LCC Applications for Bridges and Integration with BMS

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Cover photo: Uddevallabron, Bridge No. [14-989-1], Uddevalla, Sweden. Source: BaTMan.

Abstract

Bridges are vital links in many transport networks and represent a big capital investment for both governments and taxpayers. They have to be managed in a way that ensures society's needs are optimally met. In many countries, bridges are mainly managed using bridge management systems (BMSs). Although many BMSs contain some forms of life-cycle costing (LCC), the use of LCC in bridge engineering is scarce. LCC in many BMSs has mainly been applied within the bridge operation phase, even though it has several useful applications within the bridge entire life, from cradle to grave. This licentiate thesis discusses the need of a BMS with integrated comprehensive LCC tools that can assist decision-makers at all levels and within all phases in selecting the most cost-effective alternative from an array of applicable alternatives.

The thesis introduces the Swedish Bridge and Tunnel Management System (BaTMan). A comprehensive integrated LCC implementation scheme is illustrated, taking into account the bridge investment and management process in Sweden. The basic LCC analytical tools as well as other helpful LCC techniques are addressed. Detailed case studies for real bridges at different investment phases are presented to demonstrate the recent improvement of BaTMan practically in the LCC integration. Cost records for 2,508 bridges extracted from BaTMan inventory data are used as input data in the presented case studies. Considering the same records, the average real and anticipated initial costs of different bridge types in Sweden will schematically be presented.

The thesis introduces a bridge LCC program developed over this research named "BaTMan-LCC". The reason for which this program was developed is to combine all possible LCC applications for bridges in one tool and facilitate its implementation. The sensitivity analysis as well as the LCC saving potential highlighted in the presented case studies emphasizes the feasibility and the possibility of developing BaTMan to accommodate the applications of BaTMan-LCC.

Keywords: Bridge, Management, life-Cycle Costing, LCC, Bridge Management System, BMS, BaTMan, repair, Optimization, Trafikverket.

Preface

The research presented in this licentiate thesis has been conducted at the *Department of Civil and Architectural Engineering,* the division of *Structural Engineering and Bridges*, at *KTH Royal Institute of Technology*. It has been financed by the Swedish Transport Administration (Trafikverket). The thesis was mainly supervised by Professor *Håkan Sundquist* to whom I want to thank for valuable guidance and advice. I especially thank him for giving me the opportunity to immerse myself in my favorite subject.

After thanking God for granting me the strength and the will to fulfill the targets of this research, I would like to express my best wishes and thanks to my beloved home country Palestine, parents and all of my family who have instilled in me the drive and encouragement to complete this work.

I express my sincere gratitude to my assistant supervisor Professor *Raid Karoumi* for the support and constructive guidance throughout my studies. I am impressed by his sound knowledge of the various fields I have come across.

Thanks are also due to my germane supervisor from Trafikverket Dr. *George Racutanu*. Many thanks to the bridge specialists in Trafikverket *George Chamoun* and *Johan Severinsson* for their close collaborations and fruitful discussions. Special thanks are also due to Mr. *Peter Rosengren* from CNet Svenska AB and all staff on BaTMan-Helpdesk for giving me licenses to WebHybris and BaTMan.

I also express my gratitude to my former teachers in Egypt, Professor *Baher Abou Stait* and Professor *Ahmed Al-Laithy* for introducing me to the field of research.

My deepest appreciation goes to my wife *Shaymaa* for giving me a life beyond my profession and filling it with joy and meaning.

I would like to acknowledge and thank everybody contributed to my pleasant time at KTH especially my colleagues at the Division of Structural Engineering and Bridges.

Stockholm, February 2012

Mohammed Safi

Publications

- ## Appended Journal Papers

Paper I: Mohammed Safi, Håkan Sundquist, Raid Karoumi and George Racutanu, Development of the Swedish Bridge Management System by Upgrading and Expanding the Use of LCC, accepted for publication on the *Structure and Infrastructure Engineering Journal,* UK.

Paper II: Mohammed Safi, Håkan Sundquist, Raid Karoumi and George Racutanu, Life-Cycle Costing Applications for bridges and Integration with Bridge Management Systems, Case-Study of the Swedish Bridge and Tunnel Management System (BaTMan), accepted for publication on the *Transportation Research Record (TRR): Journal of the Transportation Research Board (TRB),* USA

Paper III: Mohammed Safi, Håkan Sundquist and George Racutanu, Life-Cycle Costing Integration with Bridge Management Systems, submitted to the *ICE-Bridge Engineering Journal,* UK.

All the processing, writing and analysis included in all papers have been performed by the first author. The co-authors have participated in the planning of the work and contributed with comments and revisions.

- ## Other Relevant Publications

1) Mohammed Safi, Håkan Sundquist, Raid Karoumi and George Racutanu, Life-Cycle Costing Applications for bridges and Integration with Bridge Management Systems, Case-Study of the Swedish Bridge and Tunnel Management System (BaTMan*),* orally presented and published on the *Transportation Research Board's 91st annual meeting compendium of papers,* USA.
2) Mohammed Safi, Håkan Sundquist, Raid Karoumi and George Racutanu, Bridge Management System with an Integrated LCC Tool, accepted on the *fib Symposium 2012,* Stockholm-Sweden.
3) Mohammed Safi, Håkan Sundquist, Raid Karoumi and George Racutanu, Bridge Management System with an Overall Integrated LCC Tool, Submitted to the *18th IABSE Congress 2012,* Seoul-Korea.
4) Mohammed Safi, Bridge Life-Cycle Optimization, presented poster in the *KTH Transport Day Conference,* November 2011, Stockholm-Sweden.

List of Acronyms

ADT	Average daily traffic
BaTMan	The Swedish bridge and tunnel management system
BLCCA	Bridge life-cycle cost analysis
BMS	Bridge management system
C_{ACC}	Accident cost
CC	Condition class
C_F	Average cost per fatal accident
C_I	Average cost per serious injury accident
C_n	Sum of all cash flows in year n
C_o	Future cash flow expected to fall due every year during the service life-span L
C_P	Future cash flow expected to fall due periodically every p years during the service life-span L
C_{TDC}	Traffic delay cost
C_{VOC}	Vehicle operating cost
EAC	Equivalent annual cost
EL	Elemental cost (Purchasing, Construction, & Installation)
INS	Inspection cost
INV	Investment cost
L	Service life-span
LCC	Life-cycle costing
LCRA	Life-cycle remedial actions
L_D	Detour length
NEL	Non elemental cost
NPV	Net present value
NS	Net saving
NVDB	The Swedish national road database
O&M	Operation and maintenance
OL	Opportunity loss
O_P	Average hourly operating cost for one passenger car
O_T	Average hourly operating cost for one truck
P_F	Average number of killed persons in bridge related accidents
P_I	Average number of injured persons in bridge related accidents
Pontis	Full-featured BMS used in more than 40 state departments of transportations in USA
r	Discount rate
R,D&L	End of life management cost (recycling, demolition and landscaping)
RRR	repair/rehabilitation & replacement cost
r_{TG}	Traffic growth rate
SEK	Swedish Kroner
STR	Strengthening cost
Trafikverket	The Swedish Transport Administration
V_D	Detour speed
WebHybris	Software navigation tool can access BaTMan's database
WLC	Whole-life costing
w_p	Hourly time value for one passenger car
w_T	Hourly time value for one truck
WZUC	Work zone user cost.

Contents

1 Introduction

1.1 Background

Generally, bridge investment and management decisions are multi-alternative-oriented. Several alternatives might technically be feasible when implementing for example a bridge design proposal or a bridge repair strategy. The alternatives may provide the same required function. However, each of them may have different life-cycle cost and anticipated service life. Moreover, the cost categories associated with the various alternatives are incurred at varying points in time. Currently, conventional financial costing is guiding the agencies' decisions to implement a particular proposal. Life-Cycle Costing (LCC) is an appropriate decision supporting tool that can be used by decision-makers to specify the most cost-effective alternative taking into account all affected parameters. In many countries, bridges are mainly managed using bridge management systems (BMSs). Although many BMSs contain some forms of LCC, the use of LCC in bridge engineering is scarce. LCC in many BMSs has mainly been applied within the bridge operation phase to support decisions related to existing bridges. LCC has several useful applications within the bridge entire life, from cradle to grave. The development of BMSs with integrated comprehensive LCC tools has been necessitated by the large imbalance between the need for extensive repairs or replacements in a large bridge stock and the limited budget available to municipalities and agencies for implementing the required repairs. This licentiate thesis discusses the need of a BMS with integrated comprehensive LCC tools that can assist decision-makers at all levels and within all phases in selecting the most cost-effective alternative.

1.2 Aims and Scope

The project presented in this thesis is financed by the Swedish Transport Administration (Trafikverket). The project aims at enhancing the bridge investment and management decisions within Trafikverket by integrating LCC in the decision making process. The Swedish Bridge and Tunnel Management System (BaTMan) is the main tool used by Trafikverket to manage and maintain the bridges. All bridge related technical and financial data are stored in BaTMan's database. Such data are of a great important to conduct reliable bridge LCC analysis. Therefore, this research was directed toward enhancing the bridge investment and management decisions within Trafikverket by upgrading and expanding the use of LCC in BaTMan. This thesis presents several possible LCC applications for bridges within their different investment phases. Two practical case studies will be illustrated to demonstrate two possible applications.

1.3 Thesis Outline

This licentiate thesis presents the research results of two years. The thesis is based on three journal papers and another three conference papers. The journal papers will only be appended in this thesis. All of the three appended papers present the possible LCC applications for bridges in general. However, each of them handles a specific LCC application and each paper is supported with a different case study. The case study in the first paper (Annex A), demonstrates the LCC implementation on whether to repair or to replace an entire bridge. The case study in the third paper (Annex C) demonstrates the LCC implementation on whether to repair or to replace a specific bridge structural member. The second paper (Annex B) has the same aim of the first paper but the analysis in the included case study is related to a different bridge. The main aim of the case studies in these three papers is to step by step clarify how LCC can be implemented and integrated within BMSs. Some of the introduced LCC applications in this thesis will not be illustrated by detailed case studies. This will be done in the future tasks of this research project.

The research results can be concluded in the following main points:

- Discuss LCC and BMS in general
- Address the possible LCC applications for bridges
- Introduce the Swedish Bridge and Tunnel Management System (BaTMan)
- Present the LCC analysis tools and techniques
- Supported with a detailed case study, demonstrate the LCC implementation on whether to repair or to replace a bridge
- Supported with a detailed case study, demonstrate the LCC implementation on whether to repair or to replace a specific bridge structural member
- Introduce the bridge LCC program "BaTMan-LCC"

The case studies in the appended first two papers will briefly be repeated in the extended summary in this thesis with more detailed analysis and new graphs.

1.4 LCC and BMS in General

Life-cycle Cost is the cost of an asset, or of its parts, throughout its life cycle whilst it fulfils the performance requirements while life-cycle costing (LCC) is a methodology for systematic economic evaluation of the Life-cycle cost over a specified period of analysis as defined in the agreed scope *[10]*. Whole-life cost considers all the significant and relevant initial and future costs and benefits of an asset throughout its life cycle, whilst fulfilling the performance requirements while whole-life costing (WLC) is a methodology for systematic economic consideration of all Whole -life cost and benefits over a specified period of analysis as defined in the agreed scope *[10]*. LCC is appropriately applied to compare project implementation alternatives that would yield the same level of service and benefits to the project user. The agency that uses this tool has already decided to undertake a project or improvement and is seeking to determine the most cost-effective means to accomplish the project’s objectives. Unlike LCC, WLC considers the benefits of an improvement as well as its costs and therefore can be used to compare design alternatives that do not yield identical benefits (e.g. bridge replacement alternatives that vary in the level of traffic that they can accommodate). Moreover, WLC can be used to determine whether or not a project should be undertaken at all. For bridge engineering, LCC is an appropriate decision supporting tool which can be used by decision-makers to specify the most cost-effective solution taking into account all affected parameters.

A Bridge Management System (BMS) with an integrated comprehensives LCC tool can be defined as a rational and systematic approach to organize and carry out all the activities related to managing a network of bridges, including optimizing the selection of maintenance and improvement actions in order to maximize the benefits while minimizing the life-cycle cost. The development of BMSs with integrated LCC tool has been necessitated by the large imbalance between the need for extensive repairs or replacements in a large bridge stock and the limited budget available to municipalities and agencies for implementing the required repairs. The purpose of a BMS is to combine management, engineering and economic input in order to determine the best actions to take on a network of bridges over time *[1]*. A BMS should include the following basic components: data storage, cost models, deterioration models, and optimization models *[1]*, Figure 1-1.

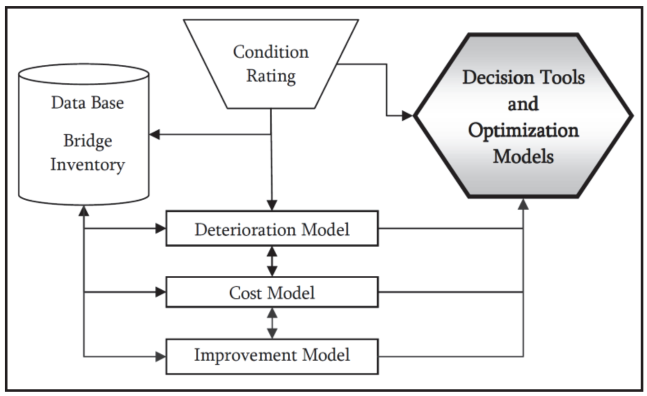

Figure 1-1 Basic components of a BMS (AASHTO, 2001)

The heart of a BMS is a database derived from the field inspections *[3]*. The integrity of a BMS is directly related to the quality and accuracy of the bridge inventory and physical condition data obtained through field inspections. Information such as the bridge name, number, location, drawings, and inspection records are stored. These data are the starting point of the system. Considering the updated inspection records, the bridges and their individual structural members are conditionally rated according to specific methodologies. The most important section in the BMS is the decision tools and the optimization models.

1.5 Literature Review and Research Contribution

BMSs as well as bridge life-cycle cost analysis (BLCCA) have been subjects of intense interest long time ago. Several important new research-and-development studies have provided essential tools and resources which previously were unavailable *[1]and [2]*.

Many BMSs have been developed in different countries. Most of them address three aspects of bridge management: assessing bridge conditions, modelling future deterioration behaviour, and the decisions to maintain, repair, or rehabilitate *[3], [12] and [17]*. A BMS should include the following basic components: data storage, cost models, deterioration models, and optimization models *[1]*. BMSs can be classified as one of two types: network level or project level *[21]*. Many agencies have adopted BMSs that operate at the network level to assist in budget allocation and prioritization within an agency's total inventory of bridges *[5]*. NCHRP Report 590 *[28]*, describes the development of methodologies for network- and project-level optimization of multiple, user-specified performance criteria.

