Life-Cycle Costing

Applications and Implementations in
Bridge Investment and Management

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KTH Architecture and
the Built Environment

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Cover Photo: Svinesund Bridge, linking Sweden (right) and Norway (left).
Source: BaTMan.

Abstract

A well-maintained bridge infrastructure is a fundamental necessity for a modern society that provides great value, but ensuring that it meets all the requirements sustainably and cost-effectively is challenging. Bridge investment and management decisions generally involve selection from multiple alternatives. All of the options may meet the functional demands, but their life-cycle cost (LCC), service life-span, user-cost, aesthetic merit and environmental impact may differ substantially. Thus, life-cycle analysis (LCCA, a widely used decision-support technique that enables comparison of the LCC of possible options), is essential. However, although LCCA has recognized potential for rationalizing bridge procurement and management decisions its use in this context is far from systematic and the integration of LCCA findings in decisions is often far from robust. Thus, the overall objective of the work underlying this thesis has been to contribute to the development of sustainable bridge infrastructures while optimizing use of taxpayers' money, by robustly incorporating life-cycle considerations into bridge investment and management decision-making processes. The work has introduced a full scheme for applying LCCA throughout bridges' entire life-cycle. Several practical case studies have been presented to illustrate how an agency could benefit from use of a bridge management system (BMS) to support decisions related to the management of existing bridges and procure new bridges. Further developments include a comprehensive approach incorporating a novel LCCA technique, "LCC Added-Value Analysis", which enables procurement of the most cost-efficient bridge design through a fair design-build (D-B) tendering process. A further contribution is a novel, holistic approach designed to enable procurement of bridges with the maximal possible sustainability (life-cycle advantages) under D-B contracts. The approach combines LCC Added-Value analysis with other techniques that make bridges' aesthetic merit and environmental impact commensurable using an adapted concept named the willingness-to-pay-extra (WTPE).

The systematic analytical procedures and potential of LCCA to deliver major savings highlighted in this thesis clearly demonstrate both the feasibility and need to integrate LCCA into bridge procurement and management decisions. This need has been recognized by Trafikverket (the Swedish Transport Administration), which has implemented a software tool developed in the research (BaTMan-LCC) in its bridge and tunnel management system (BaTMan). This thesis introduces readers to the field, considers BaTMan and the bridge stock in Sweden, discusses the developments outlined above and obstacles hindering further implementation of LCCA, then presents proposals for further advances.

Keywords: Bridge, Cost, Life Cycle Cost Analysis, Procurement, Investment, Management, Life Cycle Assessment, Repair, Sustainable, User Cost, Aesthetics, Environmental Impact, Contract, Infrastructure, Transportation, BaTMan, Trafikverket, LCC, LCA, LCCA, BMS.

Preface

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

After thanking God for granting me the strength and determination to fulfill the objectives of this research project, I would like to express my best wishes and gratitude to my beloved hometown Gaza-Palestine, my parents and all of my family who have encouraged and instilled in me the drive to achieve the goals of this work.

Thanks are also due to my germane colleagues at Trafikverket, Dr. *George Racutanu*, Dr. *Peter Simonsson* and Ms. *Karin Mehlberg*. Many thanks are due to Mr. *George Chamoun*, Mr. *Johan Severinsson* and Mr. *Martin Henriksson* of Trafikverket's operations division for their close cooperation and fruitful discussions. Special thanks are also due to Ms. *Lahja Rydberg-Forssbeck* and Mr. *Mats Karlsson* for their brave decisions regarding the implementation of my research results within Trafikverket's bridge investment division.

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

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

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

Stockholm, September 2013

Mohammed Safi

Publications

Appended Papers

This thesis is based on the work presented in the following appended publications, which are referred to in the text by the corresponding Roman numerals:

Paper I: Safi, M., Sundquist, H., Karoumi, R. and Racutanu, G., 2012. Development of the Swedish bridge management system by upgrading and expanding the use of LCC. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, DOI:10.1080/15732479.2012.682588.

Paper II: Safi, M., Sundquist, H. and Karoumi, R., 2013. Procurement of the most cost-efficient bridge through incorporating LCCA with BMSs: case study of the Karlsnäs Bridge in Sweden. Submitted to the Journal of *Bridge Engineering-American Society of Civil Engineers (ASCE).*

Paper III: Safi, M., Sundquist, H., Karoumi, R. and Racutanu, G., 2012. Integration of life-cycle cost analysis with bridge management systems: case study of Swedish bridge and tunnel management system. *Transportation Research Record (TRR)*: Journal of the Transportation Research Board (TRB), No. 2292, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 125–133, DOI: 10.3141/2292-15.

Paper IV: Safi, M., Sundquist, H. and Karoumi, R., 2012. Applications of life-cycle costing for bridges and integration with bridge management systems. Accepted for publication in the Journal of *Civil Engineering and Architecture*.

Paper V: Safi, M., Du, G., Sundquist, H. and Karoumi, R., 2013. Holistic approach to sustainable bridge procurement considering LCC, LCA, lifespan, user-cost and aesthetics. Submitted to the Journal of *Bridge Engineering-American Society of Civil Engineers (ASCE).*

The first author was responsible for all the data processing, analysis, evaluation and writing of Papers I - IV. The first co-author of the fifth paper generated the LCA results and assisted in writing its LCA section. All the co-authors participated in planning the work and contributed with comments and revisions.

Other Relevant Publications

The author also contributed to the following, unappended publications that are also related to the project:

Paper A Du, G., Safi, M. and Karoumi, R., 2013. LCA as a decision-making support tool for bridge procurement: comparing five bridge design types. Submitted to the *International Journal of Life Cycle Assessment (JLCA).*

Paper B Safi, M., Sundquist, H., Karoumi, R. and Racutanu, G., 2012. 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 in the *Transportation Research Board's 91st annual meeting compendium of papers,* USA.

Paper C Safi, M. Sundquist, H., Karoumi, R. and Racutanu, G., 2012. Bridge management system with an integrated LCC tool, *FIB Symposium 2012,* Stockholm-Sweden.

Paper D Safi, M., 2011. Bridge life-cycle optimization, *KTH Transport Day*, Stockholm-Sweden.

Abbreviations & Acronyms

ADT	Average daily traffic
BaTMan	The Swedish bridge and tunnel management system
BMS	Bridge management system
BOQ	Bill of quantity
BSM	Bridge structural-member
CC	Condition class
D-B	Design-build contract
EAC	Equivalent annual cost
Eco-value	The environmental impact of a product over its whole life cycle.
ELCD	The European reference Life Cycle Database
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
FTA	The Finnish Transport Agency
GWP	Global warming potential
INS	Inspection
INV	Initial investment
IRP	Ionising radiation potential
LCA	Life-cycle assessment
LCC	Life-cycle cost
LCCA	Life-cycle cost analysis
LCI	Life-cycle inventory
LCIA	Life cycle impact assessment
LCM	Life-cycle measure
LCP	Life-cycle plan
MEP	Marine eutrophication potential
METP	Marine ecotoxicity
NPV	Net present value
NS	Net saving
NVDB	The Swedish national road database
O&M	Operation and maintenance
OL	Opportunity loss
PMFP	Particulate matter formation potential
POFP	Photochemical oxidant formation potential
Pontis	Full-featured BMS used in more than 40 state departments of transportation in the USA
R,D&L	End of life management cost (recycling, demolition and landscaping)
ReCiPe	A life cycle impact assessment method (“recipe”), based on harmonized midpoint and endpoint category indicators
RRR	Repair/rehabilitation & replacement
SEK	The Swedish Krona, approximately equivalent to 0.12 Euro in August 2013
STR	Strengthening
TAP	Terrestrial acidification potential
TCP	Traffic control-plan
TETP	Terrestrial ecotoxicity potential
Trafikverket	The Swedish Transport Administration
WebHybris	A software navigation tool that can access the BaTMan database online
WLC	Whole-life cost
WTPE	Willingness-to-pay-extra
WTP	Willingness-to-pay
WZUC	Work-zone user-cost

Contents

1 Introduction

1.1 Background

Bridges should be procured and managed in ways that ensure that the needs of the society they serve are optimally met. Generally, bridge investment and management decisions involve selection from multiple alternatives. In an early planning phase, several bridge designs could technically provide feasible solutions in a certain location where a bridge is to be repaired or built (hereafter bridge location). During the operation phase, there could be several technically feasible strategies for maintaining or repairing a deteriorating bridge or bridge structural-member (BSM). Although all of the options may meet the functional requirements, their life-cycle cost (LCC), service life-span, user-cost, aesthetic merit and environmental impact may differ substantially. The life-cycle measures (LCMs) associated with the various alternatives might also have substantially differing impacts on the traffic flow above and/or under the bridge during their implementation. Furthermore, in addition to the traditional requirements for bridges increasing attention is being paid to the environmental and aesthetic aspects of different designs [17],[20],[22],[23],[29]. Agencies are also under severe pressure nowadays to maximize efficiency and ensure the optimum use of taxpayers' money. In tandem, they are also realizing the importance of integrating other life-cycle aspects into their procurement policies, as "green" and socially preferable assets may carry considerably higher purchasing price tags than their less sustainable alternatives [41]. Currently, conventional financial costing is guiding the agencies' decisions to implement particular proposals [45] and [48]. This approach might cause huge losses for agencies and society in some cases since it might result in the implementation of proposals that are relatively cheap in terms of INV costs, but very expensive in LCC terms.

An efficient procurement approach is essential for the efficient procurement and maintenance of sustainable bridge infrastructure. A sustainable infrastructure should minimize strains on resources and the environment, and contribute to the overall sustainability of socio-economic development [14]. A major hindrance to the procurement of sustainable bridge infrastructures is the lack of a reliable framework combining and integrating all the bridges' life-cycle aspects into procurement processes [46]. Thus, life-cycle cost analysis (LCCA, a widely used decision-support technique for comparing the LCC of possible options), is essential. LCCA is particularly used by decision-makers in the industrial sector to identify the most cost-efficient alternatives from arrays of feasible alternatives that would meet specific functional needs. However, although LCCA has great recognized potential for rationalizing bridge procurement and management decisions, its use in this context is far from systematic and the integration of LCCA findings in decisions is often far from robust [46].

1.2 Aims and Scope

The project this thesis is based upon was financed by the Swedish Transport Administration (Trafikverket). The aims were to enhance Trafikverket's bridge investment and management decisions by integrating LCCA into its procurement processes, thereby helping to optimize use of taxpayers' money and improve the sustainability of bridge infrastructure. Further goals were to develop convenient parameters and techniques for evaluating other life-cycle aspects of bridges, such as user costs, environmental impacts and aesthetic values. The thesis contribution will be demonstrated in a later heading while specific goals were to:

- Address the possible applications of LCCA for bridges
- Investigate and highlight the benefits of LCCA in bridge investment and management
- Define the parameters affecting the accuracy of LCCA
- Develop approaches and techniques for interpreting and integrating the results of LCCA in real procurement processes
- Develop methodologies for evaluating bridges' user costs, aesthetic values and environmental aspects
- Develop convenient procedures for integrating life-cycle considerations into public agencies' established bridge procurement decision-making processes
- Explore and present pilot case studies illustrating the practical implementation of the various applications
- Establish an overall outline of a LCCA database for bridges
- Develop a software tool to ease implementation of the applications
- Define the main obstacles hindering implementation of the applications and formulate milestones for further research and development

The research work presented in this thesis mainly focuses on project-level decisions. Some presented results and conclusions are object-specific. However, the proposed methods could be readily applied to similar structures. Regarding the scope of life-cycle costing, only solutions meeting the same functional requirements are considered. The LCCA applications, approaches and techniques developed in the work are intended to dovetail with Trafikverket's established bridge procurement and management procedures. However, other bridge procurers and managers all over the world could easily adopt and employ them to procure and manage both bridges and various other structures.

Bridge records extracted from the Swedish Bridge and Tunnel Management System (BaTMan) have been exploited to support the developed approaches and techniques, although other agencies could use data from their own BMSs. Values of general parameters, such as the discount rate used in LCCA, aesthetic merit and environmental impact willingness-to-pay-extra have been left to Trafikverket's economists and policy-makers to decide. However, values for such parameters based on systematic evaluations that could be used are suggested in this thesis.

The approach presented in Paper II is still under development and in an initial implementation phase within Trafikverket. The holistic approach presented in Paper V has been proposed to Trafikverket, but further development and efforts are needed to improve its robustness and implement it in practice. The case studies included in the appended papers and this thesis are intended to illustrate the practical implementation of the proposed approaches and techniques, address the roles of both contractors and agencies in such approaches, and provide valuable insights into the various aspects of bridge procurement and management.

1.3 Thesis Outline

This doctoral thesis presents the results of four years research work. It consists of an extended summary, five appended papers and two appendixes. Most results are presented in the appended papers. The extended summary consists of six chapters. The first explains the research structure, the relations between the studies, highlights the objectives of each study and its contribution to the overall research work. Chapter 2 discusses LCCA in general and the parameters involved. Valuable information about BMSs, the bridge stock in Sweden, BaTMan and the various LCC categories is also presented in Chapter 2. Chapter 3 briefly presents the possible applications of LCCA for bridges and discusses the obstacles hindering its implementation in bridge investment and management.

A practical case study is presented in Chapter 4 to illustrate how an agency could apply its BMS to support an LCCA-based decision on whether a heavily deteriorated railway bridge should be repaired or replaced. Chapter 5 describes the computer tool “BaTMan-LCC”, which has been developed to ease implementation of the introduced LCCA applications for bridges. Chapter 5 also presents the measures taken by Trafikverket towards the implementation of BaTMan-LCC. The last chapter in the extended summary presents a short summary of the thesis and proposals for further research and improvements.

Appendix A presents the LCCA analytical tools and techniques developed in the studies while Appendix B introduces rough life-cycle plans (LCPs) for the various bridge structural members (BSMs) of Swedish bridges. These LCPs collectively represent an initial step towards a comprehensive LCCA database for bridges. The appended papers can be read independently, but readers are encouraged to read the extended summary first for an overview of the subject matter.

1.4 Research Structure and Contributions

The results presented in this thesis have contributed to both the state-of-the-art and state-of-the-practice of LCCA in both bridge investment and management. Figure 1 depicts the general research structure, the role of each study in the overall research, and the investment phase most relevant to each paper's contribution.

