (sliding)	90 000	-	**90 000**	90 000	-	**90 000**	90 000	-	**90 000**
Impregnated panels	4 833	-	**4 833**	4 866	-	**4 866**	5 004	-	**5 004**
Moisture indicators	2 000	-	**2 000**	2 000	-	**2 000**	2 000	-	**2 000**
Sum			**96 833**			**96 866**			**97 004**

As seen in Table 7.4 above, there is only one activity, the installation of link plates that causes traffic costs due to MR&R works. All the other activities/improvements are either performed at the initial stage, or do not disturb the traffic flow when carried out. A consequence of that the costs are being incurred at the initial stage is that there is no discounting of these costs. One would interpret this as that the activities become more expensive if they occur today, compared to if they would have occurred after some time into the future.

To draw conclusions on how effective the suggested improvements were, a direct comparison of the LCC results between case 0 and case 1 needed to be performed. The next section presents the results of this comparison.

7.4.3.1 Comparison of the results for case 0 and 1

After having performed LCC-analyses both for case 0 and case 1, a comparison could be carried out. Table 7.5 below presents a compilation of the LCC results from case 0 and 1.

Table 7.5 Comparison between the LCC (SEK) of each activity's individual LCC results from case 0 and 1

Reinforced concrete beam bridge with back-walls (Comparison case 0 and case 1)

Activity		BroLCC				BridgeLCC				Vännen07			
		MR&R-costs	Traffic	Tot. LCC	Difference	MR&R-costs	Traffic	Tot. LCC	Difference	MR&R-costs	Traffic	Tot. LCC	Difference
Edge beam	Case 0	39 925	7 610	47 535	- 12 465	41 522	7 914	49 436	- 10 564	41 182	-	41 182	- 18 818
	Case 1	60 000	-	60 000		60 000	-	60 000		60 000	-	60 000	
Bearings	Case 0	9 529	41 392	50 921	- 39 079	9 910	44 290	54 200	- 35 800	10 834	-	10 834	- 79 166
	Case 1	90 000	-	90 000		90 000	-	90 000		90 000	-	90 000	
Cone erosion	Case 0	8 870	-	8 870	- 39 130	9 225	-	9 225	- 38 775	12 149	-	12 149	- 35 851
	Case 1	48 000	-	48 000		48 000	-	48 000		48 000	-	48 000	
Link plate	Case 0	79 677	5 695	85 372	- 20 659	82 865	5 923	88 788	- 17 484	82 865	-	82 865	- 23 233
	Case 1	105 629	402	106 031		105 854	418	106 272		106 098	-	106 098	

Composite steel/concrete beam bridge with back-walls (Comparison case 0 and case 1)

Activity		BroLCC				BridgeLCC				Vännen07			
		MR&R-costs	Traffic	Tot. LCC	Difference	MR&R-costs	Traffic	Tot. LCC	Difference	MR&R-costs	Traffic	Tot. LCC	Difference
Edge beam	Case 0	39 925	7 610	47 535	- 12 465	41 522	7 914	49 436	- 10 564	41 182	-	41 182	- 18 818
	Case 1	60 000	-	60 000		60 000	-	60 000		60 000	-	60 000	
Bearings	Case 0	9 529	41 392	50 921	- 39 079	9 910	44 290	54 200	- 35 800	10 834	-	10 834	- 79 166
	Case 1	90 000	-	90 000		90 000	-	90 000		90 000	-	90 000	
Cone erosion	Case 0	8 870	-	8 870	- 39 130	9 225	-	9 225	- 38 775	12 149	-	12 149	- 35 851
	Case 1	48 000	-	48 000		48 000	-	48 000		48 000	-	48 000	
Link plate	Case 0	79 677	5 695	85 372	- 20 659	82 865	5 923	88 788	- 17 484	82 865	-	82 865	- 23 233
	Case 1	105 629	402	106 031		105 854	418	106 272		106 098	-	106 098	
Cleaning steel	Case 0	204 701	-	204 701	33 444	212 889	-	212 889	44 222	280 121	-	280 121	101 410
	Case 1	171 257	-	171 257		168 667	-	168 667		178 711	-	178 711	
Gap corrosion	Case 0	7 941	-	7 941	- 42 059	8 259	-	8 259	- 41 741	9 686	-	9 686	- 40 314
	Case 1	50 000	-	50 000		50 000	-	50 000		50 000	-	50 000	

Transversally prestressed glulam slab bridge (Comparison case 0 and case 1)

Activity		BroLCC				BridgeLCC				Vännen07			
		MR&R-costs	Traffic	Tot. LCC	Difference	MR&R-costs	Traffic	Tot. LCC	Difference	MR&R-costs	Traffic	Tot. LCC	Difference
Bearings	Case 0	9 529	41 392	50 921	- 39 079	9 910	44 290	54 200	- 35 800	10 834	-	10 834	- 79 166
	Case 1	90 000	-	90 000		90 000	-	90 000		90 000	-	90 000	
Timber panel	Case 0	9 344	-	9 344	4 511	9 555	-	9 555	4 689	9 717	-	9 717	4 713
	Case 1	4 833	-	4 833		4 866	-	4 866		5 004	-	5 004	
Damage end timber	Case 0	10 553	277 408	287 961	285 961	10 976	274 688	285 664	283 664	11 455	-	11 455	9 455
	Case 1	2 000	-	2 000		2 000	-	2 000		2 000	-	2 000	

In Table 7.5 above a comparison of each problem and its suggested improvement can be seen. It was concluded that comparing entire bridge solutions including all improvements at the same time could be misleading, since one single improvement could be either favourable or unfavourable with regard to LCC. Combining all chosen improvements could cancel out the positive effect of one really good detail by another really poor, or the other way around.

An LCC difference marked in a red colour and negative value in table 7.5, represents a negative outcome of an improvement; correspondingly, a green number and a positive value represents a positive outcome. Surprisingly, five out of the eight proposed improvements showed to be unfavourable (negative) to implement with regard to LCC. A first thought would be to question whether most of the suggestions for improvements were poor or not.

A further analysis of the output data was performed to figure out the reason(s) for why the improvements did not have the anticipated effect. The following facts were observed:

1. By iterations of moving the activities, considered in case 0, in time, showed that the LCC was significantly sensitive to at what age of the bridge an activity occurred. The later in time, the larger the decrease in LCC
2. The traffic costs did not have the impact on the LCC that was expected
    a. The *ADT* was thought to have been set moderately high, but affecting a relatively small 50 m stretch of road
3. The cost margin to make the proposed improvements favourable ranged from ~10,000-40,000 SEK
4. Assuming that that the costs of the activities and improvements were correct, the **only** variables that could affect the LCC in a way that could justify the improvements for these bridge types, in this particular analysis were:
    a. The ADT
    b. The size of the workzone
    c. When the activities, in case 0, would occurs in time

Considering the results and observations from the comparison between case 0 and 1, sensitivity factors on the LCC-analyses for short-span bridges were to be identified. These are described in Section 7.5 below.

7.5 Identification of sensitivity factors

Before the comparative LCC-analysis, described in Section 7.4.3.1, between case 0 and 1 was performed, it was expected that most of the improvements would be favourable if applied. Thereafter an identification of sensitivity factors, factors that had great influence on the LCC, would be performed.

When the analyses had been performed and the results compared, it stood clear that most of the suggested improvements were unfavourable from an LCC point of view. This unexpected result needed to be further investigated, and maybe the sensitivity factors were something different than what they initially were thought to be.

Three primary factors were identified from the comparison in Section 7.4.3.1 above.

1. The assumed *ADT*
2. The assumed size of the workzone
    a. Related to the size of the bridge and surrounding conditions, which then directly affect the traffic costs
3. When in time the activities considered were assumed to occur

Slight variations to these three factors could completely change the outcome of the LCC-analysis. The *ADT* and the size of the workzone were closely related, nevertheless still independent from each other, but both affecting the traffic costs. For that reason they are both treated in the same Section 7.5.1 below, followed by a description of how and why the age of the bridge when an activity occurs could be considered to be a sensitivity factor.

7.5.1 Sensitivity factor 1 and 2

As mentioned in Section 7.2.3, Vännen07 did not take the traffic costs, induced by MR&R activities, into account. Therefore, Vännen07 will not be considered further in the remaining parts of this chapter. Nevertheless, this lack of consideration of traffic costs in Vännen07 gave a first clue concerning the importance of the traffic costs in the analysis, when comparing the calculated LCC in case 0 of the various softwares, seen in Table 7.2 above. In the cases where both lanes needed to be closed, the major portion of the total LCC was incurred on the traffic costs, which further backs up this assumption. Most of the activities performed on a bridge do not require both lanes to be closed. Therefore, a situation with one out of two lanes closed will be considered in the further discussion.

In the sections below the effects the *ADT* and the size of the workzone have on the analysis results are described.

7.5.1.1 Sensitivity factor 1 – ADT

In the analyses that were performed for case 0 and 1, a certain ADT was assumed. However, the ADT may vary during the service life of a bridge and depending on where a bridge is located. If the ADT is assumed to increase for an arbitrary bridge, keeping the other variables constant, the traffic costs due to the delay increases exponentially. This effect can have a significant influence on the total LCC. The exponential effect is due to that the waiting time (t_{wait}) that is dependent on the *ADT*, see calculations in Appendix G. More information regarding these relationships is presented in Chapter 8. Figure 7.3 below presents how the LCC for an activity causing delays varies with a varying *ADT*.

The graph below shows how the traffic costs, due to an activity causing delays, influences the LCC and varies with a varying *ADT*. There were however four other variables that had to be assumed for this condition to apply:

1. **The length of the workzone**
2. The decrease in speed (v_{norm}-v_{red}) through the workzone
3. Vehicle operating cost (SEK/h), which type and proportion
4. Duration of the activity causing the delay

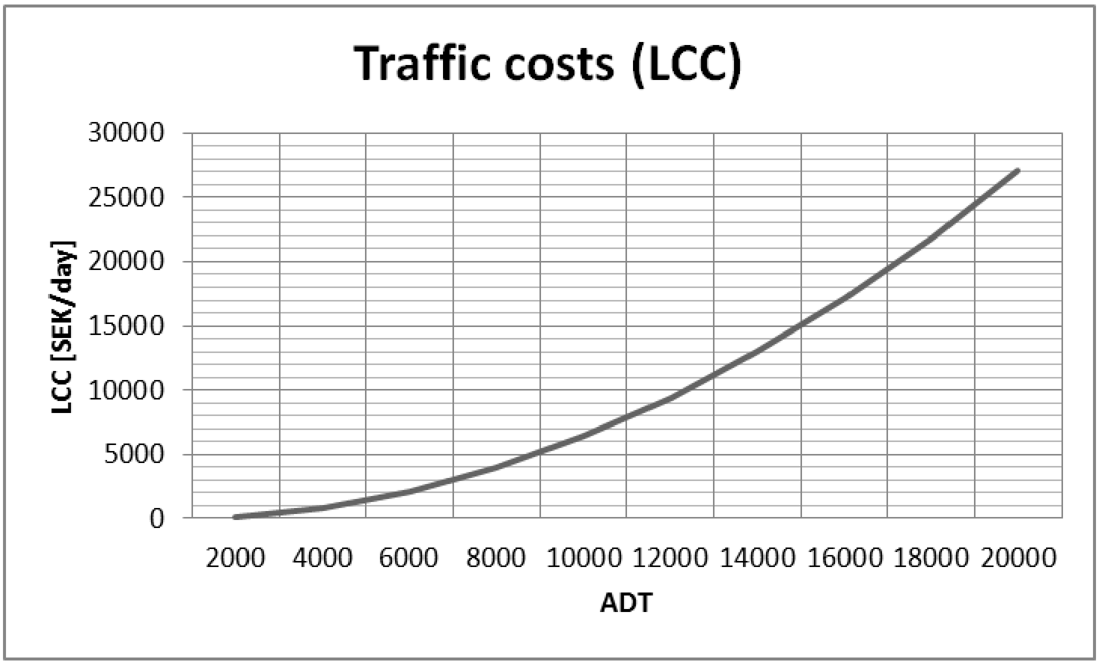


Figure 7.3 Illustration on how the LCC for an activity that causing delays to the traffic, varies with a varying ADT, TrafficWizard2011 (2011)

Of the four conditions mentioned above, the workzone could be considered to be of particular interest. If assuming the same bridge conditions as previously stated and then increasing the size of the bridge from one span to two, leaving all other conditions unchanged, the size of the workzone would become twice the original size. How the size of the workzone affects the life cycle traffic cost is explained below in Section 7.5.1.2.

One might argue that the duration of an activity also would increase if the workzone increased, but not necessarily, e.g. the replacement of an edge beam. The only time-factor that cannot be controlled by utilising more labourers in this case is the curing time of the concrete, and that time can be considered to be the same regardless of how long the edge beam is. So it is reasonable to assume that the duration of activities will generally not be affected, neither by the ADT or the size of the workzone.

How the decrease of speed could vary and how one might reason on this matter was considered to lie outside of the scope of this project. Hence it was decided to keep this variable as a constant and not consider it as a sensitivity factor.

Vehicle operating costs is a highly fictional, standard-based value, and needs to be kept constant as suggested by the Swedish Road Administration.

7.5.1.2 Sensitivity factor 2 – The size of the workzone

The size of the workzone assumed in the original analyses of case 0 and 1 was a certain, reasonable length of 50 m. This value was assumed on the basis that it would extend an additional 15 m on each side of the bridge. Since the traffic costs due to delays could have a large impact on the LCC and the size of the workzone was closely related to the traffic costs, a further investigation of how a variation in the size of workzone could affect the LCC was performed. By looking at the general equation for calculating the costs of traffic due to reduced speed below, it can be seen that a linear dependency of the workzone could be expected, see Equation (7.2.

$$C_{driver}=\left(\frac{L_{workzone}}{v_{red}}-\frac{L_{workzone}}{v_{norm}}\right)*ADT*D_{days}*C_{delay} \qquad (7.2)$$

An increase in size of the workzone ($L_{workzone}$) increases the time it would take to drive through the zone. As time has been given a cost (C_{delay}) for the vehicles, the LCC for traffic has a linear dependency to the size of the workzone, seen in Figure 7.4 below. The graph presents how the LCC for traffic varies with a varying size of the workzone.

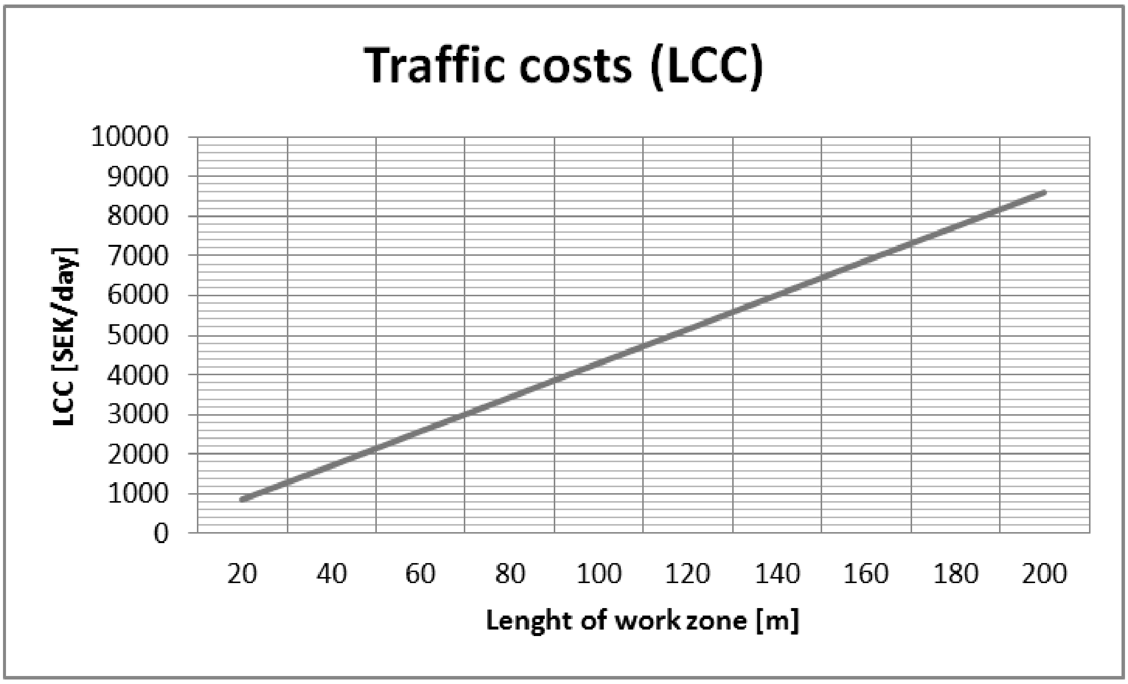


Figure 7.4 Illustration of how the LCC for traffic varies with a varying size of the workzone, conditions as previously assumed, TrafficWizard2011 (2011)

7.5.1.3 Combined influence of sensitivity factor 1 and 2 on the LCC

In conclusion it can be said that a linear relationship prevails when considering the size of the workzone and an exponential relationship for the *ADT*, where both of them contribute to the final LCC. So there are two variables affecting the life cycle traffic costs, their combined effect is shown in Figure 7.5 below.

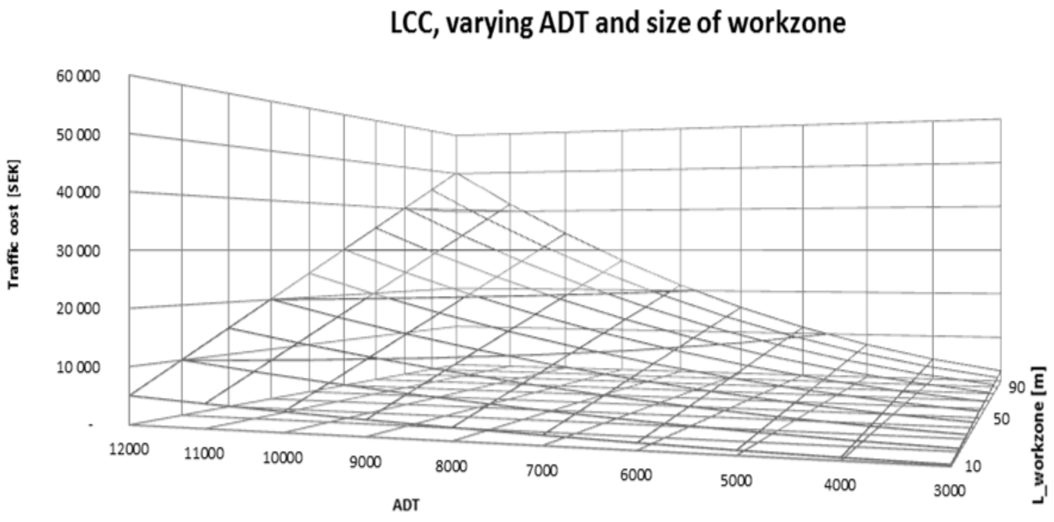


Figure 7.5 Illustration of the relationship between the two sensitivity factors ADT and size of the workzone and their impact on the life cycle traffic cost, TrafficWizard2011 (2011)

7.5.2 Sensitivity factor 3 – Age of the bridge when an activity occur

As it was noted in Section 7.4.3.1, when in time an activity takes place could have a significant influence on the total LCC. For instance if looking at the edge beam again, the repair activity had an assumed cost of 10,500 SEK/m, on 40 m of edge beam, thus resulting in a gross cost today of 420,000 SEK. This activity is however considered to take place at a bridge age of 60 years, resulting in an LCC of ~40,000 SEK. This is less than 10% of today’s cost. If it would be assumed that the edge beam need to be replaced at a bridge age of 40 years instead, like most of the existing edge beams today. That would increase the LCC to ~90,000 SEK, an increase with 125% compared to a replacement of the edge beam 20 years later. Adding the effect of traffic delay costs associated with this kind of activity, a misjudgement of when a repair activity needs to take place can have a large impact on the actual LCC result.

Figure 7.6 below shows how the LCC of an arbitrary activity with an initial cost of 420,000 SEK varies, depending on at what age of the bridge it takes place.

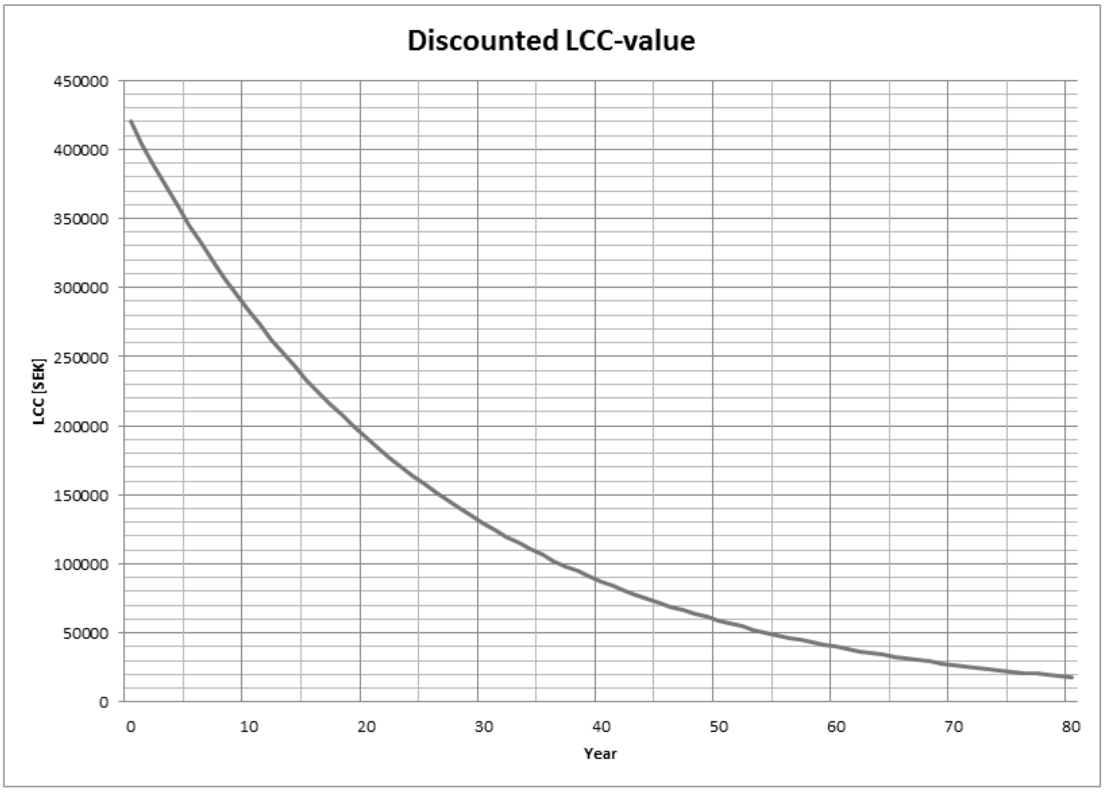


Figure 7.6 Illustration of how the LCC for an arbitrary activity with an initial cost of 420,000 SEK varies depending on when it takes place

Another conclusion that can be drawn is that the later the activities take place, the more inexpensive they become from an LCC point of view.

It could be suggested that special consideration should be taken to such activities where an uncertainty of at which age of a bridge they need be carried out. An overestimation of age could otherwise turn out to be much more expensive than expected LCC-wise. One approach could be to base the LCC-analysis on an uncertainty time interval for the occurrence of an activity.

7.6 Summary – Comparative life cycle cost analysis

This chapter described the two analyses performed, case 0 and 1. Case 0 represented the three bridge types selected in Chapter 5, assigned with the problems based on the experience drawn from similar existing bridges, described in chapter 6. Case 1 represented an alternative way to design 3 new bridges of the same types as in case 0. This time fitted with improvements to mitigate the problems considered in case 0 instead. When the two analyses were performed, a comparison was carried out to evaluate the effects of the improved detailing solutions. This comparison allowed for an identification of three previously unknown sensitivity factors that showed to have a significant effect to the final LCC results.

To be able to perform these analyses, a number of assumptions needed to be made. They were decided by first finding the information in the BaTMan pricelist, secondly by asking experienced bridge managers, and finally by carrying out single-handed assumptions.

The outcome of the comparison first turned out as a failure, since only three out of eight improvements proved to be favourable from an LCC perspective. But by further investigating the results and their reasons, it was found that the outcome could be traced back to the initially assumed conditions.

The next step was to identify the sensitivity factors, and logically these factors were the same factors that had spoiled the justifications of the improved solutions. It was noted that the following three factors could have a significant effect on the final LCC result and needed to be handled with care when carrying out an LCC-analysis:

1. **The ADT**
2. **The size of the workzon**e
    a. Related to the size of the bridge and surrounding conditions, which then directly effects the costs due to traffic delays
3. **When** in time the activities considered were assumed to occur

The further investigations based on this new knowledge, concluded from the results above, were hereafter to be implemented it into a recommendation for an LCC method. This intended method was to be used as an aid for the use of LCC-analysis as decision-making tool when designing new bridges. This process and the actual method are described in the next Chapter 8.