NCHRP Report 483 *[5]*, describes a great research effort leading to a recommended methodology and includes a guidance manual for carrying out BLCCA. However, the criteria for the project selection are not clear in that report particularly when comparing investment projects of unequal life-spans. Techniques that highlight the feasibility of the LCC results are also missing in that report. Several bridge LCC case studies have been presented in different research papers. A comparison between the life-cycle cost of a concrete slab bridge and a composite steel/concrete bridge has been presented by *[11]*. The life-cycle cost of alternative designs according to stainless steel reinforcement compared to traditional materials is examined by *[7]*. Huang Y. *[8]*, has developed a performance-based BLCCA model using visual inspection inventory data. A performance-based life-cycle cost management model for reinforced concrete bridges with regard to chloride-induced reinforcement corrosion was presented by *[18]*. A simplified case study on whether to repair or to renew a bridge deck without taking into account the bridge user costs has been demonstrated by *[9]*.

An obvious gap between the practice and the theory of BLCCA was detected and discussed in *[14] and [12]*. Even though BMSs and BLCCA are interrelated, many bridge management researches have treated them as separate aspects; therefore, neither may lead to the best usable decision-support tools. Some bridge inventory and inspection systems do not make use of LCC. Current challenges involve making sense of the increasing volume of information and integrating and processing it to help manage bridges through their life cycle as effectively as possible *[17]*. Web-based BMSs with cradle-to-grave, integrated, and comprehensive LCC tools may provide an opportunity to greatly improve the current bridge LCC state-of-practice.

2 The Swedish BMS

2.1 BaTMan

Sweden has a long tradition in bridge management. Since 1944, information about the condition of the national road network has been documented and stored in different archives. The Swedish Transport Administration (Trafikverket) is the largest bridge manager in Sweden. Over the years, Trafikverket has developed an information technology based bridge and tunnel management system that is widely used by Trafikverket and other owners of transport infrastructure. The latest update of Trafikverket's BMS is called a Bridge and Tunnel Management system (BaTMan), which was introduced in 2004. BaTMan is a computerized Internet based system, which means that users can always have access to updated information about the actual bridges online (https://batman.vv.se/). Furthermore, the system consists of a separate navigation tool (WebHybris) that can access the BaTMan's database and answer any related question for any research or management purposes. BaTMan is recognized as the best-known software-based digital BMS in Europe *[15]*.

The system is a tool for operational, tactical and strategic management where the complete system encompasses systems and tools for collecting, storing, processing, analyzing and presenting administrative, technical and inspection data *[4]*. The system includes codes and manuals to provide guidance for carrying out bridge management activities as properly and as uniformly as possible. The inspection manual gives information on bridge types and their structural members and types of damage and their causes *[20]*. Along with the inspection manual there is a measurement and condition assessment manual, which includes methods and codes for measuring and assessing the physical and functional condition of bridges *[23]*. All information is given on repair, strengthening, and maintenance, including their costs.

2.2 BaTMan's Conditions Class System

The main purpose of the bridge inspections is to establish the physical and functional conditions of a bridge individual structural members and consequently the entire bridge. The physical condition is determined with reference to the development of previous or new damage and certain known deteriorating processes. The functional condition is described by the bridge inspector in terms of condition class (CC). The CC describes to what extent a certain structural member satisfies the designed functional properties and requirements at the time of inspection *[16]*. In BaTMan, the bridge inspectors are responsible for assessing the residual service life of the bridge structural members as well as the entire bridge. Along with the inspectors' own experience, well-developed tools and devices based on well-established methods and techniques are used to assess the CC for the bridge individual structural members. In contrast to many BMSs, BaTMan does not contain deterioration models. However, some devices used for inspection consist of integrated deterioration models that can assist the bridge inspectors in anticipating the future performance of the inspected structural members. It can be said that the assessment of the condition classes is composed on previous and current measured values (the physical condition) and the inspector's competence in the propagation of different deterioration processes. The CC for a structural member can be registered on a scale of four. Table 2-1 presents and describes the BaTMan's CC system.

Table 2-1 Condition classes (CC) system used in BaTMan

CC	Assessment	Description
3	Defective function	Immediate action is needed
2	Defective function within 3 years	Action has to be taken within 3 years period
1	Defective function within 10 years	Action has to be taken within 10 years period
0	Defective function beyond 10 years (No damage at time of inspection)	No action is needed within the coming 10 years

Using this CC system, the functional conditions of the structural members will automatically be translated to numerical numbers that can easily be used in the LCC analysis. This CC system is a good feature in BaTMan in comparison with the condition rating system used in Pontis (a full-featured BMS used in more than 40 state departments of transportations in USA), *[*12*]*.

Another term used within the Trafikverket is the overall condition class (OCC). The OCC reflects the function of the entire structure with respect to the bearing capacity, traffic safety and durability. The OCC for a bridge is determined by the assigned CC for the different structural members. The assigned condition classes are given different weights *[*16*]*. The different bridges structural members as well as their structural elements are clearly defined in several Trafikverket's publications, *[24]*.

2.3 The Swedish Bridge Stock

BaTMan is the main tool used in Sweden for the effective management of the public and the private Infrastructure. Bridges, tunnels, harbours and other infrastructure are all managed by BaTMan.

2.3.1 BaTMan's and Trafikverket's bridges

Trafikverket is the largest bridge manager in Sweden and the main user of BaTMan. National municipalities and private companies are also users of BaTMan. Table 2-2 presents the details of the bridge stock in BaTMan and the bridges owned by Trafikverket. Note that the data presented in this table are extracted from BaTMan on January 2012. Some of the bridges in this table are perhaps under construction or not yet inaugurated.

Table 2-2 BaTMan's and Trafikverket's Bridge Stock

	Bridge Function Type				Total No. Of Bridges	Bridge Total Area (m^2)	Bridge Total Length (m)
	Roadway	Railway	Pedestrian & Bicycle	Other			
BaTMan's Bridges	23,848	4,411	1,619	251	**30,129**	7,644,208	668,381
Trafikverket's Bridges in BaTMan	20,050	3,179	207	14	**23,450**	5,858,570	528,905

Trafikverket's bridge stock, published in Trafikverket's official reports at the end of 2011, is presented in Table 2-3.

Table 2-3 Trafikverket's Bridges Stock (Built Bridges) 2011 Official Report

Bridge Owner	Total No. Of Bridges	Bridge Total Area (m^2)	Bridge Total Length (m)
Trafikverket-Road	15,884	4,412,547	386,491
Trafikverket-Rail	4,110	878,256	95,861
Trafikverket-Private Road Joint Property	3,954	225,787	42,388
Total	**23,948**	**5,516,590**	**524,740**

2.3.2 Classification of Trafikverket's bridges

Trafikverket's bridges stock presented in Table 2-3 consists of several bridge types with different length categories. The different bridge types according to the Swedish system are clearly defined in the Trafikverket's publications, *[24]*. Figure 2-1 schematically presents Trafikverket's bridges stock classification, construction material and the number of each bridge type.

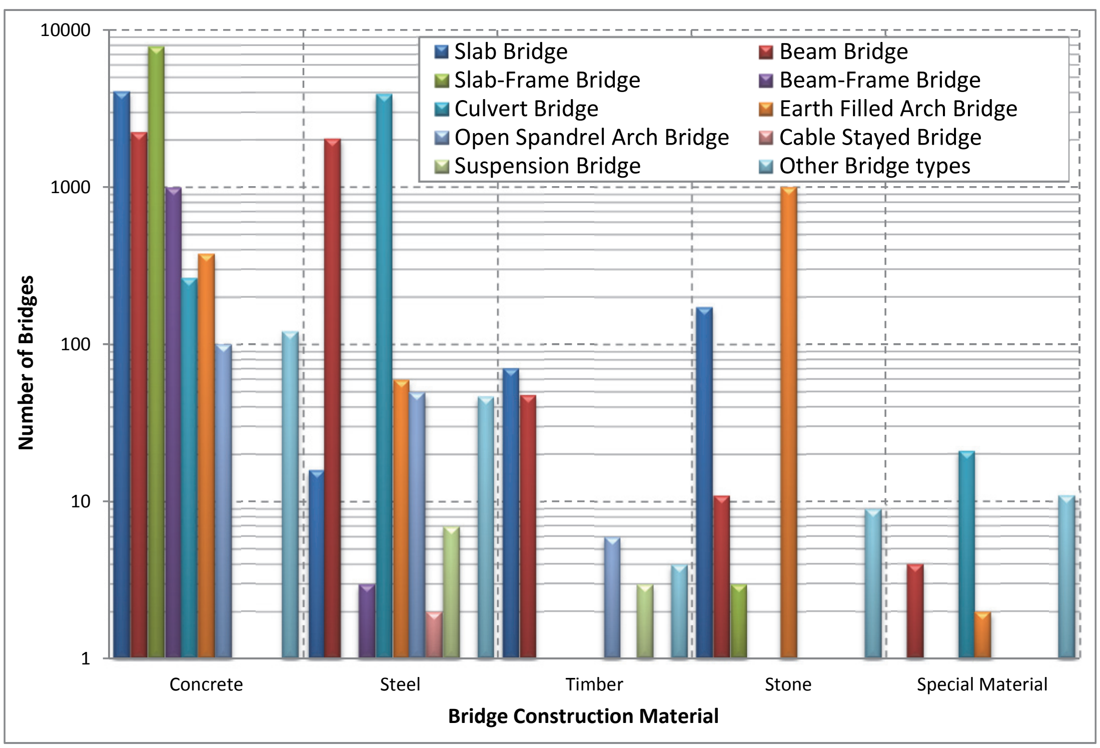

Figure 2-1 Classification of Trafikverket's bridge stock considering the bridge type and construction material

The classification of this bridge stock considering the bridge total length is presented in Figure 2-2. Figure 2-3 presents the annually built number of bridges by Trafikverket.

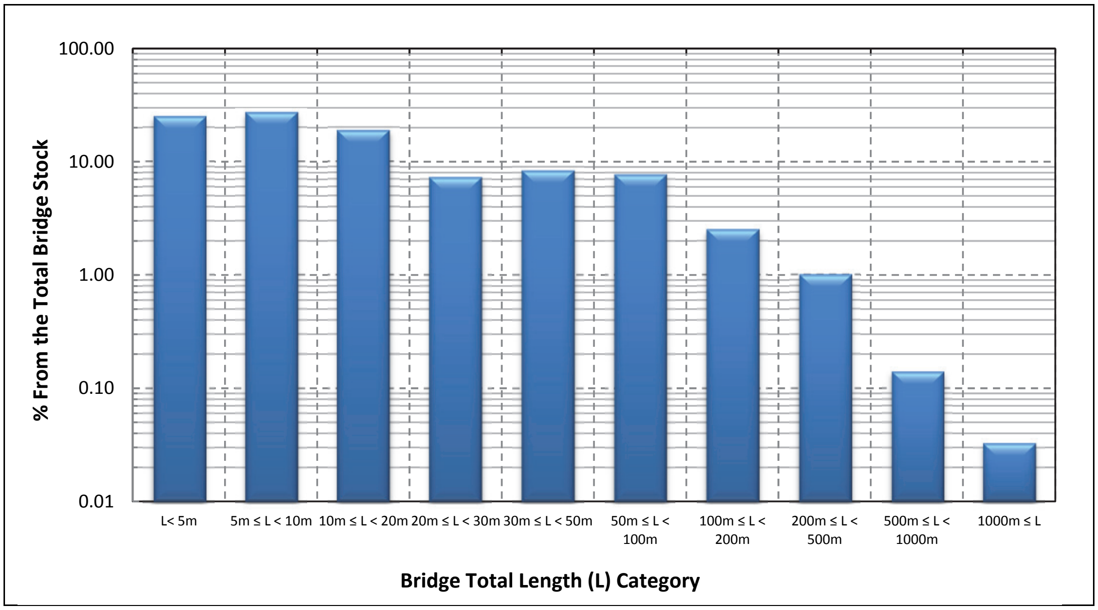

Figure 2-2 Classification of Trafikverket's bridges stock considering the bridge total length

2.3.3 Trafikverket's annually built bridges

The annually built m^2 bridge area is considered to be the characteristic property when anticipating the future bridge stock. Figure 2-4 presents Trafikverket's historical annually built bridge m^2 area.

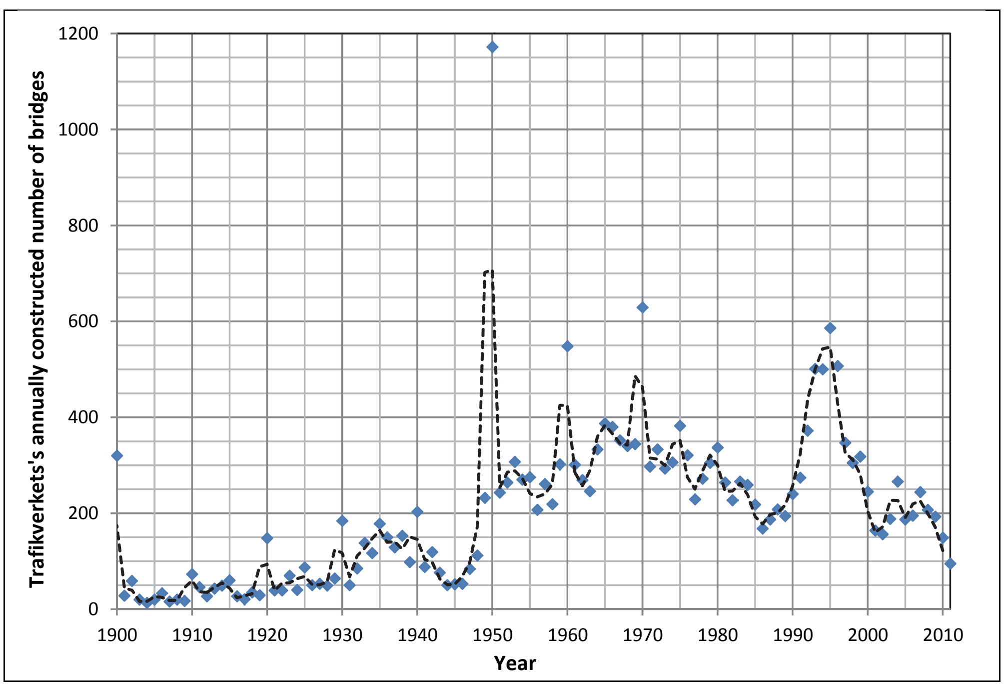

Figure 2-3 Trafikverket's annually built number of bridges

Figure 2-4 Trafikverket's annually built m^2 bridge area

A large scatter can clearly be seen in Figure 2-3 and Figure 2-4, which makes it difficult to predict the future annually built number of bridges and m^2 bridge area. An attempt was made to relate the annually built m^2 bridge area to the annual population density in Sweden. The results of this attempt yielded even larger scatter. Perhaps this scatter is related to some other factors like the available annual budget for Trafikverket or some other the financial concerns. However, it can roughly be said that Trafikverket is expected in the coming ten years to annually build an average of 200 bridges or an average of 55000 m^2 bridge total area. This parameter is necessary to highlight the LCC large-scale saving potential as it will be seen in the case studies.

2.3.4 Bridges types used for different span lengths

A survey investigation was made to explore the bridge types used for the different span lengths in Sweden. Note that, a bridge might consist of various numbers of spans with different lengths and each span might be a different bridge type. Figure 2-5 presents the number of the different bridge types used for the different span lengths in Sweden. This figure is based on 56,291 spans for 34,591 bridges. Bridges for all functions were included in this figure including pedestrian bridges.