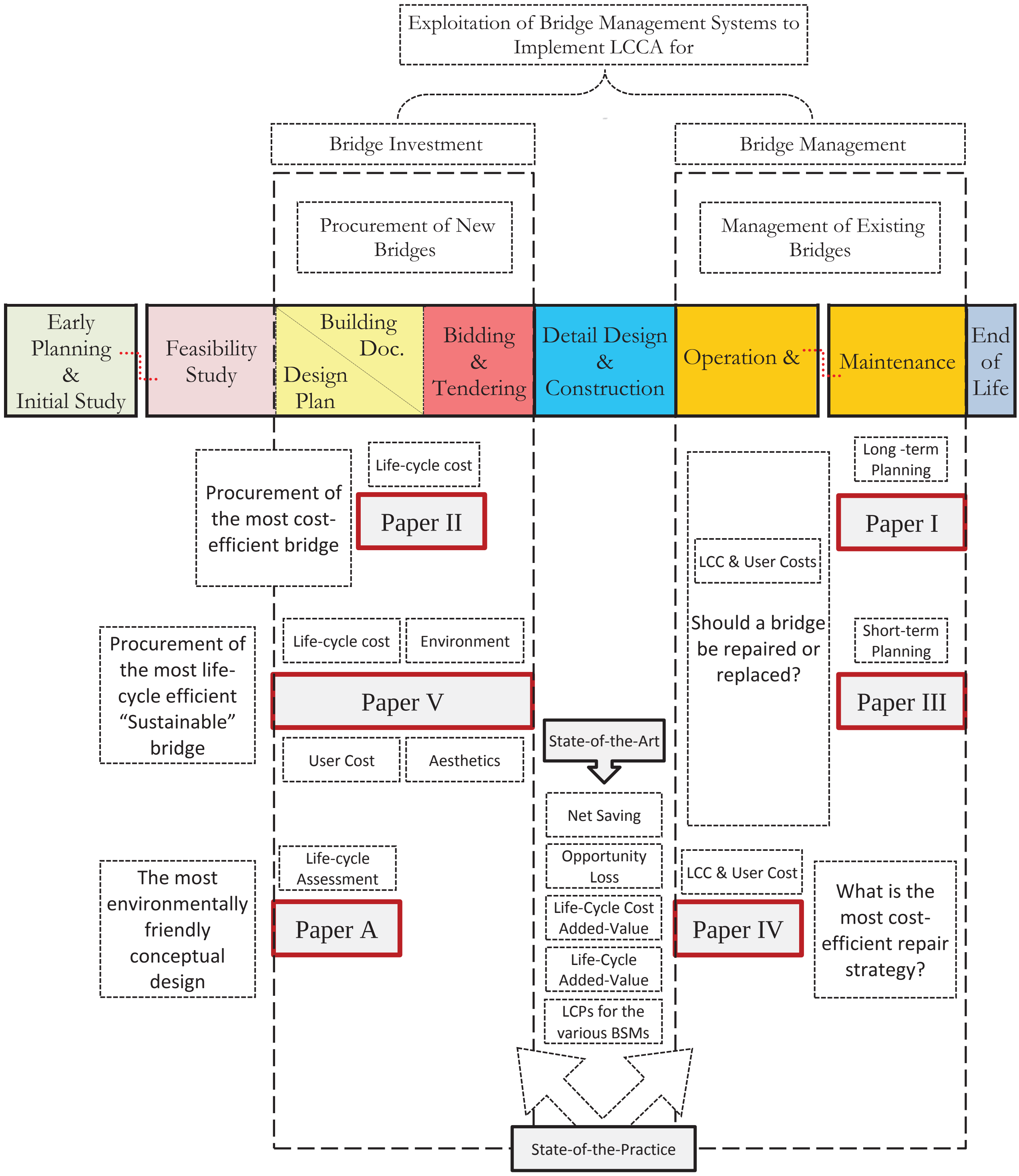


Figure 1. Research structure and contributions

1.4.1 Contributions to the state-of the-art

Bridge management

A comprehensive framework that details the possible applications of LCCA for bridges during their entire life-cycle has been introduced. A technique based on equivalent annual cost (EAC) has been developed and employed for comparing overall costs of design alternatives and repair strategies with unequal life-spans. In addition, two new parameters, the Net Saving (NS) and Opportunity Loss (OL), have been developed and employed in all of the studies. These two parameters highlight advantages and disadvantages of the options from different LCC perspectives. Conventional parameters with some similarities to OL and NS are not suitable for comparing alternatives with unequal life-spans. Consideration of NS and OL will enable bridge decision-makers to estimate the consequences of their decisions more thoroughly and promote forward thinking. Besides, a simplified efficient method for highlighting the feasibility of LCCA considering the network-level is introduced and applied in all appended papers.

Bridge investment

Two other novel (to the author's knowledge) parameters have also been added to the set employed in LCCA methodology. The first, "LCC Added-Value", is intended to enable agencies to procure the most cost-efficient bridge design through a tendering process using a D-B. It allows bridge procurers to properly interpret the results of a LCCA process performed to compare feasible design solutions for a certain bridge location, and thus provide contractors with LCC-efficient monetary benchmarks in the tender documents. The other parameter, "Life-Cycle Added-Value", is intended to enable the procurement of the most "sustainable" (advantageous over the life-cycle) bridge design through a tendering process under a D-B. Using this parameter, agencies will be able to establish and provide contractors with monetary benchmarks in their tender documents concerning not only the LCC aspects, but also environmental, aesthetic, life-span and user-cost aspects.

Appendix B includes recommended LCPs for the various bridge structural-members (BSMs) compose the various bridge types in Sweden. The LCPs are based on statistical analysis of intensive historical records of LCM performed on existing bridges in Sweden. The compilation of data in this appendix represents the first step towards a comprehensive database that will support the LCCA of new bridges with valuable input parameters. The appendix also provides notations for further development and improvements. The main contribution in this respect is the use of real repair records while other existing methods are based on sophisticated hypothetical degradation models.

1.4.2 Contributions to the state-of the-practice

Bridge management

Paper I includes a practical case study (in which the NS and OL parameters were used) illustrating how an agency could apply its BMS to support a decision on whether a heavily deteriorated road bridge should be repaired or replaced considering LCC and user-cost aspects. The objectives of the study reported in Paper III were similar, but it demonstrated in more detail how LCCA applications could be integrated with a BMS. Paper III also discusses the long-term and short-term planning involved in the repair strategy included in the optimization process, and recommends a suitable method to apply in such LCCA. The results presented in these two papers have been implemented in several real bridge projects by Trafikverket. The future target for the application demonstrated in these papers is to integrate it in BaTMan, thereby allowing automatic data extraction and facilitating online use.

Paper IV includes a practical case-study illustrating how an agency could exploit its BMS to support a decision on whether to repair or replace a deteriorated superstructure of an existing road bridge considering LCC and user costs. The paper provides valuable insights into the various parameters affecting the final decision.

Bridge investment

Paper II introduces a comprehensive approach (including the LCC Added-Value technique) for an agency to maximize benefits from its BMS to procure the most cost-efficient bridge design through a fair D-B tendering process. The paper demonstrates the measures needed to ensure that the proposed approach is robust. It also includes a detailed practical case study that clearly addresses the roles of both agencies and contractors in such a procurement process. The approach and specific techniques presented in the paper have been recently employed by Trafikverket in the procurement of several bridge projects.

Paper V introduces a holistic procurement approach intended to enable the procurement of the most “Sustainable” (advantageous in life-cycle terms) bridge under D-Bs. The approach combines the LCC Added-Value technique with other techniques that make bridges’ aesthetic and environmental aspects commensurable. Thus, agencies will be able to establish monetary benchmarks concerning those aspects in early planning phases and embed them in tender documents as core specifications. The case study included illustrates the practical implementation of that approach, addresses the roles of both contractors and the agencies in it, provides valuable insights into the various bridge aspects and addresses shortcomings that require further attention.

Paper A includes the same case-study included in Paper II “the Karlsnäs Bridge”. However, Paper A looks to the problem from an environmental perspective. The paper provides full life-cycle assessments of the various designs considered. The author of this thesis contributed to Paper A by providing the full details of the included case study, the LCPs and quantities of materials required for the various included designs.

The main milestone achievements of the project were the development and implementation of the LCCA software tool BaTMan-LCC Further contributions to the state-of the-practice of LCCA in bridge investment and management were two intensive courses provided to teach bridge-specialists and managers in Trafikverket’s bridge investment and management divisions (regarded as “super-users”) how to use BaTMan-LCC in their daily work. These courses, and the BaTMan-LCC tool, are further described and discussed in Chapter 5.

A simplified efficient method for highlighting the feasibility of LCCA considering the network level is introduced and applied in all appended papers.

2 LCCA and BMSs

2.1 LCC and WLC Definitions

Life-cycle Cost (LCC) is the cost of an asset, or its parts, throughout its life cycle while it fulfills its performance requirements. Life-cycle costing is a methodology for systematic economic evaluation of the LCC over a specified period of analysis as defined in the agreed scope [28]. Whole-life cost (WLC) incorporates all the significant, relevant initial and future costs and benefits of an asset throughout its life cycle while it fulfills its performance requirements. Whole-life costing is a methodology for systematic economic consideration of all WLC and benefits over a specified period of analysis as defined in the agreed scope [28]. Life-cycle costing is sometime called life-cycle cost analysis (LCCA), particularly in the USA [21].

LCCA is appropriately applied to compare alternatives that would yield the same level of service and benefits to the project user [62]. The agency that uses LCCA has already decided to undertake a project or improvement and is seeking to determine the most cost-efficient means to accomplish the project's objectives. Unlike LCCA, whole-life costing, sometimes called benefit-cost analysis, 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) [62]. Moreover, whole-life costing can be used to determine whether or not a project should be undertaken at all.

Decision-makers could employ LCCA to specify the most LCC-efficient alternative. However, robust techniques for interpreting and integrating results of LCCA in real bridge procurement decision-making processes are lacking. It must be recognized in this context that the objective of LCCA is not exactly to minimize bridges' LCM costs. Agencies are developing design standards, codes and guidelines to minimize those LCM costs, and require contractors to follow them. The objective of LCCA is to minimize the LCC, which includes both INV and LCM costs. The most LCC-efficient bridge design is not necessarily the one that will deliver the lowest LCM costs or longest life-span. The most LCC-efficient proposal is the one with the lowest equivalent annual cost (EAC), which incorporates the INV cost, LCM cost and costs associated with variations in life-span, as highlighted in the case studies presented in Paper I, II and V.

2.2 LCC Categories of Bridges

Several LCCA systems are available. Although the basic calculations applied in each system seem to be similar, the cost categories included in the cost breakdown schemes differ to varying degrees [22][21]. Furthermore, there has been no consensus on the cost categories that should be included in the LCCA of new bridges to date. There are three reasons for establishing a LCC classification scheme or taxonomy for use when analyzing bridges' LCC. First, it should ensure that all costs associated with the project are taken into account. Second, it should allow for a detailed, consistent breakdown of LCC and net savings estimates at several levels, thereby providing a clear understanding of the cost differences between the material/design alternatives considered. Third, actual costs classified by the structural elements and categories can be used to compile historical unit cost data for use in future LCCA.

Figure 2 presents a scheme for classifying the total LCC of a bridge and Figure 3 presents the direct costs incurred during a bridge's life-cycle. There are indirect costs also which incurred by the users of bridge and society. The various bridge designs that could be feasible solutions for a specific bridge location will usually have different direct and indirect costs.

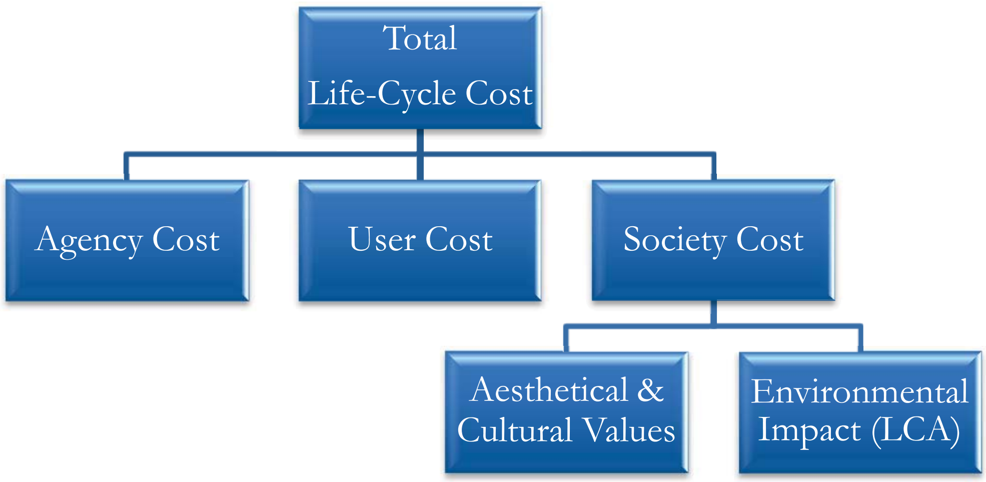


Figure 2. Life-Cycle Cost Categories of Bridges

The agency cost of a bridge could be defined as all direct costs incurred by an agency for acquiring it during its entire life-span, from idea until demolition. Figure 3 presents the typical bridge investment phases in Sweden, and the sequence of events associated with each direct cost category. The capital investment cost of a bridge could be defined as the total amount of money required to put the bridge into operation and can be divided into two categories: pre-contract and initial investment (INV) costs.