8 LCC approach for new bridges

This chapter describes how the conclusions drawn from the comparative LCC-analysis and the effect of the sensitivity factors, described in Chapter 7, could be utilised to develop a general method for using LCC-analysis as a decision-making tool in design, when planning new bridges.

8.1 General reasoning around the LCC approach

The method was primarily focused on how detailing solutions could be optimised when two or more alternative detailing solutions were available. The detailing solutions should be accompanied by as accurate or reasonable assumptions as possible, with regard to:

- **Costs**
  - Investment cost
  - MR&R cost
- **Time**
  - Interval for reoccurring activities
  - Uncertainty interval for single activities
  - Duration of activity (s)
  - Age of the bridge when an activity takes place
- **Traffic**
  - ADT
  - Vehicle operating cost (SEK/h), which type and proportion
  - Size of the workzone

With the assumptions above available, a parametric study of whether a detailing solution, compared to an alternative one, could be justified or not can be performed by the means of an LCC-analysis.

It was concluded in the previous Chapter 7 that the most sensitive variables, the sensitivity factors, of an LCC-analysis for short-span bridges were:

- ADT
- Size of the workzone
- Age of a bridge when an activity takes place

The costs for the activities themselves can of course vary with time, but costs for activities toady can however be assumed quite accurately and it was therefore not of any interest to study this issue any further. The same reasoning could be applied to the age when an activity would take place; however, there is an inherent uncertainty in estimating this age. This is because the LCC-analysis is highly sensitive to exactly when an activity is assumed to occur, as it was showed in Section 7.5.2. It is therefore recommended that a reasonable uncertainty interval for an activity is estimated with regard to:

- At what age of the bridge it can be assumed that it is very unlikely that a repair activity would take place before?
- At what age of the bridge is the activity expected to have taken place for certain?

Since the costs of delayed traffic in the LCC-analyses are dependent on the activities, it will add further to the effect of the assumed age of the bridge when a repair activity takes place. An evaluation of the costs related to the alternative solutions, depending on when in this time interval an activity takes place, allows for a better basis when making decisions in design.

The following section describes the background and assumptions that formed the basis for the suggested method of using LCC-analysis as a decision-making tool.

8.2 Background and new assumptions for the development of an LCC method

To develop a method for how to use LCC-analysis as a decision-making tool when planning new bridges, an understanding of how the variables of interest varied depending on each other was needed. The focus was put on the following two parameters, as it had been concluded by studying the sensitivity factors in Section 7.5:

1. ADT
2. Age of the bridge when an activity occurs

It should be noted that the size of the workzone has been left out in contradiction to what was argued in Section 7.5. The reason was that when considering a bridge to be designed, there is a limit on how small the size of a workzone can be. Depending on which activity that is taking place, there is a practical limit on how small the workzone can be for the intended activity. This practical limit can be considered to be constant, depending on which activity that is considered on each unique bridge. Therefore, the obvious conclusion from what was argued in Section 7.5, is to keep the size of the workzone to a minimum. Consequently, the size of the workzone can be assumed to be a minimum constant for each specific bridge.

8.2.1 Consideration taken to the ADT

It had already been concluded that the costs of traffic delay was an important factor to consider when working with LCC-analyses for bridges. These costs in turn were influenced by the variable *ADT*.

As described in Section 7.5.1.1, the LCC of traffic delays caused by MR&R activities was exponentially dependent on the waiting delay, t_{wait}, and the delay to pass the bridge with a reduced speed, Δt. In Section 7.2.2.2, where the assumptions regarding the traffic conditions were explained, t_{wait} was solely acquired from the computer software CapCal that performed these types of calculations. Further investigation was therefore considered necessary to better understand the effect of this variable.

In the original analyses for case 0, t_{wait} had an assumed value of 12 s. This value was dependent on the following specific input data set for the arbitrary bridge(s) that were analysed:

- v_{red}
- $L_{workzone}$
- *ADT*
    - 10% of the traffic running in one direction

Unfortunately, the CapCal software was only available during short periods of time during this project, and the proposed design method could not be allowed to depend on a software requiring an industrial licence. An alternative approach was to evaluate how t_{wait} varied when the input data was varied and derive an expression that reflected the result from CapCal. On the basis of iteration, an equation with a factor named the *D*-factor (*D*) was suggested. By studying the fairly small interval that *D* varied within when one parameter at the time varied, whilst keeping the other variables constant, it could be assumed that one weighed constant value could be assigned to *D*. Equation (8.1), seen below, and the correlation of *D* when the input data varied can be seen in Appendix H.

$$t_{wait} = D * ADT_{mod} * \left(\frac{L_{workzone}}{V_{red}}\right) \tag{8.1}$$

Where:

t_{wait}	= Extra travelling time due to MR&R work on the bridge
D	= *D*-factor (0,009 in the project)
ADT_{mod}	= Worse hour of traffic (5 % of the total ADT)
$L_{workzone}$	= Size of workzone
v_{red}	= Reduced speed through the workzone

By deriving the above expression and combining it with the previously used expression for calculating the costs of traffic delays, seen in Appendix F, all the necessary assumptions to evaluate the LCC's dependency on the *ADT* have been made.

A useful way to manage the involved equations and their relationship to one another is to use Excel. Consequently an Excel toolbox was developed and named TrafficWizard2011. By the use of this toolbox, a critical *ADT* with regard to specific activity can be derived, where an excess of this value would justify the use of an alternative/improved detailing solution. More information on TrafficWizard2011's functions, limitations, how it works and what output data it delivers is explained in the following sections of this chapter and explained in more in detail in Appendix I.

8.2.2 Consideration taken to the bridge age for an MR&R activity

As it was stated in Section 7.5.2, the age of the bridge when an activity occurs also has a large influence on the LCC. Without any reliable input data, e.g. data from BaTMan, an experience-based estimation could be an acceptable approach in this matter.

However, as discussed in Section 8.1 above, it could be recommended to dedicate more time into assessing an uncertainty interval on the estimated age of the bridge for a specific activity, due to the radical influence it can have on the outcome of an LCC-analysis.

Below follows an example, using the functions included in the TrafficWizard2011, to illustrate how an uncertainty interval on the timing of an activity could be performed. The purpose of assessing an uncertainty interval would be to verify whether a case 0 or 1 solution, is justified or not. The outcome will depend on which interval the case 0 activity is estimated to occur within.

8.2.2.1 Example on how to find the critical bridge age for a specific activity

To illustrate this example, the improved edge beam with stainless reinforcing steel, described in Section 7.3.1.2, was considered. According to Section 6.2.3, today's design of edge beams should have a design service life of 80 years, according to Thunstedt (2011-11-09). Darholm (2011-11-09) that also was interviewed during this project stated that experience of edge beams suggests a need for replacement at an interval of approximately 40 years. A rather large interval regarding when the actual replacement can be expected to take place is concluded. There are several models on how to predict the service life of different structural elements, edge beams too. The accuracy of these models in correlation with reality is what the mentioned uncertainty interval is based on.

What is interesting to figure out at this stage is when in time, counted from the inauguration of a bridge, a yet unknown critical age could be found. This critical age was defined to be the age where the LCC for case 0 and 1 was equal to each other, i.e. where the functions for the costs intersect. A replacement taking place after this critical age would result in a higher LCC for case 1, due to that the LCC for case 0 decreases with time, whereas case 1 remains constant. See Figure 8.1 below.

This type of LCC-analysis could be performed entirely by the use of TrafficWizard2011. By inserting the required input data into TrafficWizard2011, a graph labelled *"*Critical age when an activity occur*"* will be generated. This graph displays how the LCC for case 0 and 1 varies during a bridge's design service life.

The previously assumed input data for the edge beam was:

- *ADT*: = 6,000 vehicles
- Size of the workzone: = 50 m
- Extra investment cost for case 1: = 60,000 SEK
- MR&R cost for case 0: = 420,000 SEK
- v_{norm}: = 70 km/h
- v_{red}: = 50 km/h
- Duration of MR&R activity: = 28 days
- Cost per vehicle: = 140 SEK/h
- Cost per heavy (commercial) vehicle: = 320 SEK/h
- Proportions of heavy vehicles: = 10 %
- Discount rate: = 4 %
- Design service life: = 80 years

The graph generated by TrafficWizard2011, after inserting the input data above, can be seen below in Figure 8.1 below.

The critical age mentioned above can be found at the intersection between the LCC result for case 0 and 1. In this actual example, the critical age was found to be at an age of 53 years.

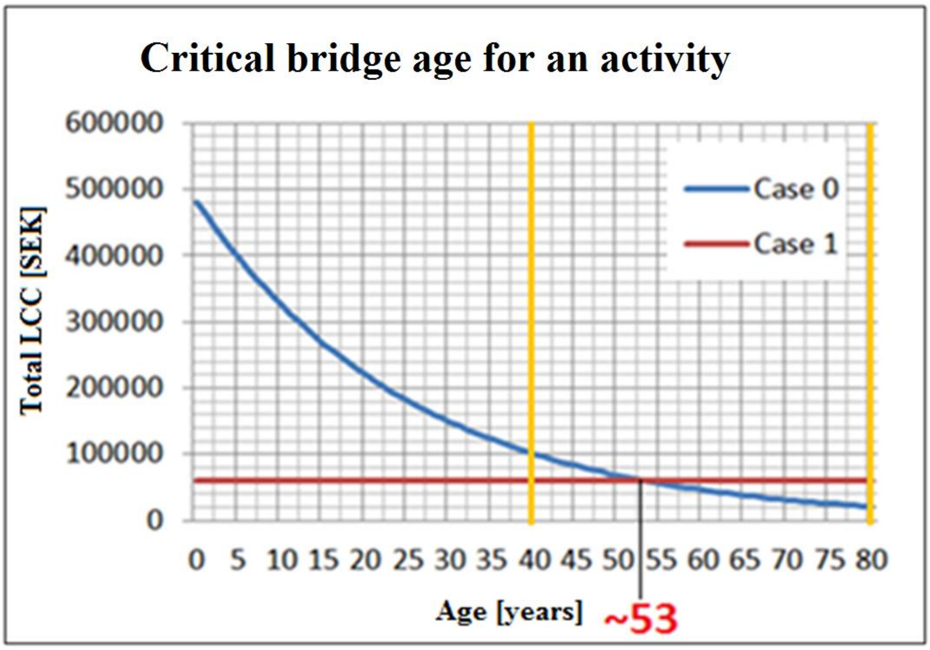


Figure 8.1 Taken from TrafficWizard2011 and shows the critical age of when a conventional edge beam earliest can be replaced to justify not using the alternative solution with stainless reinforcing steel

For a bridge with the conditions as mentioned above, the age of 53 years represents the critical age of the bridge for the replacement of the edge beam. That means that if the replacement occurs at age 53, both case 0 and 1 has the same LCC. If the predicted age of the bridge for the replacement were earlier than year 53, the alternative detailing solution would be the more favourable option. Consequently, if the replacement were predicted to take place after the critical age, the conventional design solution would be the more favourable option.

The uncertainty interval mentioned above was concluded to be within an age of 40 to 80 years and is illustrated by the yellow lines in Figure 8.1. This uncertainty assumption results in that the critical age would fall within this uncertainty interval. In that case the designer or the client would have to make a decision on which detailing solution to use. Note that an uncertainty interval of 40 years would be practically unreasonable. This interval is just used as an example in this case to illustrate how an uncertainty interval could be handled.

8.3 Development of an LCC method for new bridges

In order to develop an LCC method for new bridges, the two sensitivity factors were studied as described in Section 8.2, and transformed into two branches that form the basis of the suggested method.

As stated in Section 1.2, the purpose of this project was to: *"find an approach on how to use the LCC-analysis as a decision-making tool in design when planning new bridges"*. The flow chart, divided into two parts and seen in Figure 8.2 and Figure 8.3, illustrates the suggested approach for this very method.

Succeeding the flow chart, a practical example is presented in order to show how the method can be used in practice. A more detailed explanation of the different steps in the flow chart can be seen in Appendix J.

8.3.1 Limitations concerning the LCC method

The proposed method has the following limitations:

- Only one activity at the time can be analysed

- The default value of the factor D is a weighed value and is only applicable for:
    - $ADT > 3{,}000$ vehicles
    - Size of the workzone > 30 m

- Only applicable for road bridges

- The road is assumed to have two lanes

- A traffic situation where one out of two lanes is closed for traffic

8.3.2 Flow chart describing the LCC method

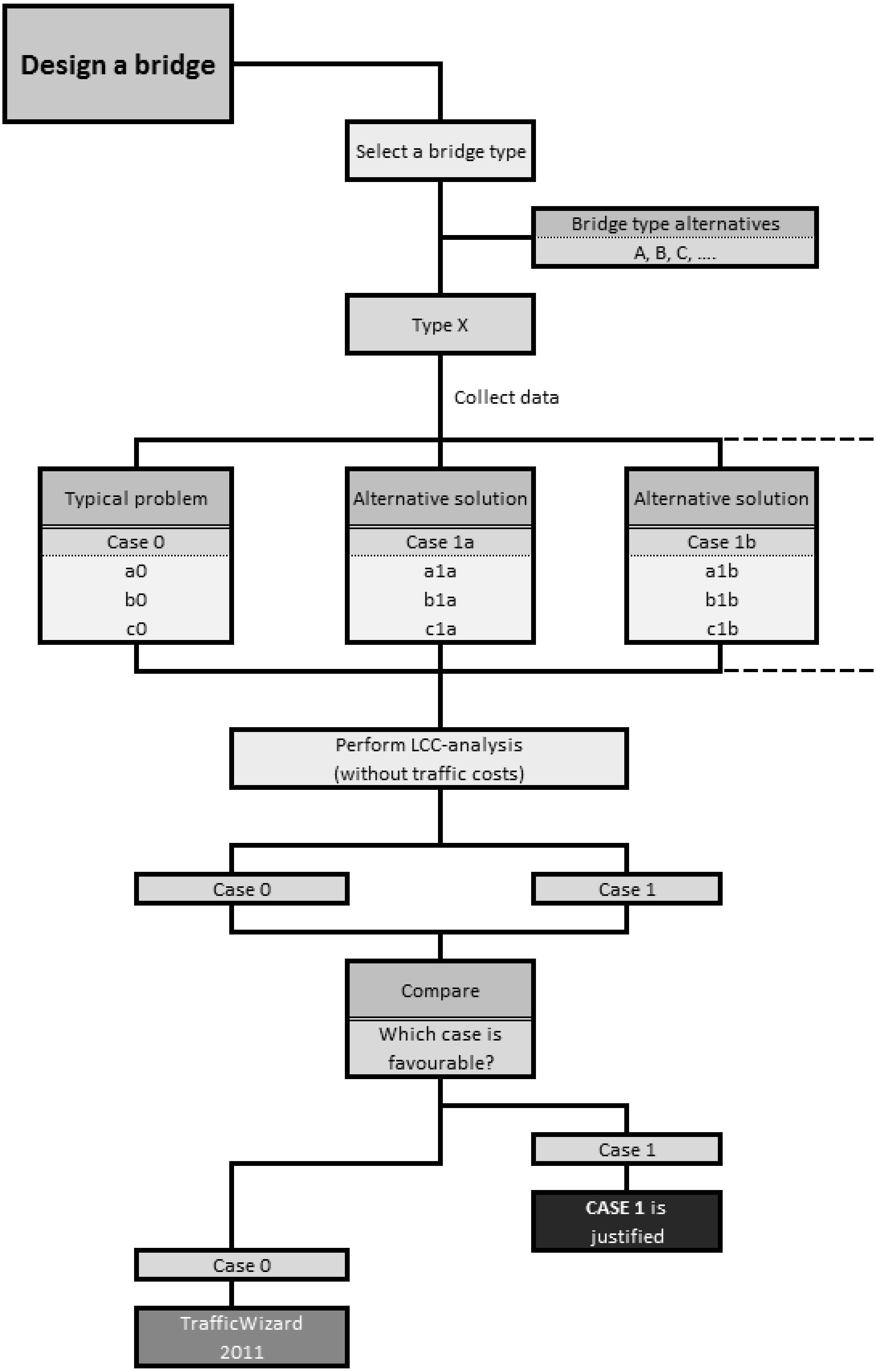


Figure 8.2 Flow chart, part 1 of 2, illustrating the recommended method for using LCC-analysis as decision-making tool

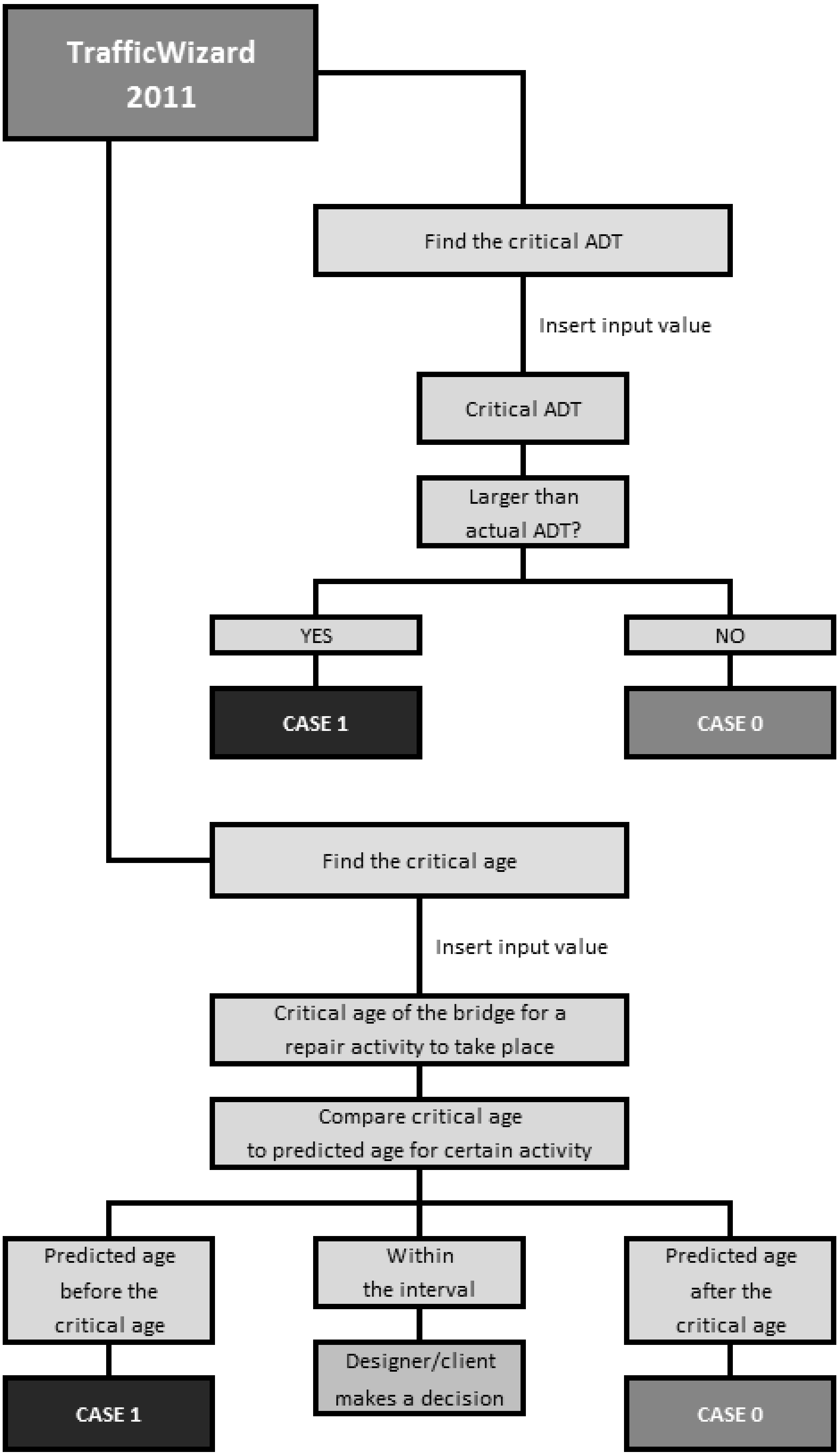


Figure 8.3 Flow chart, part 2 of 2, illustrating the recommended method for using LCC-analysis as decision-making tool

8.3.3 Practical example describing the LCC method

A practical example on how to use the LCC method for new bridges suggested above is described in this section.

For instructive purposes, the same example as explained in Section 8.2.2.1 will be considered. In this case a 7-step analysis was needed:

1. A bridge is to be designed

2. A back-wall concrete bridge will be used
   a. As decided during a possible conceptual design

3. A collection of data of common problems and alternative detailing solutions is performed, (suggested in the same manner as in Chapter 6 and 7):
   a. Case 0: Edge beam with conventional reinforcing steel
      i. Typical design practice
   b. Case 1: Edge beam with stainless reinforcing steel
      i. Alternative design solution to avoid edge beam replacement and minimise need for MR&R

4. An LCC-analysis was performed (without taking traffic costs due to MR&R work into consideration, at this stage)
   a. Edge beam replacement for case 0 was assumed to occur at a bridge age of 60 years
   b. Stainless steel reinforcement was considered only to incur an additional investment cost of 60,000 SEK

5. Comparison of LCC-analysis results, as seen in Figure 8.4 and Table 8.1 below
   a. Case 0 was concluded to be the most favourable detailing solution with regard to LCC

6. Continued work with TrafficWizard2011
   a. Find the critical ADT, explained in Appendix I
      i. Critical ADT > 6,000 vehicles
   b. Find the critical age, explained above in Section 8.2.2.1
      i. Critical age falls within the uncertainty interval, but after assumed age of the bridge to the benefit of case 0
         1. Designer and/or client has to make a decision

This method is thought to allow for a quick and easy procedure to justify whether a detailing solution's conventional or alternative design is favourable or not from an LCC point of view.

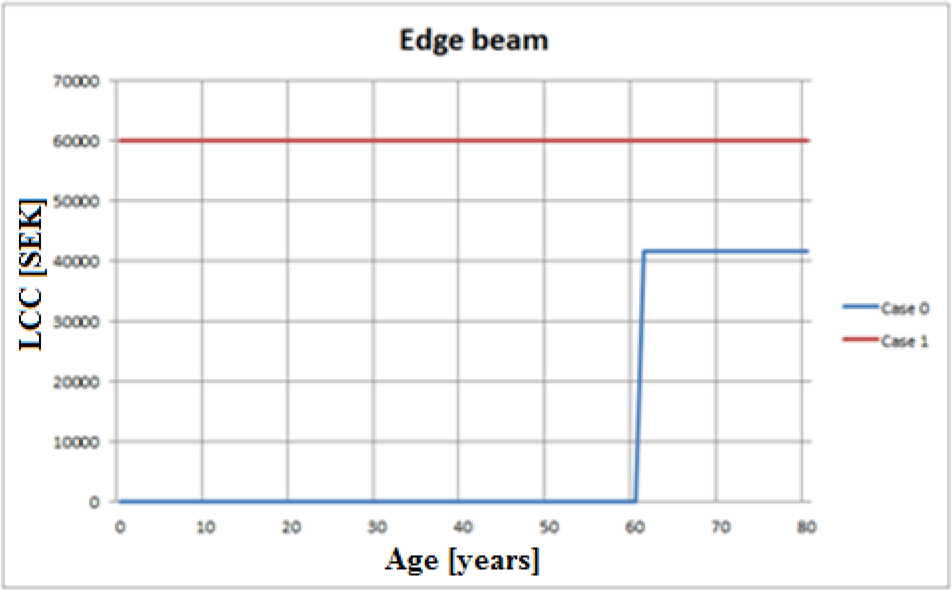


Figure 8.4 Difference in LCC between the two solutions for the edge beams, case 0 and 1 as presented by the BridgeLCC software

Table 8.1 Input data for the LCC differences illustrated in Figure 8.4 above

Activity		BridgeLCC			
		MR&R-costs	Traffic	Tot. LCC	Difference
Edge beam	Case 0	41 522	-	41 522	**- 18 478**
	Case 1	60 000	-	60 000	

8.4 Summary – LCC approach for new bridges

It was stated in the purpose of this project that: "*The purpose of the project was to find an approach on how to use the LCC-analysis as a decision-making tool in design when planning new bridges*". This method was developed primarily focusing on how bridge detailing solutions could be optimised when two or more alternative detailing solutions were available. These detailing solutions were in turn required to be accompanied by as accurate, or reasonable, assumptions as possible with regard to cost, time and traffic conditions.

From the analyses performed in Chapter 7, three sensitivity factors were identified. Two of these sensitivity factors, ADT and the age of the bridge when activity occurs, were in this chapter studied in further detail to understand the LCC's dependency on them. The outcome was that an Excel toolbox was developed where two critical values regarding ADT and age of occurrence could be derived from graphs. These graphs are believed to aid designers to justify detailing solution on an LCC basis. The Excel toolbox was named TrafficWizard2011, and the two critical values it could generate were:

1. Critical ADT
2. Critical age for an activity to occur

These critical values were retrieved by graphically by investigating and evaluating at which ADT or bridge age when an activity occurred, the LCC of two detailing solutions would be equal. A comparison of these two critical values to the prevailing design situation, allowed for an easily performed LCC-analysis based detailing optimisation. How the LCC is influenced by a varying *ADT* and age of the bridge for when an activity will occur is shown in Figure 8.5 below.