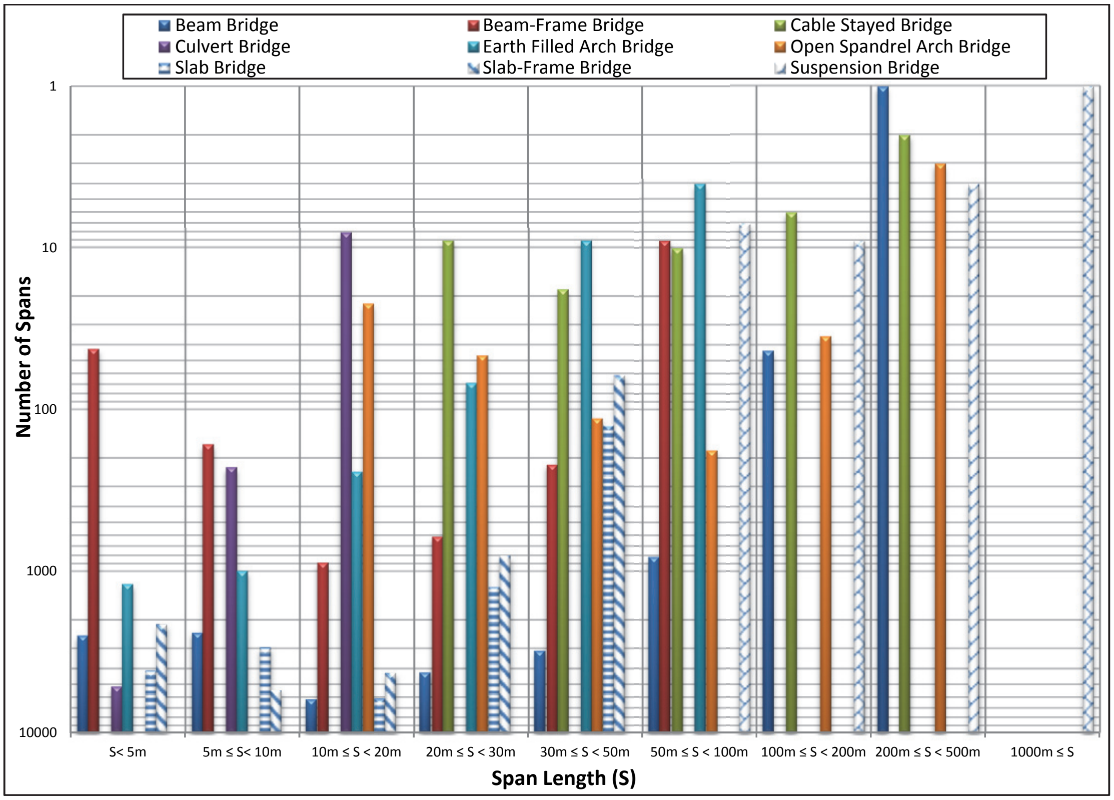

Figure 2-5 Bridge types used for different spans in Sweden

3 Bridge Life-Cycle and the Possible LCC Applications

LCC is appropriately applied to compare project implementation alternatives that would yield the same level of service and benefits to the project user. The agency that uses this tool has already decided to undertake a project or improvement and is seeking to determine the most cost-effective means to accomplish the project's objectives. To effectively implement LCC for bridges, it is important to be aware of the different bridge investment phases and their internal activities. It is also important to be familiar with the various types of bridge contracts.

3.1 LCC Applications

Figure 3-1, described in more details below, shows the typical Swedish bridge investment phases, the possible LCC applications and saving potential.

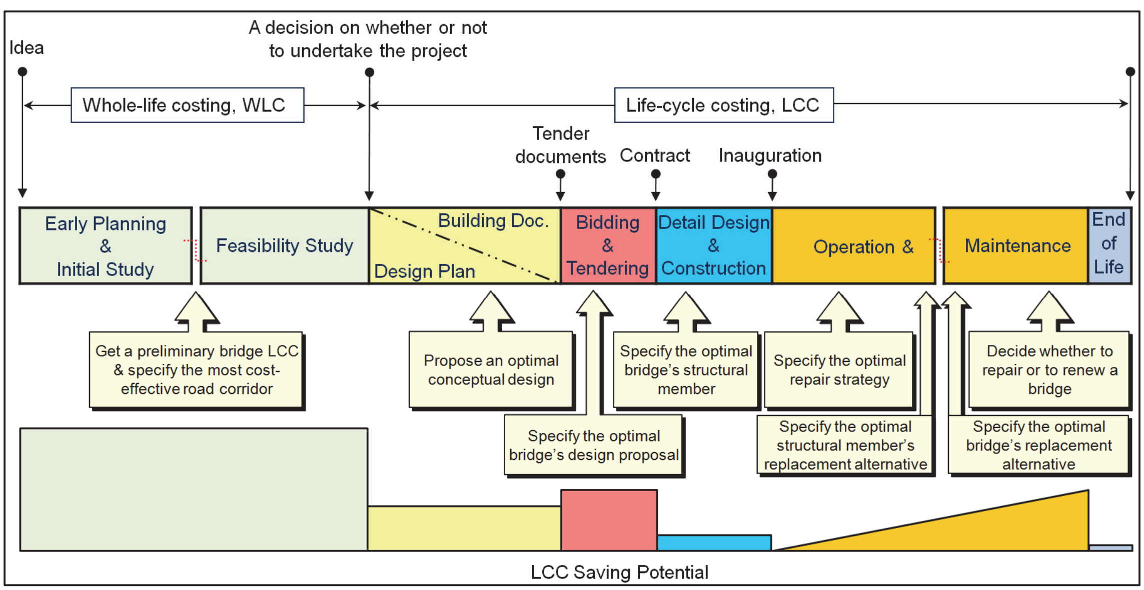

Figure 3-1 Bridge investment phases in Sweden, the possible LCC applications and saving potential

3.1.1 Early planning

The bridge investment is generated from an early planning that has been originated from an idea, followed by an initial study. A feasibility study will be carried out later on to analyse the benefits and the costs of the project. In this particular phase, decision-makers are considering whether or not to undertake the project. Whole-life costing (WLC) is a methodology for systematic economic consideration of all whole-life cost and benefits over a specified period of analysis as defined in the agreed scope *[10]*. Therefore, WLC is the appropriate tool that can be used in this stage. In Sweden, usually, bridges are built at the same time of building an entire corridor which may consist of many bridges. In such cases, the feasibility study will be conducted to compare the life-cycle costs with the life-cycle benefits of the entire corridor, not only the corridor's bridges. Several alternative corridors might be proposed, and each of them may consist of various numbers of bridges with different bridge lengths and heights. Rough data will be available for the bridges in each corridor; numbers, width, preliminary length and height. Preliminary bridge LCC analysis that can be based on similar historical bridge's data is of great importance in this phase to specify the most cost-effective corridor. From a network-level perspective, LCC has the largest saving potential in this phase.

3.1.2 Tendering and construction

If the decision to carry out the project is taken, many legal permissions have to be issued. Many parties with different interests and demands will be involved to assign the corridor final alignment. In doing so, more accurate data for the bridges in the chosen corridor will be available. For each bridge site, different bridge types might technically be feasible. However, each bridge type may have different initial costs, expected service life and life-cycle costs. LCC can effectively be implemented here to propose an optimal conceptual design.

Depending on the nature of the contract, the intensity and details of the tender documents may differ. When using a "design and build contract" as well as a "performance requirements contract," the tender documents will consist of brief outlines for the bridge together with intensive functional and performance requirements. The tender documents of these forms are usually prepared by the bridge owner or the owner's consultants in the design plan phase. In a "construction contract," the tender documents usually consist of more detailed drawings, and quantities. The tender documents of this contract-form are usually delivered to the interesting contractor after the building document phase. Using the first two contract forms, the horizon is broader for the contractor to propose an alternate design. Generally, a conceptual design for the bridge will be prepared and attached with the tender documents. However, the possibility of accepting an alternate design varies from one contract-form to another. The first two contract forms encourage the contractors not only to submit the least first cost, but also to integrate their staff knowledge and experience in proposing the optimal bridge design alternative. LCC can be used in these two investment phases to propose an optimal conceptual design.

During the tendering phase, which may be the shortest investment phase, the agency seeks to specify the most cost-effective design among all the proposed alternatives. The alternatives may differ in their static systems, types, structural members and construction materials. However, all of them provide the required function. Currently, the concept of the lowest bid is normally used when deciding a contractor. However, the lowest bid conventionally reflects the lowest first cost, not the lowest cost of ownership. The greatest saving potential for the project occurs in this particular phase. In case of alternative design, the contractors are required to attach general drawings for their proposal along with their cost estimate. Therefore, LCC can properly be implemented taking into account the available bridge's drawings.

Following the selection of the bridge proposal, the agency will sign the contract with the contractor and request that he begins the preparation of the detailed design. Once a rough detailed design is prepared, the construction phase will start. During the detail design and construction phase, LCC can be implemented by the agency and the contractor to choose the most cost-effective bridge structural members or structural elements for the chosen proposal.

3.1.3 Operation and end of life

After the bridge inauguration, the operation phase commences. It might be the longest investment phase and will end when the agency demolishes the bridge. LCC has many useful applications during this phase. It can be implemented to choose the most cost-effective repair strategy for repairing an individual bridge structural member. It can also be implemented to choose whether to repair or to replace a specific bridge structural member. When the bridge grows old and heavily deteriorates, LCC can be implemented to decide whether to repair or to renew the bridge. When deciding to replace the bridge, several replacement options might be available. LCC can be used here to optimize between the available replacement options. Several demolition strategies with different impacts on the traffic might be available for a bridge replacement. LCC can be used here to specify the most cost-effective bridge demolition strategy.

3.2 Bridge Life-Cycle Cost Categories

A new bridge is normally designed for a service life of 80-120 years. After inauguration, the bridge needs many remedial actions to keep it available for public. The bridge initial cost and the required remedial actions cost are all direct costs usually paid by the bridge owner. Other indirect costs will be incurred by the bridge user and society. The different bridge types that might technically be feasible for a specific bridge location will not only have different direct cost but usually will have different direct and indirect costs. To assist in providing more sustainable bridges, these indirect costs should be included in any reliable BLCCA. The bridge life-cycle cost can be classified as shown in Figure 3-2.

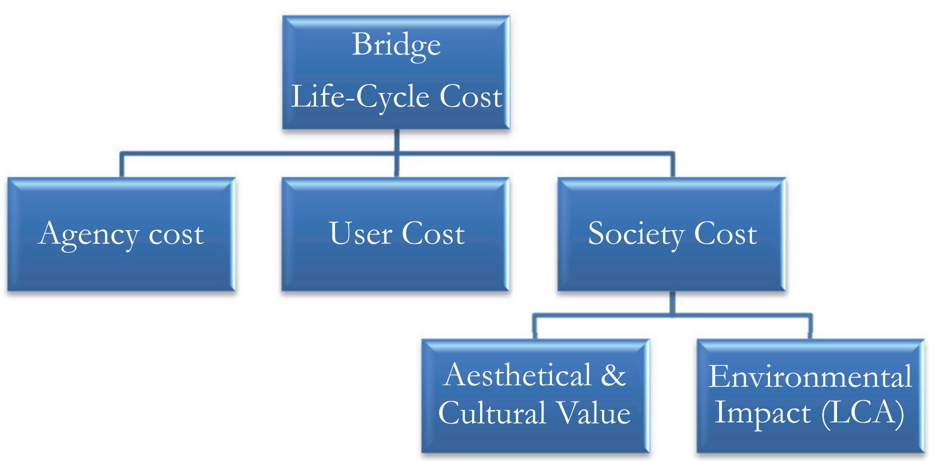

Figure 3-2 Bridge Life-Cycle Cost Categories

Many BLCCA systems are available. Although the basic calculations seem to be similar, the cost items included in the cost breakdown schemes are varying to different degrees. Up till now there has been no consensus on what cost items should be included in the BLCCA and their breakdown scheme. There are three reasons for establishing a life-cycle cost classification scheme or taxonomy when analyzing bridges life cycle-costs. First, the classification insures that all costs associated with the project are taken into account. Second, the classification scheme allows for a detailed, consistent breakdown of the life-cycle cost and net savings estimates at several levels so that a clear picture can be presented for the respective cost differences between material/design alternatives. The third benefit is that, actual costs classified by the structural elements and categories can be used to compile historical unit cost data to be used in future BLCCA.

3.2.1 Agency costs

The agency cost is all direct costs incurred by the bridge owner over the bridge entire life span. Figure 3-3 presents the different agency cost categories and their occurrence events during the bridge life. The agency cost categories sorted in ascending order regarding their occurrence events are as follow:

1) Investment Cost (INV)
    a. Non Elemental Cost (NEL)
    b. Elemental Cost (Purchasing, Construction, & Installation) (EL)
2) Life Cycle Remedial Actions Cost (LCRA)
    a. Inspection Cost (INS)
    b. Operation & Maintenance Cost (O&M)
    c. Repair/Rehabilitation & Replacement Cost (RRR)
    d. Strengthening Cost (STR)
3) End of life Management Cost (Recycling, Demolition and Landscaping)(R,D&L)

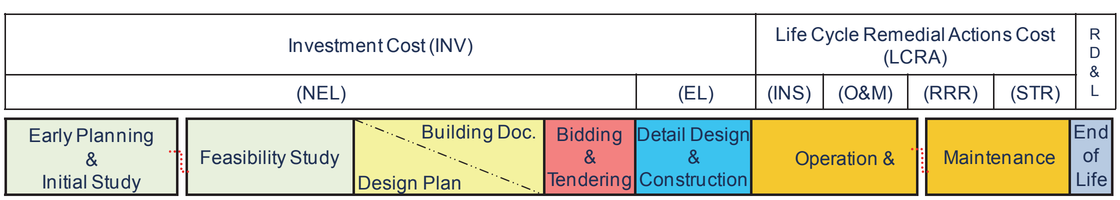

Figure 3-3 Agency costs categories and their occurrence events

The Investment cost of a bridge is the cost offered by the contractor in his cost estimate during the tendering phase. Historical cost data for similar bridges under similar circumstances can reveal the investment costs of a new bridge.

True enough, it is not possible to draw distinct lines between the bridge life-cycle remedial actions (LCRA). The difference between the LCRA types lies essentially in the purpose of the actions whereas the method and the technique in many instances may be similar. When repairing a concrete structure, for instance, it is often a matter of replacing damaged concrete and reinforcement with a corresponding amount of fresh concrete and reinforcement. The same technique can be used for strengthening; with the difference that new concrete and reinforcement are provided over and above what was there from the beginning.

3.2.2 Bridge user cost

Bridges are public-use property and any roadwork to repair or maintain a bridge might paralyze the entire transport network. Bridge user costs can mainly be classified into two types; long-term user cost and work zone user cost (WZUC). The long-term user cost is due to permanent characteristics of the bridge. The WZUC are costs incurred by the users of the bridge as a result of deteriorating conditions of the bridge, such as a narrow width or low load capacity, which result from maintenance, repair and rehabilitation activities, leading to an increase in the vehicle trip time *[6]*. Figure 3-4 presents the possible bridge WZUC occurrence events during a bridge life-cycle. By including the WZUC in the LCC analysis, the importance of avoiding traffic disruptions will be considered.