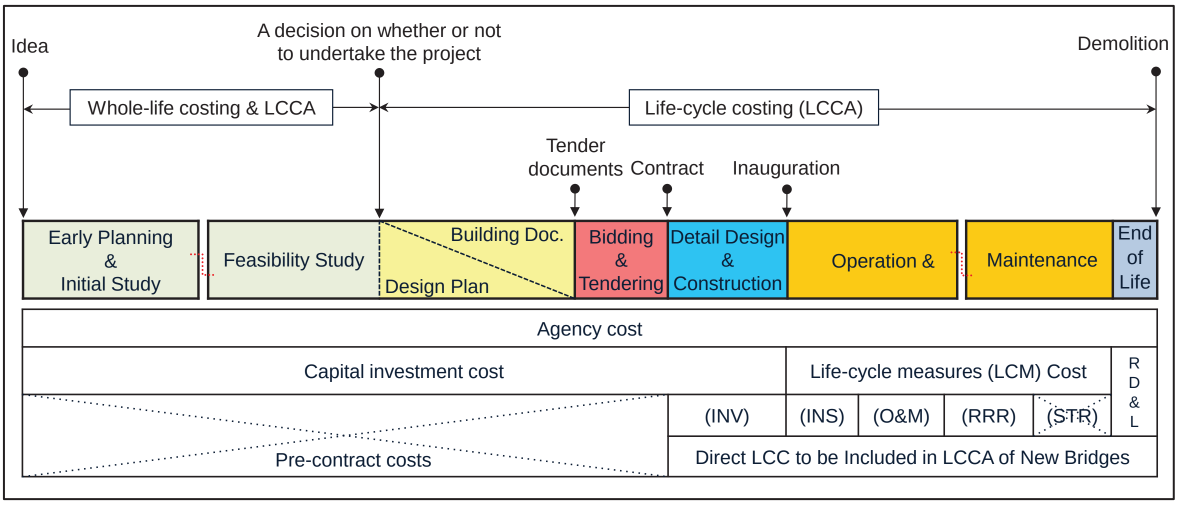


Figure 3. Bridge investment phases and the sequence of events associated with the agency's direct costs

The pre-contract costs are all costs paid by a bridge procurer from the time the bridge is an idea until a contract is signed with a contactor to construct it. The INV cost is the total amount of money paid from the time of signing the contract until the bridge’s inauguration. The INV cost is what the contractors normally request from the bridge procurer in their cost estimate “bids” in D-B tendering processes. The INV cost could include the cost of the construction material, construction and labor work, transportation, mobilization, contractor profit, taxes, management and overheads cost, etc. Different contractors usually offer different bids for a typical bridge design depending on several issues such as their capability and experience, profit margin, etc. The costs of measures required to keep the bridge serviceable during its life-span, from inauguration until demolition, are named life-cycle measures (LCMs) costs. The LCC of a bridge that should be included in a LCCA process of new bridges should include both the INV and LCM costs. However, only the LCMs required to maintain the bridge’s designed function during its designed service life-span should be included. Strengthening (STR) actions should not be included in the LCMs since they are intended not only to restore the original capacity of the bridge but to increase it. In addition, it is difficult to anticipate possible STR actions in an early planning phase.

2.2.1 Life-cycle measures (LCMs) cost

It is not possible to draw distinct lines between the various LCMs, which may have substantially differing purposes although the materials and methods are often similar. Repairing a concrete structure, for instance, often involves simply replacing damaged concrete and reinforcement with corresponding amounts 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. The LCMs included in the LCCA of a new bridge could include inspection (INS), operation and maintenance (O&M), repair, replacement and rehabilitation (RRR), recycling, demolition and landscaping (RD&L). Under D-B contracts, the LCM costs are ultimately incurred by agencies. Contractors under these contracts are not generally obligated in the long-run, and are not normally expected to provide any routine LCM during the lease period. However, they will normally be responsible for any non-routine LCM necessitated by potential design or construction mistakes.

When comparing various bridge designs in an early planning phase, all LCMs required to keep a bridge serviceable during its entire life-cycle should be considered. The unit cost of a certain LCM, such as regular inspection, could be the same for all bridge designs regardless of their type or outline. However, the reference quantities or BSMs that the LCMs would be applied to usually differ from one design to another.

Inspection

Along with the annual superficial inspection, two main kinds of bridge inspections are performed in Sweden: major and general. The purposes of a major inspection are to identify and estimate damage that may affect the function or safety of a structure within 10 years, and damage that may lead to increased maintenance and repair costs if not addressed within that time. The major inspection is performed for all BSMs, including those components underwater in daylight or equivalently lit conditions and from a distance of an arm's length. A major inspection is performed at least once every six years, and the inspector decides at the site when the next inspection should be performed. It is important to emphasize that the condition of the bridge is a major determinant of the frequency of inspections. Deteriorating bridges are inspected more frequently. The purposes of a general inspection are to monitor repairs, corrections or further propagation of damage identified during the last major inspection, and to identify and estimate the extent of any new damage that could lead to insufficient carrying capacity, traffic safety issues, or increased maintenance costs if not addressed before the next major inspection. Table 1 presents a recommended list of inspection activities to be considered in LCCA of new road bridges in Sweden, which are commonly applied to most road bridge types in the country.

Table 1. Inspection activities to be considered in LCCA of new bridges in Sweden

Activity	Recommended Intervals, years	Reference Quantity			Average Unit Cost in 2012, SEK
		%	of	Unit	
Regular superficial inspection	1	100	total bridge area	m^2	12
General inspection	3	100	total bridge area	m^2	40
Major inspection	6	100	total bridge area	m^2	70

In addition to these two types of inspections, a special inspection may be routinely performed for mechanical and electrical equipment on movable bridges. Special inspections are also performed whenever a regular inspection has indicated a need to investigate stated or presumed damage in more detail. Normally, only the specific damage or deficiency is investigated in these inspections.

Operation and maintenance (O&M)

The O&M actions applied to road bridges in Sweden differ from one bridge design to another, depending on several variables such as its structural members, location, and environmental conditions. Table 2 presents the common O&M actions performed on most road bridges in Sweden.

Table 2. O&M actions generally performed on most bridges in Sweden

Activity	Recommended Intervals (Year)	Reference Quantity			Average Unit Cost in 2012, SEK
		%	of	Unit	
Cleaning salts and gravel from the bridge	1	100	total bridge area	m^2	6
Cleaning and rodding the drainage system	1	100	drainage system points	St	325
Cleaning vegetation and other impurities from the bridge and cones	1	10	total bridge area	m^2	7
Maintenance and local repair of paving, surface finishes and lining	2	10	paved area	m^2	1,400
Maintenance of parapets, guardrail, safety screens and railings	2	10	railing length	m	250
Improvement of paintwork	2	5	painted area	m^2	900
Maintenance of joints and covering plates	2	20	joints length	m	800

Repair, replacement and rehabilitation (RRR)

According to BaTMan's handbook manual, bridges are broken down into 14 bridge structural members (BSMs). Detailed information about the various BSMs can be found in Appendix B. The RRR actions are the largest contributors to total LCM costs. The need for these types of actions is highly dependent on numerous variables, including the bridge type, location, type and quality of its BSMs, and environmental conditions. Table 3 presents rough LCPs for five

BSMs recommended for consideration in LCCA of new road bridges in Sweden, assuming a bridge life-span of 100 years. The methods used to assess those LCPs and the other assumptions involved are presented in Appendix B. In Table 3 a fixed time type means that the action should be performed once at a specific time while interval type means that the action should be performed at specified time intervals during the bridge's life-span. The probability of an action's necessity refers to the likelihood that it will be required. The costs of the actions presented in Table 3 are annually updated by Trafikverket and published in BaTMan's bridge LCM unit price lists.

Table 3. Recommended preliminary LCPs for five BSMs

Structural member name	Action type	Action time, year	Time type	Probability of the actions' necessity,%
Expansion joint	Refreshment	25	interval	100
	Replacement	50	fixed	60
Edge beam	Impregnation	25	interval	50
	Replacement	50	fixed	20
	Concrete repair	25	interval	20
Railing	Supplementation	25	interval	20
	Replacement	50	fixed	40
Bearings	Repainting	25	interval	40
	Replacement	50	fixed	35
Drainage system	Basic drain - retrofit	25	interval	100
	Basic drain - exchange	50	fixed	100
	Down pipes - exchange	50	fixed	100
	Surface drainage - supplementation	25	interval	100

2.2.2 Bridge user costs

Road bridges are generally intended for public use 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 and work-zone user costs (WZUC) [48]. Long-term user costs are due to permanent characteristics of the bridge. The establishment of a work-zone to safely construct or repair a bridge often disrupts the normal traffic flow above and/or under the bridge, which may increase normal travel times and thus WZUC incurred by the bridge's users. The WZUC are usually evaluated with respect to the traffic delay costs, additional vehicle operating costs and extra costs due to the increased risk of accidents. Appendix B presents equations for computing the various WZUC categories. The WZUC costs are not direct costs, as they do not affect the relevant agency's budget, but they do directly affect the public it serves [54]. Different bridge proposals are usually associated with different WZUC. The WZUC might be the main parameters considered during the bid evaluation process, especially if the bridge is situated over a congested road/railway or if it carries a large average daily traffic (ADT) volume. Figure 4 presents the possible sequence of a bridge's WZUC-incurring events, which should be considered (together with the associated costs) in the LCC analysis in order to consider the importance of avoiding traffic disruption and any other costs that could potentially be incurred by work-zone users.

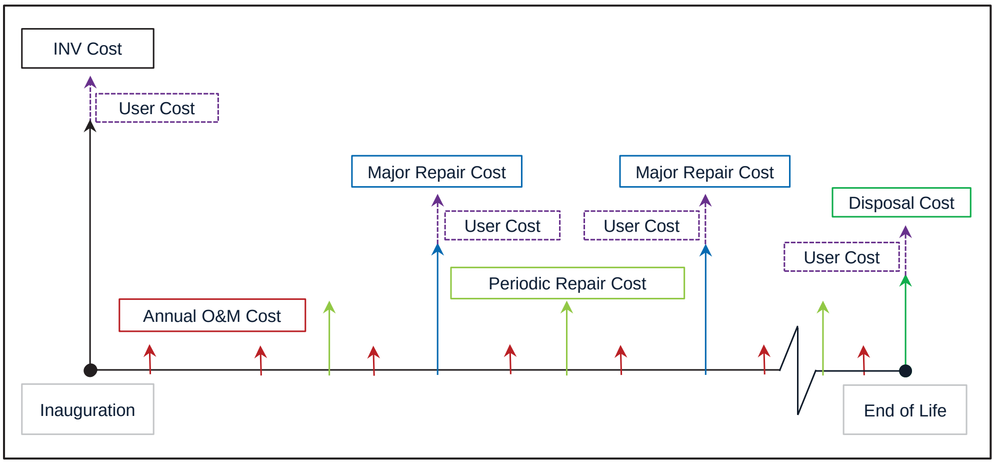


Figure 4 possible occurrence events of WZUC of a bridge

2.2.3 Bridges' aesthetic and cultural values

Bridges are sometimes seen as monuments and icons for a city or even a country [23]. Historic bridges manifest the power and influence of past societies, while modern bridges exploit the latest technologies and reflect the culture and engineering innovations of their society. For a bridge to be aesthetically successful, the aesthetic features must be integral parts of the design and should be considered in terms of both the general form and all the supporting details. Some design proposals have exceeded all cost estimates, but have been chosen because they were most aesthetically pleasing. Therefore, a "soft" value is associated with the appearance of bridges in some locations, particularly where there are high aesthetic demands. Paper V presents an approach for converting the aesthetic values of bridges into commensurable values that could be included in the LCCA of new bridges. That approach is based on a novel concept named the willingness-to-pay-extra. The inclusion of aesthetic values in the LCCA process leads to elimination of the worst aspects of bridge design and encourages the best.

2.2.4 Bridges' environmental impact

The effects of human activities on the natural environment have become increasingly clear in recent years, and environmental problems have attracted much attention. One issue raised in the construction of new infrastructure nowadays is its impact on the immediate environment. Thus, in addition to the traditional requirements for bridges, increasing attention is being paid to the environmental impacts associated with different designs, and different maintenance, repair and rehabilitation strategies. Paper V presents an approach for converting the environmental impact of various bridge designs into commensurable values that could be included in the LCCA of new bridges using life-cycle assessment (LCA) techniques. The concepts of willing-to-pay and willingness-to-pay-extra have been employed in that approach.

2.3 BMS

A bridge management system (BMS) with an integrated, comprehensive LCCA tool can be defined as a rational and systematic approach to organize and carry out all activities related to managing a network of bridges, including optimization of the selection of maintenance and improvement actions to maximize the benefits while minimizing the LCC. The development of BMSs with integrated LCCA tools has been necessitated by the disparity 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 inputs to determine the optimal actions to take on a network of bridges over time.

Many BMSs have been developed in different countries. Most of them address three aspects of bridge management: assessment of bridge conditions, modelling future deterioration, and the decisions to maintain, repair or rehabilitate [13]. BMSs can be classified as one of two types: network level or project level. Many agencies have adopted network-level BMSs to assist in budget allocation and prioritization within their total inventory of bridges. Report 590 of the US National Cooperative Highway Research Program (NCHRP) describes the development of methodologies for network- and project-level optimization of multiple, user-specified performance criteria. A BMS should include the following basic components: data storage, cost models, deterioration models, and optimization models, as shown in Figure 5.

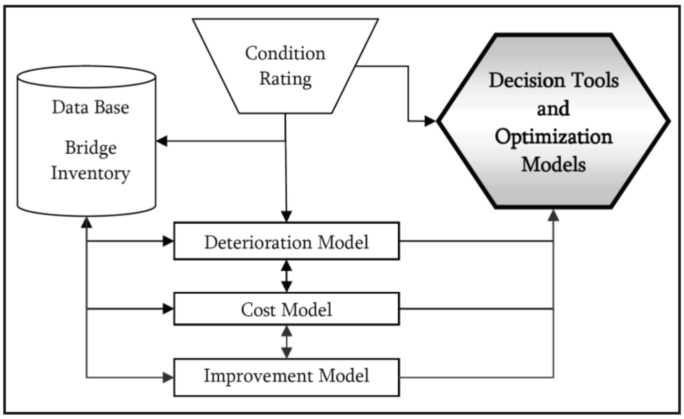


Figure 5. Basic components of a BMS (AASHTO, 2001)

The heart of a BMS is the database [13], which usually includes general information such as each bridge’s name, code or number, type, cost, construction year, location and coordinates, the manager's name, the owner's name, capacity and construction material. The types and quantities of the bridges’ BSMs and structural elements are also registered, together with as-built-drawings. All inspection records and LCMs performed are registered for each bridge. 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. Using the updated inspection records, the conditions of the bridges and their individual BSMs are rated according to specific methodologies. The decision tools and optimization models are required when an action is needed for the upkeep of a certain deteriorated bridge. A LCCA tool should be integrated with this section to compare the cost-effectiveness of possible repair strategies.