This new knowledge was later implemented into a flow chart, suggesting a systematic method on how to analyse and compare the profitability of two different detailing solutions for; short-span, two-lane, road bridges.

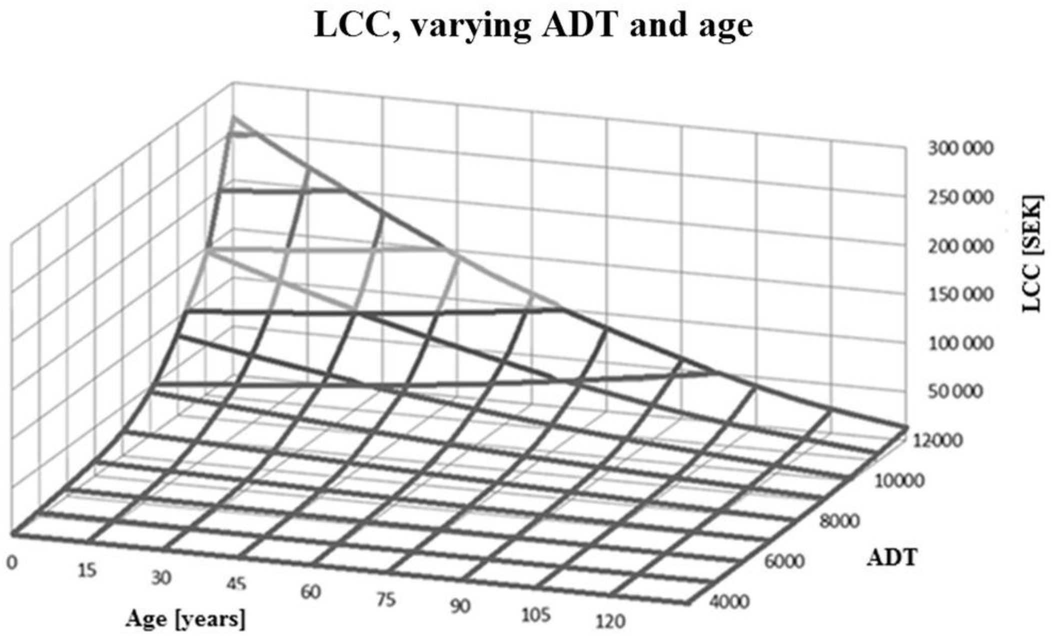


Figure 8.5 Illustration of how the LCC is varying with both ADT and age of the bridge when an activity occurs

The next chapter will summarise the conclusions drawn from this project and bring up suggestions for further research and development in the field of LCC for bridges.

9 Conclusions and Recommendations for Further Studies

This chapter presents the conclusions and recommendations for further studies in the field of LCC for bridges.

9.1 Conclusions

The concept of LCC is a method of interpreting the present value, which is a way of determining how the value of a cost decreases when postponed into the future. Having the present value of one particular cost-item by itself is basically useless. It is when its present value is compared to another that the LCC concept becomes useful. To carry out an LCC analysis, a number of assumptions needs to be made. Therein lays an uncertainty that has raised doubts on whether the LCC concept resolves, or introduces as many uncertainties as it initially was intended to resolve.

By using the knowledge of the LCC concept, three computer softwares were chosen to aid the work; WebLCC, BridgeLCC and Vännen07. A verification of the softwares showed that the newly developed WebLCC was not fit for use, which also led to its closure and it was replaced by its predecessor, BroLCC.

To perform the intended LCC analysis, three in Sweden commonly reoccurring short-span bridge types were selected; a reinforced concrete beam bridge with back-walls, a composite steel/concrete bridge and a transversally prestressed glulam slab bridge. All three bridge types suffer from their own typical problems, where most of them could be minimised by using alternative design solutions. These design solutions are unfortunately not common practice, mostly due to the associated increase of investment costs. To demonstrate whether these alternative design solutions could be justified from an LCC perspective, a parametric comparative LCC-analysis could be performed.

Consequently, a comparative analysis was performed and showed that it was not the specific detailing solutions themselves that could be favourable or not, but the effect of not implementing them that was the decisive factors. The conventional solutions often required future MR&R activities. When in time these activities would occur and their impact on the traffic, concluded to be the actual sensitivity factors to whether the improved detailing solution could be justified or not.

It was also noted that it was unsuitable to run a full scale alternative LCC-analysis at an early design stage, i.e. implementing all improvements together at once. Favourable and unfavourable detailing solutions for a specific case could easily be obscured by the results cancelling each other out. It was therefore concluded that an initial optimisation, carried out through a parametric study of various detailing solution was to be preferred.

In order to, as it is stated in the purpose of this thesis, "*find an approach on how to use the LCC-analysis as a decision-making tool in design when planning new bridges*", a design approach, illustrated by a flow chart, was developed. This design approach was aided by an Excel toolbox that also was developed, TrafficWizard2011. This design approach, or method, presents a systematic way of how to carry out a parametric analysis and compare the profitability of two different detailing solutions on short-span; two lane, road bridges. The Excel toolbox complements the flow chart by performing the necessary LCC calculations and presents graphs where the critical values called; critical ADT and critical age can be derived.

The authors' opinion is that this method can provide designers with an extended basis to choose the most viable long term design solutions, and the ability to financially motivate its implementation, even if it initially tend to appear to be a more expensive design solution.

9.2 Recommendations for further studies

The concept of LCC-analyses for bridges is relatively new and it has a lot of potential for further development in the pursuit of developing a more sustainable society. At the Royale Institute of Technology (KTH) in Stockholm, much work has been and is being carried out in this particular field. Amongst other projects, the ETSI project was in direct collaboration with professors and PhD students at KTH. This master thesis project was however the first to be carried out at Chalmers in this field, but after finishing this thesis, there are still a lot more to investigate and many improvements to be carried out.

The authors' suggestions for further studies in the field of LCC for bridges are:

- **Further development of TrafficWizard2011**
    - Refined traffic delay models
        - The *D*-factor, derived from the CapCal software, actually varies (however not much) with the input data
        - Evaluate other traffic delay models
            - According to Sundquist[6], there is a promising, fairly advanced computer model developed by the New Jersey Department of Transportation
    - More traffic situations can be included
        - More than 2 lanes crossing the bridge
        - Railway traffic
    - An upgraded English version of the software of BroLCC, called BridgeLCC, will soon be released by KTH. BridgeLCC will like TrafficWizard2011 be Excel-based. These two softwares could most likely be united into one, including more versatile functions
- **Increased risk for accidents**
    - Evaluating how to put a price on the increased risk for accidents during MR&R activities
        - This increased risk of accidents was not taken into consideration in this project, but duly noted
        - There are models available in this area, e.g. BridgeLCC

[6] Håkan Sundquist, Royal Institute of Technology. Interviewed 2011-10-27

- **Development of an LCC database**
    - Collection of data on problems commonly associated with different bridge types
    - Collection of data on alternative design solutions, minimising the commonly reoccurring problems associated with the corresponding bridge types
    - The following data is of particular interest for each problem and alternative design solution:
        - **Costs**
            - Investment cost
            - MR&R cost
        - **Time**
            - Interval for activities that are assumed to be repeated during the design service life
            - Uncertainty interval for a single activity
            - Duration of activity(s)
        - **Traffic**
            - ADT
            - Increase of ADT (%)
            - Size of the workzone
    - The BaTMan database contains objective information on these matters, but the extraction process is lengthy. An early request to BaTMan, formulated in the correct way, could allow for a more accurate data retrieval, see Appendix C

10 References

Atterhög K-F (2008) *Förenklad livscykelanalys (LCA) och livscykelkostnad (LCC) för en kvällstidning*. Stockholm: Royal Institute of Technology. (ISSN-1653-5715)

BaTMan (2010) *A'prislista för broåtgärder år 2011*. Trafikverket, januari 2011

Burley, E. and Rigden, S. R. (1997) *The use of life cycle costing in assessing alternative bridge design*. Proc. Instn Civ. Engrs Mun. Engr

Ehlen, M. (1997) *The life cycle cost of New Construction Materials*, Journal of Infrastructure Systems, Vol. 3, No. 4, p. 129-133, December 1997.

Forsman, J (2010) *Förbifart Stockholm - Jämförande LCCA -studier av de övergripande tekniska lösningarna vägbank, tunnel och bro*. Luleå: Luleå University of Technology

Hjort, C. and Tenskog, M. (2008) *Vägverkets samhällsekonomiska kalkylvärden*, Borlänge: Vägverket. (publication 2008:67, ISSN: 1401-9612)

Julita, A. and Sundquist, H. (2007) E*TSI Procejt (stage 1) Bridge Life Cycle Optimisation*. Helsinki: Helsinki University of Technology. (TKK-SRT-37)

Julita, A., Noponen, S. (2008) *LCC case studies for bridges in different design phases*, p 852.

Julita, A., Salokangas, L., Rautakorpi, H. and Tirkkonen, T (2005) *Bridge Life Cycle Optimisation (ETSI) – Project plan.* Helsinki: Helsinki University of Technology.

Karlsson, R (2008) *Underlag till schabloner för DoU-kostnader i EVA och Vägverkets effektsamband för nybyggnad och förbättring*. Linköping: VTI

Lyrstedt, F (2005) *Measuring Eco-Efficiency by a LCC/LCA Ratio*. Göteborg: Chalmers University of Technology. (ESA report no. 2005:11)

Nedev, G. Khan, U. (2011) *Guidelines for conceptual design of short-san bridges.* Göteborg: Chalmers University of Technology. (Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design).

Robinsson, R., Danielson, U. and Snaith, M. (1998) *Road Maintenance Management, Concept and Systems.* London: Macmillian Press Ltd

Ronnebrant, R. and, Troive, S. (1999) *Förstudie till FoU-ramprojekt –LCC modeller (bro).*Borlänge: Vägverket.

Rutgersson, B. (2008) *Bridge an Tunnel Management – Kodförteckning och beskrivning av brotyper.* Borlänge: Vägverket

Safi, M. *Bridge Life Cycle Cost Optimization - Analysis, Evaluation, & Implementation.* Stockholm: Royal Institute of Technology. (Master of Science Thesis in the Master's Programme Structural Design and Bridge).

Salokangas, L. (2009) *ETSI Procejt (stage 2) Bridge Life Cycle Optimisation.* Helsinki: Helsinki University of Technology. (TKK-R-3)

Sonesson, T. (2011) ”*Samhällsekonomiska lönsamhetskalkyler*”, Linköping: Linköpings universitet

Veshosky and Beidleman (1992) *Life-Cycle Cost Analysis Doesn't Work for Bridges.* Civil Engineering, July 1992.

Vägverket. (2009) *TK Bro – Juli2009 – Samhällsbyggande i Samverkan.* Borlänge: Vägverket, July 2009

Trafikverket. (2008) *Manual Vännen07 – Excelverktyg för Drift- och underhållskalkyler*, 2008-02-11.

Troive, S. (2000a) *Förstudie till FoU-ramprojekt –Verifieringsmetoder för upphandling av broars egenskaper*. Borlänge: Vägverket

Troive, S. (2000b) *Förstudie till FoU-ramprojekt –Optimala nya broar.* Borlänge: Vägverket

Conferences

Ang and Wyatt (1999) Performance concept in the procurement of durability and serviceability of buildings. At *Proc. 8th International Conference On Durability of building Materials and Components;* May 30 – June 3 1999, Vancouver

Online sources

ETSI. (2011) www.tkk.fi/yksikot/silta/etsiwww3/tg3.html (2011-08-15)

Martinsons, (2011a) *Träbroar*. www.martinsons.se, 2011-11-09

Martinsons, (2011b)www.martinsons.se/trabroguide/tvarspanda-broar, (2011-11-16)

NIST (2011), National Institute of Standards and Technology. *BridgeLCC*. www.nist.gov (2011-09-01)

Stålbyggnadsinstitutet, (2011a) *Moderna samverkansbroar*, www.sbi.se, (2011-09-08)

Stålbyggnadsinstitutet, (2011b) *Samverkansbroar*, www.sbi.se, (2011-09-08)

Computer softwares

BridgeLCC (2011). Developed at National Institute of Standards and Technology (NIST), www.nist.gov

BroLCC (2011). Developed at Royal Institute of Technology (KTH), www.kth.se

Vännen07 (2011). Developed by the Swedish Road Administration (Trafikverket), www.trafikverket.se

WebLCC (2011). Developed at Royal Institute of Technology (KTH) www.kth.se

CapCal (2011). Developed by Trivector. www.trivector.se

Oral sources

Magnus Bäckström (COWI), *2011-11-14*

Thomas Darholm (COWI), *2011-11-09*

Daniel Göransson (COWI), *2011-11-10*

Peter Jacobsson (Matrinsson Träbroar), *2011-11-14*

Eva Larsson (Verta Konsult), *2011-11-03*

Jan Sandberg (Private consultant), *2011-11-09*

Martin Skoglund (COWI), *2011-11-08*

Tomas Svensson (COWI) , *2011-10-28*

Per-Olof Sörling (Trafikverket), *2011-11-08*

Per Thunstedt (Trafikverket), *2011-11-09*

Bengt Uvhage (Trafikverket), *2011-11-03*

Appendix A: LCC softwares

WebLCC

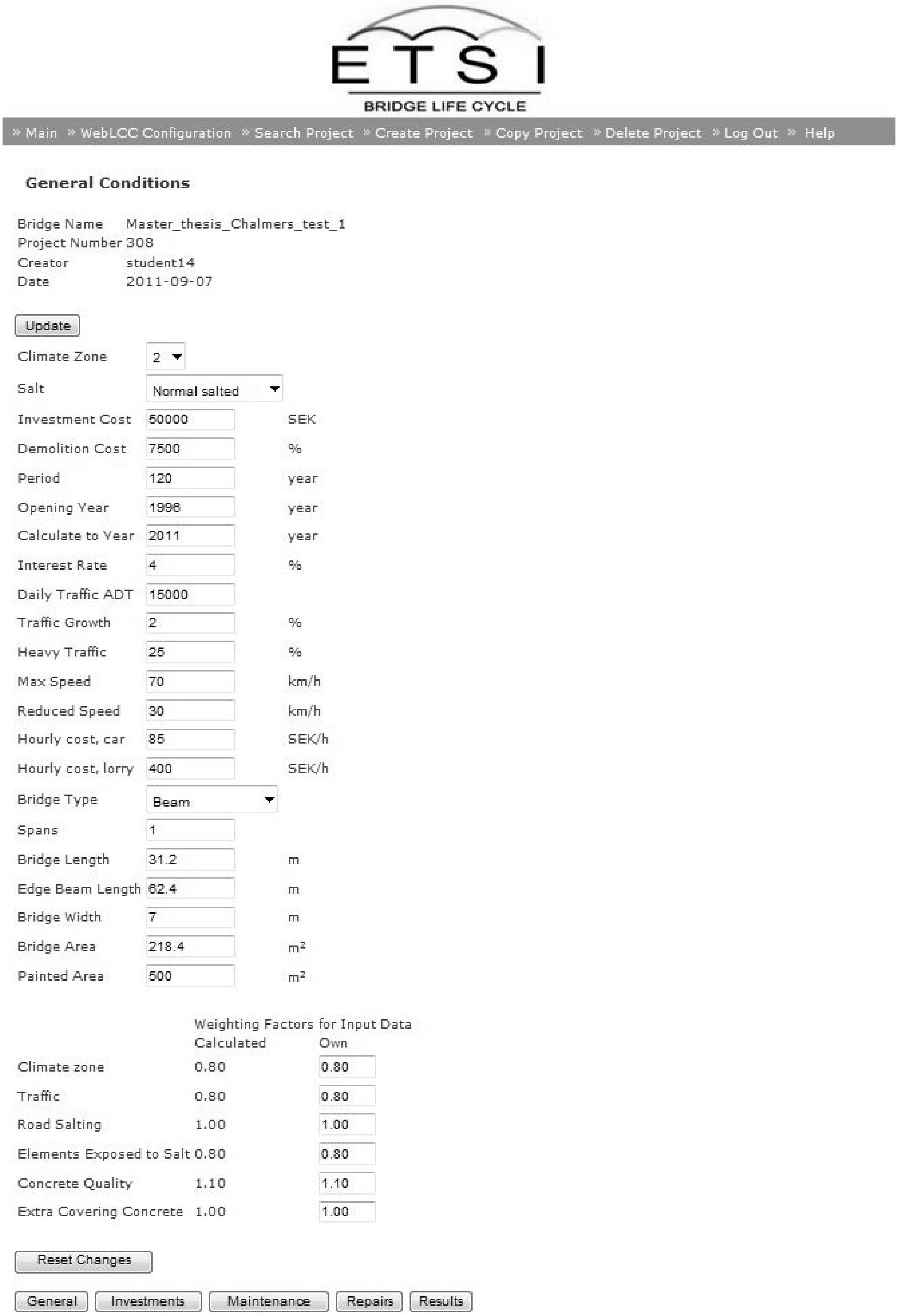


Figure A.1. View of "General conditions" page of WebLCC. Input values regarding the general conditions for the bridge can be defined

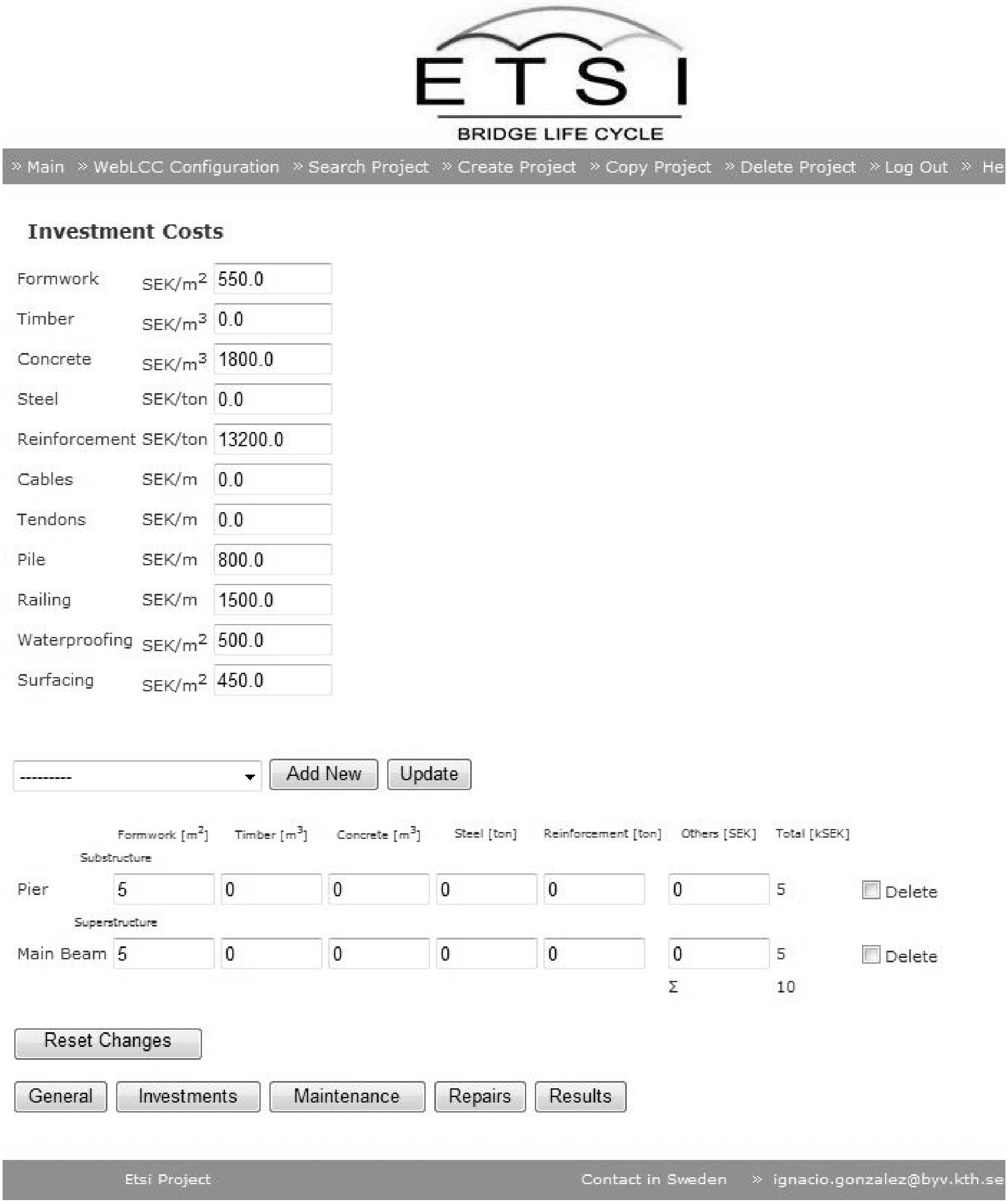


Figure A.2. In WebLCC, the investment cost for the bridge are defined in the "investment cost" page

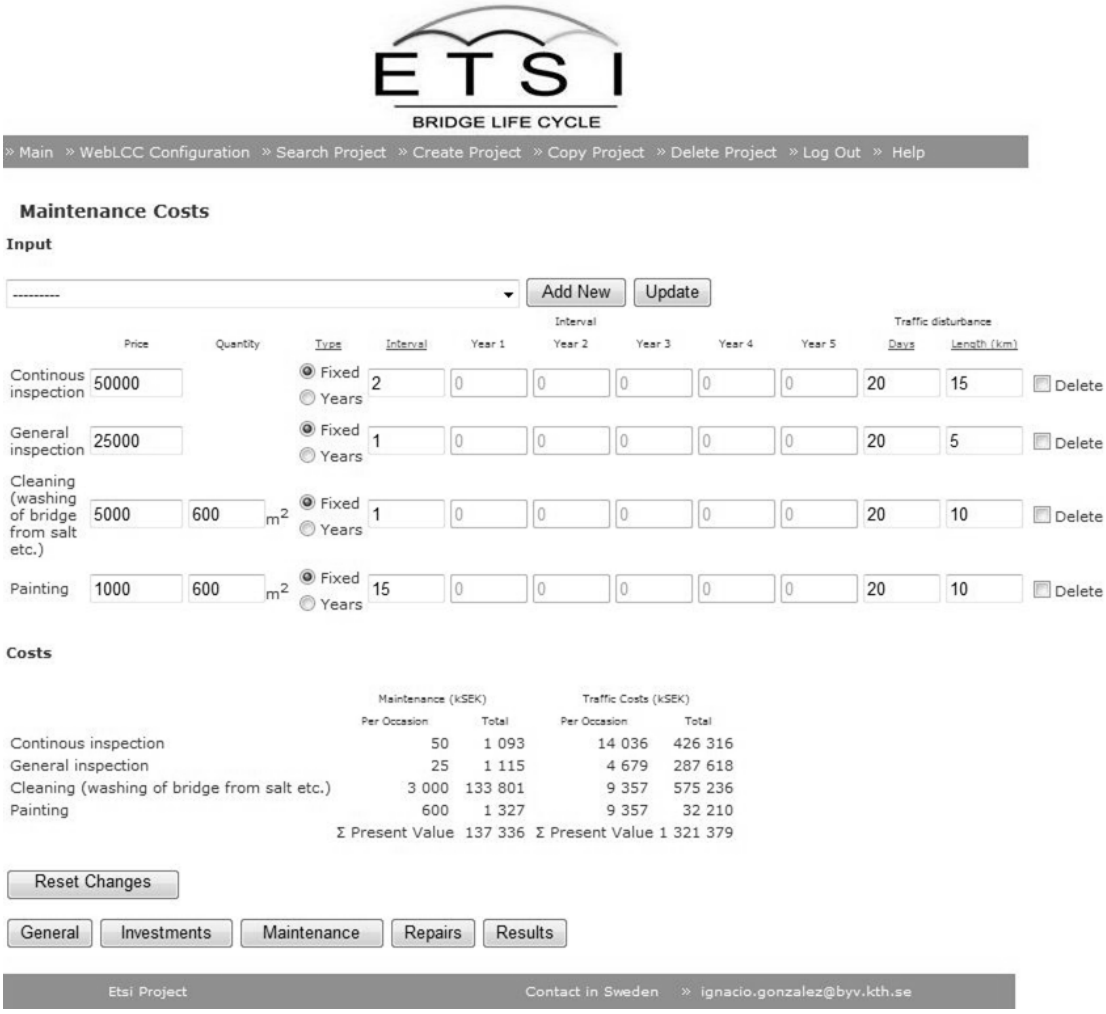


Figure A.3. In WebLCC, the assumed costs for operation and maintenance are defined in the "maintenance cost" page