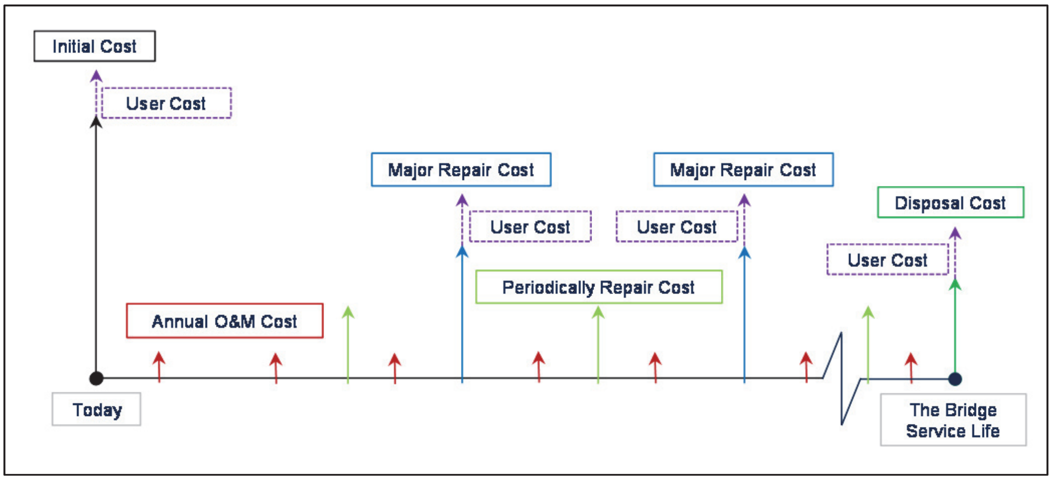

Figure 3-4 WZUC occurrence events during a bridge life-cycle

3.2.3 Bridge aesthetical and cultural value

Bridges are often seen more or less as monuments and icons which the citizens may relate with the soul of the city. This atmosphere and the will to identify the town and its values with an icon may motivate for bold and spectacular solutions. Some alternatives have exceeded all cost estimates but they have been chosen as aesthetically the best. Certainly, there is a hidden value behind the external shape of the bridges in some special bridge locations. The inclusion of this value in the evaluation process leads to eliminating the worst aspects of bridge design and encourages the best. This value should be computed for the different feasible proposals in fair-bases and converted to a measurable value to be able to include it in the BLCCA.

3.2.4 Bridge environmental impact

One issue, brought up in the construction of a new bridge nowadays, is the impact this structure will have on the immediate environment. Beside traditional requirements for the bridge, a trend toward extended attention to the environmental impacts due to different designs, and different maintenance, repair and rehabilitation strategies, is growing stronger. Requirements for long term considerations regarding renewable and non-renewable resources for infrastructure construction are missing or unclear. For specific bridge location, different bridge types can be used, however, each of them produces different environmental impact.

Life-cycle assessment, LCA, is a technique for assessing the potential environmental aspects associated with a product, a product system or an activity. In LCA, the energy and materials used, and the wastes released to the environment, are identified and quantitatively described. Then, the impacts of those energy and material uses and releases to the environment are assessed. The assessment includes the entire life-cycle of the product or activity, encompassing extracting and processing raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, final disposal, and all transportation involved. The environmental impact should be computed for the different feasible proposals in a fairly bases and converted to a measurable value to be able to include it in the BLCCA.

4 LCC Analysis Tools and Techniques

The time value of money is germane to LCC because the costs included in the analysis are incurred at varying points in time. For LCC, costs occasioned at different times must be converted to their value at a common point in time *[27]*.

4.1 Net Present Value Method

The commonest method used to compare past, present and future cash flows with those of today is termed the Net Present Value method (NPV). Costs occur at different times, therefore it is necessary to use a discount rate in the calculations to reflect the "time value of money". This can be expressed as the NPV equation *[19]*:

$$NPV = \sum_{n=0}^{L} \frac{C_n}{\left(1+r\right)^n} \tag{4.1}$$

Where:

NPV is the life-cycle cost expressed as a present value,
n is the year considered,
C_n is the sum of all cash flows in year n,
r is the discount rate, and
L is the service life-span.

The net present value for a future cash flow C_o, expected to fall due every year during the service life-span L , e.g. annual operation cost, can be calculated by *[27]*:

$$NPV = C_o \times \frac{1-(1+r)^{-L}}{r} \tag{4.2}$$

Future cash flow C_P expected to fall due periodically every p years during the L years, e.g. periodically repair cost, can be discounted to present value by *[27]*:

$$NPV = C_p \cdot \frac{1-(1+r)^{-mp}}{(1+r)^p - 1} \tag{4.3}$$

Here m is the number of times the cash flow is expected to fall during the L years; $mp \leq L$. If the cash flow relates to some kind of maintenance, repair or rehabilitation cost, the cash flow at year L is not relevant and should therefore not be accounted for. The number of times the cash flow is expected to fall due, m, may then be calculated by *[27]*:

$$m = TRUNC\left(\frac{L-1}{p}\right) \tag{4.4}$$

4.2 Equivalent Annual Cost Technique

When comparing investment projects of unequal life-spans, it would be improper to simply compare the NPVs of the two projects unless neither project could be repeated to let all projects have the same analysis period. Equivalent Annual Cost (EAC) is often used as a decision support-tool in capital budgeting when comparing investment projects of unequal life-spans. In finance the EAC is the cost per year of owning and operating an asset over its entire life-span. The alternative associated with the lowest annuity cost is the most cost-effective choice. The EAC is calculated by multiplying the NPV by the annuity factor *[27]*:

$$EAC = NPV \times A_{t,r} = NPV \times \frac{r}{1-(1+r)^{-L}} \tag{4.5}$$

Where:

EAC	is the equivalent annuity cost,
$A_{t,r}$	is the annuity factor,

4.3 Net Saving and Opportunity Loss

The Net Saving (NS) and the Opportunity Loss (OL) are two techniques to present the feasibility of implementing the promoted alternative in the LCC optimization. The NS is the amount of money that can be saved by implementing the most cost-effective alternative compared with implementing the other alternative, while the OL is the amount of money that can be lost by implementing the least cost-effective alternative compared with implementing most cost-effective one.

When comparing two alternatives with the same service life, the NPV can be used to specify the best. In this case, the NS as well as the OL are the same and can be calculated by subtracting the NPV of the both alternatives from each other.

When comparing two alternatives that have unequal service lives, the EAC can be used to specify the most cost-effective one. Here, the NS can be presented in two ways. Firstly, as an annual saving which can be calculated by subtracting the EAC of both alternatives from each other. Secondly, as a total saving amount during the implemented alternative anticipated life-span. This can be calculated by converting the annual NS to a present value. Equation 4.6 and 4.7 respectively present the present value of the NS and the OL in case of comparing two alternatives A and B, where alternative B is the most cost-effective choice.

$$NS = \left(EAC_A - EAC_B\right) \times \frac{1-(1+r)^{-L_B}}{r} \tag{4.6}$$

$$OL = \left(EAC_A - EAC_B\right) \times \frac{1-(1+r)^{-L_A}}{r} \qquad \textbf{(4.7)}$$

4.4 Bridge User Cost

The user costs during a work zone closure are usually evaluated with respect to the traffic delay costs C_{TDC}, the additional vehicle operating costs C_{VOC} and the related accident costs C_{ACC}. The following equation is used to determine bridge user cost during a work zone:

$$C_{\mathrm{User}} = C_{\mathrm{TDC}} + C_{\mathrm{VOC}} + C_{\mathrm{ACC}} \qquad \textbf{(4.8)}$$

The costs should be calculated in a present value and added up for all foreseen remedial actions works within the period studied.

4.4.1 Traffic delay cost

Traffic delay cost (C_{TDC}) results from an increase in travel time through the work zone due to speed reductions, congestion delays or increased distances as a result of a detour. The C_{TDC} during a work zone can be calculated by the following equation, *[19]*:

$$C_{\mathrm{TDC}} = \sum_{t=0}^{L} T \times ADT_t \times N_t \times (r_T w_T + (1-r_T) w_P) \frac{1}{(1+r)^t} \qquad \textbf{(4.9)}$$

Where:

T is the travel time delay for one vehicle in the case of a work zone (*hours*),
ADT_t is the average daily traffic at time t (*vehicles/day*),
N_t is the number of days needed to perform the work at time t (*day*),
r_T is the percentage of trucks from all ADT,
w_T is the hourly time value for one truck,
w_p is the hourly time value for one passenger car, and
L is the alternative expected life span.

4.4.2 Vehicle operation cost

Vehicle operation cost (C_{VOC}) is an additional cost incurred by the bridge user, expressed as extra costs to operate the vehicle additional time due to the traffic disturbances because of the work zone or detour. The C_{VOC} includes fuel, engine oil, lubrication, maintenance and depreciation. The C_{VOC} during work zone can be calculated by the following equation, *[19]*:

$$C_{\mathrm{VOC}} = \sum_{t=0}^{L} T \times ADT_t \times N_t \times (r_T O_T + (1-r_T) O_P) \frac{1}{(1+r)^t} \qquad \textbf{(4.10)}$$

Where:

O_T is the average hourly operating cost for one truck including its goods operation,
O_P is the average hourly operating cost for one passenger car.

4.4.3 Accident cost

Accident cost (C_{ACC}) represents the costs due to an increase in the risk of accidents, health-care and deaths resulting from the traffic disturbances due to the work zone on the bridge. Although bridge-related accidents represent only about 1.7 % of all traffic accidents, the degree of severity is estimated to be from 2 to 50 times the severity of general roadway traffic accidents *[2]*. In a study by the North Carolina Department of Transportation, the average number of people killed in bridge-related accidents was determined to be 0.019 persons/accident, while this number is reduced to 0.009 persons/accident in other traffic accidents *[2]*. Consequently, the C_{ACC} during the work zone can be calculated by the equation proposed in *[19]* with slight improvement:

$$C_{\text{ACC}} = \sum_{t=0}^{L} ADT_t \times N_t \times (A_n - A_a) \times \left[(C_F \times P_F) + (C_I \times P_I) \right] \frac{1}{(1+r)^t} \qquad \textbf{(4.11)}$$

Where:

- A_n is the bridge accident rate during normal conditions (*accident/vehicle/day*),
- A_a is the bridge accident rate during the work activities (*accident/vehicle/day*),
- C_F is the average cost per fatality for the society,
- C_I is the average cost per serious injury accident for the society,
- P_F is the average number of persons killed in bridge-related accidents, and
- P_I is the average number of persons injured (not killed) in bridge-related accidents.

4.4.4 Traffic growth rate

Due to factors such as population growth and economic prosperity, the volume of traffic on bridges may increase each year. The current or future *ADT*, based on the desired construction year, should be obtained from the traffic monitoring section. If the future *ADT* is not readily available the following formula can be used *[3] and [22]*:

$$ADT_t = ADT \times (1 + r_{TG})^{Year_t - Year_0} \qquad \textbf{(4.12)}$$

Where:

- ADT_t is the *ADT* to be used in the analysis at year *t* (*vehicles/day*),
- ADT is the measured average daily traffic (*vehicles/day*),
- r_{TG} is the expected traffic growth rate,
- $Year_t$ is the year in which the *ADT* has to be calculated, and
- $Year_0$ is the year in which the *ADT* is measured.

4.4.5 Challenges in bridge user cost evaluation

The main challenge in the WZUC evaluation is in the estimation of the travel delay time to cross the bridge during a work zone condition. One approach to calculate this time delay is to subtract the time needed to cross the bridge during the normal condition using the normal speed from the time needed to cross the bridge during work zone condition using the work zone reduced speed. However, this approach does not consider the traffic flow conditions. Therefore, it is only suitable when the traffic volume is below the work zone capacity. When the traffic volume exceeds the work zone capacity, the traffic flow breaks down and a queue of vehicles develops. Once a queue develops, all approaching vehicles must stop at the approach to the work zone and creep through the length of the physical queue under forced flow conditions at significantly reduced speeds. The time delay estimation considering the different traffic flow conditions was properly presented by *[22]*. The structural engineering and bridges division at the Royal Institute of Technology, developed a bridge WZUC model adopted for the Swedish bridges similar to the model demonstrated by *[22]*. This model was integrated within a stand-alone bridge LCC program named "BaTMan-LCC". Using this program, the bridge user cost will be estimated for both case studies in this thesis.

5 Case Studies

5.1 Case-Study (1): Repair or Replace a bridge?

5.1.1 Bridge outlines

On some occasions, the choice has to be made between two or more strategies to upkeep a specific bridge. Lillån Bridge in Sweden was constructed in 1934. The bridge is a simply supported concrete beam,Figure 5-1. The total bridge length is 9.3 m with a total width of 5.5 m. The average daily traffic is 619 and design speed limit is 80 km/h. The average number of trucks that cross the bridge on a daily bases is 43. The traffic growth rate in the bridge region is expected to be 1 %. According to BaTMan, this bridge has a number [6-367-1], which refers to [County number-Section/Junction number in the rout-Bridge number in the Section/Junction].

Figure 5-1 [6-367-1] Bridge’s layout

The bridge superstructure and substructure are deemed to be in such a condition that their residual service life is not more than three years, if no action is taken (BaTMan's CC 2). Few strategies were proposed to upkeep this bridge. The choice stands between immediately repairing the bridge or utilizing its residual service life without action then replacing the entire bridge, respectively shown in Figure 5-4 and Figure 5-5.

Using an updated on-line well-defined price list for all bridge repair actions in BaTMan, it is estimated that the repair strategy will cost 895,000 SEK; mending the substructure, new bridge deck, surfacing, waterproofing and railings. Considering a statistical treatment of an intensive historical data extracted from BaTMan related to similar actions performed on similar bridges, the bridge after implementing this repair strategy is expected to last for 20 years at most with normal maintenance.

5.1.2 Benefits of using BaTMan's inventory data

Currently, although the BaTMan inventory data is accessible by Webhybris, the decision-makers do not effectively benefit from it. However, in this case study, cost records for 2,508 bridges constructed between 1980 and 2011 were extracted from BaTMan using WebHybris and sorted according to the bridge types and length categories. Figure 5-2 presents the bridge types applicable for each length category as well as the average costs/m^2 for each type. The average inflation rate was calculated, Figure 5-3, and included in the costs/m^2 presented in Figure 5-2.