2.4 BaTMan

Sweden has a long tradition of bridge management [19]. Since 1944, information about the condition of the national road network has been documented and stored in different archives [35]. 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 not only by Trafikverket but also by other owners and managers of transport infrastructure in Sweden. 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 access updated information about all of the bridges included in the database online (https://batman.vv.se/). Furthermore, the system provides a separate navigation tool (WebHybris) that can access BaTMan’s database and answer related questions for any research or management purposes.

BaTMan is designed to facilitate operational, tactical and strategic management, incorporating systems and tools for collecting, storing, processing, analyzing and presenting administrative, technical and inspection data. It includes codes and manuals that provide guidance for carrying out bridge management activities as properly and uniformly as possible. The inspection manual provides information on bridge types, their structural members, types of damage and their causes. As well as 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 All available information on the repair, strengthening and maintenance of the bridges, including costs of the operations, is also provided. BaTMan is recognized as the best-known software-based digital BMS in Europe [42].

2.4.1 BaTMan’s Condition Class System

The main purpose of bridge inspections is to establish the physical and functional conditions of a bridge’s structural members and hence 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 a condition class (CC) [43], which describes the extent to which a certain structural member satisfies the designed functional properties and requirements at the time of inspection. In BaTMan, the bridge inspectors are responsible for assessing the residual service-life of the BSMs as well as the entire bridge. Together with the inspectors' own experience, well-established tools and devices, based on thoroughly verified methods and principles, are used to assess the CC of the various BSMs.

In contrast to many BMSs, BaTMan does not contain deterioration models. However, some inspection devices are equipped with integrated deterioration models that can help the inspectors to anticipate the future performance of each inspected BSM. Thus, the assessment of the condition classes is based on previous and current measured values (the physical condition) and the inspector's competence in evaluating the likely propagation of deterioration processes. The CC for a structural member can be registered on a scale ranging from 0 to 3, as summarized in Table 4.

Table 4. Condition classes (CC) 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
1	Defective function within 10 years	Action has to be taken within 10 years
0	Defective function beyond 10 years (No damage at time of inspection)	No action is needed within the coming 10 years

Using the CC system, the functional conditions of the BSMs are automatically converted to numbers that can be easily used in an LCCA. This CC system is a highly useful feature of BaTMan that is not shared by the condition rating system used in Pontis (a BMS used by more than 40 state departments of transportation in the USA). Another term used by Trafikverket is the overall condition class (OCC), which reflects the function of an entire structure with respect to its bearing capacity, traffic safety and durability. The OCC for a bridge is determined from the assigned CC for each of its structural members. The assigned condition classes are given different weights, and each type of BSM and the associated structural elements are clearly defined in several Trafikverket publications.

2.5 Bridge Stock in Sweden

Currently, 29,751 bridges in Sweden (with a total length of 539,184 m and total area of 6,547,941 m^2, equivalent to 0.83 m^2/capita in 2013) are registered in BaTMan. Around 80% of those bridges are registered in BaTMan as road bridges, 14.5% as railway bridges and the rest as pedestrian or “other function” bridges. About 58% of the road bridges are registered as bridges carrying public roads and 15% as bridges carrying private roads. Trafikverket is responsible for about 83% of the bridges, thus it is by far the largest bridge manager in Sweden. Table 5 presents summary statistics of the bridges owned and managed by Trafikverket. Further details about the road bridges owned by Trafikverket can be found in Appendix B.

Table 5. Trafikverket’s Bridge Stock

Bridge function	Number of bridges	% of total number of bridges	Bridge total area (m^2)	Bridge total length (m)
Road	20,318	82.68%	5,358,183	454,010
Railway	3,837	15.61%	838,321	99,156
Pedestrian & Cycling	404	1.64%	97,627	20,451
Other functions	15	0.06%	18,461	1,088
Grand Total	**24,574**	**100%**	**6,312,592**	**574,705**

About 78% of Trafikverket’s road bridges are registered in BaTMan as bridges carrying general roads and 21% as bridges carrying private roads. Based on the construction years registered in BaTMan for the bridges presented in Table 5, about 85% of Trafikverket’s road bridges were constructed after 1950. Thus, Trafikverket has built roughly 280 road bridges, with an average total area of 80,000 m2, per year since 1950. Proportions of Trafikverket’s road bridges in different total length classes are presented in Figure 6. As shown in this figure, about 56% of Trafikverket’s road bridges are shorter than 10 m while 96.7% are shorter than 100 m.

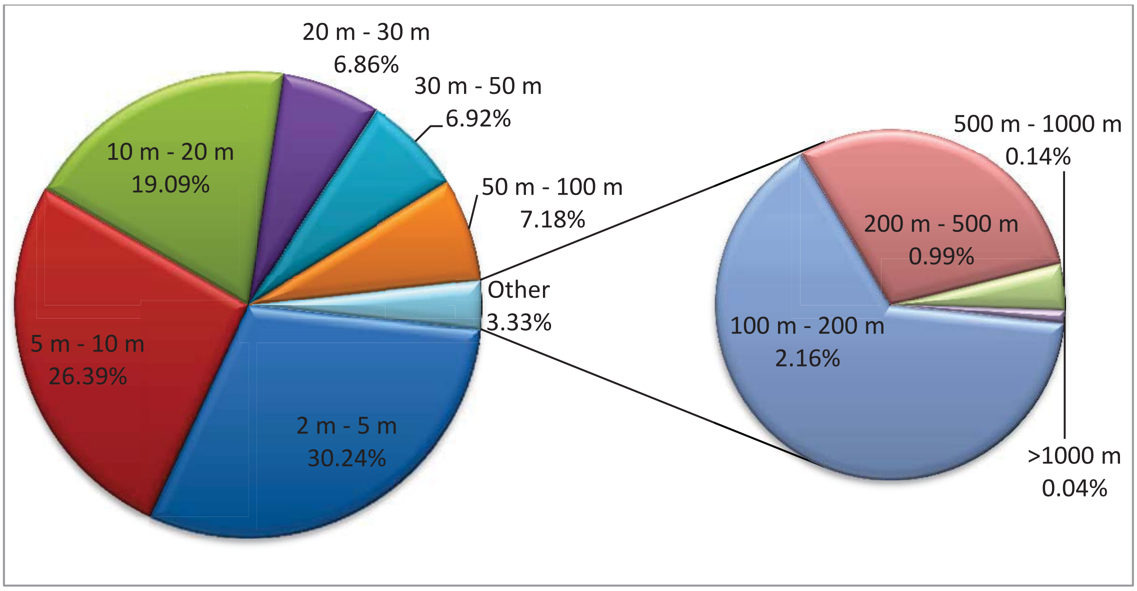


Figure 6. Proportions of Trafikverket's stock of bridges in indicated total length classes

Figure 7 schematically presents construction material and the bridge types of Trafikverket's bridges stock presented in Table 5. The different types of bridges according to the Swedish system are clearly defined in Trafikverket’s publications. As shown in Figure 7, the most common bridge types in Sweden are concrete slab-frame and steel culvert bridges.

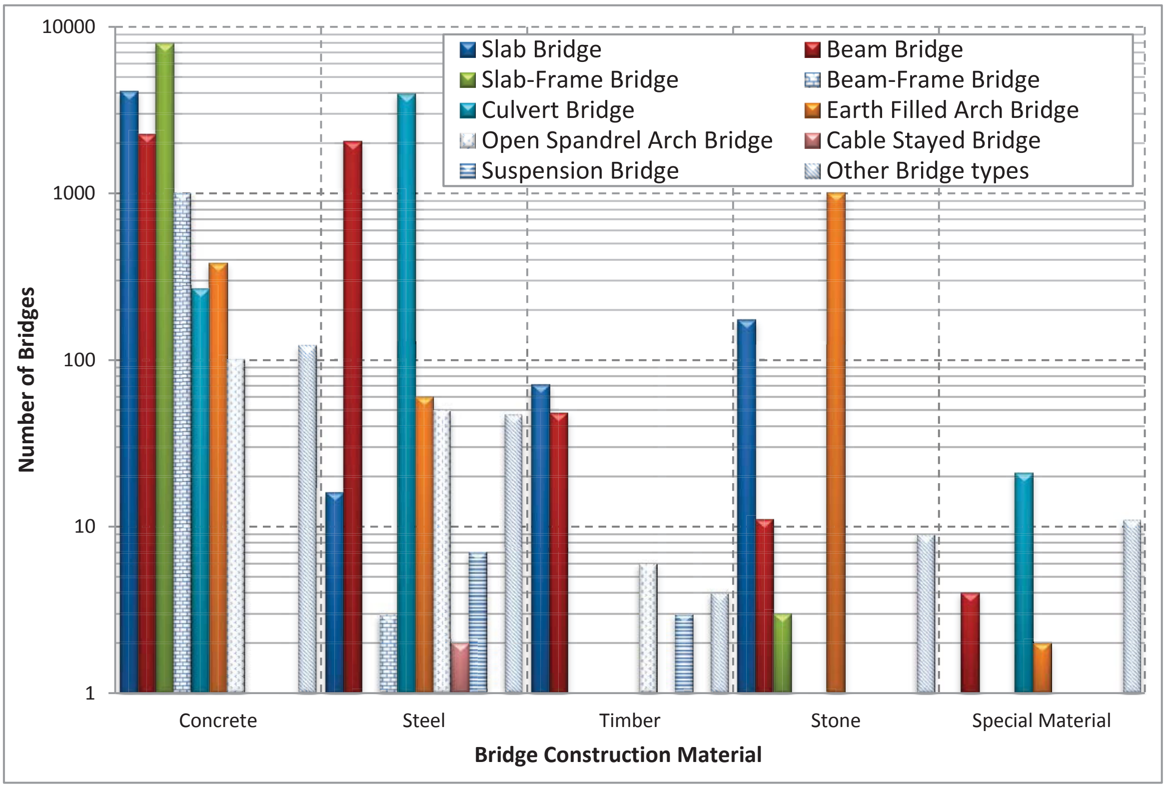


Figure 7. Bridge and construction material types of Trafikverket's bridges

A bridge may consist of several spans with different lengths, possibly constructed from different bridge types. Figure 8 presents the bridge types and length categories of the various spans make up the Trafikverket’s bridges presented in Table 5. The total number of spans composed on Trafikverekt’s bridges presented in Table 5 is 40,556 spans. The main construction materials of 71, 24, 4 and 0.82% of these spans are concrete, steel, stone and timber, respectively. The rest are largely constructed from aluminium or other material. The data in Figure 8 are based on 39,017 spans comprising 24,094 road and railway bridges. As shown in this figure, around 85% of the spans are shorter than 30 m, 27% are 10 m to 20 m long, 26.5% are 2 m to 5 m long, and 19.5% are 5 m to 10 m long. The most common bridge type for a span between 2 m to 5 m is the culvert type while the slab-frame bridge type is the most common for spans between 5 m to 10 m.

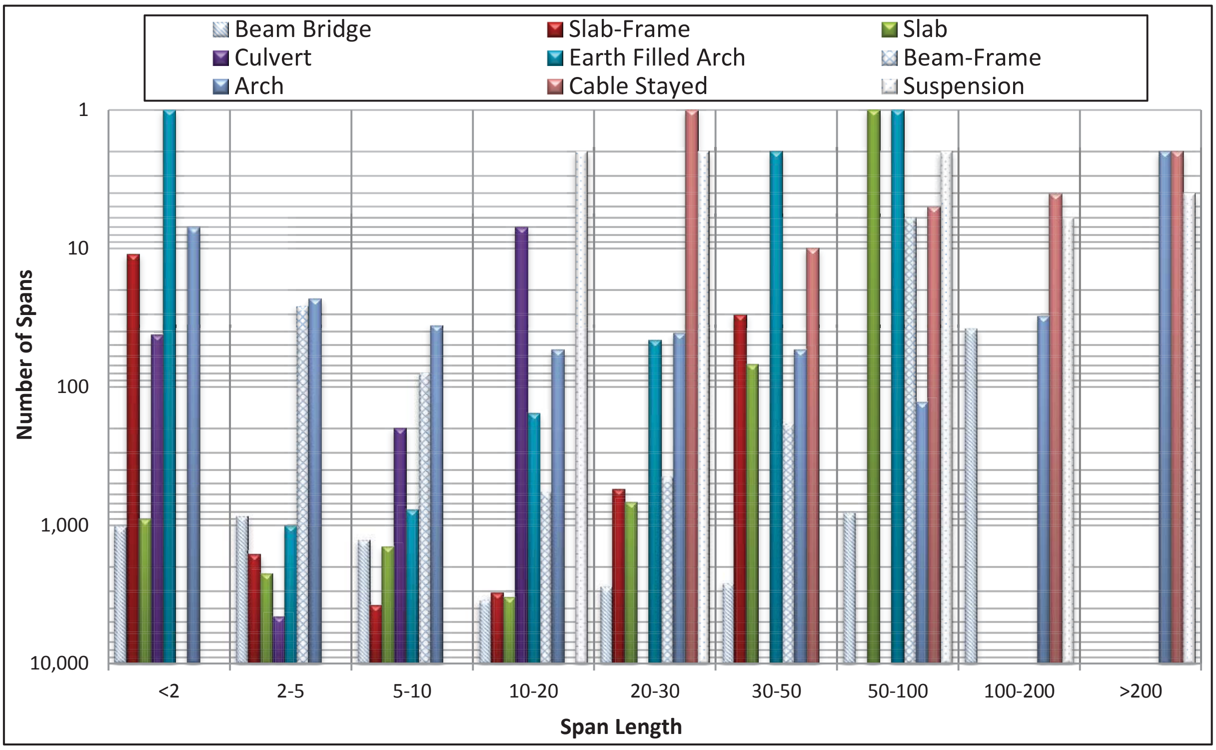


Figure 8 Numbers of spans of each span class and the bridge types make the various span classes in Sweden

2.6 Design Service Life-spans of New Bridges

In current design codes a specific fixed service life is usually set, and if the detailed design recommendations and specifications are satisfied, and the planned LCMs are properly performed, the bridge is likely to reach that expected service life. Usually this approach is called the deemed-to-satisfy approach [61]. Trafikverket defines three life-span classes: 40, 80 and 120 years, see Table 6. The meaning of the durations in Table 6 is not entirely clear, but one can assume that “minimum” means the lower 5th percentile [35]. This interpretation seems reasonable as it is in line with characteristic values for concrete and steel in Swedish regulations and these are the main construction materials of almost all of the bridges in Sweden.