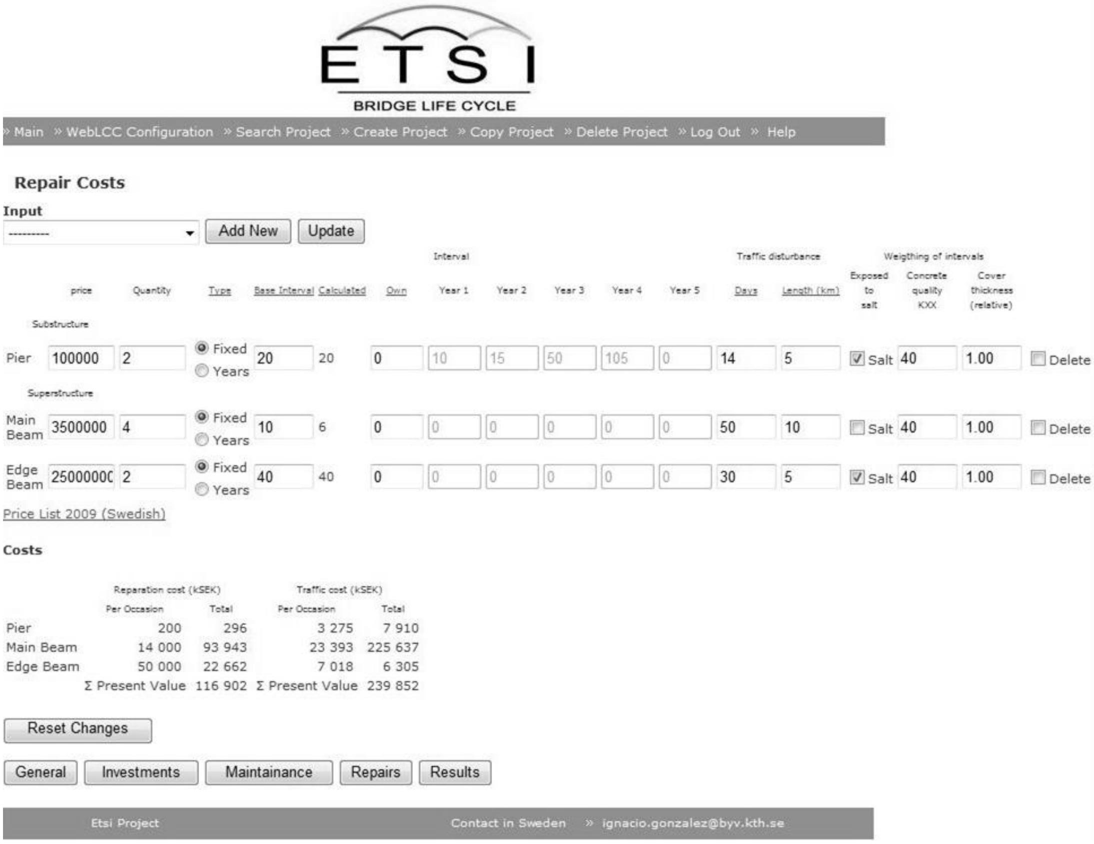


Figure A.4. In WebLCC, the assumed costs and intervals for the repair activities are defined in the"Repair costs" page

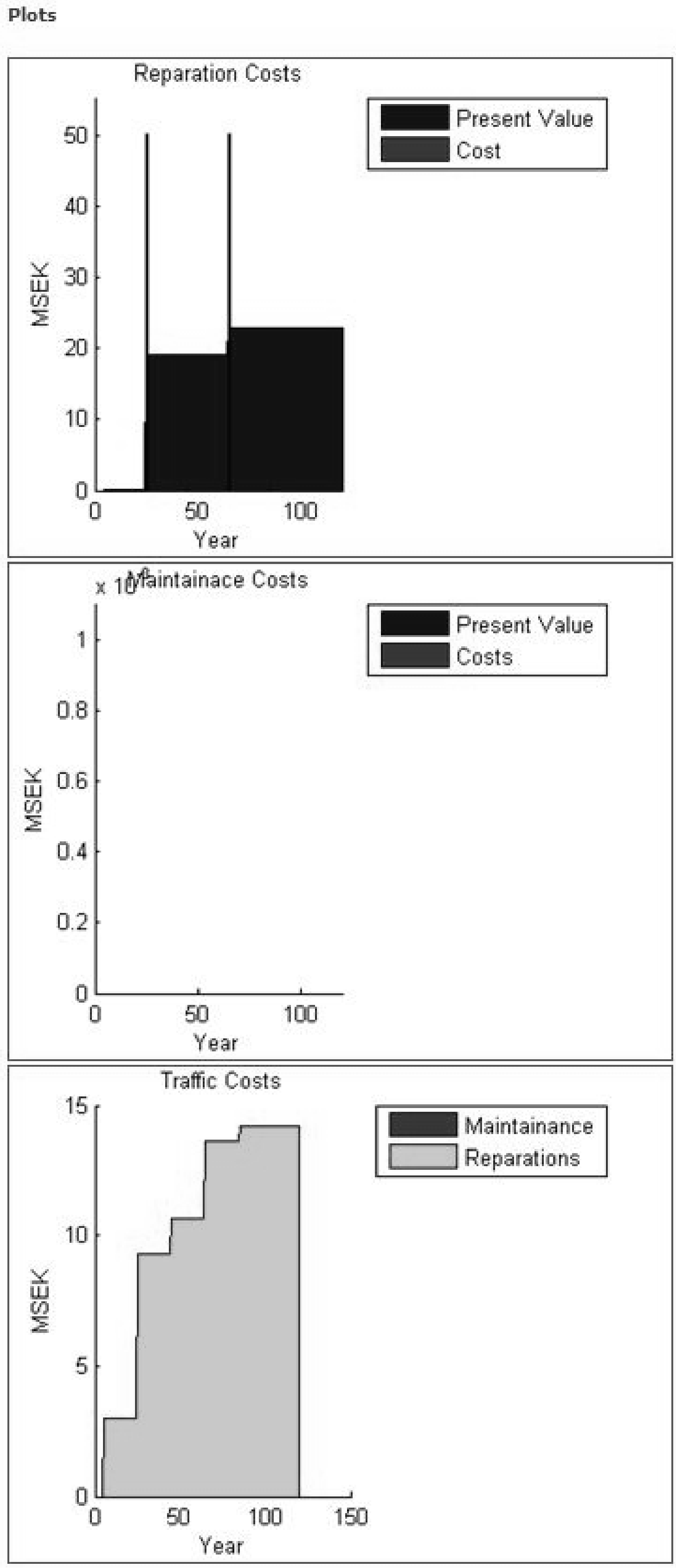


Figure A.5 Part 1 of 2 of the result page in WebLCC, where the results of the analysis are presented in graphs

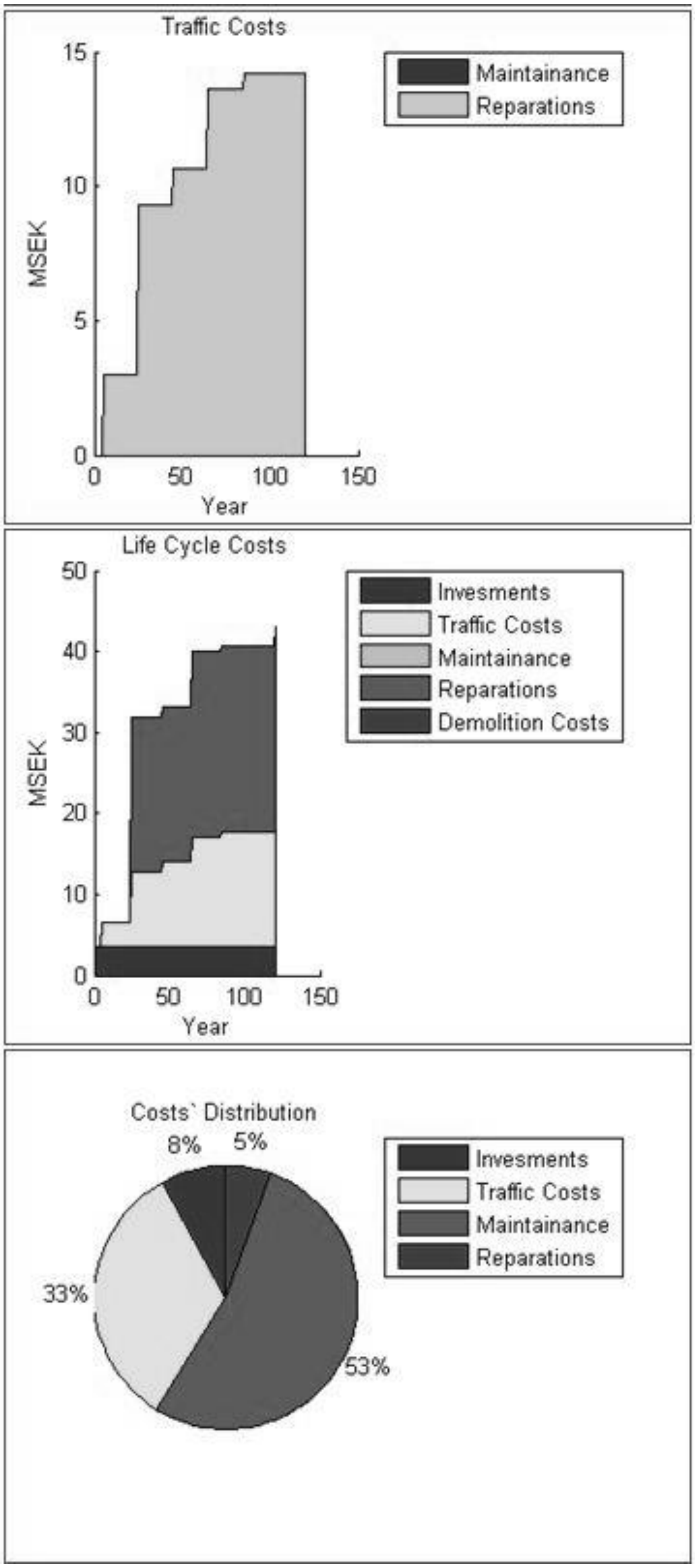


Figure A.6. Part 2 of 2 of the result page in WebLCC, where the results of the analysis are presented in graphs

BroLCC

Allmänna Förutsättningar

Bronamn:	Broviken
Projektnummer:	1234-15
Handläggare:	Raid Karoumi & Håkan Sundquist
Datum:	2002-11-01

Klimatzon		Mellersta Sverige
Saltning på vägen		Normal Saltning
Investeringskostnad enligt offert	kr	227 910 000
Rivningskostnad i % av investeringskostnad	%	10,0
Kalkylperiod	år	120
Årlig real ränta	%	4,0
Årsdygnstrafik, ÅDT		6000
Andel tung trafik	%	14,0
Tillåten hastighet på bron	km/h	90
Reducerad hastighet pga vägarbeten	km/h	50
Timkostnad, personbil	kr/h	85
Timkostnad, lastbil	kr/h	400
Brolängd (total)	m	753,0
Kantbalkslängd	m	1506
Brobredd	m	19,5
Broyta	m^2	14300
Beläggningsyta	m^2	14300
Målningsyta (stålbalkar mm)	m^2	1500
Antal räcken	st	3
Räckeslängd	m	2259

	viktning av inmatade intervall	
	faktor	egen faktor
klimatzon	0,7	0,0
Årsdygnstrafik, ÅDT	0,8	0,0
saltning på vägen	1,0	0,0
konstruktionsdel utsatt för saltangrepp	0,8	0,0
betongkvalité > K40	1,1	0,0
täckande btg > Norm	1,0	0,0

Figure A.7. View of the General conditions tab of BroLCC where input values regarding the general conditions for the bridge are defined

Investeringskostnad

	Priser för nyproduktion á-priser	
form	550	kr/m^2
betong	1 800	kr/m^3
stål	24 500	kr/ton
armering	13 200	kr/ton
kablar	5 000	kr/m
pålar	800	kr/m
räcke	1 500	kr/m
tätskikt	500	kr/m^2
beläggning	450	kr/m^2

prickade fält innehåller default-värden utvärderade mha tidigare inmatade uppgifter. Du har möjlighet att mata in egna värden i fälten.

	Mängder för beräkning av investeringskostnad							
	form [m^2]	betong [m^3]	arm [ton]	stål [ton]	kablar [m]	pålar [m]	övrigt: tot pris	kostnad
UNDERBYGGNAD								
bottenplattor	40	200	2			25		428 400
pelare	60	400	3			10		800 600
frontmur	200	300	2					676 400
vingmur	150	50	1					185 700
lagerpall	10	1						7 300
grusskift								0
fyllning								0
övrigt-underbyggnad								0
ÖVERBYGGNAD								
huvudbalkar				20				490 000
tvärbalkar				5				122 500
fackverk								0
båge								0
pyloner								0
kablar								0
brobaneplatta	14300	500	20					9 029 000
kantbalk	300	100	2					371 400
övrigt-överbyggnad								0
BRODETALJER								
upplagsanordning								0
tätskikt							7150000	7 150 000
beläggning							6435000	6 435 000
räcke							3388500	3 388 500
övergångskonstr								0
dräneringssystem								0
övrigt-brodetaljer								0
ÖVRIGT								
estetik							250000	250 000
övriga anläggningskostnader								0
							Σ Investeringskostnad	29 334 800 kr

Figure A.8. In BroLCC, the assumed values for investment costs are defined in the“Repair costs” tab

Drift- och underhållskostnad

prickade fält innehåller default-värden utvärderade mha tidigare inmatade uppgifter. Du har möjlighet att mata in egna värden i fälten.

	DoU á-priser & mängder			DoU intervall alternativt enstaka år				Trafikstörningar		DoU-kostnad		Trafikantkostnad	
	á-priser		mängder	intervall, år	år för åtgärd	år för åtgärd	år för åtgärd	dagar	längd	kost. per gång	tot kostnad	kost. per gång	tot kostnad
löpande årlig tillsyn	10 000	kr		1	0	0	0	0,0	0,0	10 000	247 741	0	0
allmän inspektion	20 000	kr		3	0	0	0	0,5	0,3	20 000	158 727	1 033	8 197
huvudinspektion	25 000	kr		6	0	0	0	0,5	0,3	25 000	93 375	1 033	3 857
rengöring (tvättning av bron från salt mm.)	50	kr/m^2	14 300	1	0	0	0	0,5	0,2	715 000	17 713 473	689	17 058
rengöring av dräneringssystem	4 000	kr		5	0	0	0	0,0	0,0	4 000	18 296	0	0
impregnering & underhåll av kantbalkar	300	kr/m	1 506	5	0	0	0	5,0	0,8	451 800	2 066 519	25 923	118 572
underhåll av räcke, ytbehandling	600	kr/m	2 259	20	0	0	0	3,0	0,8	1 355 400	1 127 635	15 554	12 940
underhåll av lagerpall	5 000	kr		20	0	0	0	10,0	1,0	5 000	4 160	68 853	57 283
underhåll av övergångskonstr.	6 500	kr/m	39	15	0	0	0	4,0	0,8	253 500	313 642	20 739	25 659
fyllning och återställande av erosionskydd	12 000	kr		20	0	0	0	0,0	0,0	12 000	9 983	0	0
bättringsmålning	450	kr/m^2	1 500	20	0	0	0	5,0	1,0	675 000	561 571	34 427	28 642
Avfuktningsanläggning, el-kostnad+underhåll	25 000	kr/år		1	0	0	0	0,0	0,0	25 000	619 352	0	0
ommålning av stållåda,utv., hela bron	6 000 000	kr		0	60	0	0	20,0	0,8	6 000 000	570 362	110 165	10 472
byte av gummiprofil i övergångskonst.	40 000	kr		15	0	0	0	5,0	0,1	40 000	49 490	3 443	4 259
mata in här övriga DoU (tot. kostnad)	0	kr		0	0	0	0	0,0	0,0	0	0	0	0
mata in här övriga DoU (tot. kostnad)	0	kr		0	0	0	0	0,0	0,0	0	0	0	0
										Σ Nuvärde	23 554 325 kr	Σ Nuvärde	286 940 kr

Figure A.9. In BroLCC, the assumed costs for operation and maintenance are defined in the "operation and maintenance" tab

Reparationsskostnad

<Reparation alternativt Utbyte>

prickade fält innehåller default-värden utvärderade mha tidigare inmatade uppgifter. Du har möjlighet att mata in egna v

Hänvisning SAFEBRO-konto		Reparationsmängder och á-priser			DoU intervall alternativt enstaka år			
		á-priser		mängder	intervall, år	år för åtgärd	år för åtgärd	år för åtgärd
	UNDERBYGGNAD							
	bottenplattor	1 000	kr/m^2	40	80	0	0	0
0340.x	pelare	2 800	kr/m^2	60	50	0	0	0
0310.x	frontmur	2 800	kr/m^2	200	50	0	0	0
0410.x	vingmur	2 800	kr/m^2	150	50	0	0	0
0320.x	lagerpall	2 000	kr/m^2	10	40	0	0	0
0330.x	grusskift	2 800	kr/m^2	60	40	0	0	0
0190.x ; 210.x ...	fyllning	900	kr/m^3	130	50	0	0	0
	ÖVERBYGGNAD							
0630.x	huvudbalkar	1 300	kr/m^2	50	30	0	0	0
0730.x	tvärbalkar	1 300	kr/m^2	8	35	0	0	0
0660.x	fackverk	1 300	kr/m^2	0	30	0	0	0
0650.x	båge	1 300	kr/m^2	0	30	0	0	0
	pyloner	1 300	kr/m^2	0	30	0	0	0
	kablar	4 000	kr/m	0	40	0	0	0
0800.x; 0610.x	brobaneplatta	4 000	kr/m^2	2000	40	0	0	0
0900.x	kantbalk	5 000	kr/m	1 506	40	0	0	0
	BRODETALJER							
500.x	upplagsanordning	80 000	kr/st	2	40	0	0	0
1000.x	tätskikt	1 000	kr/m^2	14300	60	0	0	0
1100.x	beläggning	500	kr/m^2	14300	60	0	0	0
1200.x	räcke och bullerskydd	7 000	kr/m	2259	40	0	0	0
1300.x	övergångskonstr	55 000	kr/m	40	40	0	0	0
1400.x	dräneringssystem	2 500	kr/st	4	40	0	0	0
	ÖVRIGT							
	estetik	100 000	kr		50	0	0	0
	mata in här övriga reparationer (tot kostnad)	0	kr		0	0	0	0
	mata in här övriga reparationer (tot kostnad)	0	kr		0	0	0	0

Figure A.10. In BroLCC, the assumed costs and intervals for repairs are defined in the "repair costs" tab. This figure illustrates part 1 of 2 of the "repair costs" tab

Reparationkostnad		Trafikantkostnad	
kost. per gång	tot kostnad	kost. per gång	tot kostnad
40 000	1 735	0	0
168 000	68 948	0	0
560 000	276 717	0	0
420 000	140 242	0	0
20 000	14 404	0	0
168 000	43 799	0	0
117 000	18 780	0	0
65 000	43 889	0	0
10 400	5 442	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
8 000 000	1 604 058	51 847	10 396
7 530 000	2 390 857	114 062	36 216
160 000	41 714	0	0
14 300 000	2 507 620	51 847	9 092
7 150 000	1 253 810	51 640	9 055
15 813 000	6 158 835	51 847	20 193
2 200 000	856 854	25 923	10 097
10 000	4 941	0	0
100 000	26 071	5 185	1 352
0	0	8 262	0
0	0	0	0
Σ Nuvärde	**15 458 716 kr**	**Σ Nuvärde**	**96 400 kr**

Figure A.11. In BroLCC, the assumed costs and intervals for repairs are defined in the "repair costs" tab. This figure illustrates part 2 of 2 of the "repair costs" tab

BroLCC Optimala Nya Broar - Livscykelkostnadsanalys	
Livscykelkostnad Broviken	
INVESTERINGSKOSTNAD	29 334 800 kr
REPARATIONSKOSTNADER	15 458 716 kr
DRIFT- & UNDERHÅLLSKOSTNADER	23 554 325 kr
TRAFIKANTKOSTNADER	383 340 kr
RIVNINGSKOSTNADER	205 950 kr
SUMMA NUVÄRDE	68 937 132 kr
SUMMA NUVÄRDE / BROYTA [kr/m^2]	4 821

Figure A.12. Part 1 of 2 of the result tab in BroLCC, where the result of the analysis are presented in graphs

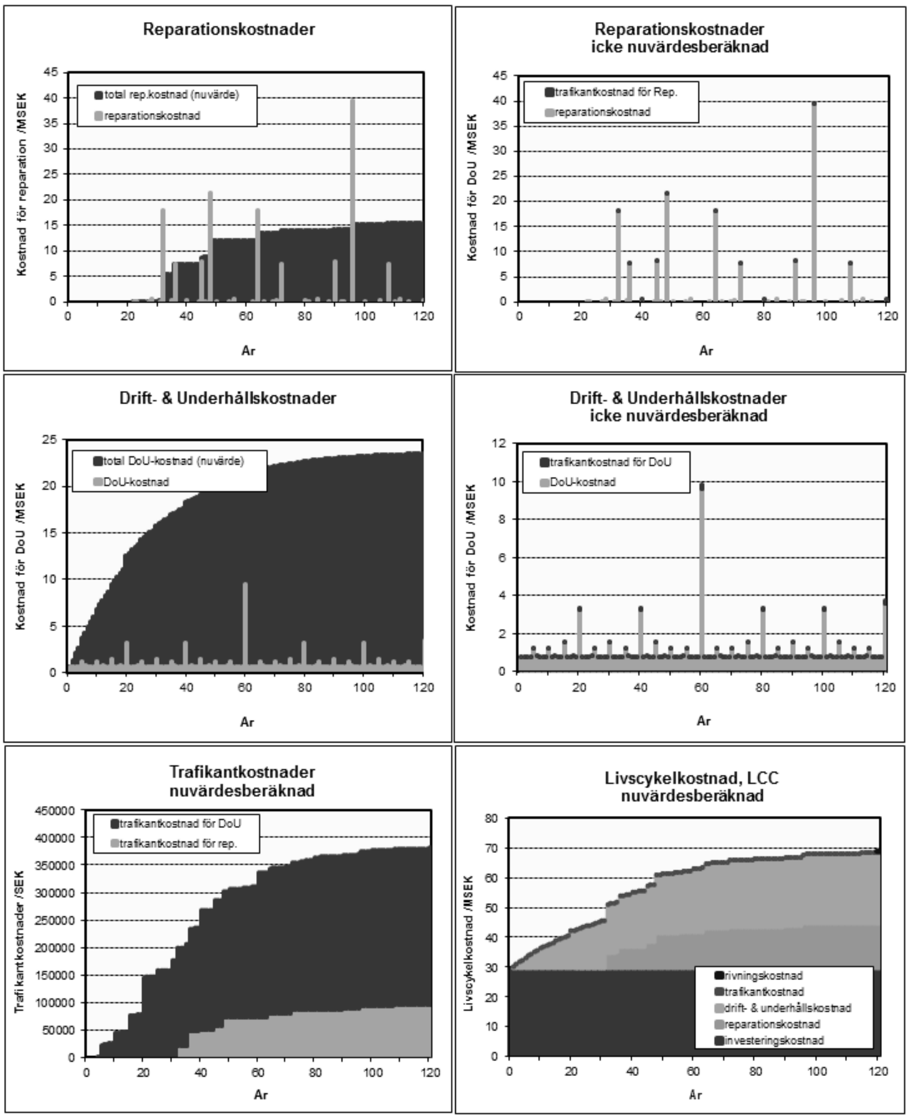


Figure A.13. Part 2 of 2 of the result tab in BroLCC, where the results of the analysis are presented in graphs