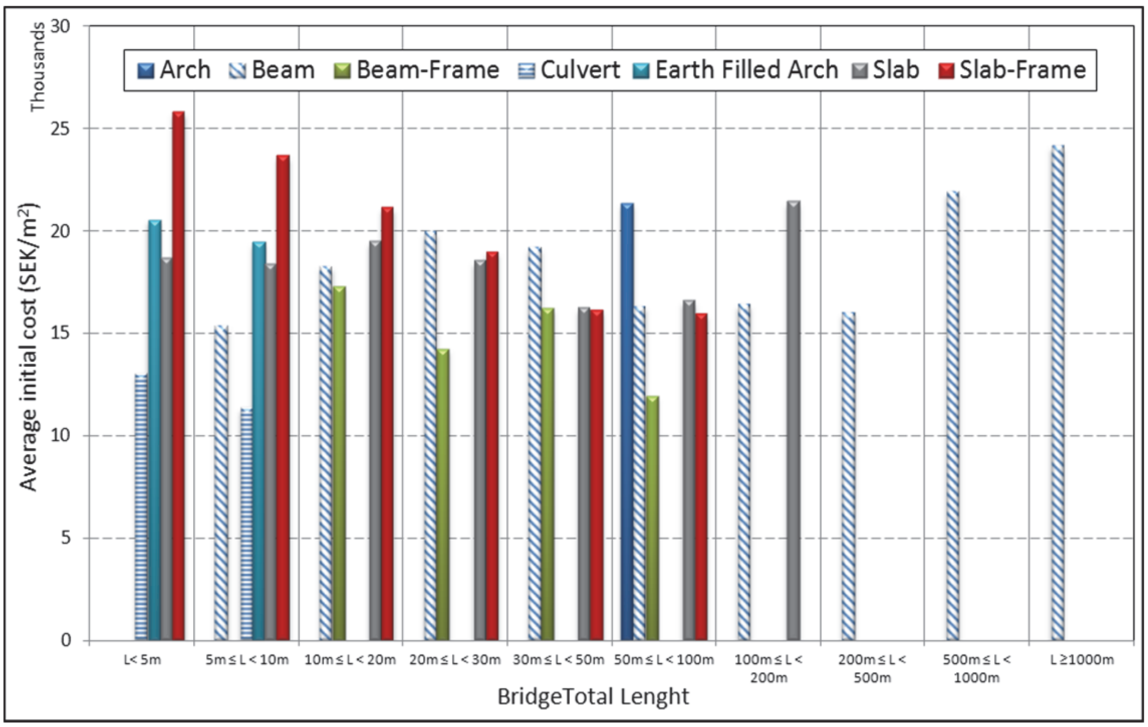

Figure 5-2 The average real initial costs of the Swedish bridges' different types with respect to the total bridge length

Considering Figure 5-2 and deeper classification of the extracted data, three replacement options were proposed and presented in Table 5-6. It is important to note that, in Figure 5-2, the lowest cost/m^2 does not necessarily mean the cheapest bridge type because the required bridge total area, for a certain bridge location, differs from one bridge type to another.

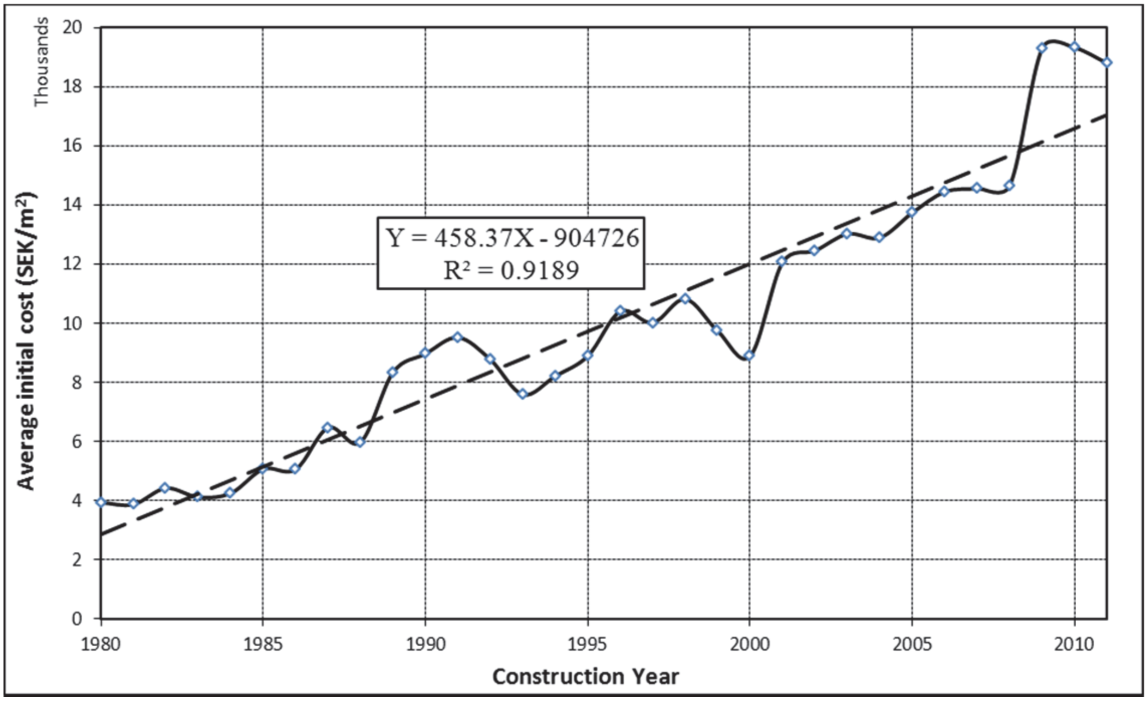

Figure 5-3 The inflation rate for the Swedish bridge's initial costs

Table 5-1 Description of the bridge replacement proposals

Proposal NO.	**Proposal description**	**Bridge Width(m)**	**Bridge Length (m)**	**Anticipated initial cost (SEK/m2) at year 2015**	**Anticipated service life (Year)**	**Required annual O&M (SEK)**	**Required construction duration (Day)**
1	Steel-Timber Composite Beam	7	16,5	12,578	80	8,500	100
2	Concrete Beam	7	16,5	23,510	100	5,000	100
3	Steel Open-Bottom Arch Culvert	8	9,5	19,400	60	2,500	80

The analysis was conducted in two steps. The first step is to optimize between the available replacement options. The second step is to optimize between the promoted replacement proposal and the repair strategy.

5.1.3 Replacement options optimization

Considering the proposals' data given in Table 5-1, the BLCCA was conducted. Only the bridge initial cost and annual operation and maintenance (O&M) cost were included in analysis. The inflation rate presented in Figure 5-3 is used to anticipate the initial cost of the proposals at year 2015. The real service life of the different types of the Swedish bridges was presented in *[13]*. The required O&M cost of the different proposals was assessed by some of Trafikverket's specialists. The O&M costs for the first proposal are including the needed periodic repainting of the steel superstructure and the annual tightening of the timber deck. Because the proposals have unequal anticipated service life, the EAC is used as the criteria for the project selection. The discount rate used in 4 %. The analysis, excluding the use cost, shows that the arch culvert is associated with the least EAC of 67,671 SEK/year. The analysis including the user cost has furthermore promoted the culvert alternative. Therefore, the culvert bridge is chosen as the most cost-effective replacement option.

5.1.4 Replacement or repair optimization

In this step, an optimization process will be conducted to compare the repair strategy (A) with the steel arch culvert as the replacement strategy (B). Table 5-2 presents the strategies' specifications. Figure 5-4 and Figure 5-5 present the cash flow of strategy (A) and (B) respectively.

Table 5-2 Bridge repair and replacement strategy's data

Strategies Input Data	Strategy (A)	Strategy (B)	
Strategies description	Immediate repair	Utilizing the bridge residual service life without action and then replace it by a steel open-bottom arch culvert	
Bridge's Residual service life without action, (Years)	3		
Discount rate (%)	4		
Anticipated service life after an action (Year)	20	60	
Strategy initial cost (SEK)	895,000	1,474,400	
Annual O&M cost (SEK)	7,000	During the current bridge residual service life	After the bridge replacement
		8,500	2,500
The required construction duration (Days)	60	80	

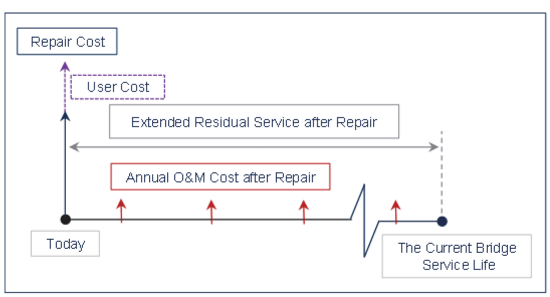

Figure 5-4 Strategy (A): Immediately repair the bridge

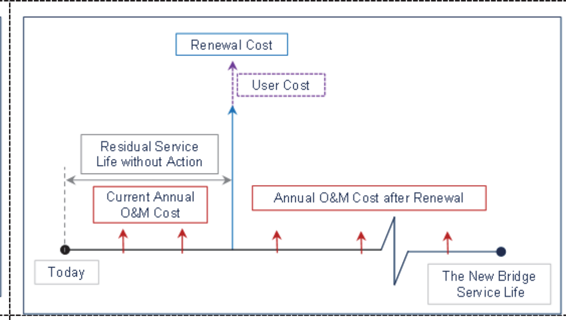

Figure 5-5 Strategy (B): Utilizing the bridge's residual service life without action and then renew it

5.1.5 Analysis excluding the bridge user cost

The LCC analysis was conducted based on the given strategies' specifications on Table 5-2. As shown in Table 5-3, The NPV of strategy (A) is less than (B). However, this does not mean that strategy (A) is the most cost-effective, simply because the strategies have unequal life-span. Therefore, the EAC was calculated for each strategy, shown In Table 5-3.The EAC of strategy (B) is less than (A). Consequently, strategy (B) is the most cost-effective strategy.

Using equation 4 and 5, the NS and the OL were calculated. The NS is equal to 282,864 SEK/63 years or 12,359 SEK/year for a life span equals to 63 years. The OL is equal to 167,963 SEK/20 years or 12,359 SEK/year for a life span equals to 20 years.

Table 5-3 LCC analysis results excluding the bridge user cost

Cost Category &Term	Strategy (A)	Strategy (B)
Net Present Value (SEK)	990,132	1,384,605
Equivalent Annual Cost (SEK/year)	72,856	60,497

By performing sensitivity analysis to study the impact of varying the discount rate (*r*) from zero to 2*r*, Figure 5-6, strategy (B) remains the most cost-effective strategy as the discount rate is less than 8 %. Therefore, in this case, the discount rate does not have any considerable impact on the final decision.

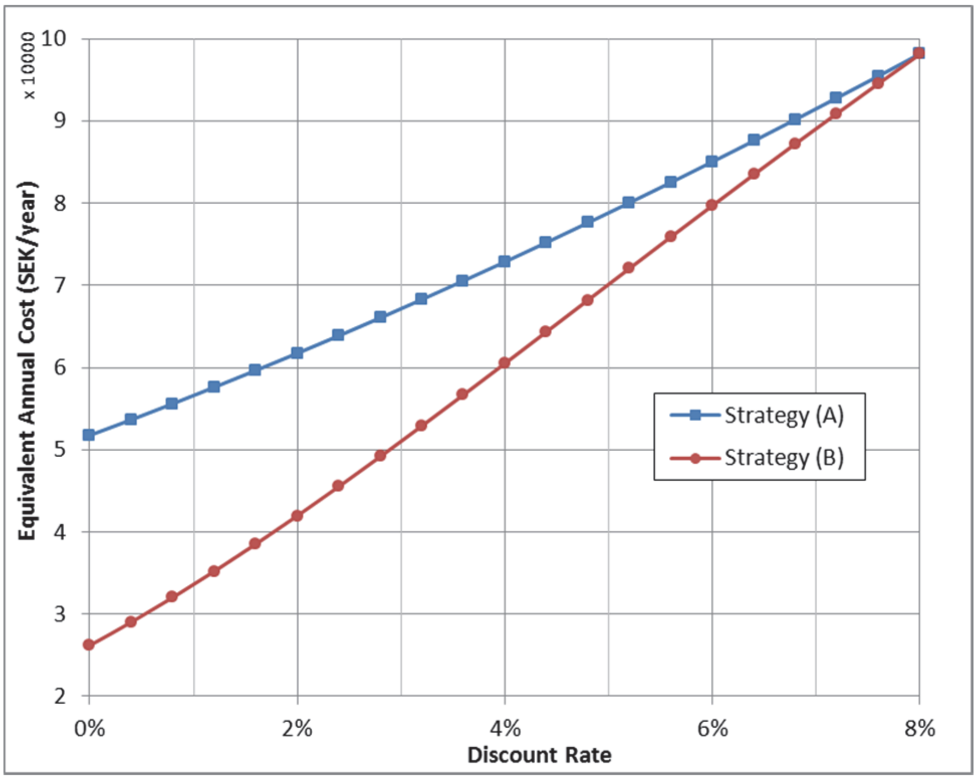

Figure 5-6 The discount rate's variation impact on final decision

If there is a possibility to negotiate the initial cost of strategy (A), it might be more profitable to choose it as the most cost-effective solution when its initial cost is less than 727,037 SEK instead of 895,000 SEK.

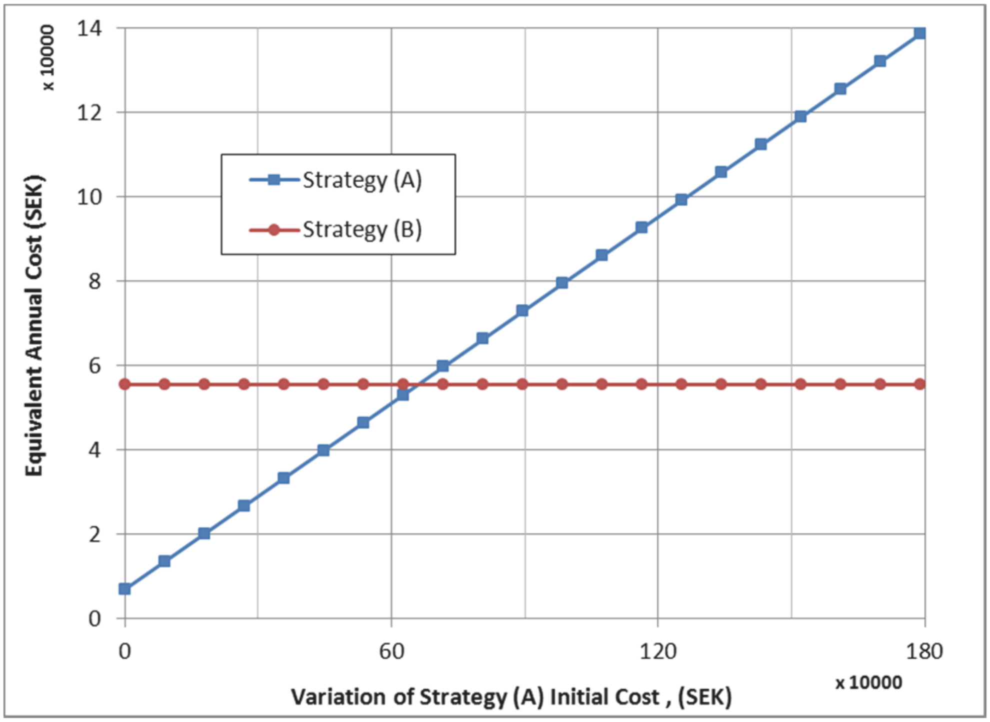

Figure 5-7 The impact of varying the initial cost of strategy (A)

It is not an easy task to anticipate the long-term performance of the bridge or its individual structural members. The assessment of the service life extension after repair was assessed based on statistical treatment of an intensive historical data extracted from BaTMan related to similar actions performed on similar bridges. Therefore, the bridge's service life extension after performing the repair strategy is subjected to uncertainties in the assessment. The impact of this uncertainty on the final decision was studied and presented in Figure 5-8. Strategy (B) remains the most cost-effective choice while the bridge's service life extension is less than 28 years, Figure 5-8. If the repair strategy can guarantee a bridge's service life extension longer than 28 years, then strategy (A) can be chosen as the most cost-effective choice instead of strategy (B). This is fairly impossible according to the feedback from the historical data. Therefore, this parameter, in this case, does not have that considerable impact on the final decision.