Table 6. Technical bridge life-spans (Trafikverket, VGU 2004)

Class	Min (years)	Median (years)	Type of bridge
TLK 120	120	150	Bridges with a span >200 m or length >1,000 m
TLK 80	80	100	Other bridges, culverts
TLK 40	40	50	Culverts

Requesting a fixed service life in the tender documents under D-B might both remove solutions with shorter life-spans from consideration and disadvantage proposals offering longer life-spans. However, in some cases, a short life-span alternative may be more LCC-efficient than a long life-span alternative, particularly for example when comparing conventional concrete bridge options with steel culverts for short-span bridge locations. Thus, the incorporation of LCC added-values in analyses of proposals offering different life-spans will broaden the range of proposals that could be considered and potentially provide great savings for agencies and society.

2.6.1 Recommended design life-spans for LCCA of new bridges in Sweden

Table 7 presents recommended design life-spans for the various Swedish bridge types, based on the data in Table 6, the survival analysis presented in [35] and the recommended LCPs for the various BSMs presented in Appendix B. These recommended life-spans should be used in the preliminary LCCA process performed by an agency in an early planning phase to compare proposed bridge designs for a certain bridge location. The life-cycle added values computed for the various bridge designs should be based on these recommended design life-spans and contractors should be pre-informed.

Table 7 Recommended design life-spans LCCA of new bridges in Sweden

Type of bridge	Construction material/ Environment	Recommended design life-span (years)
Bridges with a span >200 m or length >1,000 m	Steel, concrete or both	120
Other bridges	Steel, concrete or both	100
Steel culverts	On water or wet conditions	60
	On land or dry conditions	80

2.7 Discount and Inflation Rates

One parameter that could significantly affect LCCA results is the discount rate considered. Theoretically, applying a high discount rate will tend to favour alternatives with low INV costs, short life-span and high LCM costs, and vice versa. Generally, the discount rate has greater impact in bridge management than in bridge investment. This was highlighted in the case studies included in the appended papers. In bridge investment, the major factor affecting LCCA results is the INV cost of the various alternatives, which is not affected by the discount rate. However, in bridge management the main parameter affecting results is the considered strategies' effects on the residual service life of the focal bridge or BSM. Sensitivity analysis of the impact of varying the discount rate on the final decision is highly important in both bridge management and investment, as it allows decision-makers to evaluate their confidence that they have chosen the optimal solution. Usually, when the NS is substantial, variation of the included discount rate will not substantially influence the final decision and vice versa.

Inflation should also be taken into account. In economics, inflation is a rise in the general level of prices of goods and services in an economy over a period of time. Consequently, inflation reflects a reduction in "purchasing power" per unit of money. As a simple example, assume a person deposits 100 SEK in a bank for one year at a 4% interest rate. This means that the bank agrees to return 104 SEK to the person after a year, irrespective of the amounts of goods or services that he or she can then buy for this sum. The sum of 104 SEK is nominal (not adjusted for the impact of inflation), thus 4% is the nominal rate of return on that person's investment.

If the rate of inflation is expected to be 2% next year, prices prevailing today are expected to rise by 2% in the coming year. If so, goods or services that can be bought for 1 SEK now could be bought for 1.02 SEK next year. Thus, the purchasing power of 1.02 SEK next year would be equivalent to that of 1 SEK today, and the purchasing power of 104 SEK received next year would equal 104/1.02 (101.96) SEK, meaning that the 104 SEK received next year could buy goods worth 101.96 SEK now. The 104 SEK next year and 101.96 SEK today are equivalent in terms of purchasing power if the rate of inflation is 2%. The 104 SEK is expressed in nominal terms since the sum has not been adjusted for the effect of inflation. In contrast, the 101.96 SEK is a real-terms sum since it has been adjusted for the effect of inflation. Therefore, the 4% nominal rate of return means a 1.96% rate of return in this example. However, it should be emphasized that the rate of inflation is an expected rate, so the real rate of return is also an expected rate. In addition, the actual rate of inflation may differ (sometimes dramatically) from the expected rate.

2.7.1 Recommended discount rate for LCCA in bridge investment

According to the notations of Trafikverket 2013, a discount rate of 3.5% should be considered in LCCA. The main question in this respect is whether this 3.5% discount rate refers to a real or nominal discount rate. In other words, does that 3.5% discount rate include the inflation rate or not? We should treat inflation consistently. The discount rate is generally market determined and is usually stated in nominal terms. An intensive analysis of an array of unit-price lists for the various bridges' LCM costs published annually by Trafikverket from 2008 to 2012 detected an average inflation rate of 1.5 - 2.5%. This inflation rate should somehow be included in the LCCA. There are several methods for handling the inflation rate in LCCA. One is to consider the real costs of the LCMs at their times of occurrence instead of their present costs. Another practical way is to deduct the inflation rate from the nominal discount rate. Thus, a real discount rate of 2% is recommended in a LCCA process performed in an early planning phase to compare different feasible bridge designs for a certain bridge location in Sweden.

3 LCCA Applications and Obstacles

3.1 LCCA Applications for Bridges

In order to implement LCCA for bridges effectively it is important to be familiar with the various bridge investment phases and the associated activities. Familiarity with the various forms of bridge contracts and the public agencies' established procurement procedures is also highly important. Figure 9 shows the typical Swedish bridge investment phases, the possible applications of LCCA for bridges and the saving potential of those applications. Similar figures are included and discussed in Papers I and III. However, after publication of the papers, in February 2013, Trafikverket introduced a minor modification to the standard bridge investment phases presented in them. Therefore, Figure 9 is an updated version of the figure included in the papers, based on Trafikverket's modified rules. Trafikverket's modification concerning the bridge investment phases is briefly discussed and another possible application of LCCA for bridges is addressed below.

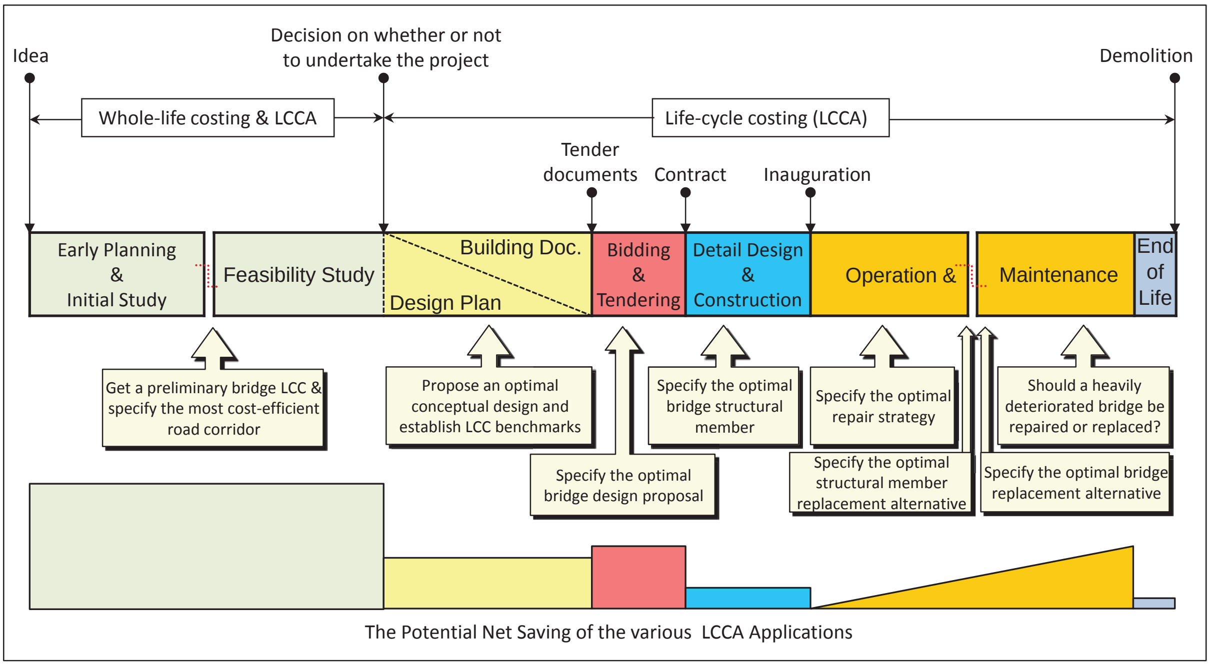


Figure 9. Bridge investment phases in Sweden, the possible LCC applications and their saving potential

The main change in bridge investment phases introduced in Trafikverket's 2013 rules is the combination of the feasibility study, design plan and building documents phases in a single investment phase instead of three separate phases. This is intended to facilitate the handling of bridge procurement and eliminate some technical constraints. However, the internal activities and tasks involved will be the same, regardless of whether the phases are separate or combined, which is why dashed lines have been drawn between these phases in Figure 9.

From a LCCA perspective, that modification could significantly improve the possibilities of implementing LCCA in bridge procurement. Previously, if a conceptual design for a planned bridge was chosen in one of those phases, it would be very difficult to change it in a later phase due to the separation. However, under this combination, the staff handling all tasks work together and several obstacles have been removed.

3.2 LCCA and structural-health monitoring systems

A possible application for LCCA in bridge management, not included in the appended papers, is in monitoring bridges' structural health. Advanced health monitoring systems are widely used nowadays in the bridge industry, and several studies have examined their potential for extending bridges' residual service life-spans. However, there have been few reliable investigations of their cost-effectiveness, which could be addressed by LCCA.

This approach could be applied when a heavily deteriorated bridge or a bridge's super-structure, for example, needs to be replaced after a specific number of years according to inspection records and LCCA results. Since uncertainty is involved in the assessment of the time when the replacement action will be needed, advanced structural health-monitoring systems could be installed to closely monitor the bridge's condition and damage propagation. This might allow the anticipated residual service life of the bridge to be extended by some estimated time, and LCCA could be applied to compare costs of the required monitoring systems and the cost equivalent of the potential extension of the bridge' residual service life. The case study included in Paper I is used as an example to illustrate this application.

Figure 10 presents results of a sensitivity analysis of the uncertainty's impact on the final decision for the assessed bridge's residual service life without action.

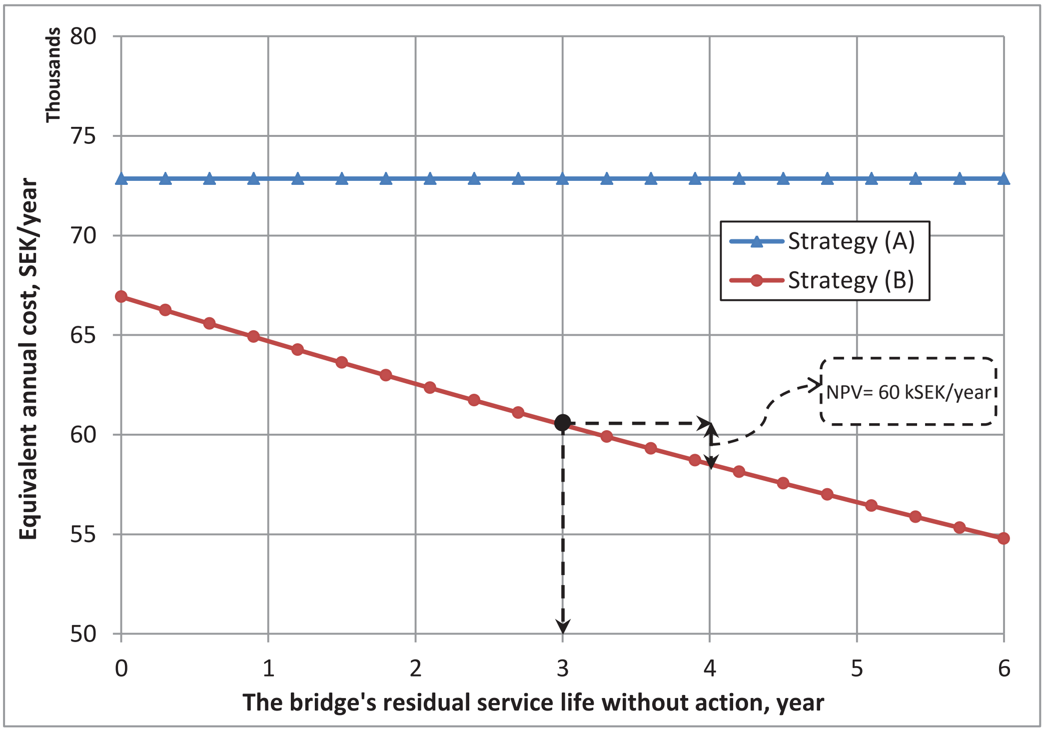


Figure 10 Results of sensitivity analysis of the cost-effectiveness of installing structural-health monitoring systems in the case study presented in Paper I

Strategy A in this figure refers to "immediately repair the bridge", while strategy B refers to "utilizing the bridge's residual service life without action then replacing it with a new bridge". Assessment, based on the bridge's inspection records, indicates that the bridge's residual service life, without action, will be three years. As shown in Figure 10, the sensitivity analysis confirms that strategy B is the most cost-efficient strategy, regardless of the residual service life extension. The LCCA results presented in this figure show that the cost equivalent of replacing the bridge after four years instead of three years is equal to 60,000 SEK (approximately 4% of the cost of a new, similar bridge). Therefore, it would only be cost-effective to install health-monitoring systems if they can ensure a residual service life extension of at least one year and they cost less than 60,000 SEK. The viability of this application would be clearest for large, heavily trafficked bridges.

3.3 LCCA Implementation Obstacles

BMSs as well as LCCA applications and implementations for bridges have long been subjects of intense interest. Several important recent research and development studies have provided valuable tools and resources that were previously unavailable. Current challenges involve systematically compiling, integrating, processing and interpreting the increasing volumes of information to help manage bridges throughout their life cycle as effectively as possible [49]. An obvious gap between the practice and theory of LCCA has been detected and discussed in several research articles [33].