BridgeLCC

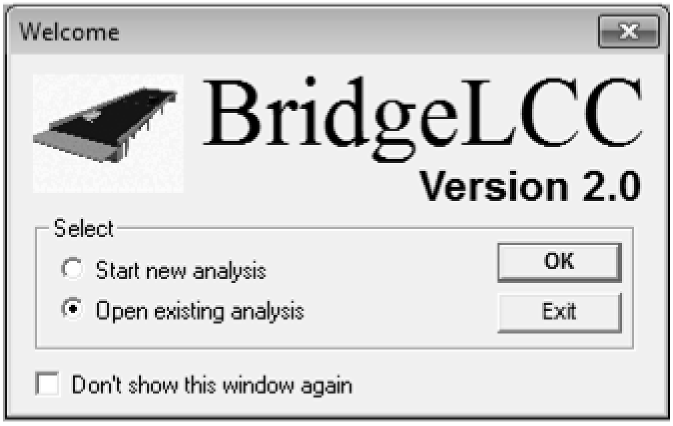


Figure A.14. Welcome page, BridgeLCC

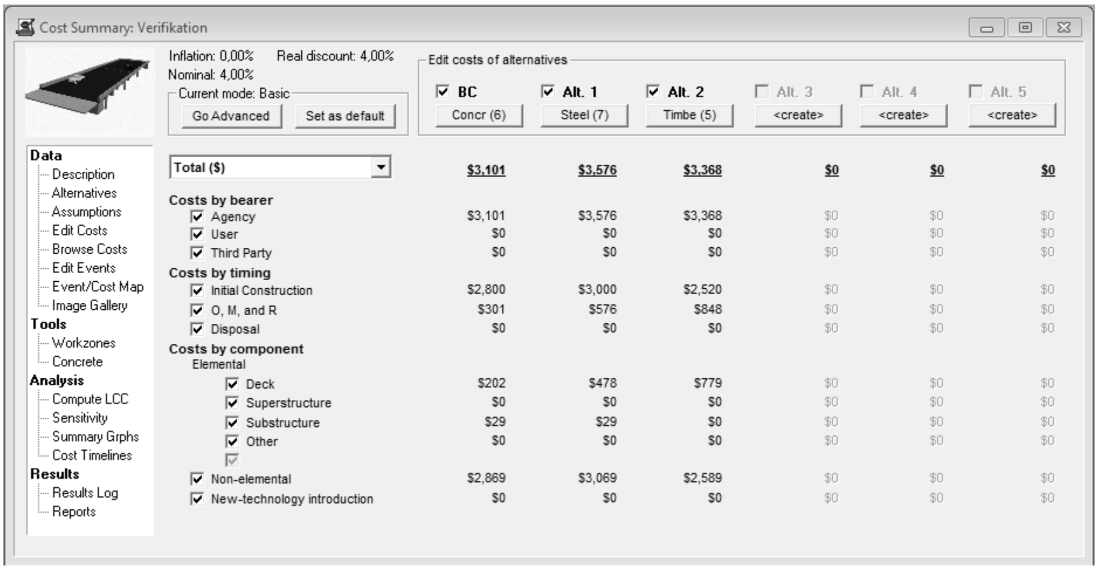


Figure A.15. View of the "Cost Summary Window" as seen in BridgeLCC. From this window, all settings and function can be chosen

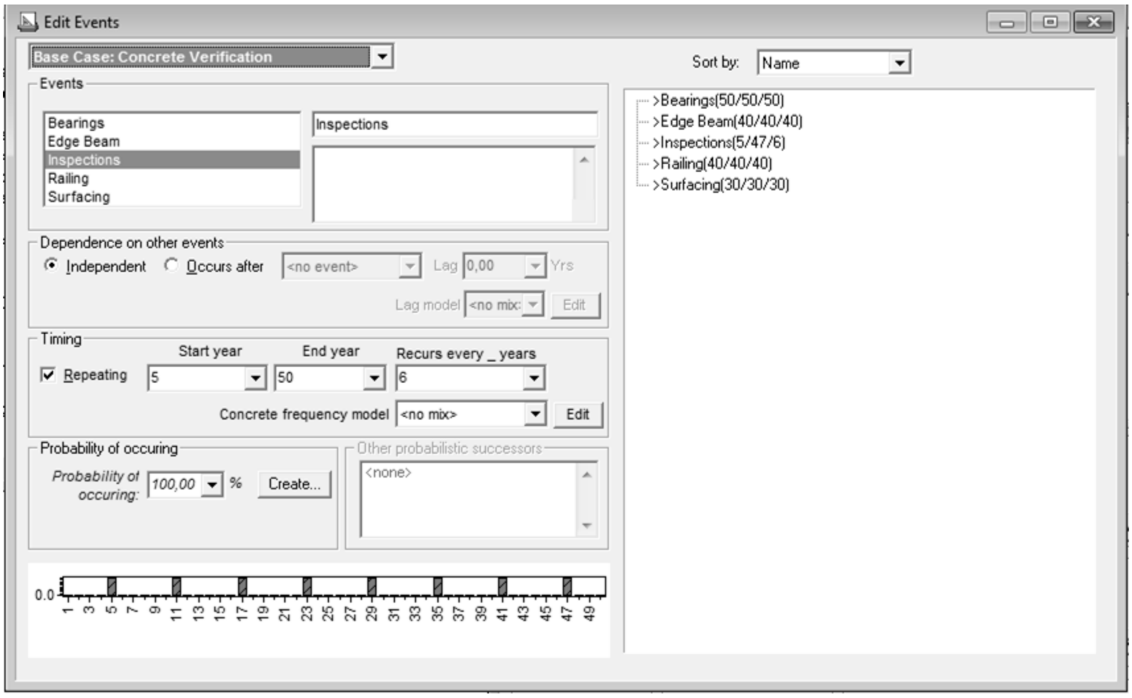


Figure A.16. View of the "Edit Event Window" as seen in BridgeLCC. From this window, it is possible to create activities for the bridge model

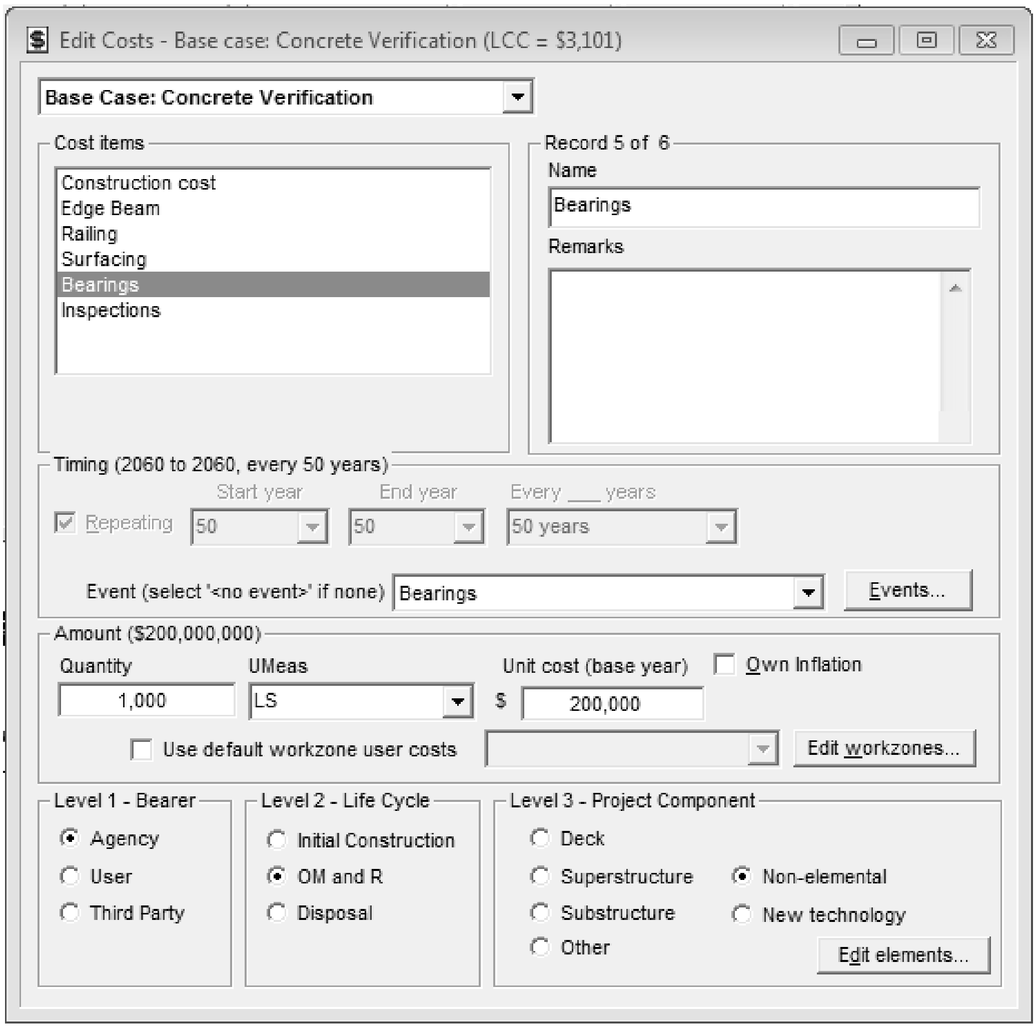
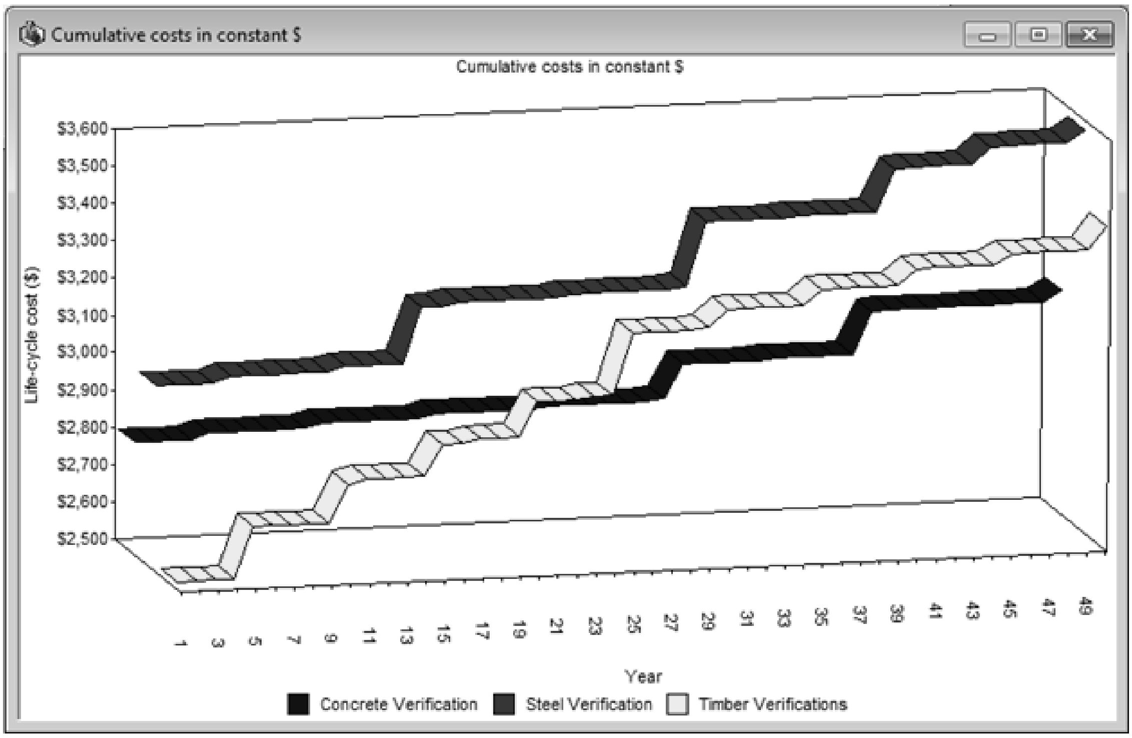


Figure A.17. View of the "Edit Cost Window" as seen in BridgeLCC. From this window, it is possible to create "Costs" for the bridge model



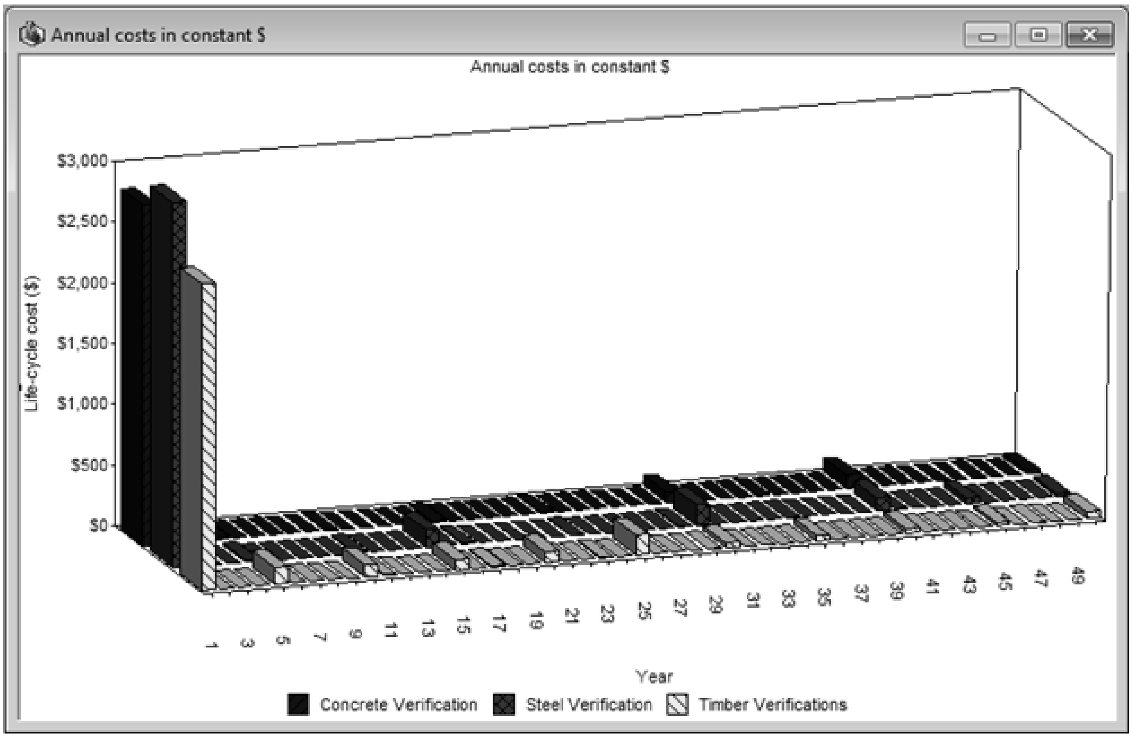
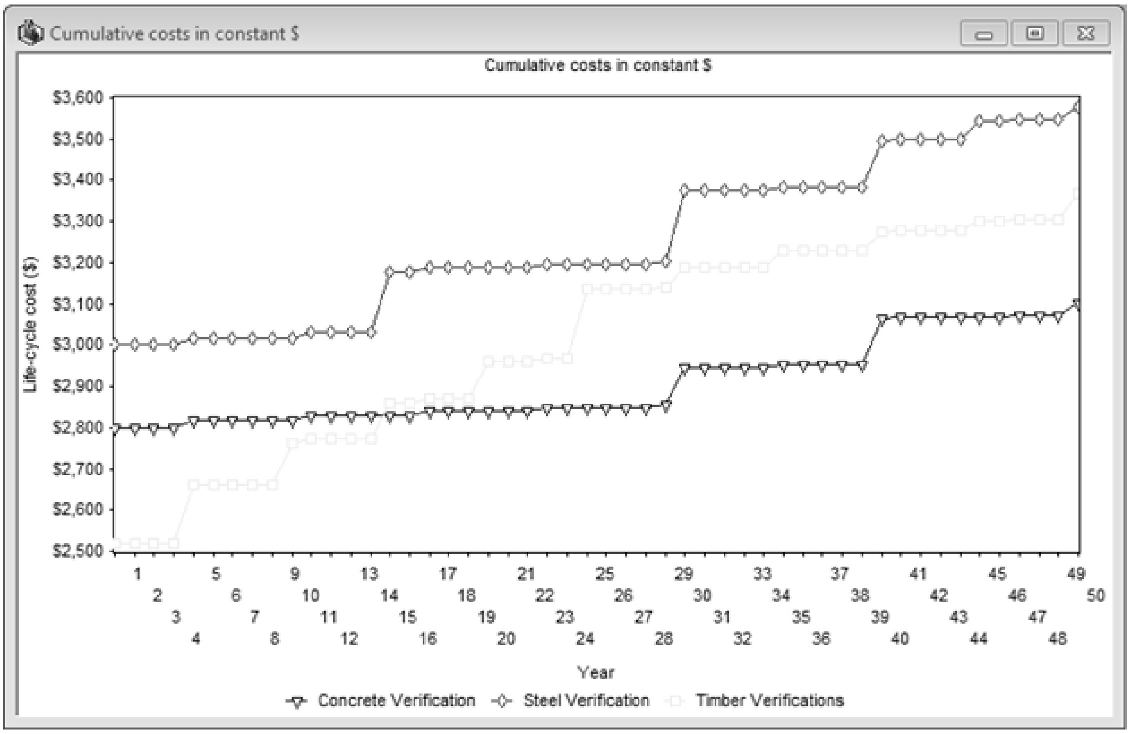


Figure A.18. The results in BridgeLCC presented in a "Cumulative costs in constant dollar" graph and an "Annual costs in constant dollar" graph in a 3D-view



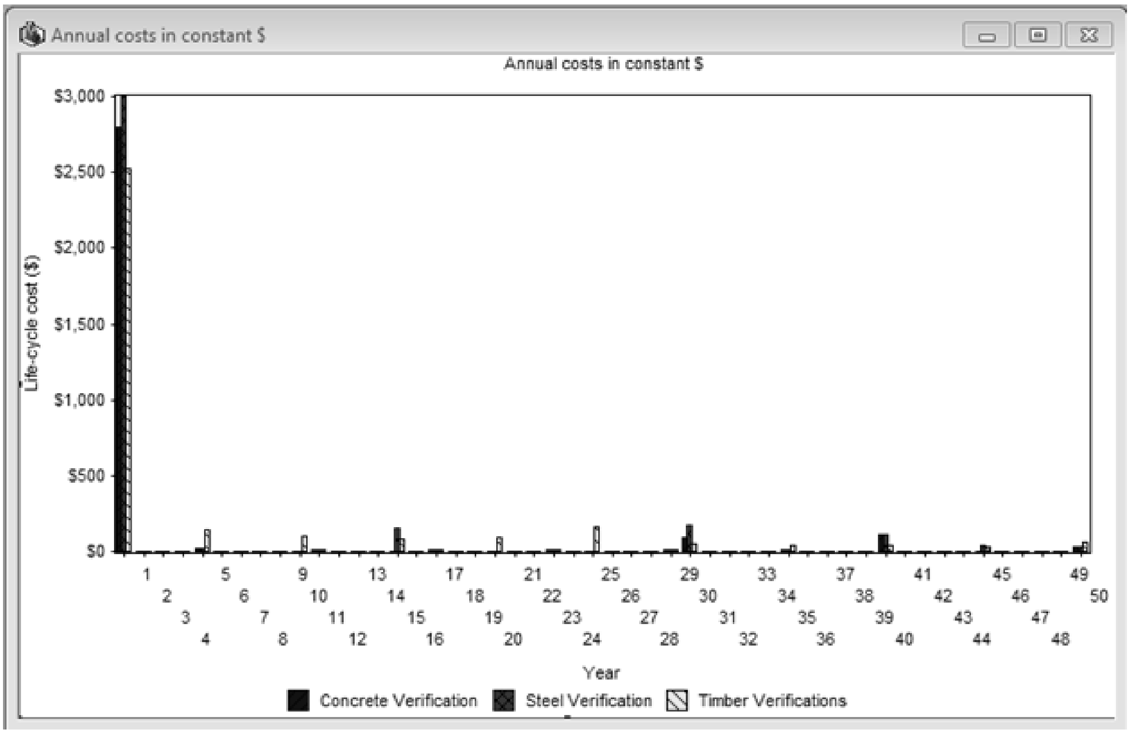


Figure A19. The results in BridgeLCC presented in a "Cumulative costs in constant dollar" graph and a "Annual costs in constant dollar" graph in a 2D-view