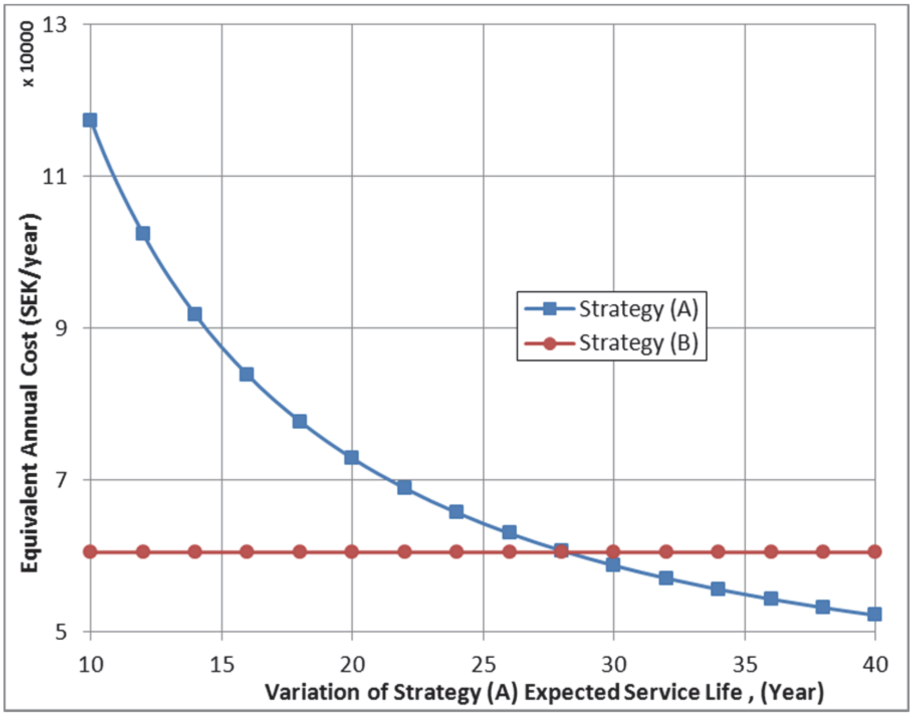

Figure 5-8 The impact of varying the bridge's expected service life extension on the final decision

The bridge's residual service life without action, presented in Table 5-2 is also subjected to uncertainty in the assessment. According to BaTMan's inspection manual *[20]*, bridges with such deterioration have to be more frequently inspected. The next year inspection results might assign the bridge superstructure and substructure CC2 also or CC3. A sensitivity analysis was conducted to study the impact of this uncertainty on the final decision, Figure 5-9. This sensitivity analysis shows that, even if the three years in Table 5-2 becomes zero (CC3), strategy (B) remains the most-cost effective, Figure 5-9.

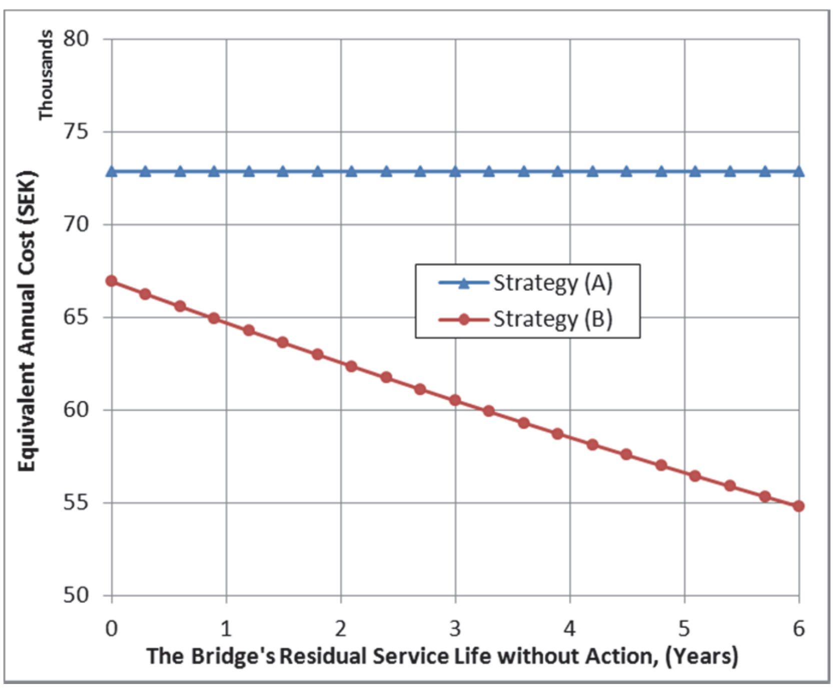

Figure 5-9 The impact of varying the bridge's residual service life on the final decision

5.1.6 Analysis including the bridge user cost

The traffic data on BaTMan is automatically updated each year as BaTMan is directly connected to the Swedish National Road Database (NVDB). Furthermore, it is possible to get a map and online-view for the bridge itself as well as its surrounding network. For this bridge case, the bridge has to be completely closed and the traffic has to follow a detour with an increased distance of 12.5 km. the user cost data used in the analysis are presented in Table 5-4.

Table 5-4 Bridge user cost assumptions

Abbreviation	Description	Value	Unit
w_p	The hourly time value for one passenger car	100	SEK/h
w_T	The hourly time value for one truck	196	SEK/h
O_T	The average hourly operating cost for one truck	151	SEK/h
O_P	The average hourly operating cost for one passenger car	67	SEK/h
C_F	The average cost per fatal deaths accident *[6]*	10500000	SEK/accident
C_I	The average cost per serious injury accident *[6]*	1120000	SEK/accident
L_0	The optimum work zone length	1500	m
r_{TG}	The traffic growth rate	1.1	%
L_D	The length of the detour	12500	m
V_D	The detour Speed	68	km/h
r_T	The percentage of trucks from the AVD	7	%
A_n	The bridge accident rates during the normal condition	3.15E-07	accident/veh/day
A_a	The bridge accident rates during work activities	1.15E-06	accident/veh/day
r	The discount rate	4	%
P_F	The average number of killed persons in bridge related accidents	0.019	Persons/Accident
P_I	The average number of injured persons in bridge related accidents	0.981	Persons/Accident

The bridge WZUC was calculated for the different strategies using the BaTMan-LCC program. Figure 5-10 presents the NPV of the bridge user cost for both strategies.

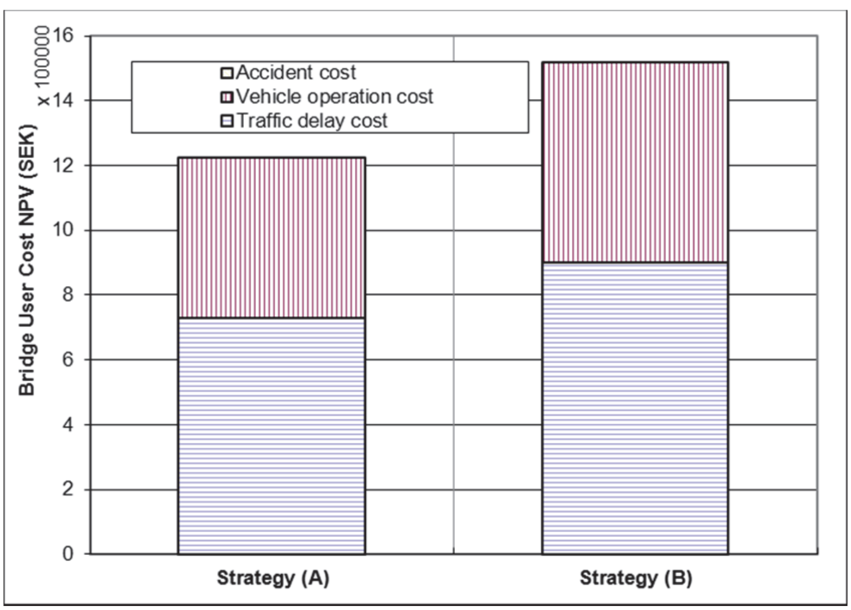

Figure 5-10 Bridge user cost

By including the user cost in the analysis, the EAC for strategy (A) and (B) are presented in Table 5-5. Consequently, strategy (B) remains the most cost-effective choice. By including the bridge user cost in the analysis, it will be more profitable to choose strategy (A) as the most cost-effective option when the repair's initial cost becomes less than 402,706 SEK instead of 895,000 SEK.

Table 5-5 LCC analysis results excluding the bridge user cost

Cost Category &Term	Strategy (A)	Strategy (B)
Net Present Value (SEK)	2,215,523	2,902,067
Equivalent Annual Cost (SEK/year)	163,022	126,798

The anticipated service life of the new concrete slab bridge is also subjected to uncertainty in the assessment. The impact of this uncertainty on the final decision was also studied. Strategy (B) remains the most cost-effective choice as much as the service life of the new bridge is longer than 33 years. It is fairly well known that the new steel open-bottom arch culvert, under normal conditions, can stand more than 40 years *[13]*. Therefore, the new bridge anticipated service life does not also have that considerable effect on the final decision.

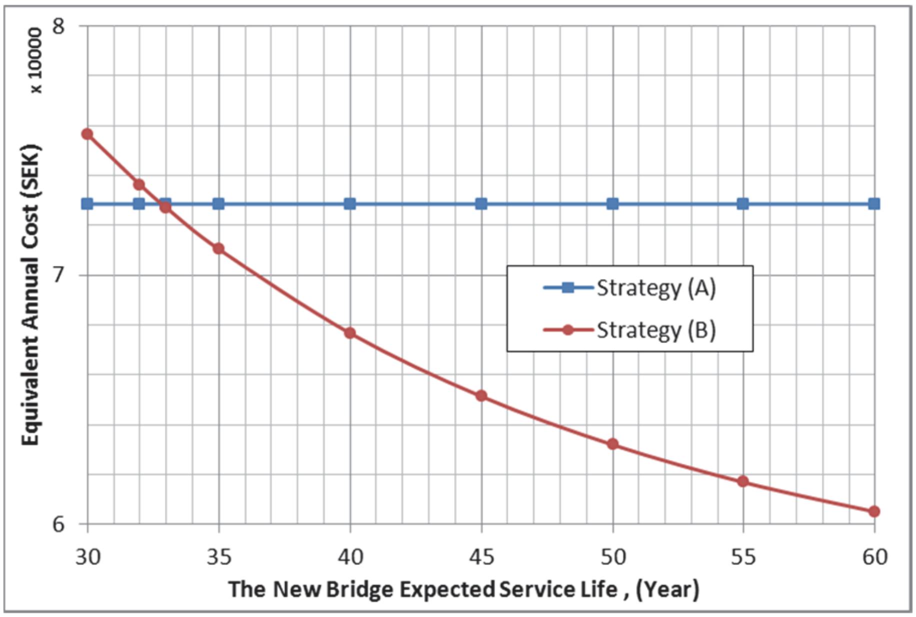

Figure 5-11 The impact of the new bridge anticipated service life

An alternative method of formulating the strategies is to consider a long-term planning. In this case, strategy (A) will comprise the immediate repair and a later renewal of the entire bridge after utilizing the repair's anticipated service life extension, Figure 5-12.

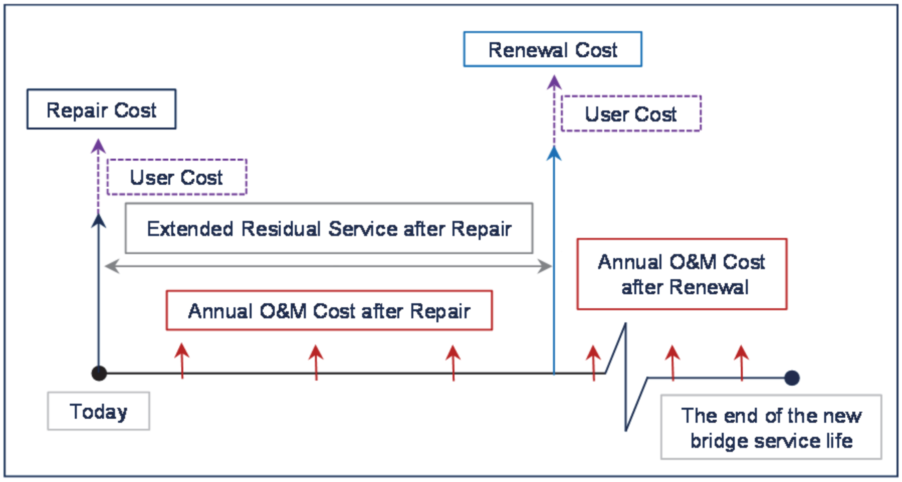

Figure 5-12 Long-term planning for strategy (A)

Considering Figure 5-12, the anticipated initial cost of building a typical new steel open-bottom arch culvert after 25 years from today (year 2035) is 1,609,300 SEK. The life span of strategy (A) in this case will be equal to 80 years instead of 20 years. For this strategy, the required annual O&M cost after the repair is assumed to be 7,000 SEK/year and the required annual O&M for the new bridge is assumed to be 2,500 SEK/year. Considering this long-term planning for strategy (A) and keeping the same specification of strategy (B), the analysis was performed. The EAC for strategy (A) and (B) are equal to 69,612 SEK/year and 60,497 SEK/year respectively. Consequently, strategy (B) remains the most cost-effective choice. The EAC of strategy (A) does not have that considerable variation in comparison with the short-term planning that is presented in Figure 5-4. Therefore, it is recommended to only consider one action in each strategy without complicating the analysis by considering long-term planning.

5.2 Case-Study (2): Repair or Replace a Bridge Structural Member?

5.2.1 Bridge outlines

On some occasions during the bridge operation phase, the choice has to be made between two or more strategies to repair a specific bridge structural member or structural element. The choice is directed by numerous factors such the strategy's initial cost, the bridge or the bridge structural member residual service life without action, the anticipated service life extension after each repair strategy, user cost, financial prerequisites, etc.

Vårbyvägen Bridge in Sweden was constructed in 1969. The Bridge is a continuous beam and slab concrete type composes four spans. The total bridge length is 102 m and the total bridge width is 21 m. The bridge is a Four-Lane Divided, situated in an interstate region and serves an average daily traffic of 9100 vehicles per day with a design speed limit of 90 km/h. The traffic growth rate in the bridge region is expected to be 1.1 %. According to BaTMan, the Vårbyvägen Bridge has a number [1-813-1], which refers to [County number-Section/Junction number in the rout-Bridge number in the Section/Junction]. Figure 5-13 and Figure 5-14 show the bridge layout and the bridge cross-section, respectively.