3.3.1 Bridge investment and management from a LCCA perspective

The main difference between bridge management and bridge investment, from a LCCA implementation perspective, lies in the procurement method. In public agencies, both bridge investment and management procurements are usually conducted through a tendering process. A bridge management decision-maker may investigate the feasible repair strategies to identify the optimal strategy before inviting tenders. Thus, LCCA could be employed to identify the most LCC-efficient strategy. After the (hopefully) optimal strategy has been identified it is usually specified in the tender documents as the target strategy that all contractors should consider when preparing their bids. Since all the bids then provide cost estimates for an identical strategy, the lowest bid is properly employed in this context as the criterion for selecting a contractor. However, this is not usually the case in bridge investment.

In bridge investment processes, a decision-maker could also investigate the technically feasible bridge designs for a certain bridge location before inviting tenders and LCCA could also be employed in this context to identify the most LCC-efficient bridge design. However, that design could not usually be stated in the tender documents as the only target design, particularly under D-B.

Contractors under D-B are usually free to choose the design characteristics, considering the description of the required function stated by the agency in the tender documents. Consequently, a bridge procurer might have to choose one of several proposals. Even though all the proposals fulfil the design standards and provide the required functional performance, the proposed designs may differ radically in terms of construction material, bridge type, bridge layout, and BSMs. Furthermore, the associated INV costs, LCM costs and life-spans may also substantially differ.

Due to the lack of other reliable, credible and transparent award criteria, the lowest bid is currently used as the sole criterion for choosing a contractor under D-B and no consistent LCC guidelines are stated in the tender documents. Consequently, the contractors' bids usually include only the proposal's INV cost, ignoring the LCM costs. Thus, use of the lowest bid criterion may cause huge losses for agencies and society in some cases since it might result in implementation of proposals that are relatively cheap in terms of INV costs, but very expensive in LCC terms. A D-B tendering process combined with the lowest bid criterion does not normally stimulate the contractors to think about the LCC aspects. Thus, current bridge procurement models are clearly not delivering the best value for taxpayers' money [41], and a new award criterion that takes LCC aspects into account under D-B should be employed. In addition, this new award criterion should be part of a comprehensive approach that maintains not only the contractors' freedom under D-B contracts, but also a credible and transparent procurement process, as further discussed in Paper II.

3.3.2 Obstacles: Bridge management

Many bridge management studies have treated BMSs and LCCA as separate rather than as strongly inter-related complementary tools, which may reduce their utility for decision-support. Moreover, some bridge inventory and inspection systems do not make use of LCCA. The main obstacles hinder the implementation of LCCA in bridge management could be concluded as follow:

- The lack of a comprehensive framework clarifying the possible applications of LCCA in bridge management
- Shortcomings of conventional LCCA sub-techniques that obscure the value of LCCA applications in bridge management'?
- The limited access to reliable, detailed historical bridge cost and repair records
- The shortage of reliable case studies illustrating the potential practical implementation of LCCA applications and addressing parameters that could affect LCCA results
- The lack of competence and knowledge within agencies of LCCA and its possible applications and implementation within bridge management
- The complex internal structure of large governmental transport agencies, the inflexibility of their established procurement and budget allocation procedures and the difficulties in amending those procedures
- The difficulties in formulating parameters included in LCCA that are inherently uncertain
- The lack of web-based BMSs with cradle-to-grave, integrated, comprehensive LCCA tools that could assist decision-makers at all levels during all phases to select the most cost-efficient solution
- The complexity of some bridge management cases in which several parties, aspects and concerns other than the direct costs are involved in the decision-making process

The studies presented in Papers I, III, and IV are all attempts to improve the current state-of-practice of LCCA in bridge management.

3.3.3 Obstacles: Bridge investment

LCCA is rarely applied as yet to support decisions related to investment in new bridges, although it has great saving potential. Since it involves adjusting established procurement procedures, the implementation of LCCA in bridge investment seems to be more difficult and more demanding than its implementation in bridge management. The main obstacles hindering the implementation of LCCA in bridge investment can be summarized as follows:

- The lack of competence and knowledge among both transport agencies and contractors of the possible applications of LCCA and the potential savings it can deliver in bridge investment
- Shortcomings of conventional LCCA sub-techniques that hinder clear interpretation, interpolation and presentation of the results of prior LCCA in tender documents
- The limited access to reliable data sources and the difficulties in assessing LCCA parameters that are inherently uncertain
- The lack of reliable, unified LCPs for the various BSMs taking into account the variety of conditions
- The shortage of reliable case studies illustrating the potential practical implementation of LCCA applications and addressing the parameters that could affect their results
- The complex internal structure of large governmental transport agencies, the inflexibility of their established procurement and budget allocation procedures, and the difficulties in amending those procedures
- The lack of user-friendly tools capable of performing reliable LCCA for new bridges and clearly presenting the results in the tender documents in a legally acceptable manner.
- The complexity of some bridge investment cases, in which several parties, aspects and concerns other than the direct LCC may significantly influence the decision-making process
- The absence of a reliable, systematic approach that combines and integrates the various bridge life-cycle aspects into decision-making processes and can also be conveniently integrated with established procurement procedures

Papers I, III, and IV all present attempts to improve the current state-of-practice of LCCA in bridge investment**.**

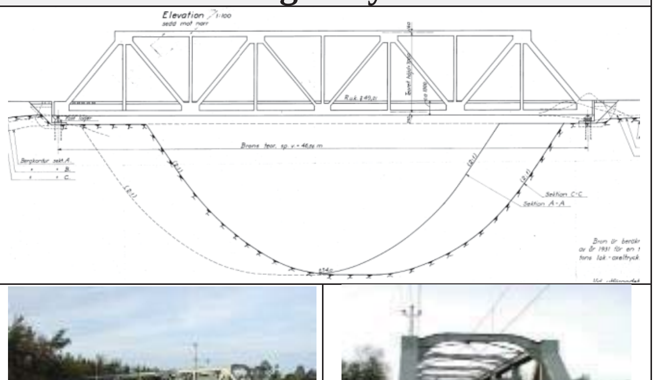
4 LCCA for Railway Bridges: A Case Study

The case study below illustrates how an agency could apply its bridge BMS to support a decision on whether a heavily deteriorated railway bridge should be repaired or replaced based on LCCA. Papers I and III present similar case studies, but for clarifying the implementation of LCCA applications to road bridges. The main intention of the case study below is to demonstrate how LCCA applications could be implemented to optimize the repair or replacement of railway bridges and clarify the differences between railway and road bridges in that perspective.

4.1 Existing Bridges

Sometimes a choice must be made between two or more strategies to maintain a specific bridge. Huvudnäskanalen Bridge in Sweden, a simple supported steel truss railway bridge (total length 47 m, total width 5.7 m; Table 8) was constructed in 1937. The number of this bridge in BaTMan is 3500-2593-1. The condition of the superstructure, bearings and the electrical cable tray of this bridge has been designated class (CC) 3: requiring immediate action. However, few viable upkeep strategies are available. A LCCA process to investigate if this bridge should be repaired or replaced is presented below.

Table 8. Layout of Huvudnäskanalen Bridge and general information according to BaTMan

<table>
<tr><th>Bridge General Information</th><th colspan="2">Bridge Layout</th></tr>
<tr><td rowspan="2">Bridge name: Bro över Huvudnäskanalen km 29+709
Bridge number in BaTMan: 3500-2593-1
Bridge type: simple supported steel truss
Construction year: 1937
Bridge total length= 47 m
Total width= 5.7 m
Bridge area= 268 m^2
Mid-section water depth: 12 m
Superstructure depth restrictions <1.8 m</td><td colspan="2"></td></tr>
<tr><td></td><td></td></tr>
</table>

4.2 Repair Strategy

There is a choice between immediately repairing the bridge and utilizing its residual service life without action then replacing the entire bridge, as schematically illustrated in Figure 11 and Figure 12, respectively.

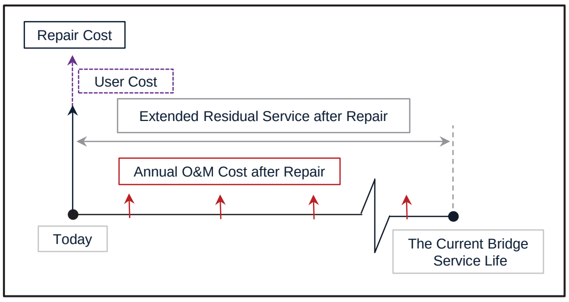


Figure 11. Strategy A: Immediately repair the bridge

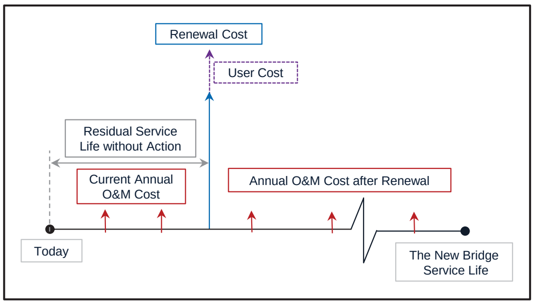


Figure 12. Strategy B: Utilize the bridge for its residual service life without action and then renew it

Using the 2012 BaTMan unit-price list for the various bridges' LCMs, it is estimated that the repair strategy will cost 2.23 Million SEK (as shown in Table 9). The bridge is currently 76 years old, and several similar bridges that are more than 120 years old are still in service. Furthermore, statistical analysis of extensive historical data extracted from BaTMan related to similar actions applied to similar bridges indicates that the repair strategy would extend the bridge's residual service life by at least 25 years. The strategy proposed by the bridge specialist at Trafikverket who is responsible for this bridge is lighter than the strategy summarized in Table 9.

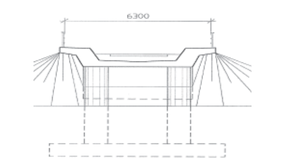
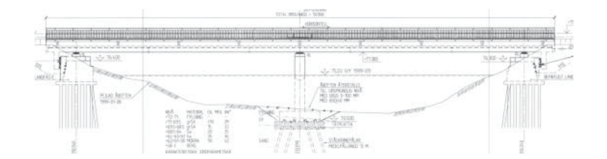
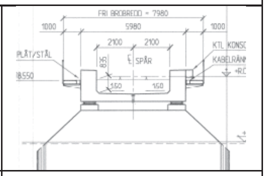
Table 9. Repair strategy cost

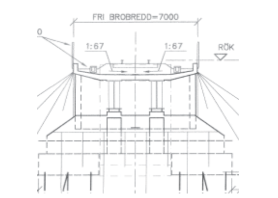
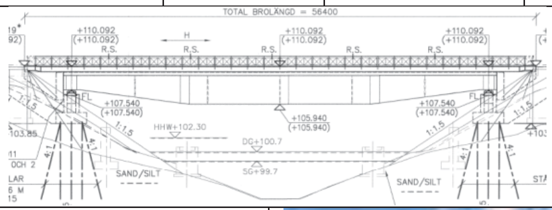
Activity	Quantity	Unit	Cost SEK/unit	Sub-Total (SEK)
Repaint the entire bridge superstructure	940	m^2	1,700	159,8000
Replace the bridge bearings	4	unit	33,000	132,000
Repair and fix all secondary **damage**				250,000
Overheads and Mobilization				250,000
Total				2,230,000

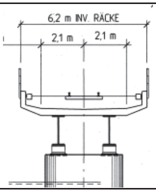
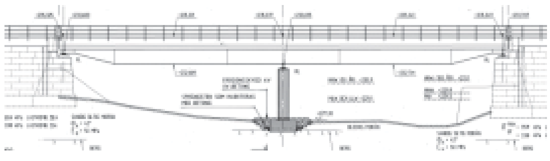
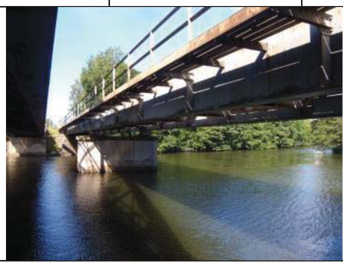
4.3 Replacement Strategy

Currently, although BaTMan's inventory data can be accessed via Webhybris, decision-makers at Trafikverekt do not effectively benefit from it. Using the Webhybris tool, historical data related to similar existing bridges have been extracted from BaTMan. Based on a deep classification and analysis of the extracted data, four replacement proposals are considered technically feasible, as summarized in Table 10.

Table 10. Technically feasible replacement options

No.	Bridge type and construction material	Anticipated INV cost, 2012 SEK/m^2	Anticipated INV cost Million SEK	Similar bridge No.	Remarks
1	Pre-stressed concrete, two continuous spans, beam or slab bridge type	36,000	10.7	3500-1522-1 3500-2048-1 3500-4810-1 3500-4391-1 3500-5909-1* 3500-5757-1* 17-1271-1* 3500-5776-1	• Is it possible to have an intermediate support? • The mid-span water depth is 12 m. • Bridge 3500-4834-1 is a one-span concrete bridge with a 36.5 m span, the anticipated super-structure's depth for a similar one-span concrete bridge with a 47 m span is 3.6 m • 3500-5776-1 is a slab bridge with 2 m depth
					
					

No.	Bridge type and construction material	Anticipated INV cost 2012, SEK/m^2	Anticipated INV cost Million SEK	Similar bridge No.	Remarks
2	Simply supported beam bridge, steel-concrete composite, beam bridge type	72,000	20.3	3500-1517-1 3500-5288-1 3500-5703-1* 3500-1925-1 3500-5338-1 3500-575-1	• Bridge no. 3500-1517-1 is a typical bridge! • Need superstructure depth =3.8 m, is it possible to decrease the free height?
					
					

No.	Bridge type and construction material	Anticipated INV cost, 2012 SEK/m^2	Anticipated INV cost Million SEK	Similar bridge No.	Remarks
3	Two continuous spans, steel-concrete composite, beam bridge type	48,000	13.9	3500-1588-1	• Need superstructure depth of 2.2 m? • Intermediate support?
					
4	Two continuous spans, steel with a timber slab, beam (open-deck) bridge type	34,000	10.1	3500-3451-1	• Need superstructure depth of 2 m? • Intermediate support?
					