Vännen07

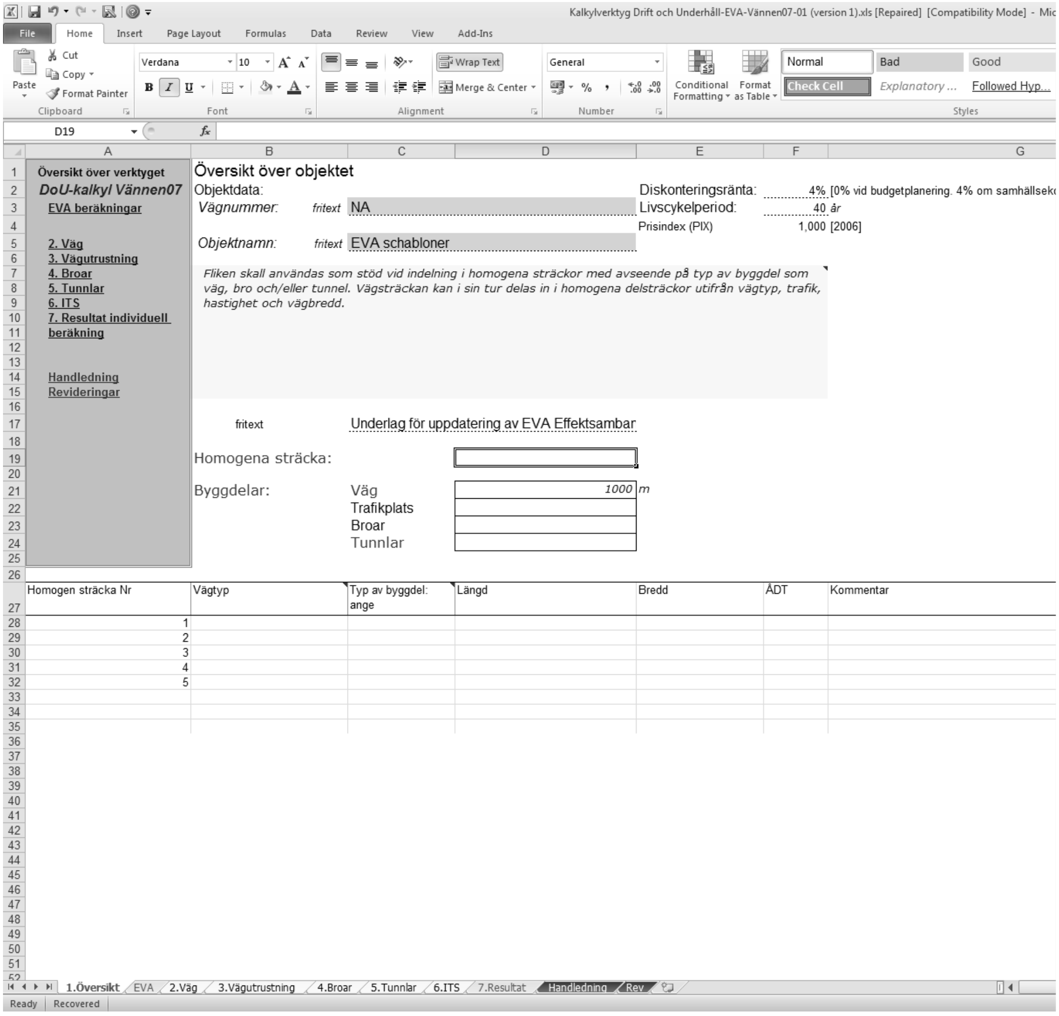


Figure A.20. View of the ''overview'' tab found in the Vännen07 toolbox

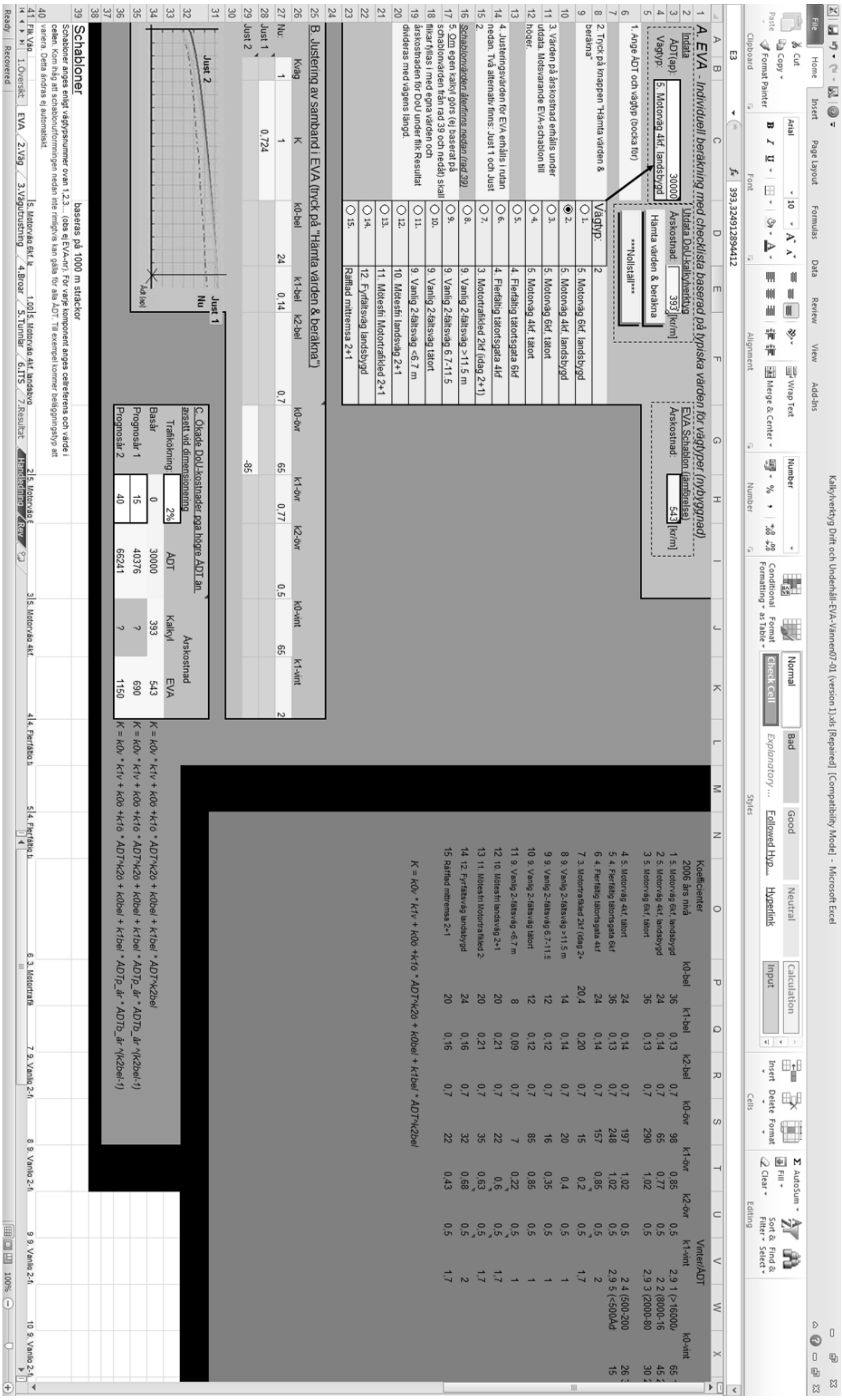


Figure A.21. View of the "EVA" –tab found in Vännen07

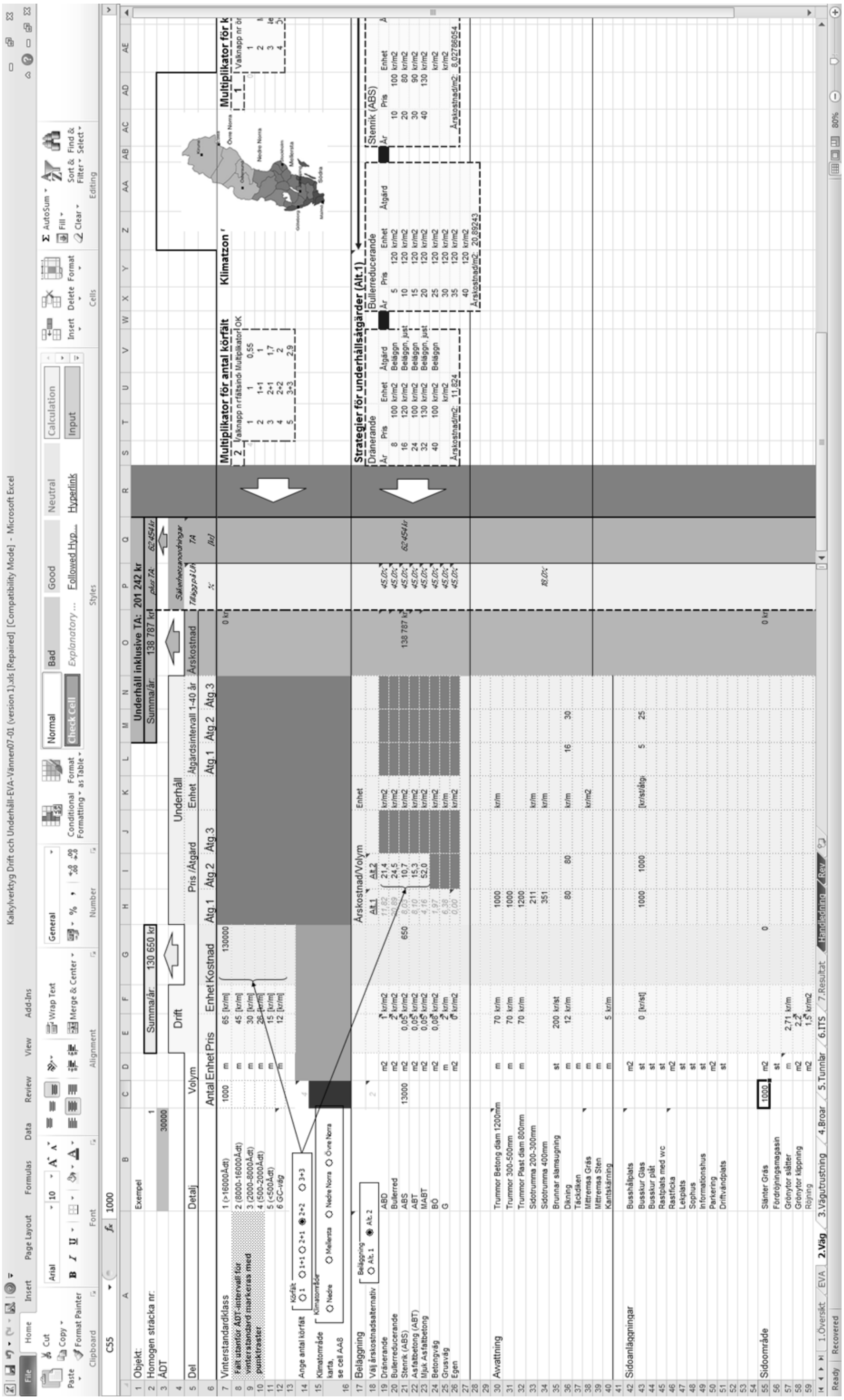


Figure A.22. View of the "Road" tab found in Vännen07

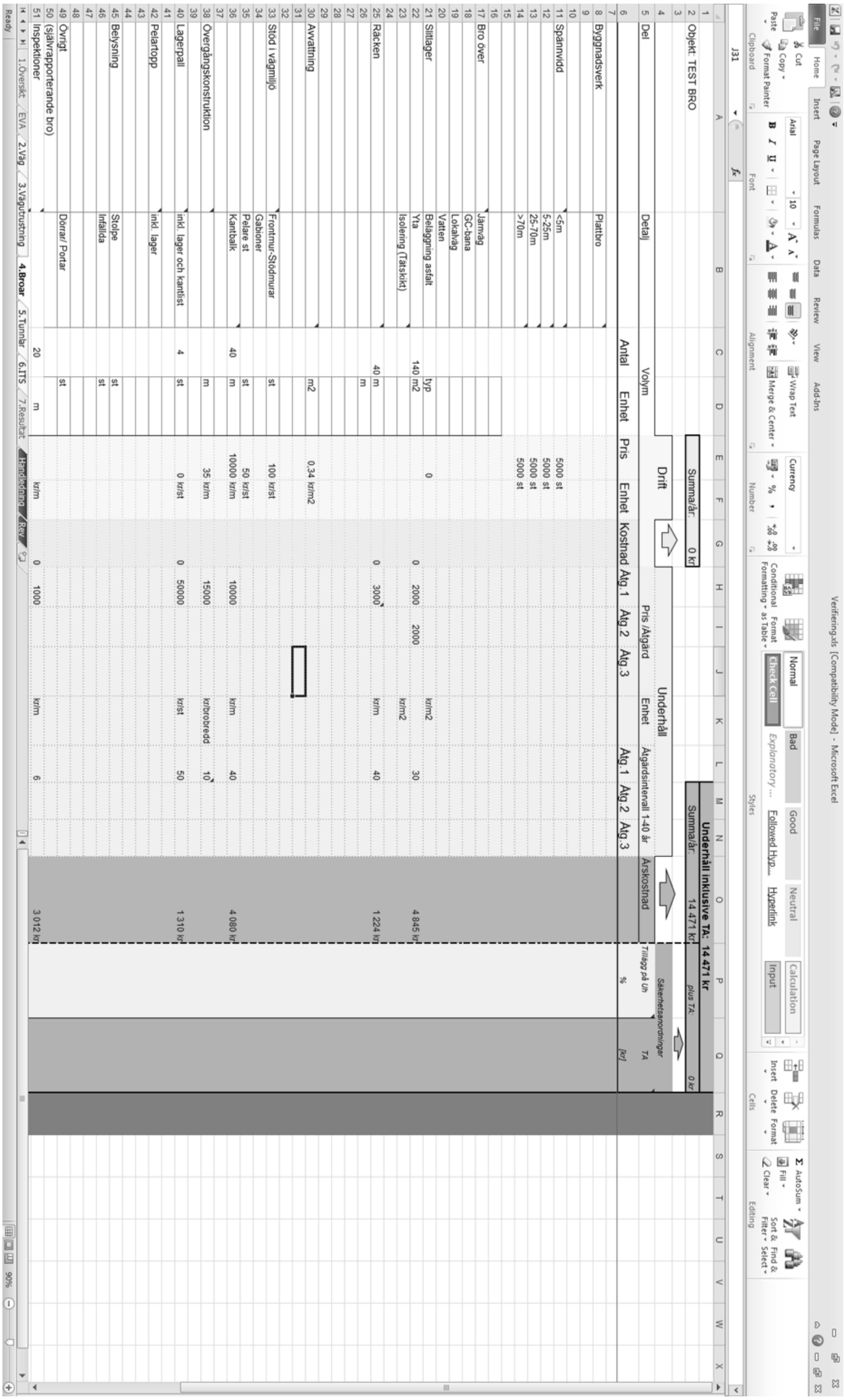
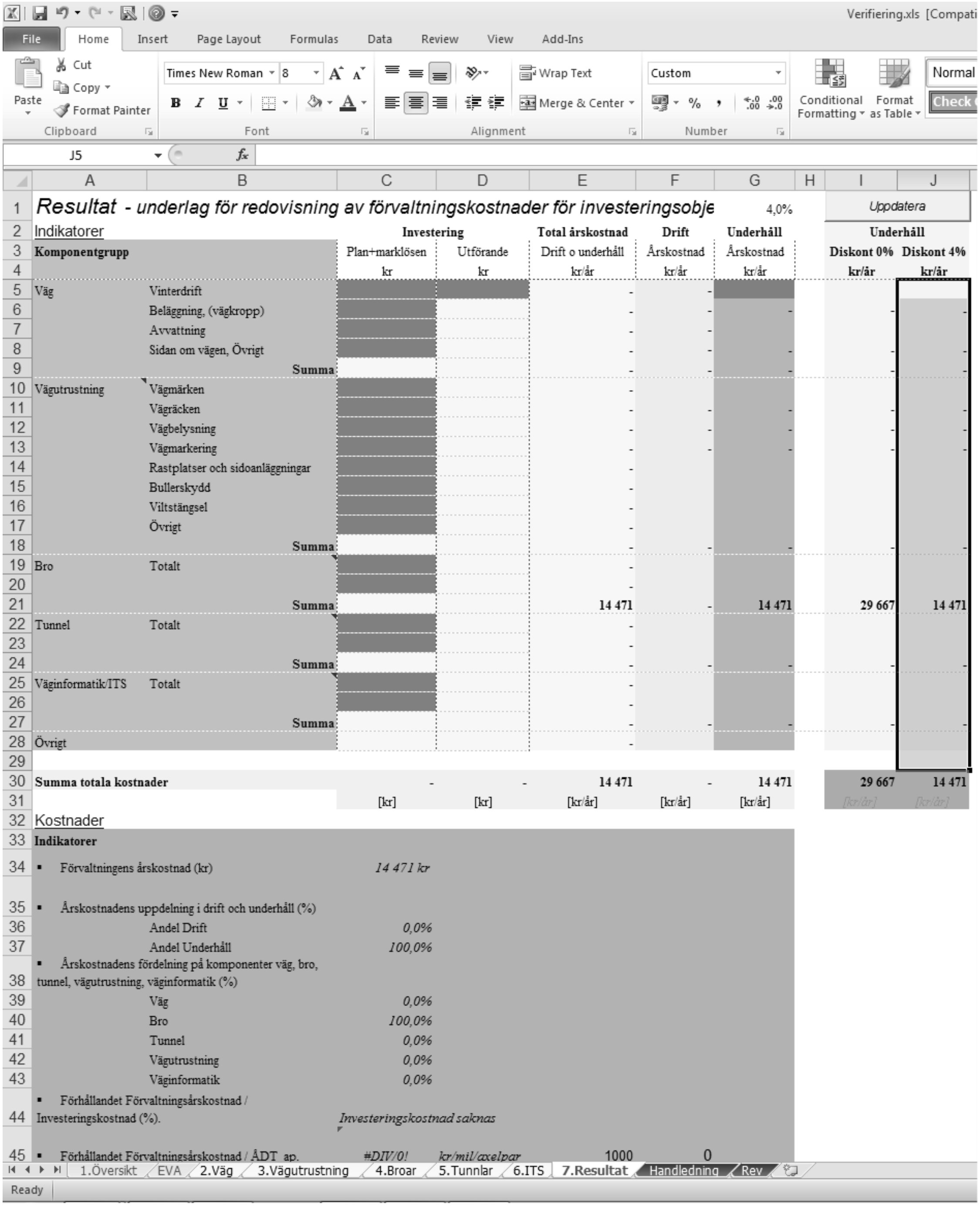


Figure A.23. View of the "Bridge" tab (including results from the verification process) found in Vännen07



	A	B	C	D	E	F	G	H	I	J
1	*Resultat - underlag för redovisning av förvaltningskostnader för investeringsobje*						4,0%			
2	Indikatorer		Investering		Total årskostnad	Drift	Underhåll		Underhåll	
3	Komponentgrupp		Plan+marklösen	Utförande	Drift o underhåll	Årskostnad	Årskostnad		Diskont 0%	Diskont 4%
4			kr	kr	kr/år	kr/år	kr/år		kr/år	kr/år
5	Väg	Vinterdrift			-	-				
6		Beläggning, (vägkropp)			-	-	-		-	-
7		Avvattning			-	-	-		-	-
8		Sidan om vägen, Övrigt			-	-	-		-	-
9		Summa			-	-	-		-	-
10	Vägutrustning	Vägmärken			-					
11		Vägräcken			-	-	-		-	-
12		Vägbelysning			-	-	-		-	-
13		Vägmarkering			-	-	-		-	-
14		Rastplatser och sidoanläggningar			-					
15		Bullerskydd			-					
16		Viltstängsel			-					
17		Övrigt			-					
18		Summa			-	-	-		-	-
19	Bro	Totalt			-					
20					-					
21		Summa			14 471	-	14 471		29 667	14 471
22	Tunnel	Totalt			-					
23					-					
24		Summa			-	-	-		-	-
25	Väginformatik/ITS	Totalt			-					
26					-					
27		Summa			-	-	-		-	-
28	Övrigt				-					
29										
30	Summa totala kostnader		-	-	14 471	-	14 471		29 667	14 471
31			[kr]	[kr]	[kr/år]	[kr/år]	[kr/år]		[kr/år]	[kr/år]
32	Kostnader									
33	Indikatorer									
34	▪ Förvaltningens årskostnad (kr)		*14 471 kr*							
35	▪ Årskostnadens uppdelning i drift och underhåll (%)									
36		Andel Drift	*0,0%*							
37		Andel Underhåll	*100,0%*							
38	▪ Årskostnadens fördelning på komponenter väg, bro, tunnel, vägutrustning, väginformatik (%)									
39		Väg	*0,0%*							
40		Bro	*100,0%*							
41		Tunnel	*0,0%*							
42		Vägutrustning	*0,0%*							
43		Väginformatik	*0,0%*							
44	▪ Förhållandet Förvaltningsårskostnad / Investeringskostnad (%).		*Investeringskostnad saknas*							
45	▪ Förhållandet Förvaltningsårskostnad / ÅDT ap.		*#DIV/0!*	*kr/mil/axelpar*	1000	0				

Figure A.24. View of the "Results" tab found in Vännen07

Appendix B: Hand-calculations

Verification of BridgeLCC

PRESENT VALUE METHOD

$ORIGIN := 1$

$L := 50$	Service life
$r := 4.0\%$	Discount rate
$n := 1..L$	year of which the present value is dicounted to (from where to which year)
$costs := 5$	Number of costs (events) to be summed (Ki)
$a := 1..costs$	Ammount of cost-events to be summed
$Invest := 2800$	Investment cost (Gross)
$L_{dist} := 500m$	Distance affected by action/event
$V_{norm} := \frac{70}{3.6}\frac{m}{s}$	Normal speed on road
$V_{red} := \frac{40}{3.6}\frac{m}{s}$	Reduced speed due to roadwork
$T_{raffic} := 10000$	ADT (Avarage Daily Traffic)
$D_{ays} := 7$	Duration of roadwork (days)
$C_{delay} := \frac{100}{3600s}$	Vehicle cost (per hour)

$$C_{driver} := \frac{\left[\left(\frac{L_{dist}}{V_{red}} - \frac{L_{dist}}{V_{norm}}\right) \cdot T_{raffic} \cdot D_{ays} \cdot C_{delay}\right]}{1000}$$

Bridge dimensions

$L_b := 20m$

$width_b := 7m$

$A_b := L_b \cdot width_b$

Costs (kSEK)

$EdgeBeam := 10\frac{1}{m}$

$Railing := \frac{3}{m}$

$surfacing := \frac{2}{m^2}$

$Bearings := 50$

$Inspection := \frac{1}{m}$

$cost_1 := EdgeBeam \cdot 2 \cdot L_b = 400$

$cost_2 := Railing \cdot 2 \cdot L_b = 120$

$cost_3 := surfacing \cdot A_b = 280$

$cost_4 := Bearings \cdot 4 = 200$

$cost_5 := Inspection \cdot L_b = 20$

Singel event discounted

$$K_1 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad K_2 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_2 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad K_3 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_3 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad K_4 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_4 \\ 0 \end{pmatrix} \quad K_5 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Edge Beam | Railing | Surfacing | Bearings | Cont inspect

$$B_n := \sum_a (K_a)$$

$$OMR := \sum_n \left[\frac{B_{n_n}}{(1+r)^n} \right]$$

$OMR = 298.158$

$$LCC := Invest + OMR$$

$LCC = 3.098 \times 10^3$

$$LCC_{BLCC} := 3.101 \cdot 10^3$$

Upper boundary = Hand calc result on the low/unsafe side

Lower boundary = Hand calc result on the high/safe side

$1 - \left(\frac{LCC_{BLCC}}{LCC} \right) = -0.092 \cdot \%$ (upper boundary)

Verification of Vännen07

PRESENT VALUE METHOD

ORIGIN := 1

$L := 50$	Service life
$r := 4.0\%$	Discount rate
$n := 1..L$	year of which the present value is dicounted to (from where to which year)
$costs := 5$	Number of costs (events) to be summed (Ki)
$a := 1..costs$	Ammount of cost-events to be summed
$Invest := 2800$	Investment cost (Gross)

Bridge dimensions

$L_b := 20m$

$width_b := 7m$

$A_b := L_b \cdot width_b$

Costs (kSEK)

$EdgeBeam := 10\frac{1}{m}$

$Railing := \frac{3}{m}$

$surfacing := \frac{2}{m^2}$

$Bearings := 50$

$Inspection := \frac{1}{m}$

$$cost_1 := EdgeBeam \cdot 2 \cdot L_b = 400$$

$$cost_2 := Railing \cdot 2 \cdot L_b = 120$$

$$cost_3 := surfacing \cdot A_b = 280$$

$$cost_4 := Bearings \cdot 4 = 200$$

$$cost_5 := Inspection \cdot L_b = 20$$

$$rest_1 := cost_1 \cdot \frac{(L - 40)}{L} = 80$$

$$rest_2 := cost_2 \cdot \frac{(L - 40)}{L}$$

$$rest_3 := cost_3 \cdot \frac{(L - 30)}{L} = 112$$

$$rest_4 := cost_4 \cdot \frac{(L - 50)}{L} = 0$$

$$rest_5 := cost_5 \cdot \frac{(L - 6)}{L} = 17.6$$

$$K_1 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad K_2 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_2 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad K_3 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_3 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ rest_3 \end{pmatrix} \quad K_4 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_4 \\ 0 \end{pmatrix} \quad K_5 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$B_n := \sum_a (K_a)$$

$$OMR := \sum_n \left[\frac{B_{n_n}}{(1+r)^n}\right]$$

$OMR = 313.918$

$LCC := Invest + OMR$

$LCC = 3.114 \times 10^3$

ANNUITY METHOD

$$AF := \frac{r}{1-(1+r)^{-L}}$$

$AF = 4.655 \cdot \%$

$1 - \left(\frac{13.879}{14.471}\right) = 4.091 \cdot \%$

With all 5 costs

(upper boundary)

$Cost_{yearly} := OMR \cdot AF$

$Cost_{yearly} = 14.613$

$1 - \left(\frac{14.613}{14.471}\right) = -0.981 \cdot \%$

With all 5 costs, accounting for a rest value on K_3

(Lower boundary)

<u>Singel event discounted</u>

$$LCC_{sing} := \sum_n \left[\frac{(K_1)_n}{(1+r)^n}\right]$$

K_i is varied from 1-5 to check the idividual results for each cost event

$LCC_{sing} = 86.648$

$$AF_{sing} := \frac{r}{1-(1+r)^{-L}}$$

$AF_{sing} = 4.655 \cdot \%$

$Cost_{yearly\_sing} := LCC_{sing} \cdot AF_{sing}$

$Cost_{yearly\_sing} = 4.033$

Edge Beam	**OK**	$1 - \frac{4.08}{4.033} = -1.165 \cdot \%$	(Upper boundary)
Railing	**OK**	$1 - \frac{1.224}{1.21} = -1.157 \cdot \%$	(Upper boundary)
Surfacing	**OK**	$1 - \frac{4.845}{4.931} = 1.744 \cdot \%$	(Lower boundary)
Bearings	**OK**	$1 - \frac{1.31}{1.362} = 3.818 \cdot \%$	(Lower boundary)
Cont inspection	**OK**	$1 - \frac{3.012}{3.094} = 2.65 \cdot \%$	(Upper boundary)

Error range -1.17 -3.8%

Most likely due to roundings in Vännen07 -Excel sheet

Upper boundary = Hand calc result on the low/unsafe side

Lower boundary = Hand calc result on the high/safe side

Verification of BroLCC

PRESENT VALUE METHOD

$ORIGIN := 1$

$L := 50$	Service life
$r := 4.0\%$	Discount rate
$n := 1..L$	year of which the present value is dicounted to (from where to which year)
$costs := 5$	Number of costs (events) to be summed (Ki)
$a := 1..costs$	Ammount of cost-events to be summed
$Invest := 2800$	Investment cost (Gross)
$L_{dist} := 500m$	Distance affected by action/event
$V_{norm} := \frac{70}{3.6}\frac{m}{s}$	Normal speed on road
$V_{red} := \frac{40}{3.6}\frac{m}{s}$	Reduced speed due to roadwork
$T_{raffic} := 10000$	ADT (Avarage Daily Traffic)
$D_{ays} := 7$	Duration of roadwork (days)
$C_{delay} := \frac{100}{3600s}$	Vehicle cost (per hour)

$$C_{driver} := \frac{\left[\left(\frac{L_{dist}}{V_{red}} - \frac{L_{dist}}{V_{norm}}\right) \cdot T_{raffic} \cdot D_{ays} \cdot C_{delay}\right]}{1000}$$

Bridge dimensions

$L_b := 20m$

$width_b := 7m$

$A_b := L_b \cdot width_b$

Costs (kSEK)

$EdgeBeam := 10\frac{1}{m}$

$Railing := \frac{3}{m}$

$surfacing := \frac{2}{m^2}$

$Bearings := 50$

$Inspection := \frac{1}{m}$

$cost_1 := EdgeBeam \cdot 2 \cdot L_b = 400$

$cost_2 := Railing \cdot 2 \cdot L_b = 120$

$cost_3 := surfacing \cdot A_b = 280$

$cost_4 := Bearings \cdot 4 = 200$

$cost_5 := Inspection \cdot L_b = 20$

$$K_1 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_1 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}
\quad
K_2 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_2 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}
\quad
K_3 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_3 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}
\quad
K_4 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_4 \end{pmatrix}
\quad
K_5 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ cost_5 \\
0 \\ 0 \end{pmatrix}$$

Edge Beam — Railing — Surfacing — Bearings — Cont inspection

$$B_n := \sum_a (K_a)$$

$$OMR := \sum_n \left[\frac{B_{n_n}}{(1+r)^n} \right]$$

$$OMR = 286.69$$

$$LCC := Invest + OMR$$

$$LCC = 3.087 \times 10^3$$

$$LCC_{BroLCC} := 3.08669 \cdot 10^3$$

Low boundary = Hand calc result on the low/unsafe side

High boundary = Hand calc result on the high/safe side

$$1 - \left(\frac{LCC}{LCC_{BroLCC}} \right) = -1.356 \times 10^{-5} \cdot \%$$

(High boundary), neglectable magnitude

Appendix C: Inquiries

QUESTIONNAIRE FOR TRAFIKVERKET

(Gothenburg, October 2011)

Regarding the bridges at hand

This document refers to an inquiry regarding 3 different bridge types that will be analysed in detail for the purpose of using the knowledge of already built bridges when designing new bridges. This analysis will be performed on an LCC basis.