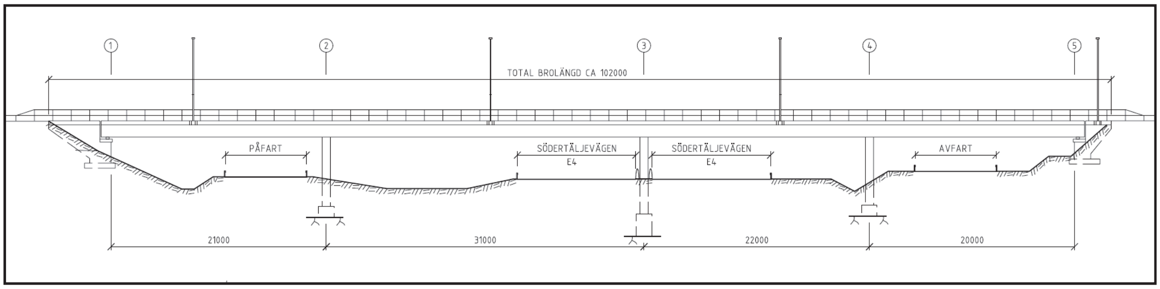

Figure 5-13 [2-813-1] Bridge layout

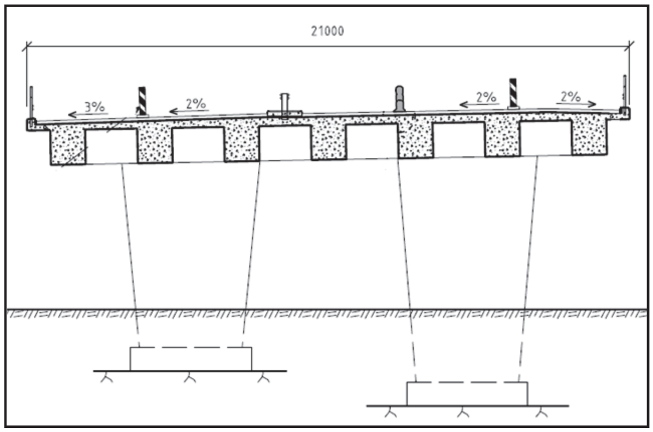

Figure 5-14 [2-813-1] Bridge cross-section

5.2.2 Strategies Specifications

The bridge deck surfacing of [2-813-1] bridge is deemed to be in such a condition that its residual service life is not more than 3 years if no action is taken (BaTMan CC 2). The bridge deck, which is the dominating structural member of the surfacing, is expected to last for at least another 50 years with normal maintenance (BaTMan Condition class 0). The choice now stands between immediately repairing the surfacing or utilising its residual service life without action and then replacing the entire surfacing. It is estimated that it will cost 1,250 SEK/m^2 to repair the bridge deck surfacing: mending the concrete, new waterproofing and paving of the deteriorated parts. Demolishing the old surfacing and placing with a new one, included paving, waterproofing and mending the bridge deck, would cost 2,900 SEK/m^2. Table 5-6 presents the strategies specifications. Figure 5-15 and Figure 5-16 show the cash flow for strategy (A) and (B), respectively.

Table 5-6 Strategies specifications

Parameter	Strategy (A)	Strategy (B)
Strategy description	Immediate repair and then renew	Utilising the residual service life without action and then renew
Dominating structural member's residual service life (years)	50	
Residual service life without action (years)	3	
Discount rate (%)	4	
Service life after a single action (year)	10	35
Initial cost (SEK/m^2)	1,250	2,900
Required installation time (h/m^2)	.75	2

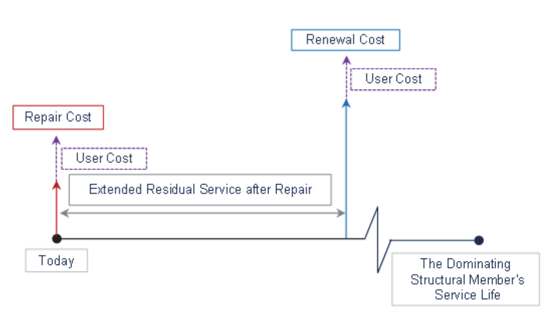

Figure 5-15 Strategy (A): Immediate repair and then renew

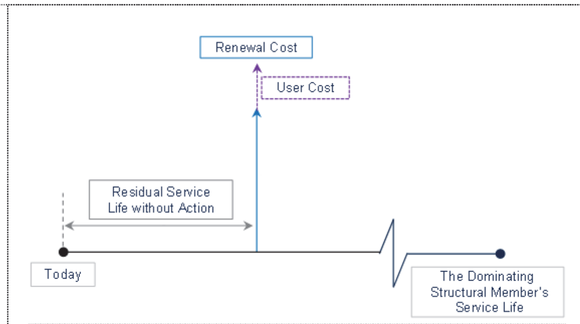

Figure 5-16 Strategy (B): Utilizing the residual service life without action and then renew

5.2.3 Analysis excluding the bridge user cost

According to the specifications given in Table 5-6, the service life span for strategy (A) will be 45 years and 38 years for strategy (B). In this case both strategies have service life spans less than the dominating structural member's expected residual service life which is 50 years. The analysis was conducted to calculate each strategy's NPV and EAC. Table 5-7 presents the results for both strategies, excluding the bridge user cost.

Table 5-7 LCC analysis results excluding the bridge user cost

Results	Strategy (A)	Strategy (B)
Net present value (SEK/m^2)	3,209	2,578
Equivalent annual cost (SEK/m^2)	155	133

As shown in Table 5-7, the EAC of strategy (B) is less than (A). Consequently, strategy (B) is the most cost-effective one. The net saving in this case equals to 903,111 SEK/38 years or 47,142 SEK/year. By performing a sensitivity analysis to study the impact of varying the discount rate (*r*) from zero to 2*r*, as shown in Figure 5-17, strategy (B) remains the superior regardless the variation of *r*.

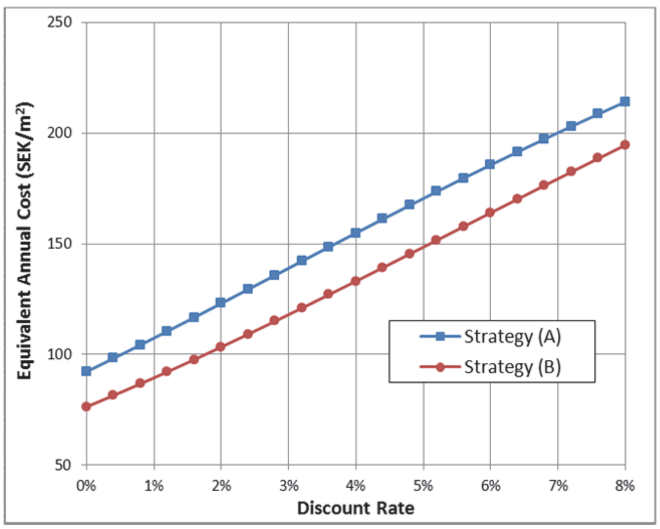

Figure 5-17 The discount rate's variation impact on final decision

If there is a possibility to negotiate the initial cost of the repair in strategy (A), it may be more profitable to choose strategy (A) as the most cost-effective solution when the repair initial cost is less than 799 SEK/m^2 instead of 1250 SEK/m^2, Figure 5-18.

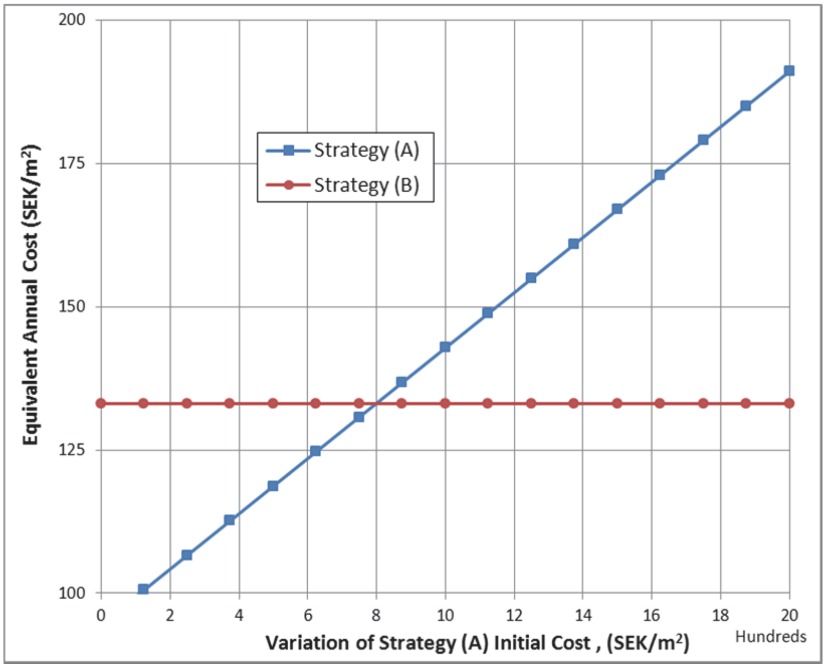

Figure 5-18 Strategy (A) initial cost variation impact on the final decision

5.2.4 Analysis including the bridge user cost

The traffic under the bridge will not be affected by any of the strategies. For this bridge case, each of the strategies will have a special installation technique does not disturb the traffic under the bridge. Therefore, only traffic disturbance over the bridge is considered in this analysis. At first glance one might say that if the WZUC is included in the analysis, strategy (B) will remain the most cost-effective choice. In strategy (A) the WZUC will occur twice; once during the immediate repair and again during renewal 15 years later, while in strategy (B) the WZUC will occur only once during renewal works after 5 years. Consequently, strategy (A) will incur more user cost than (B). The analysis shows that strategy (A) incurs a higher amount of WZUC than (B), Figure 5-19.

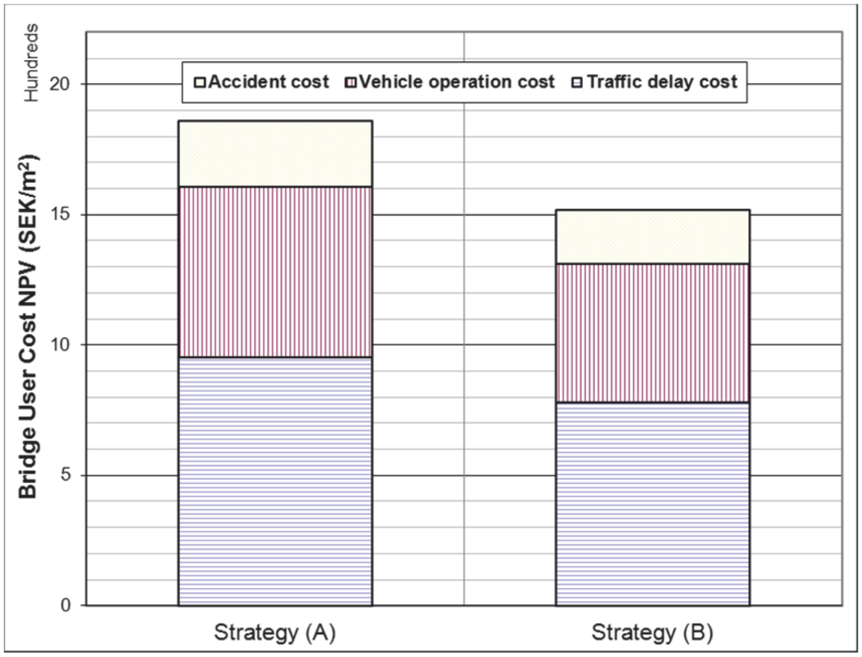

Figure 5-19 Bridge user cost analysis results

By including the user cost in the analysis, as seen in Table 5-8, strategy (B) remains the most cost-effective choice. The net saving in this case is equal to 1,372,094 SEK/38 years or 72,828 SEK/year. It might be more profitable to choose strategy (A) as the most cost-effective solution were the repair initial cost is less than 565 SEK/m^2 instead of 1,250 SEK/m^2.

Table 5-8 LCC analysis results included the bridge user cost

Results	Strategy (A)	Strategy (B)
Net present value (SEK/m^2)	5,067	4,096
Equivalent annual cost (SEK/m^2)	245	211

In view of the uncertainties in the assessment of the residual service life of the bridge deck surfacing without action, a sensitivity analysis was conducted to study its variation impact. Figure 5-20 shows that this uncertainty doesn't have significant impact on the final decision. In case of including the user costs in the analysis, Strategy (B) remains the most cost-effective choice even if the residual service life without action is zero (BaTMan CC3).

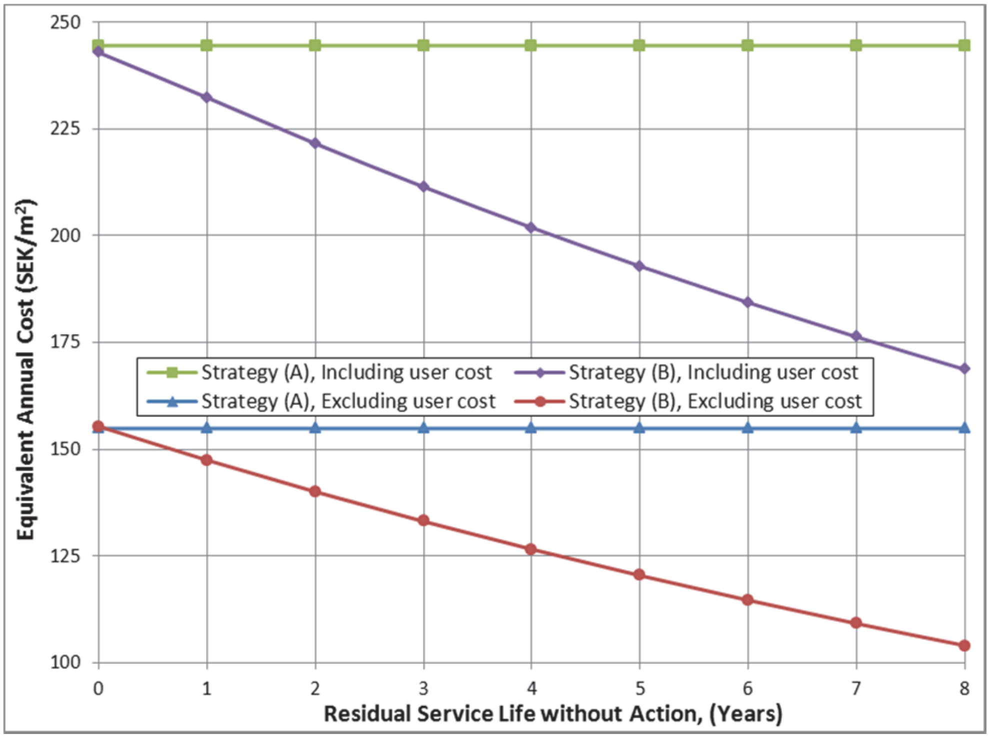

Figure 5-20 The surfcasting's residual service life without action variation impact on the final decision

The service life extension of the structural element after implementing any of the repair strategies should not be longer than the residual service life of the dominating structural member. When changing a structural member, all of its structural elements will be changed regardless if some of the elements are still functioning well. Therefore, the residual service life of dominating structural member is an important factor in the analysis. However, it is not an easy task to anticipate a long performance of the different bridge structural members. The impact of this this uncertainty on the final decision was studied and presented in Figure 5-21. Strategy (B) remains the most cost-effective choice where the residual service life of the dominating structural member is longer than 10 years otherwise strategy (A) becomes the most cost-effective. In this figure, the EAC of strategy (A) sharply drops when the residual service life of dominating structural member is less than 10 years because at this point strategy (A) will comprise of only immediate repair without the later renewal.