A major limitation when applying LCCA for optimizing the repair or replacement of railway bridges in Trafikverket is that cost records for very few bridges are registered in BaTMan. This makes it difficult to assess the INV costs of various technically feasible designs in an early planning phase. The asterisks beside some bridge numbers in Table 10 indicate that the INV cost (in SEK/m2) of the respective bridges was used to anticipate the INV cost of a new, similar bridge for the bridge location in this case study. Option 2 in Table 10 might not be technically feasible because this type of structure with a 47 m span length needs a minimum superstructure depth of 3.8 m, which could not be accommodated in the bridge location due to the limited free height.

4.4 LCCA

The analysis was conducted in two steps: identification of the optimal replacement option followed by comparison of the LCC-efficiency of the optimal replacement proposal and the repair strategy summarized in Table 9.

4.4.1 Identification of the optimal replacement option

The LCCA was based on the relevant data for the considered proposals presented in Table 10 (all of which were assigned a design service life-span of 100 years). The LCCA (which considered only the bridge’s INV and annual O&M costs) showed that proposal 1 is associated with the lowest net present value (NPV). However, it was selected as the most LCC-efficient replacement option as it would avoid the need for regular painting, unlike the steel options, hence the associated INV and LCM costs would be low.

Road and railway bridges from a LCCA perspective

The main difference between railway and road bridges to consider when performing such LCCA is in traffic management. Several traffic control plans can usually be applied during the implementation of the possible strategies on road bridges. However, it is not usually possible to close railway bridges or disrupt the train schedule for more than a few hours, as the trains cannot usually be diverted to another route. Therefore, the most important factor that could significantly affect the final choice of repair or renewal strategy is the time needed to perform the required actions. In addition, railway bridges are usually more sensitive than road bridges in which the acceptable damage or deformation in road bridges might not be permitted in railway bridges. The LCMs applied on railway bridges differ from those for road bridges since some BSMs composed in road bridges do not exist in railway bridges such as asphalt pavements. The deterioration rates of the various BSMs in railway bridges are generally lower than those in road bridges since no deicing chemicals or salts are used in railway bridges. However, the railway bridges in most countries are generally older than road bridges which might require more LCMs and LCCA attention.

In this case study, the passage of trains would not be affected during the replacement activities since the new bridge would be temporarily built beside the existing one and subsequently side-launched to the location of the existing bridge after removing it. This process is estimated to take around 24 hours, which would be permitted according to the train schedule for the rail corridor in which this bridge is situated. The intermediate support of the new bridge could be built under the existing bridge without disturbing the train passage.

4.4.2 Replacement or repair optimization

In this step, the LCC efficiency of repair strategy A was compared to that of replacement strategy B (proposal 1, the optimal replacement strategy, identified as described above). Table 11 presents the strategies' specifications, while Figure 11 and Figure 12 present the cash flows of the repair strategy (A) and replacement strategy (B), respectively.

Table 11. The repair and replacement strategies

Strategies' Input Data	**Strategy A**	**Strategy B**	
Strategies' description	Immediate repair	Utilize the bridge's residual service life without action and then replace it by proposal (1)	
Residual service life without action, year	Zero		
Discount rate	4.0%		
Anticipated service life after action, year	25	100	
Strategy's initial cost, SEK	2,230,000	10,700,000	
Annual O&M cost, SEK	7,000	During the current bridge residual service life	After the bridge replacement
		8,500	5,000

A special technique would be used during the bridge repair in strategy A that would not affect trains' passage. The LCCA was based on the respective strategies' specifications in Table 11. As shown in Table 12, the NPV is lower for strategy A than for strategy B. However, this does not necessarily mean that strategy A is the most cost-effective, because the strategies have different life-spans. Therefore, the equivalent annual cost (EAC) was calculated for each strategy, and also found to be lower for strategy A than strategy B (Table 12). Hence, strategy A is the most LCC-efficient strategy. The Net Saving (NS) arising from implementing strategy A would be equal to 4.56 Million SEK/25 years or 291,899 SEK/year over a life-span of 25 years. If it was decided to replace the bridge instead of repairing it according to strategy A, the Opportunity Loss (OL) would be 7.153 Million SEK/100 years or 291,899 SEK/year over a life-span of 100 years.

Table 12. LCCA results

Cost term	**Strategy A**	**Strategy B**
Total Net Present Value (SEK)	2,339,355	10,822,525
Total Equivalent Annual Cost (SEK)	149,747	441,646

4.4.3 Sensitivity analysis

Uncertainty is involved in the assessment of most parameters included in Table 11. The following sensitivity analysis addresses the potential impact of each parameter on the final decision.

Discount rate

As illustrated in Figure 13, sensitivity analysis of the impact of varying the discount rate (*r*) from zero to 2*r* showed that strategy A remains the most LCC-efficient regardless of the discount rate within this range. Therefore, in this case, the discount rate does not have any considerable impact on the final decision.

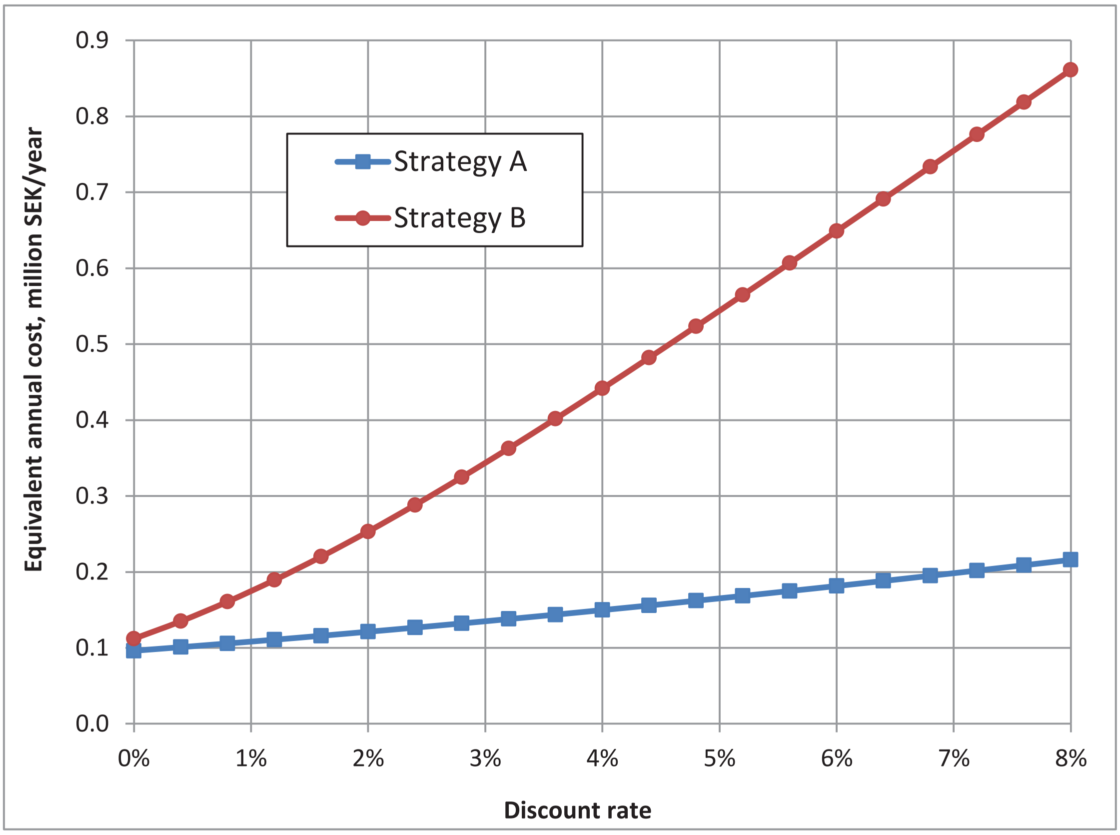


Figure 13. Impact of varying the discount rate on the final decision

The INV cost of a new bridge

At a 4% discount rate, repairing the bridge by strategy A remains the most LCC-efficient solution as long as the replacement strategy costs more than 3.6 Million SEK, as shown in Figure 14. In other words, it would be more cost-efficient to replace the bridge if the replacement strategy (B) costs less than 3.6 million SEK instead of 10.7 million SEK.

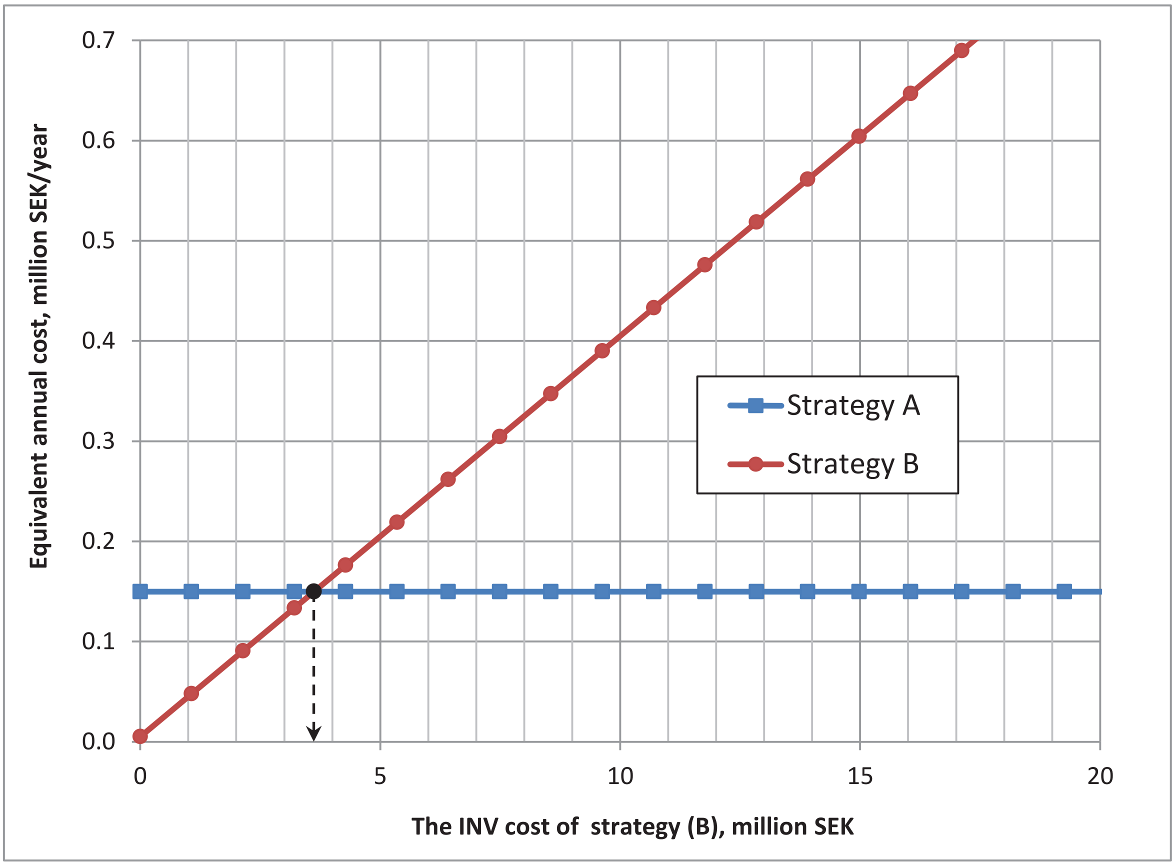


Figure 14. Impact of varying the anticipated INV cost of the replacement strategy (B)

Extension of the bridge's residual service life after repair

It is not easy to anticipate the long-term performance of a bridge or individual BSMs. Uncertainties are involved in assessment of the residual service-life extension after implementing the repair strategy since the assessment is based on statistical analysis of historical repair records extracted from BaTMan related to similar actions performed on similar bridges. Results of a sensitivity analysis of the impact of this uncertainty on the final decision (Figure 15) show that it would be more cost-efficient to repair the bridge by strategy A as long as the strategy can guarantee a residual service life extension more than six years. The statistical analysis of the related historical data clearly indicates that strategy A could do so, hence this parameter does not have considerable impact on the final decision.

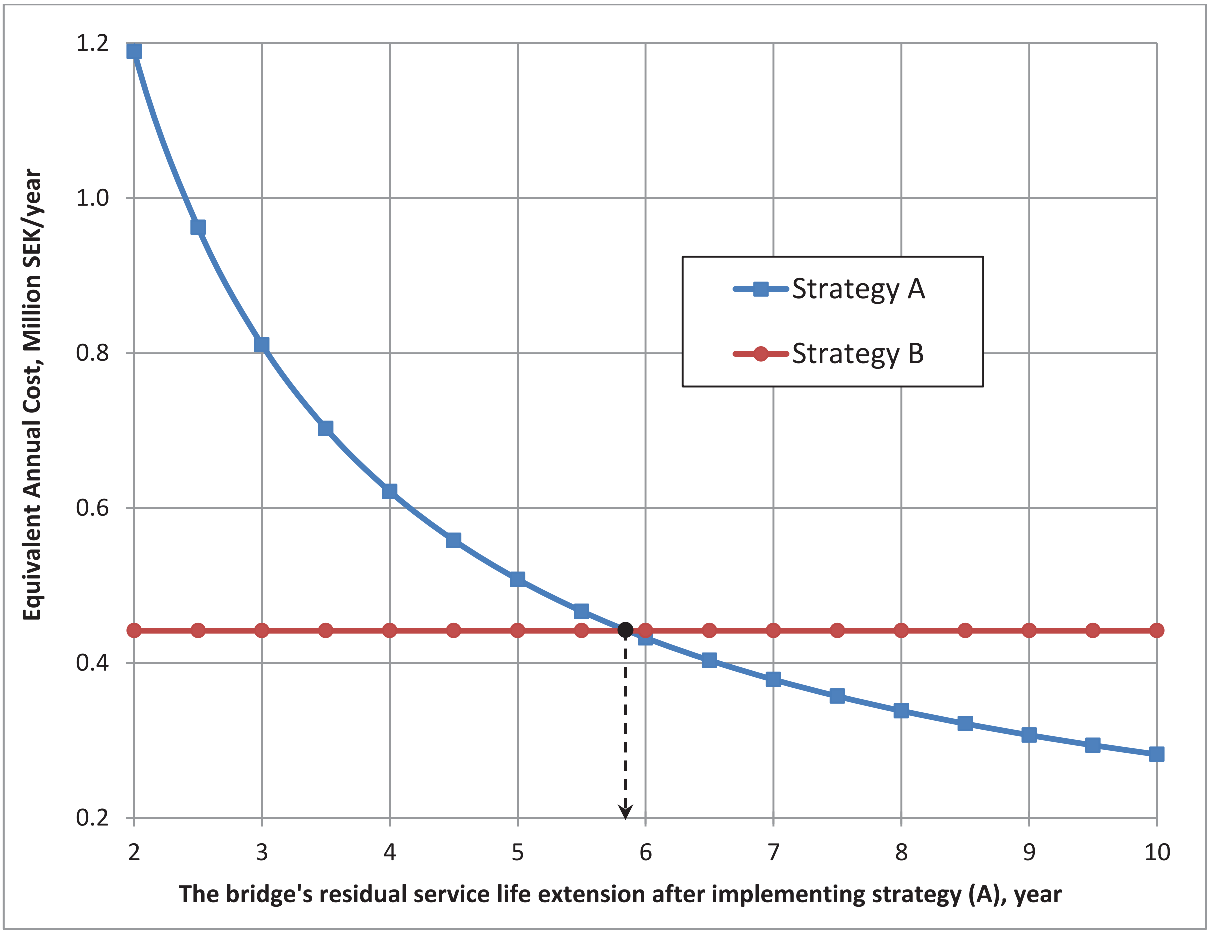


Figure 15. Impact of varying the bridge's residual service life extension after repair

Relation between the INV cost of the repair strategy and the minimum required residual service life extension

Figure 16 depicts the maximum INV cost of repair strategy A in relation to the minimum bridge's residual service life extension required after its implementation for it to be more cost-efficient than replacement strategy B, based on a 4% discount rate. As shown in the figure, if repair strategy A costs 3.5 million SEK, a residual service life extension of at least10 years is required for it to be more cost-efficient. It also shows that if repair strategy A can ensure a minimum residual service life extension of 25 years, it should be implemented even if its INV cost reaches 6.79 million SEK instead of 2.23 million SEK.