The three bridge types are meant to be frequently reoccurring, short- one span bridges (15-25 m), used for road traffic in the three main structural materials concrete, steel and timber. Since the aim is to reproduce such a general, comparative image as possible, the bridge types need to fulfil the same requirements:

- Construction year
  - The bridges should have been built during the same time interval of 10 years, when an equal level of knowledge was present. It should also be the most modern technology possible
  - At least two main inspections should have been conducted
    - Hence, the bridges should have been built during 1990's

- Bridge types
  - The most commonly reoccurring bridge types in the three main structural materials with regard to the boundary conditions above:
    - Back-wall bridge, concrete
    - Composite bridge with concrete slab, steel
    - Transversally prestressed glulam slab, simply supported on free- standing supports, timber

- Environment
  - Climate zone
    - The bridges should be located in the southern parts of the country
      - If possible, either inland or in coastal regions
  - Traffic environment
    - Medium ADT
      - 6,000-10,000 vehicles

Sought information

Basis for the analysis:

1. General information (typical problems) concerning a population of bridges with the previously mentioned properties
2. Specific data on 3 representative bridges with the same properties

Key figures for the bridge types

- Construction cost
    - Cost distribution
        - Design
        - Building
        - Etc.
- Maintenance
    - Outcome of maintenance costs compared to projected
        - Reason for cost diversion (favourable/unfavourable)
        - Break down of maintenance costs
- Repairs
    - Outcome of repair costs compared to projected
        - Reason for cost diversion (favourable/unfavourable)
        - Break down of repair costs
- Operation
    - Outcome of operation costs compared to projected
        - Reason for cost diversion (favourable/unfavourable)
        - Break down of operation costs
- Traffic
    - ADT
    - Percentage heavy vehicles (approximately)

Main research questions

- Where are the problems?
- Why did it become a problem?
- How can the problem be avoided in the future?
    - Improvements
- How well does the statistical compilation agree with the opinions of experienced bridge managers?
    - A weighting will be conducted

QUESTIONNAIRE FOR BRIDGE MANAGERS

(Göteborg, November 2011)

Bridge types

- Back-wall bridge in concrete
- Composite bridge (steel with a concrete slab), back-wall design
- Transversally prestressed glulam slab, freestanding abutments

Questionnaire

1. Which problems are generally associated with each bridge type, or common for it along with other types?
    a. How are these problems usually taken care of?
        i. How sustainable are these measures, is there a need to repeat the activity or is one time sufficient?
        ii. Standard cost?
    b. What could be a better, more sustainable activity?
        i. Why is this activity not more common?
        ii. Standard cost?

2. Is there anything that could have been done differently to avoid these problems (minimise or eliminate) at the construction (detailing)?
    a. What would be the common alternative solution?
        i. How effective would this solution be, eliminate or minimise of the problem?
        ii. Secondary effects, does this design lead to other problems?
        iii. Standard cost?
    b. What would be the best solution (that would eliminate the problem entirely)?
        i. Secondary effects?
        ii. Standard cost?

Thank you for your participation, regards

Niklas Larsson

Dan Nilsson

Appendix D: Feedback to the ETSI project

Experienced problems with WebLCC

During the process of writing our master thesis the autumn of 2011, the WebLCC was tested on a sample bridge with the intent of later on being able to use the software for more advanced LCC computations.

Unfortunately we encountered problems already at an early stage as first time users. The following document is a list of our perceived faults and shortcomings with software. Some more alarming than the others, but all items are matters that probably need to be addressed in order to get a functional and user-friendly interface.

WebLCC's overall approach appears to be straight forward, but after using the software for a while trouble with the relay of data between the sheets and other problems were observed.

The list below presents our remarks and suggestions for improvement after using the software:

- At several occasions when using the software, the server located at KTH in Stockholm, has crashed under normal use of WebLCC. The current solution to of the problem has been to via email contacting PhD student Gunagli Du, which physically has had to restart the server to make it possible to use the program again

- The costs specified in the tabs; General, Investment, Maintenance and Repairs, are referenced in a wrong way into the result tab. E.g. an increase of the repair costs is shown as an increase of traffic costs etc. In addition we have also created and worked with several different "projects" in the program. When monitoring the output data from these projects, their references are not only still incorrect, but also appear to change from project to project without any consistency. E.g. in one project, repair costs become maintenance costs, and in another it is shown as traffic costs instead

- Costs for maintenance and repairs are summed up in each tab, but the results are not transferred to the result tab for some reason, with an exception for the sensitivity analysis

- This will in turn result in that the graphs are only showing the investment costs, and usually one more costs, where the cost rarely corresponds to the correct category

- Sometimes other costs do show up, but we haven't figured out what was done differently those times

- The investment cost in the General-tab shall be specified in SEK. But when the cost is linked to the result-tab, the software converts the same numerical value into kSEK (icreasing the cost by a thousand) instead. This opposed to when the maintenance and repair costs are edited, then the costs are specified in SEK and a conversion into kSEK is conducted as a user would expect. These costs are also linked to the result-tab in an expected manner, without any up-scaling. But as mentioned before, these costs are still referred to the wrong category in the diagram, compared to the actual value that is shown in the results

- The software asks the user to decide on a climate zone for the bridge to be analysed, zone 1-7. According to "Trafikverket", Sweden is only divided into 5 climate zones
    - To be able to use the software effectively in all Nordic countries, a possible improvement could be to make it possible to initially define which country the bridge is located in, and then choose climate zones specific to that country
        - A map showing the spread of the climate zones for each country would also facilitate this selection for the user

    - Another feature could be that the currency also is adjusted based on the selected country

- The concrete class that is requested in the repair-tab is according to the obsolete BBK (Kxx). According to Euro Code, the concrete classes are given as Cxx/xx

- The link to BaTMan is dated 2009, there is a new document available from 2011 that would be more sufficient and up to date

- When selecting "bridge type" in the "General" tab, an explanation on what influence this selection has to the LCC is missing
- The option "Other" bridge types?

- In many cases the processes in the "black box" could be made more transparent to allow the user to better understand what the software is doing and how it works. This would also allow the user to more easily detect details and costs that could be improved from an LCC perspective when assessing a design option

These issues could partly be addressed by adding explanation-boxes to the different tabs (like in BridgeLCC), and perhaps also extended the help menu by a "search help" function and a more through user manual.

Minutes of Meeting (Stockholm)

COWI

Minutes of Meeting	ETSI - LCC coordination	
Title	LCC program status and test basis	
Date	2011-10-27	
Place	KTH, Stockholm	
Participants	Håkon Sundquist - HS, KTH George Racutanu - GR, Trafikverket Mohammed Safi - MS, KTH Dan Nilsson - DN, Chalmers/COWI Niklas Larsson - NL, Chalmers/COWI Birit Buhr Jensen - BBU, COWI	
Prepared by	BBU, 27 oktober 2011	
Distribution	Participants, ETSI members and COWI: Magnus Bäcksröm	

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COWI has two M.Sc students Niklas Larsson and Dan Nilsson at Chalmers Gøteborg, who as part of their M.Sc project is testing the webLCC program developed as part of the ETSI project.

During this process they discovered difficulties as described in appendix A. A meeting was arranged between the participants with the following agenda:

1 Welcome and presentation

2 Status on LCC stand alone program. Follow up on comments from COWI and the M.Sc students

3 Basis for searching in BaTman based on M.Sc student note. Possibilities and limitations to be discussed.

4 Decisions and follow up

5 Any other business

6 Next meeting

1 Welcome and presentation

The participants presented themselves. The agenda was agreed upon

2 Status on LCC stand alone program. Follow up on comments from COWI and the M.Sc students

HS

HS is of the opinion that the errors discovered by the two M.Sc students are severe and that the WebLCC program should be taken away from the ETSI homepage. The previous excel versions do not have those errors and something must have gone wrong when converting from excel to WebLCC.

The webLCC is made using mathlab and java and programmed by two IT phd students at KTH.

BBU As many programs use java without servers braking down, BBU will consult COWI's IT people for possible explanations.

The advantage by using a webLCC program is that it will be flexible for instance when it comes to number of bridge elements etc. If excel LCC program is to be used, this has to be adapted to the individual countries.

HS has translated the "broLCC" (in Swedish) program into English but it only works in excel 2003 version.

HS HS will in week 44 send the broLCC program to the meeting participants allowing the two M.Sc. students to use the program in their work.

HS HS will during week 45 send the English version of the bridge LCC program in a version that works with current excel versions.

BBU informed that the Danish road directorate plan on testing the program on a Danish case. BBU will discuss and revert.

3 Basis for searching in BaTman based on M.Sc student note. Possibilities and limitations to be discussed

The basis for conducting LCC analysis on tree different types of bridges were discussed.

MS and GR informed that for different bridge types it is different elements which are vital for the durability, as an example for a Backwall bridge with no expansion joints it can be settlement which is decisive.

When a bridge or tunnel corridor is to be planned the LCC only forms part of the decision process, where maybe 6 different connections are possible.

It was suggested that Dan and Niklas project should have a decided corridor as starting point. When the corridor is chosen, then often geometrical conditions as length of alignment and type of bridge is often given. This could be verbally written and a comparison between steel, concrete and wooden bridges still made.

GR The questions given by Dan and Niklas were considered to lead to maybe 500 bridges and delimitation is necessary. GR will consider and revert to the students hopefully during week 44.

4 Decisions and follow up

As given in minutes

5 Any other business

MS showed the LCC tools which have been developed and paid for as a separate project from Trafikverket.

MS — MS will send literature on LCC projects and articles to the meeting participants.

HS informed that the traffic model was relatively simplified in the LCC program.

MS informed that a traffic model could be downloaded from New Jerseys DOTs homepage.

BBU informed that there also is a traffic model on the Danish road directorates homepage.

6 Next meeting

Follow up in week 46 by BBU

Appendix E: Interview Objects

Below follows a list of the person that has been interviewed in this project and the main topics that were discussed during each interview:

- **Magnus Bäckström (COWI),** ***2011-11-14***
  - Erosion of embankment
  - Transition zone

- **Thomas Darholm (COWI),** ***2011-11-09***
  - Foundational drainage solutions on composite steel bridges
  - Edge beams in stainless steel
  - Strain relationship bridge/edge beam

- **Daniel Göransson (COWI),** ***2011-11-10***
  - Costs and time intervals for different maintenance and repair works

- **Peter Jacobsson (Matrinsson Träbroar),** ***2011-11-14***
  - Settlements, back-wall bridges
  - Moisture problems
  - Protective timber panel

- **Eva Larsson (Verta Konsult),** ***2011-11-03***
  - Foundational drainage
  - Potholes
  - Erosion of embankment

- **Jan Sandberg (Private consultant),** ***2011-11-09***
    - Settlement for back-wall bridges
    - Edge beams
    - Concrete covering (especially on edge beam)
    - Stainless reinforcement
    - Foundational drainage
    - Gap corrosion (composite steel bridges)
        - Solved by welding
    - Prevention of vandalism
    - Re-tensioning of prestressing bars in transversally prestressed glulam slabs
    - Bearings
        - Different choices of bearings, rubber or sliding
    - Suggestion for improvement for construction of details
        - Understanding between different fields
        - Collaborations between different field
        - TBB-group

- **Martin Skoglund (COWI),** ***2011-11-08***
    - Washing and maintenance painting of steel parts on composite bridges
    - Stainless steel for the reinforcement in the edge beams
    - Preventing of vandalism

- **Tomas Svensson (COWI) ,** ***2011-10-28***
    - Settlements for back-wall bridges
    - Re-tensioning of prestressing bars in transversally prestressed glulam slabs
    - Washer cracks
    - Epoxy/lead paint (Mönja)
    - Edge beams
    - Stainless steel reinforcement
    - Moisture problems in timber bridges
    - Avoiding moveable parts

- **Per-Olof Sörling (Trafikverket),** ***2011-11-08***
    - Link plate

- **Per Thunstedt (Trafikverket),** ***2011-11-09***
    - Settlements
    - Link plates
    - Protective painting on composite bridges

- **Bengt Uvhage (Trafikverket),** ***2011-11-03***
    - Settlements, back-wall bridges
    - Foundational drainage
    - Directly casted wearing layer, reinforced with FRP
    - Paint cracks due to fitting of bolts

- **Niklas Larsson and Dan Nilsson, [SA]**
    - Assumption of intervals where inconclusive or no information was given

Appendix F: Analysis Calculations

EDGE BEAM COST

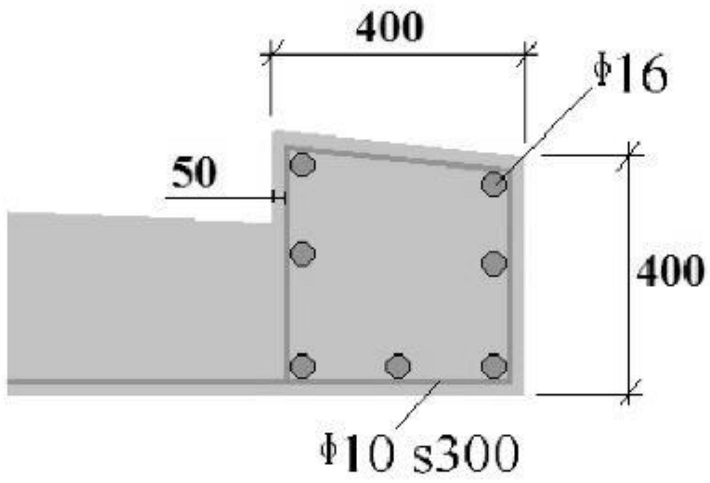


Illustration of typical edge beam section

Edge beam configuration

$\phi_{reinf} := 16mm$

$\phi_{stirrup} := 10mm$

$s_{stirrup} := 300mm$

$c_{cover} := 50mm$

$h_{e\_beam} := 400mm$

$b_{e\_beam} := h_{e\_beam}$

$l_{stirrup} := 5(b_{e\_beam} - 2 \cdot c_{cover}) = 1.5\,m$

$l_{unit} := 1000mm$

$\rho_{steel} := 7870 \frac{kg}{m^3}$

$$A_{reinf} := l_{unit} \cdot 7 \cdot \pi \cdot \frac{\phi_{reinf}^{2}}{4} = 1.407\,L$$

$$A_{reinf} = 1.407 \times 10^{-3}\,m^{3}$$

$$A_{stirrup} := l_{stirrup} \cdot \left(\pi \cdot \frac{\phi_{stirrup}^{2}}{4}\right) \cdot \frac{l_{unit}}{s_{stirrup}}$$

$$A_{stirrup} = 3.927 \times 10^{-4}\,m^{3}$$

$$A_{tot\_per\_m} := A_{reinf} + A_{stirrup}$$

$$A_{tot\_per\_m} = 1.8 \times 10^{-3}\,m^{3}$$

$$W_{steel\_per\_m\_EB} := A_{tot\_per\_m} \cdot \rho_{steel}$$

$$W_{steel\_per\_m\_EB} = 14.167\,kg$$

Cost steel (SEK)

$$Cost\_regular := \frac{12.6}{kg}$$ (www.BEgroup.com) 2011-11-14

$$Cost\_stainless := \frac{91}{kg}$$ (www.BEgroup.com) 2011-11-14

$$Cost\_regular\_per\_m := Cost\_regular \cdot W_{steel\_per\_m\_EB}$$

$$Cost\_regular\_per\_m = 178.505$$

$$Cost\_stainless\_per\_m := Cost\_stainless \cdot W_{steel\_per\_m\_EB}$$

$$Cost\_stainless\_per\_m = 1.289 \times 10^{3}$$

$$\Delta cost := Cost\_stainless\_per\_m - Cost\_regular\_per\_m$$

$$\Delta cost = 1.111 \times 10^{3}$$

TRAFFIC COST ASSUMPTIONS

$ADT := 6000$ ADT (Avarage Daily Traffic)

$V_{norm} := \frac{70}{3.6} \frac{m}{s}$ Normal speed on road

$V_{red} := \frac{50}{3.6} \frac{m}{s}$ Reduced speed due to roadwork

$L_{dist} := 50m$ Distance affected by action/event

One lane closed for traffic

$t_{wait} := 15s$ (time that a vehicle needs to wait before allowed to drive through)

$$\Delta t_{one\_lane} := t_{wait} + \left(\frac{L_{dist}}{V_{red}} - \frac{L_{dist}}{V_{norm}}\right)$$

$$\Delta t_{one\_lane} = 16.029\,s$$

$$V_{red\_eff\_1\_lane} := \left(\frac{L_{dist}}{\Delta t_{one\_lane}}\right)$$

$$V_{red\_eff\_1\_lane} = 11.23 \frac{km}{hr}$$

Both lanes closed, traffic is diverted

$L_{detour} := 7km$

$t_{norm} := \frac{L_{dist}}{V_{norm}} = 2.571\,s$

$t_{detour} := \frac{L_{detour}}{V_{red}} = 504\,s$

$\Delta t_{detour} := t_{detour} - t_{norm}$

$\Delta t_{detour} = 501.429\,s$

$V_{red\_eff\_detour} := \left(\frac{L_{dist}}{\Delta t_{detour}}\right)$

$V_{red\_eff\_detour} = 0.359\,\frac{km}{hr}$

General equation for traffic traffic costs

$D_{ays} := 7$ Duration of roadwork (days)

$C_{delay} := \frac{100}{hr}$ Vehicle cost (per hour)

$$C_{driver} := \left(\frac{L_{dist}}{V_{red\_eff\_i}} - \frac{L_{dist}}{V_{norm}}\right) \cdot ADT \cdot D_{ays} \cdot C_{delay}$$

Appendix G: Calculations performed in TrafficWizard2011

CALCULATIONS PERFORMED IN TRAFFICWIZARD2011

ORIGIN := 1

Traffic conditions (one lane closed)

$ADT := 6000$	ADT (Avarage Daily Traffic)
$L_{workzone} := 50m$	Distance affected by action/event
$V_{norm} := \frac{70}{3.6} \frac{m}{s}$	Normal speed on road
$V_{red} := \frac{50}{3.6} \frac{m}{s}$	Reduced speed due to roadwork
$C_{car} := \frac{140}{hr}$	Vehicle cost (per hour)
$C_{heavy} := \frac{320}{hr}$	Heavy vehicle cost (per hour)
$Prop_{heavy} := 10\%$	Proportion of Heavy vehicle (%)

$$C_{weighed} := (1 - Prop_{heavy})C_{car} + Prop_{heavy} \cdot C_{heavy} = 158 \frac{1}{hr}$$

LCC conditions (Case 0 & 1)

$Yr_{ofA} := 60$ Year of action

$r := 4.0\%$ Discount rate

$D_{ays} := 28$ Duration of roadwork (days)

$C_{action} := 420000$ Cost for action

$C_{alternative} := 60000$ Cost difference from conventional execution of detailing solution

LCC calculation for action

Singel event discounted

$n := 1 .. Yr_{ofA}$ year of which the present value is dicounted to (from where to which year)

$$LCC_{action} := \sum_{n} \left[\frac{(K_1)_n}{(1+r)^n} \right]$$

$LCC_{action} = 4.152 \times 10^4$

Difference in LCC, **not** taking traffic into account

$$Diff_{LCC} := C_{alternative} - LCC_{action} = 1.848 \times 10^4$$

Waiting time (one lane closed for traffic)

$D := 0.009$ — Derived factor to be used for waiting time

$$t_{wait} := \frac{(D \cdot ADT \cdot L_{workzone})}{20 \cdot V_{red}} = 9.72\,s$$

(time that a vehicle needs to wait before allowed to drive through)

$$t_{drive} := \left(\frac{L_{workzone}}{V_{red}} - \frac{L_{workzone}}{V_{norm}}\right) = 1.029\,s$$

loss in time due to reduced speed

$$\Delta t_{one\_lane} := t_{wait} + t_{drive}$$

$$\Delta t_{one\_lane} = 10.749\,s$$

total loss in time due to action

Effective reduced speed

$$V_{red\_eff\_1\_lane} := \left(\frac{L_{workzone}}{\Delta t_{one\_lane}}\right)$$

$$V_{red\_eff\_1\_lane} = 16.746 \cdot \frac{km}{hr}$$

Effective reduced speed due to both delays

General equation for traffic traffic costs

$$C_{trafficCost} := \left(\frac{L_{workzone}}{V_{red\_eff\_1\_lane}} - \frac{L_{workzone}}{V_{norm}} \right) \cdot ADT \cdot D_{ays} \cdot C_{weighed}$$

$$C_{trafficCost} = 6.029 \times 10^{4}$$

LCC calculation for traffic costs

$$LCC_{traffic} := \sum_{n} \left[\frac{(K_2)_n}{(1+r)^n} \right]$$

$$LCC_{traffic} = 5.961 \times 10^{3}$$

Difference in LCC, taking traffic into account

$$\Delta Cost := Diff_{LCC} - LCC_{traffic} = 1.252 \times 10^{4}$$

When this difference becomes zero or negative, The **critical ADT** is found.
This is performed by increasing the ADT in this case

the **critical year** of occurance is found where the (LCC_action+LCC_traffic)=C_alternative, this is performed by either increasing or decreasing the year of action

Appendix H: Derivation of the D-factor

Table H.1 Output values from CapCal and the corresponding D-factor

Input value		
V_red	40	km/h
Length	50	m
ADT	6000	

Length varies							
Length [m]	10	20	30	40	50	70	100
t_wait [s]	7,1	8,4	9,7	11,1	12,4	15	19
D_factor	0,0263	0,0156	0,0120	0,0103	0,0092	0,0079	0,0070

ADT varies							
ADT	1000	2000	3000	4000	5000	6000	10000
t_wait [s]	8,6	9,2	9,8	10,5	11,3	12,4	20
D_factor	0,0382	0,0204	0,0145	0,0117	0,0100	0,0092	0,0089

Speed varies						
Speed [km/h]	20	30	40	50	60	70
t_wait [s]	-	14,6	12,4	11,1	10,2	9,5
D_factor	-	0,0081	0,0092	0,0103	0,0113	0,0123

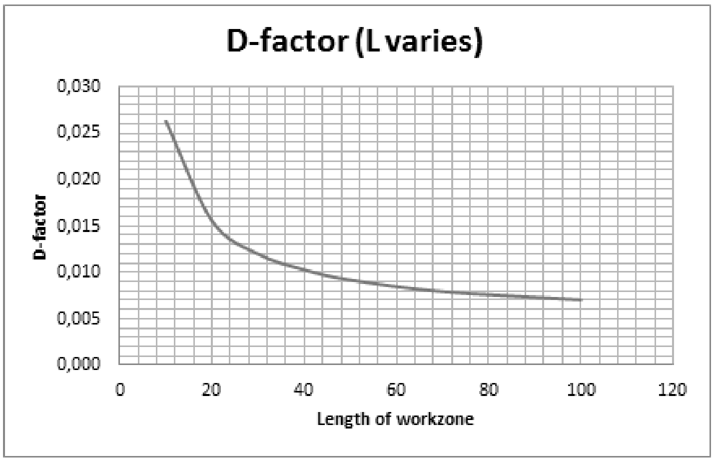
$$t_{wait} = D * ADT_{mod} \left(\frac{L_{workzone}}{v_{red}}\right) \qquad \text{(H.1)}$$

$$D = \frac{t_{wait} * v_{red}}{ADT_{mod} * L_{workzone}} \qquad \text{(H.2)}$$

- t_{wait} =Time to pass though the workzone[s]
- D = D-factor
- ADT_{mod} = 20 % of ADT
- $L_{workzone}$ = size of the workzone
- v_{red} = Reduced speed through the workzone.