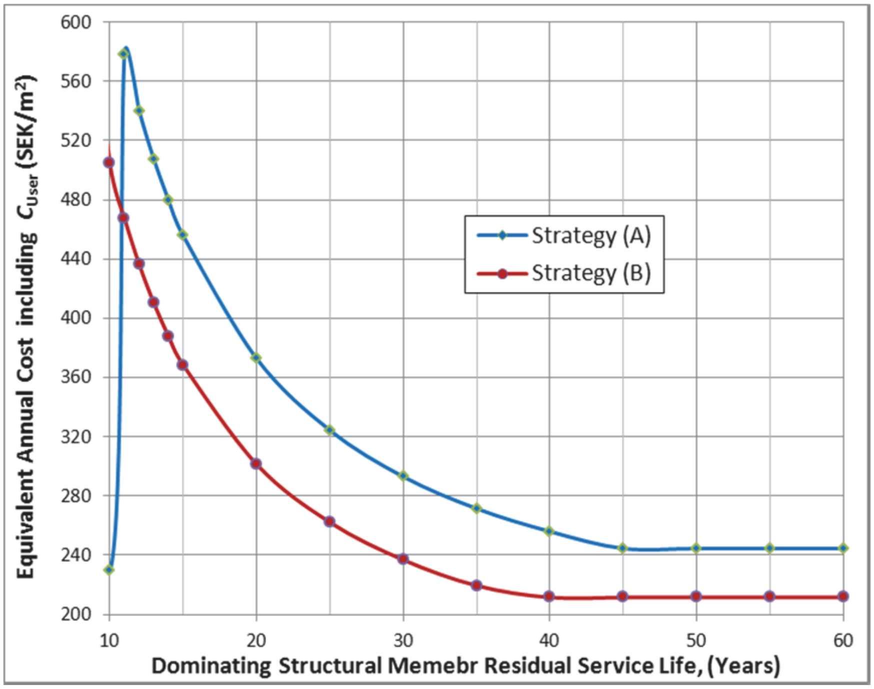

Figure 5-21 The bridge deck's residual service life variation impact on the final decision

The expected service life of the different repair strategies is also subjected to uncertainties in the assessment. The impact of these uncertainties on the final decision was also studied and presented Figure 5-22 and Figure 5-23. Keeping the same expected service life after repair and varying the expected service life after renewal, Strategy (B) remains the most cost-effective where the renewals expected service life is higher than 15 years, Figure 5-22. Keeping the same expected service life after renewal and varying the expected service life after repair, Strategy (B) remains the most cost-effective as the repair's expected service life is less than 15 years, Figure 5-23.

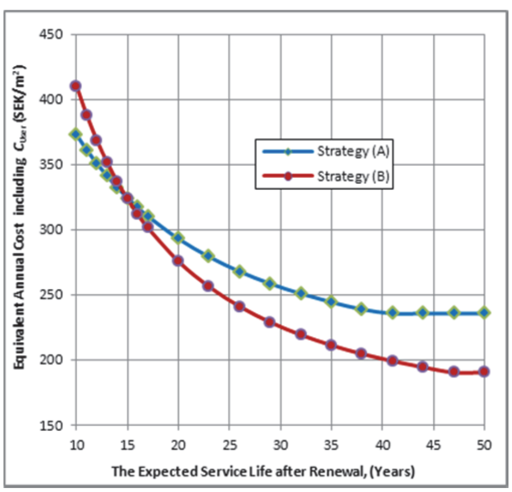

Figure 5-22 The renewal's expected service life variation impact on the final decision

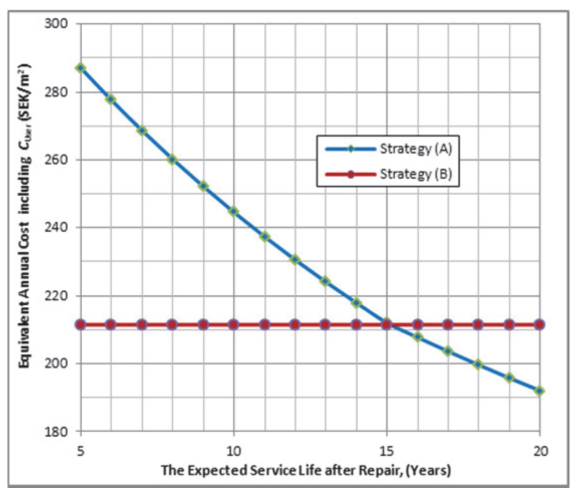

Figure 5-23 The repair's expected service life variation impact on the final decision

Other way of formulating the repair strategies for this bridge is to consider only one single action in each strategy. In this case, strategy (A) will comprise only the immediate repair without considering the later renewal. From this point of view, strategy (A) will have a life span of 10 years instead of 45 years. Considering this short-term planning, the analysis was conducted and presented in Table 5-9.

Table 5-9 Short-term planning LCC analysis results, included the bridge user cost

Results	Strategy (A)	Strategy (B)
Net present value (SEK/m^2)	1,863	4,096
Equivalent annual cost (SEK/m^2)	230	211

As seen in the Table 5-9, strategy (B) remains the most cost-effective. However, the NS becomes equal to 788,233 SEK/38 years or 40,698 SEK/year.

6 BaTMan-LCC

BaTMan-LCC is an Excel-Based LCC program developed over this research to facilitate the implementation of LCC. The program is primarily developed to assist Trafikverket's bridge specialists and decision-makers in specifying the most cost-effective proposal. The program serves both; the management of existing bridges as well as the investment of new bridges. All LCC applications presented earlier in this thesis are included this program. Embedded user-cost models specially designed for the different LCC applications were attached. The program is connected in somehow with BaTMan's database through WebHybris. User manual and guidelines are also included with this program. Figure 6-1 presents the front-page of this program.

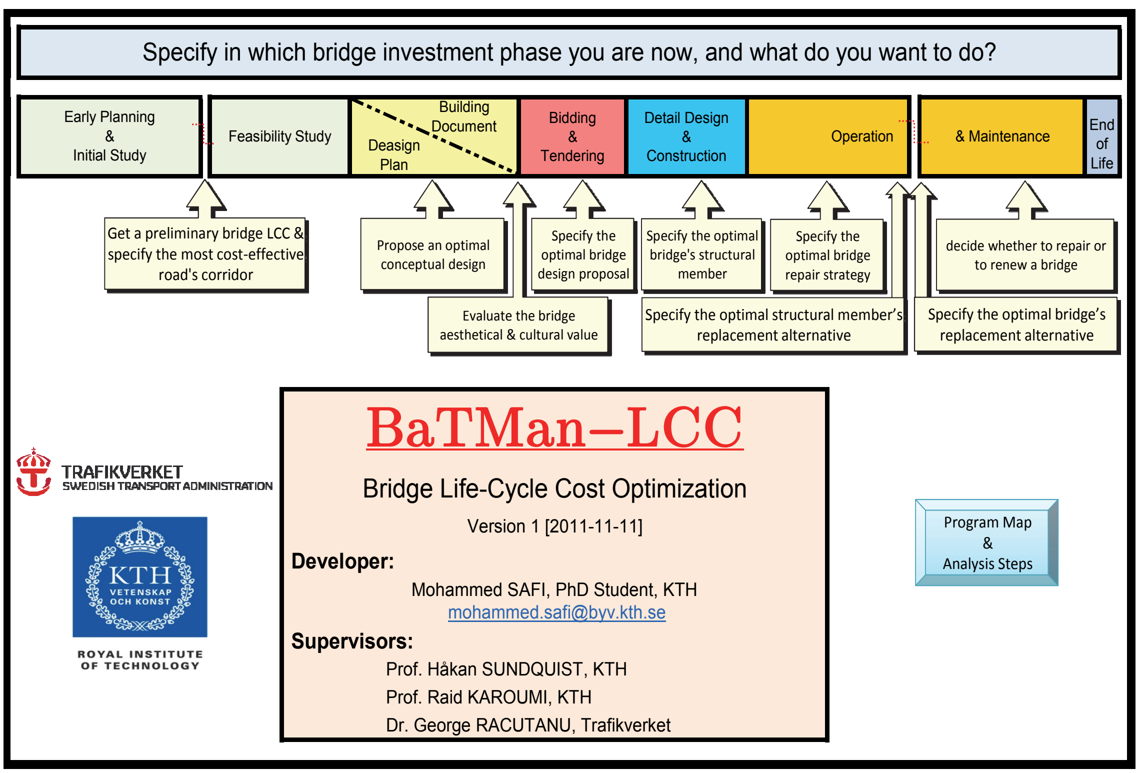

Figure 6-1 BaTMan-LCC front-page

The program is user-friendly in which not many input date are required to be inserted by the user. As it can be seen in the program front-page, the user has firstly to specify in which bridge investment phase he currently is and what he wants to do. After choosing the application, the program will direct the user to the input window. The LCC analysis results and the related sensitivity analysis will automatically be generated and presented in different windows based on the given input data. The program produces the typical analysis and sensitivity analysis as in both case studies in this thesis. Another application the program can handle is the evaluation of the bridge aesthetical and cultural value. The developer of this program aims at further develop BaTMan itself to accommodate the LCC applications of BaTMan-LCC. Consequentially the LCC applications will be an integrated part of BaTMan instead of having BaTMan-LCC as a separate stand-alone tool beside BaTMan. Doing so, an automatic data extraction will be allowed and the largest online-use can be achieved.

7 Conclusion

7.1 Conclusion

Generally, bridge investment and management decisions are multi-alternative-oriented. In many countries, bridges are mainly managed using bridge management systems (BMSs). Many BMSs contain some forms of life-cycle costing (LCC). However, the use of LCC in bridge engineering is scarce, and LCC has mainly been applied within the bridge operation phase to support decisions related to existing bridges. This thesis discuss the need of a BMS with cradle-to-grave, integrated and comprehensive LCC tools that can assist decision-makers at all levels and within all phases in selecting the most cost-effective alternative. The thesis introduces the Swedish Bridge and Tunnel Management System (BaTMan). A comprehensive integrated LCC implementation scheme was illustrated, taking into account the bridge investment and management process in Sweden. Two practical case studies are presented to demonstrate the recent improvement of BaTMan particularly in LCC integration. The presented case studies clarified how decesion-makers can benefit from BaTMan's inventory data. Before this research study, the equivalent annual cost (EAC), net saving (NS), opportunity loss (OL), and sensitivity analysis techniques were not existing in BaTMan for those particular functions. Moreover, the decision was used to be based on the net present value technique which is improper to compare alternatives having unequal life-span.

7.2 Discussion

It is not easy to draw a general conclusion from LCC analysis performed on a certain bridge case because the results are strongly dependent on the input. One of the key components of the LCC is the incorporation of uncertainty into the analysis. Therefore, the sensitivity analysis is an important step in such analysis which can address the critical parameters for the final decision. The sensitivity analysis allows the decision-makers to evaluate their confidence in whether they have chosen the correct solution. Usually, when the NS is a considerable amount, the variation of the included parameters will not have that significant influence on the final decision and vice versa. Using the OL technique, the decision-makers will be able to estimate the consequences of their decisions, and it will promote forward thinking.

According to the analysis results, as well as the sensitivity analysis presented in the first case study, the bridge should not be repaired and should be replaced after utilizing its residual service life. Perhaps, the feasibility of LCC analysis is not clear because it is only one single small bridge. However, today, Trafikverket is responsible for 23,948 bridges with a total bridge area of 5,516,590 m^2. Among of Trafikverket's bridges, there are 6,268 older than 70 years with a total area of 619,944 m^2. Considering the LCC analysis result for the first case study in this thesis, the annual OL is equal to 241 SEK/m^2 of the bridge total area. This loss will stand for 20 years. Consider that 50 % of the Trafikverket's old bridges might be subjected to a wrong decision. This means Trafikverket might lose 74.7 million SEK each year. Moreover, it means that Trafikverket might lose 1.49 billion SEK during the coming 20 years.

7.3 Further Research

Some of the research work presented in this thesis was carried out within the Nordic joint project ETSI, *[6]*. The main goal of ETSI is to develop a unified, reliable and usable Nordic methodology and an Internet-based computer tool for bridge life-cycle optimization. The analysis presented in this thesis has primarily considered the bridge investment and management process in Sweden and BaTMan. Same methodology could be adopted to fit the BMSs in other Nordic counties.

The case studies presented in this thesis clarified how a BMS with an integrated LCC tool can support project-level decisions for deciding when to replace an entire bridge or a bridge structural member. Further research can be directed towards clarifying how a BMS with an integrated LCC tool can support network-level decisions for prioritizing bridges for repair or replacement purposes, taking into account the OL from the project-level analysis.

Other research studies could be undertaken to clarify the possible LCC applications for bridges during the tendering phase where the largest LCC saving potential can be achieved.

In considering the renewal alternative, allowance should also be made for the benefits that might be afforded by a completely new bridge in view of routing, road safety, bearing capacity, traffic, etc. The historic value for some special old bridges should also be considered in the analysis. These aspects are important to consider but are beyond the scope of this thesis.

In December 2011, Trafikverkt had decided to continue financing this project. Upgrading BaTMan itself to accommodate the LCC applications of BaTMan-LCC tool is the main future task of this project. Consequentially the LCC applications will be an integrated part of BaTMan instead of having BaTMan-LCC as a separate stand-alone tool beside BaTMan. Doing so, an automatic data extraction will be allowed and the largest online-use can be achieved. Another important future task is clarifying the possible LCC application for bridges during the tendering phase as well as defining the included parameters in the analysis. Establishing a new chapter in the Swedish bridge design standard that includes a comprehensive bridge LCC guidelines and regulation is also one of the future aims of this project.

7.4 Acknowledgements

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Appendix A-Paper I

Development of the Swedish Bridge Management System by Upgrading and Expanding the Use of LCC

Mohammed Safi, Håkan Sundquist, Raid Karoumi and George Racutanu.

Bending on Structure and Infrastructure Engineering Journal.

Appendix B-Paper II

Life-Cycle Costing Applications for bridges and Integration with Bridge Management Systems

Case-Study of the Swedish Bridge and Tunnel Management System (BaTMan)

Mohammed Safi, Håkan Sundquist, Raid Karoumi and George Racutanu.

Accepted for Publication on Transportation Research Record (TRR), Journal of Transportation Research Board.

Appendix C-Paper III

Life-Cycle Costing Integration with Bridge Management Systems

Mohammed Safi, Håkan Sundquist and George Racutanu.

Submitted to the ICE-Bridge Engineering Journal.