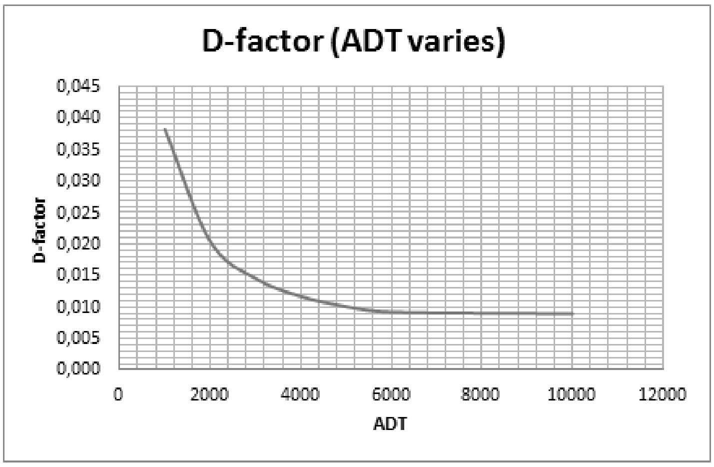
D-factor	
Length [m]	D_factor
10	0,026
20	0,016
30	0,012
40	0,010
50	0,009
70	0,008
100	0,007

D-factor	0,0086



D-factor	
Length [m]	D_factor
1000	0,038
2000	0,020
3000	0,015
4000	0,012
5000	0,010
6000	0,009
10000	0,009

D-factor	0,0109



D-factor	
Length [m]	D_factor
30	0,0081
40	0,0092
50	0,0103
60	0,0113
70	0,0123

D-factor	0,0102

D-factor	**0,009**

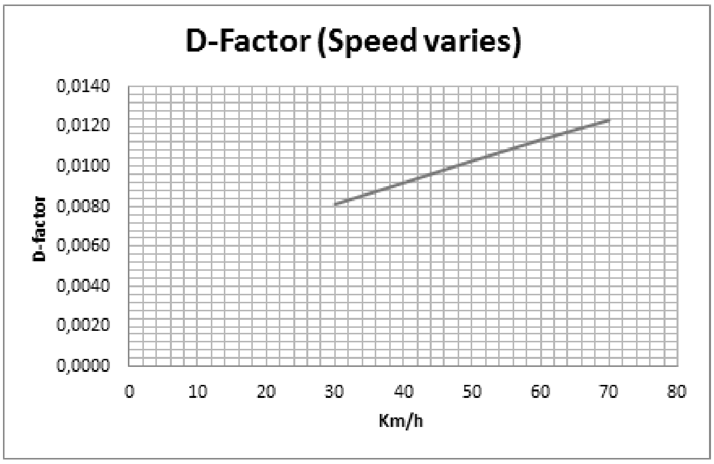


Figure H.1. Graphs illustrating how the D-factor varies with; length of the workzone, ADT and Speed

Appendix I: TrafficWizard2011

Description of the Excel toolbox:

The toolbox is divided into 6 tabs:

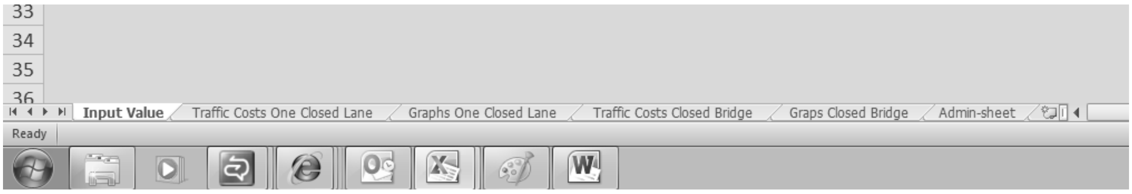


Figure I.1. Lower left corner of the screen in TrafficWizard2011

TrafficWizard2011 is organised in 6 different tabs:

1. **Input Value** – Required input values regarding traffic and LCC conditions are defined
2. **Traffic Costs One Closed Lane** – Generates Traffic costs. These costs are based on a varying ADT and bridge age of when an activity occurs with regard to:
    - MR&R works
    - Traffic situation when one out of two lanes on the bridge is closed
3. **Graphs One Closed Lane** – Generates two graphs where following can be read out on the x-axis:
    - Critical ADT
    - Critical age of the bridge when an activity occur
4. **Traffic Costs Closed Bridge** (*not yet in function*) – Generates Traffic costs. These costs are based on a varying ADT and age of the bridge when an activity occurs with regard to:
    - MR&R works
    - Traffic situation when the entire bridge needs to be closed and the traffic is diverted
5. **Graphs Closed Bridge** (*not yet in function*) – Generates two graphs where following can be read out on the x-axis:
    - Critical ADT
    - Critical age of the bridge when an activity occur
6. **Admin-sheet** – Not to be used by non-authorised personal

Input Value Tab:

Input data		
Traffic conditions		
ADT	6 000	
Size of the workzone	50	m
v_norm	70	km/h
v_red	50	km/h
c_car	140	SEK/h
c_heavy	320	SEK/h
Proportion heavy	10%	
LCC-conditions		
Age for occurrens:	60	
Discount Rate:	4%	
Duration_work	28	days
Cost of activity (case 0)	420 000	SEK
LCC (case 0), age for activity	41522	SEK
Alternative LCC (case 1):	60 000	SEK
Dif. in LCC case 0 and 1	18478	SEK
D-factor:	0,009	

Figure I.2. "Input data" table in TrafficWizard2011

The Input data is divided into 3 boxes:

1. The top box defines the relevant input data regarding the prevailing traffic situation
2. The mid box defines the relevant input data concerning the LCC conditions
3. The bottom box defines the D-factor and has a default setting to 0,009, applicable to:
    a. *ADT* > 3000 vehicles/day
    b. L_workzone > 30 meter

Traffic Costs One Closed Lane:

Traffic cost [SEK]										
		Age when activity occurs [years]								
		0	10	20	30	40	50	60	70	80
ADT	3000	12 229	8 262	5 581	3 770	2 547	1 721	1 163	785	531
	4000	24 269	16 395	11 076	7 483	5 055	3 415	2 307	1 559	1 053
	5000	40 290	27 218	18 388	12 422	8 392	5 669	3 830	2 587	1 748
	6000	60 293	40 732	27 517	18 589	12 558	8 484	5 731	3 872	2 616
	7000	84 277	56 935	38 463	25 984	17 554	11 859	8 011	5 412	3 656
	8000	112 243	75 827	51 226	34 607	23 379	15 794	10 670	7 208	4 870
	9000	144 191	97 410	65 807	44 457	30 033	20 289	13 707	9 260	6 256
	10000	180 120	121 683	82 204	55 534	37 517	25 345	17 122	11 567	7 814
	11000	220 031	148 645	100 419	67 840	45 830	30 961	20 916	14 130	9 546
	12000	263 923	178 297	120 451	81 372	54 972	37 137	25 089	16 949	11 450

Variable ADT, age and size of workzone	
Min. ADT	3000
Step ADT	1000
Min. age when activity occurs [years]	0
Intervall age [years]	10
Min. size of workzone [m]	10
Interval step workzone [m]	10

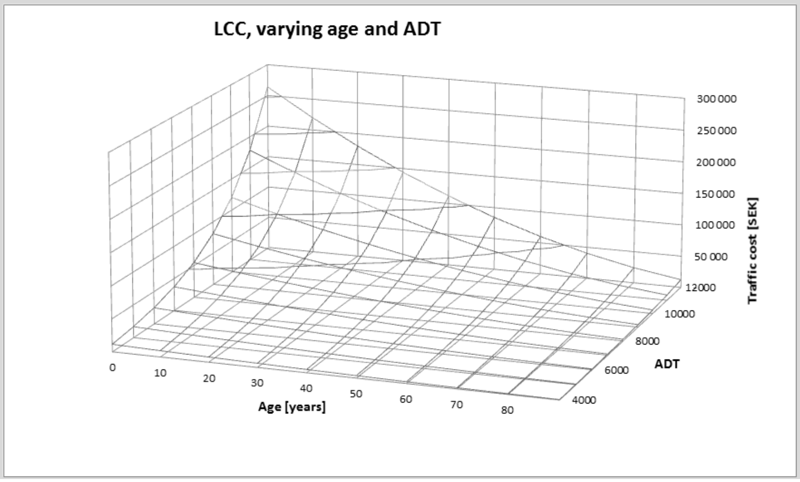


Figure I.3. “Traffic Costs One Closed Lane” tab seen in TrafficWizard2011

- **Traffic cost (SEK)** – The table displays how the traffic costs are varying with ADT and age of the bridge when the activity occurs
- **Variable ADT, age and size of workzone** – Changes the size and interval for the ADT and age when activity occurs read in the table. It is possible to start with a sparse interval, and then gradually refine the intervals to get a more accurate read of the traffic costs
- **Traffic cost (LCC)** – 3D-Graph that illustrate how the traffic costs varies with both ADT and the age when the activity occurs

Graphs One Closed Lane:

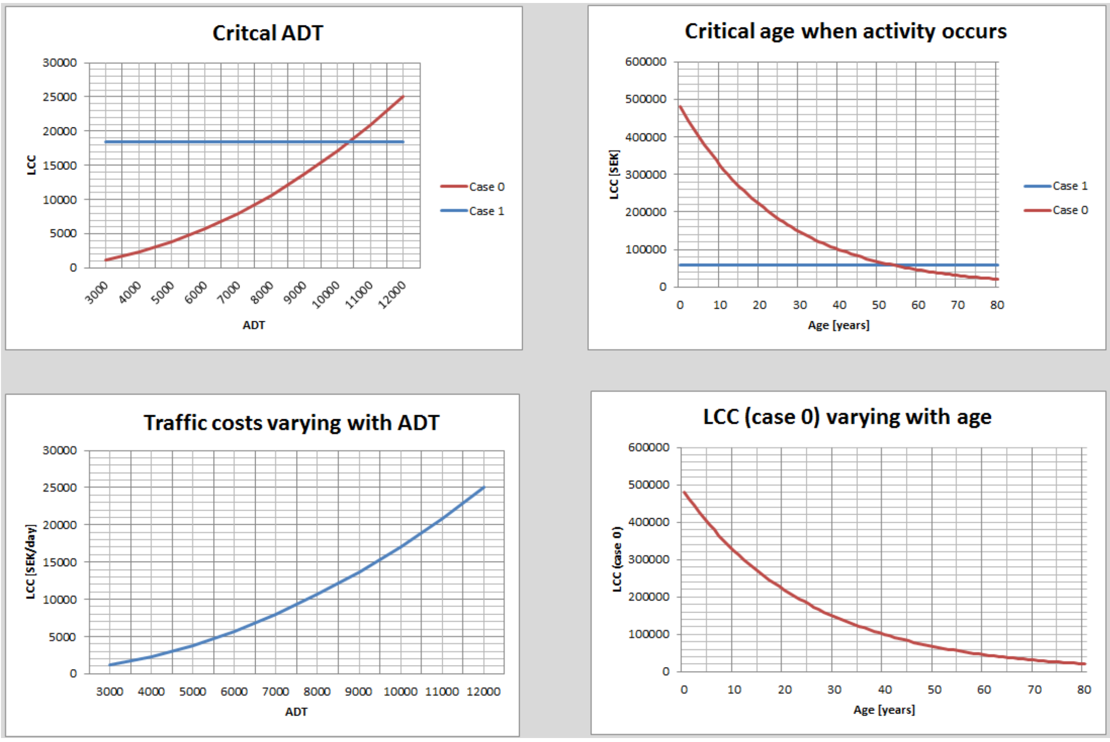


Figure I.4. *"Graphs One Closed Lane" tab when using TrafficWizard2011*

4 different graphs are generated:

1. **Critical ADT** – The intersection of the 2 lines marks the critical ADT on the x-axis. If the predicted ADT is lower than the critical, it is justified to choose case 0. Is it the other way around, case 1 is the more favourable option

2. **Critical age when activity occurs -** The intersection of the 2 lines marks the critical age of the bridge for an activity to occur. If the actual age of occurrence is earlier than the critical, it is justified to choose case 1. Is it the other way around, case 0 is the more favourable option

3. **Traffic costs varying with ADT** – Illustrate how the traffic costs varies with an increase of the ADT. The ADT range can be adjusted by the user

4. **LCC (case 0) varies with time** – Illustrate how the LCC is varying depending on at which age of the bridge the activity occurs. The range of the age for when the activity occurs can be adjusted by the user

Finding the critical ADT with TrafficWizard2011

Example from Section 8.3.3

In order to find the critical ADT with TrafficWizard2011, the input data shown in Figure I.5, needs to be inserted into the program.

Input data		
Traffic conditions		
ADT	6 000	
Size of the workzone	50	m
v_norm	70	km/h
v_red	50	km/h
c_car	140	SEK/h
c_heavy	320	SEK/h
Proportion heavy	10%	
LCC-conditions		
Age for occurrens:	60	
Discount Rate:	4%	
Duration_work	28	days
Cost of activity (case 0)	420 000	SEK
LCC (case 0), age for activity	41522	SEK
Alternative LCC (case 1):	60 000	SEK
Dif. in LCC case 0 and 1	18478	SEK
D-factor:	0,009	

Figure I.5. View of the input data table in TrafficWizard2011

1. The first box requires input data regarding the prevailing traffic conditions

2. The second box requires input data from the comparative LCC-analysis (*without traffic taken into consideration*)

    - **Age for occurrence** – Age of the bridge when an activity occur
    - **Discount rate** – Set to 4 % in Sweden
    - **Duration_work** – Number of days it will take to perform an activity
    - **Cost for activity (case 0)** – Base year value of case 0
        - Required for finding the critical age
    - **LCC (case 0), age for activity** – Present value of case 0 (automatically calculated)
    - **Alternative LCC (case 1)** – Present value of case 1 (*cost difference from conventional execution of detailing solution*)
    - **Dif. In LCC case 0 and 1** – Difference in present value between case 0 and 1(automatically calculated)

3. The third box requires input data of the D-factor
    - Default setting = 0.009

When the input data is set, TrafficWizard2011generates a graph, seen in Figure I.6 below, where the **critical ADT can be read** from the intersection of case 0 and 1.

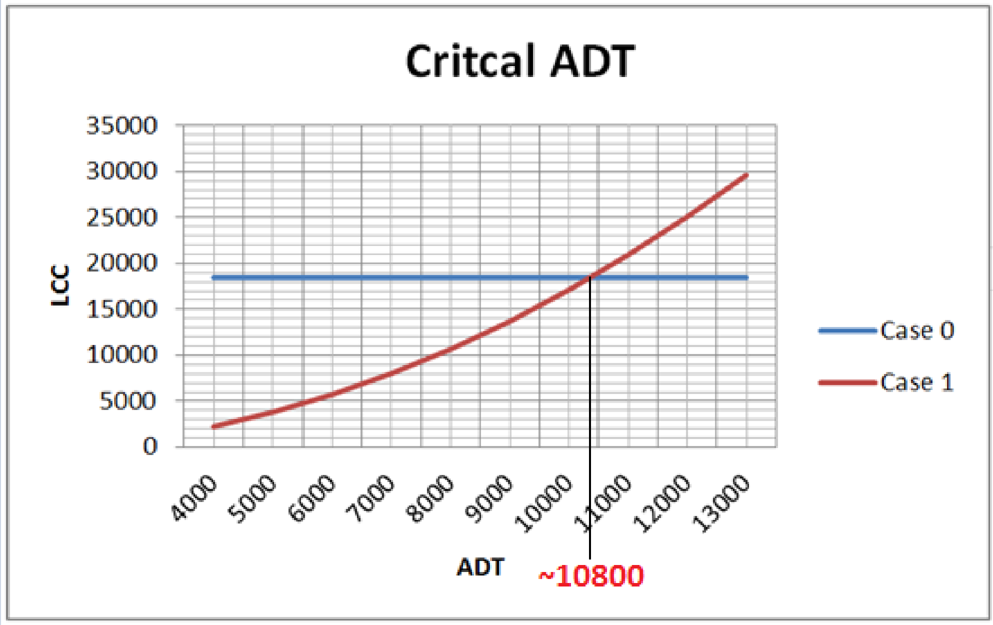


Figure I.6. TrafficWizard2011's graphical illustration of how to read out the critical ADT

Alternatively, a table is also available for a more accurate read of the critical ADT:

1. Start out from the age for when an activity is expected to occur
    a. An option to refine the ADT read is available in the "*Variable ADT, age and size of workzone*" box, seen in Figure I.8 below (not required in this case)
2. Find the value closest to the corresponding difference in LCC in the column
    a. The same option to refine the ADT read is also available in the "*Variable ADT, age and size of workzone*" box, seen in Figure I.8 below
3. **Read the ~critical ADT,** see Figure I.7

Traffic cost (SEK)										
		Year of action to occur								
		0	10	20	30	40	50	60	70	80
ADT	3000	12 229	8 262	5 581	3 770	2 547	1 721	1 163	785	531
	4000	24 269	16 395	11 076	7 483	5 055	3 415	2 307	1 559	1 053
	5000	40 290	27 218	18 388	12 422	8 392	5 669	3 830	2 587	1 748
	6000	60 293	40 732	27 517	18 589	12 558	8 484	5 731	3 872	2 616
	7000	84 277	56 935	38 463	25 984	17 554	11 859	8 011	5 412	3 656
	8000	112 243	75 827	51 226	34 607	23 379	15 794	10 670	7 208	4 870
	9000	144 191	97 410	65 807	44 457	30 033	20 289	13 707	9 260	6 256
	10000	180 120	121 683	82 204	55 534	37 517	25 345	1[illegible]22	11 567	7 814
	11000	220 031	148 645	100 419	67 840	45 830	30 961	20 916	14 130	9 546
	12000	263 923	178 297	120 451	81 372	54 972	37 137	25 089	16 949	11 450

Figure I.7. Presents the table found in TrafficWizard2011, where the critical ADT can be read for a specific activity at a specific age when an activity occurs

Flexible ADT, year of occurrence and size of workzone	
Min. ADT	10000
Step ADT	100
Min. year of occurrence	0
Intervall year	10
Min. size of workzone	10
interval step WZ	10

Figure I.8. Presents the "Variable ADT, age and size of workzone" box for a refined read of the critical ADT, seen in Figure I.9 below

Traffic cost (SEK)									
	Year of action to occur								
ADT	0	10	20	30	40	50	60	70	80
10000	180 120	121 683	82 204	55 534	37 517	25 345	17 122	11 567	7 814
10100	183 932	124 258	83 944	56 710	38 311	25 882	17 485	11 812	7 980
10200	187 784	126 860	85 702	57 897	39 113	26 424	17 851	12 059	8 147
10300	191 675	129 489	87 478	59 097	39 924	26 971	18 221	12 309	8 316
10400	195 607	132 145	89 272	60 309	40 743	27 524	18 594	12 562	8 486
10500	199 578	134 828	91 085	61 534	41 570	28 083	18 972	12 817	8 659
10600	203 589	137 537	92 915	62 770	42 405	28 647	19 353	13 074	8 833
10700	207 639	140 274	94 764	64 019	43 249	29 217	19 738	13 334	9 008
10800	211 730	143 037	96 631	65 280	44 101	29 793	20 127	13 597	9 186
10900	215 861	145 828	98 516	66 554	44 961	30 374	20 520	13 862	9 365

Figure I.9. Presents the refined table generated in TrafficWizard2011, where the critical ADT can be read out more accurately for a specific activity

Two or more MR&R activities during the design service life

The following section is a complement to the calculations mentioned above in the example – "Finding the critical ADT with TrafficWizard2011".

The following calculation presents a method to when two or more MR&R activities are considered during the design service life of a bridge. Before the critical value for the ADT can be read out, additional calculations need to be performed.

Figure I.10, seen below, shows the LCC result for a reoccurring activity regarding gap corrosion in bolted connections, also described in Section 6.3.1.1. For case 0, treatment of the gap corrosion is needed with a time interval of 35 years. The alternative solution, case 1, has welded connection where there is no risk for gap corrosion.

In the example above, it was necessary to know the difference in LCC for case 0 and 1 to be able to read out the critical ADT. But for reoccurring activities it is not that simple. Then it is of interest to know the portion of the difference in LCC that should be "covered" by traffic cost at the first occurrence of a reoccurring activity.

By using the graph shown in Figure I.10, it is possible to calculate the reduced value for the difference between two LCC cases. When this value is known the critical ADT can be read out in the same way as shown in Figure I.7 and Figure I.9:

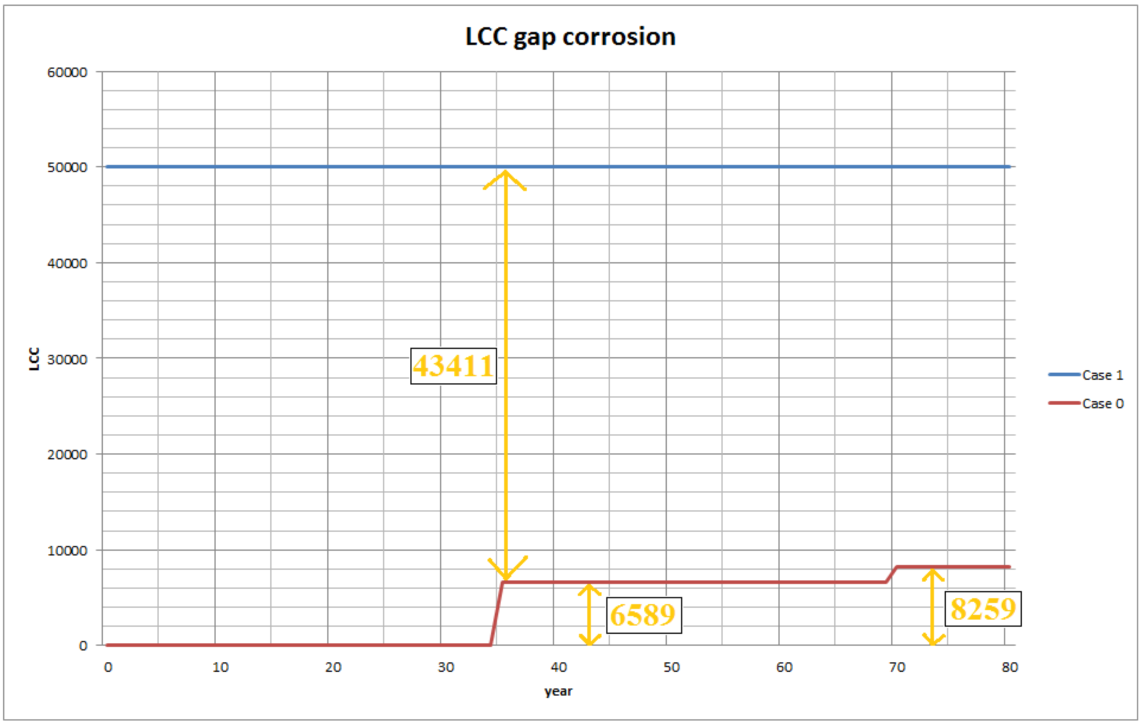


Figure I.10. LCC-analysis result from BridgeLCC for case 0 and 1, with gap corrosion at connection details representing case 0 and case 1 by welded connection

To get the portion of the difference in LCC that should be “covered” by traffic cost, the following 2 steps needs to be performed:

1. Calculating the ratio between the LCC after the occurrence of one activity (6,589 SEK) and the total LCC for case 0 (8,259 SEK):

$$\frac{6589}{8259} = 0{,}80$$

2. Multiply this ratio with the difference in LCC between case 0 and 1 after the occurrence of one activity (43,411 SEK):

$$43411 * 0{,}80 = 34728 \text{ SEK}$$

In TrafficWizard2011, this value can be read out from the column representing the age of the bridge when the first activity occurs. This is made in the same way as described in Figure I.7 and Figure I.9.

Appendix J: Explanation of the flow chart

1. **Design a bridge** – A bridge is to be built

2. **Select a bridge type** – Select the bridge type that is the most suitable based on the prevailing conditions. Usually done through conceptual design

3. **Type X** – When bridge type X has been selected, relevant information and data regarding the bridge need to be collected
   - **Typical problems** – Case 0. Collect information about typical problems and disadvantages with the conventional execution of detailing for the bridge type
   - **Alternative solution** – Case 1. Collect information regarding alternative solutions to minimise or prevent the problems stated in case 0. (*The investment costs might be higher, but the alternative solutions usually decrease the need for MR&R work during service life of the bridge*)

4. **Perform the LCC-analysis** – Perform the LCC-analysis (without taking traffic costs into consideration) for both case 0 and 1, e.g. by using an LCC software, described in Chapter 3, like; BroLCC or BridgeLCC (*recommended*), alternatively hand-calculations. (*Single activity, single occurrence is performed automatically in TrafficWizard2011*)
   - In Chapter 7 it is described how an LCC-analysis, using the above mentioned softwares could be performed
     - Traffic costs should be disregarded from at this stage when using this method. This is because the traffic costs mainly are incurred on the conventional solutions. Adding the traffic costs will be more unfavourable for case 0 compared to case 1

5. **Compare** –Compare the LCC-analysis results for each detail individually, for case 0 and case 1. Determine which case that is the most favourable
   - **Case 1** – If case 1 is favourable, the analysis is finished and it is justified from an LCC point of view to use case 1. (*Represented by a negative value in the cell "Diff. in LCC case 0 and 1" in TrafficWizard2011's input data window*)
   - **Case 0** – If case 0 is favourable, (*Represented by a positive value in the cell "Diff. in LCC case 0 and 1" in TrafficWizard2011's input data window)*, further analysis in TrafficWizard 2011 is required considering the:
     - Critical age of the bridge when the MR&R activity occurs (*associated with case 0*)
     - Critical ADT (*associated with the MR&R activity for case 0)*

6. **TrafficWizard2011** – Two steps when using TrafficWizard2011
    - **Critical ADT**
        - **Finding the critical ADT –** Insert the input data corresponding to the predicted traffic situation, and graphs will automatically be generated. The critical ADT for the activity can be read on the ADT-axis where from the point where the two lines are intersecting, found in the tab "*Graph, one closed lane*"
        - **Critical ADT larger than predicted ADT?**
            1. **YES** – Case 0 is justified
            2. **NO** – Case 1 is justified
    - **Critical age**
        - **Finding the critical age –** Insert the input data corresponding to the predicted age of the bridge for when an activity will occur, and graph will automatically be generated. The critical age for the activity can be read on the time-axis where the two lines are intersecting, found in the tab "*Graph, one closed lane*"
        - **Compare the critical age to the predicted age/time-interval for an activity**
            1. **Predicted age/time-interval earlier than the critical age** – Case 1 is justified
            2. **Critical age within the interval –**The designer and/or client needs to make a decision of which alternative that is the most favourable
            3. **Predicted age/age-interval later than the critical age** – Case 0 is justified