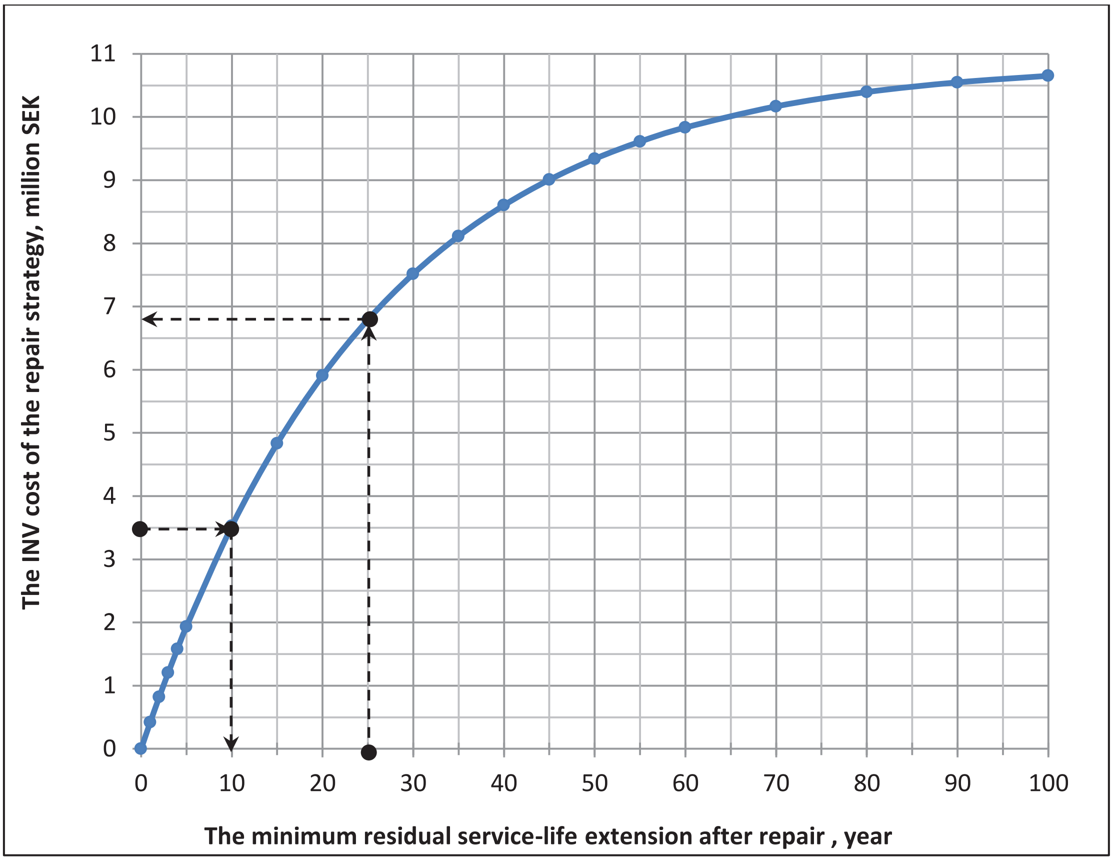


Figure 16. Relation between the maximum INV cost of strategy A and the minimum required residual service life extension in order for it to be more cost-efficient than strategy B

The bridge's residual service life without action

The residual service life without action, presented in Table 11, is also subject to uncertainty in the assessment. According to BaTMan's inspection manual, bridges with such heavy deterioration have to be more frequently inspected. Although essential BSMs are assigned to CC3, the bridge replacement might be postponed to the next year instead due to possible budget limitations. The potential postponement of the replacement strategy might reduce the LCC of strategy B, which may influence the LCCA results. Thus, a sensitivity analysis was conducted to study the impact of this uncertainty on the final decision. The results show that repairing the bridge today using strategy A remains more cost-efficient than replacing the bridge using strategy B after six years, if feasible (Figure 17). Therefore, this parameter does not have any considerable impact on the final decision.

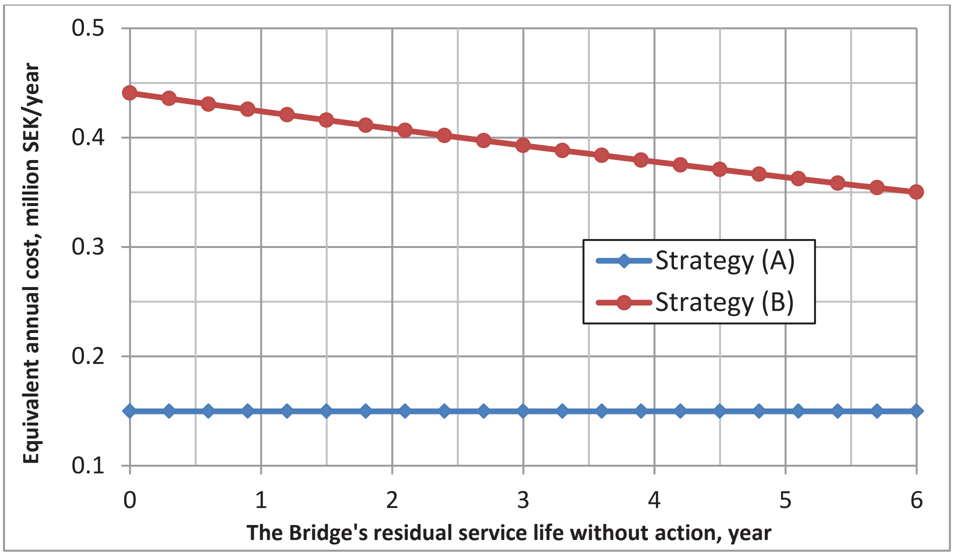


Figure 17. Impact of varying the bridge's residual service life without action on the final decision

The actual service life of a new bridge

A new bridge such as that described in proposal 1 (Table 10) might remain in service for more than 100 years. If so, the replacement strategy might become more cost-efficient since a longer life-span for strategy B would be considered in the LCCA. The impact of this uncertainty on the final decision was also studied. As shown in Figure 18, even if the service life of a new bridge is considered to be 200 years instead of 100 years, repairing the bridge using strategy A remains more cost-efficient than replacing it using strategy B. Therefore, the service life-span of the new bridge does not have considerable effect on the final decision.

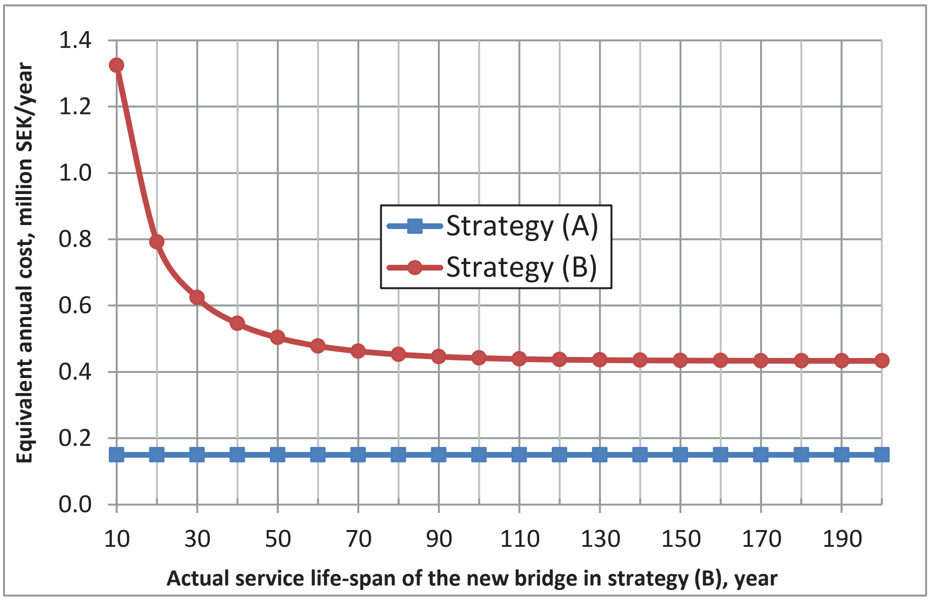


Figure 18. Impact of varying the service life of a new bridge on the final decision

Long- and short-term planning of the repair strategy

An alternative method of formulating the strategies is to consider long-term planning. In this case, strategy A would comprise the immediate repair and later renewal of the entire bridge after the anticipated service life extension provided by the repair, as illustrated in Figure 19.

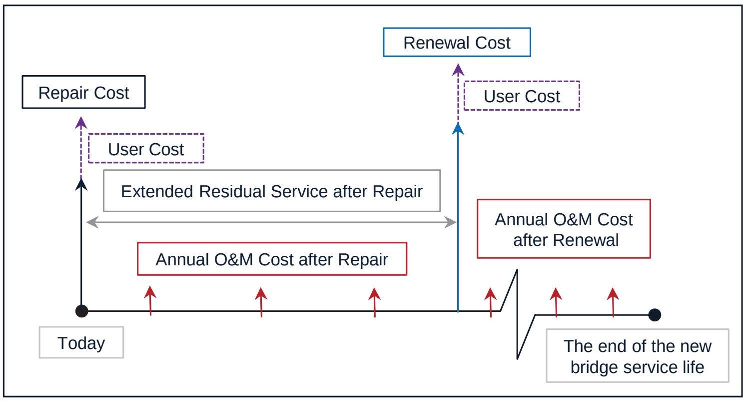


Figure 19. Long-term planning for strategy A

The LCC effects of long-term planning (as schematically shown in Figure 19) were assessed using typical data (as given in Table 11), but with adjustment for inflation of the INV cost of the new bridge to be installed after 25 years. The life-span of strategy A is considered to be 125 years instead of 25 years. Considering this long-term planning for strategy A and keeping the same specification of replacement strategy B, the conclusion is the same as that obtained from the short-term planning: strategy B remains the most cost-efficient. Furthermore, the EAC of strategy A is much less than variable than in the short-term planning analysis presented in Figure 11. Therefore, it is recommended to only consider one action in each strategy without complicating the analysis by considering long-term planning.

4.5 Conclusions from the Railway Bridge Case Study

The presented LCCA results are based on comparisons of a repair strategy costing 2.23 million SEK and a replacement strategy costing 10.7 Million SEK, with a discount rate of 4%. If the repair strategy could ensure a minimum residual service life extension of six years, it would be more cost-efficient to repair the bridge instead of replacing it. If the repair strategy could ensure a minimum residual service life extension of 25 years, as expected, it would be more cost-efficient to repair the bridge instead of replacing it, even if the cost of the repair strategy reached 6.79 million SEK instead of 2.23 million SEK. The replacement option should not be implemented unless the INV cost of a new bridge was less than 3.6 Million SEK instead of 10.7 million SEK.

The LCCA and sensitivity analyses presented above indicate that the bridge should be repaired using strategy A. The amount of money Trafikverket could save as Net Saving (NS) if the bridge was repaired instead of replaced would be equal to 4.56 Million SEK/25 years or 291,899 SEK/year over a life-span of 25 years. If Trafikverket decided to replace the bridge instead of repairing it, the agency would lose an amount of money equal to 7.153 Million SEK/100 years or 291,899 SEK/year over a life-span of 100 years as an Opportunity Loss (OL).

Instead of optimizing the choice between repairing and replacing this bridge, an optimization process should focus on specifying the most cost-efficient repair strategy. In this respect, the INV cost as well as anticipated residual service life extension after implementing each of the repair strategies should be taken into account. In considering the replacement strategy, allowance should also be made for the benefits that might be afforded by a completely new bridge in terms of potential improvements to routing, road safety, bearing capacity, traffic volumes, etc.

5 BaTMan-LCC

5.1 General

BaTMan-LCC is an Excel-Based program that was developed during the course of the research this thesis is based upon to facilitate implementation of LCCA applications for bridges. The program has been designed to dovetail with Trafikverket's established procurement procedures and allow convenient analysis of Swedish bridges. It serves the implementation of LCCA in both the management of existing bridges and procurement of new bridges. All LCCA applications presented in the appended papers and this thesis are automated using this program, and user-cost models that are specially designed for the different applications of LCCA are embedded in it. The program is connected to BaTMan's database through WebHybris, which allows the embedded bridge data sources to be updated. Figure 20 presents the front-page of this program.

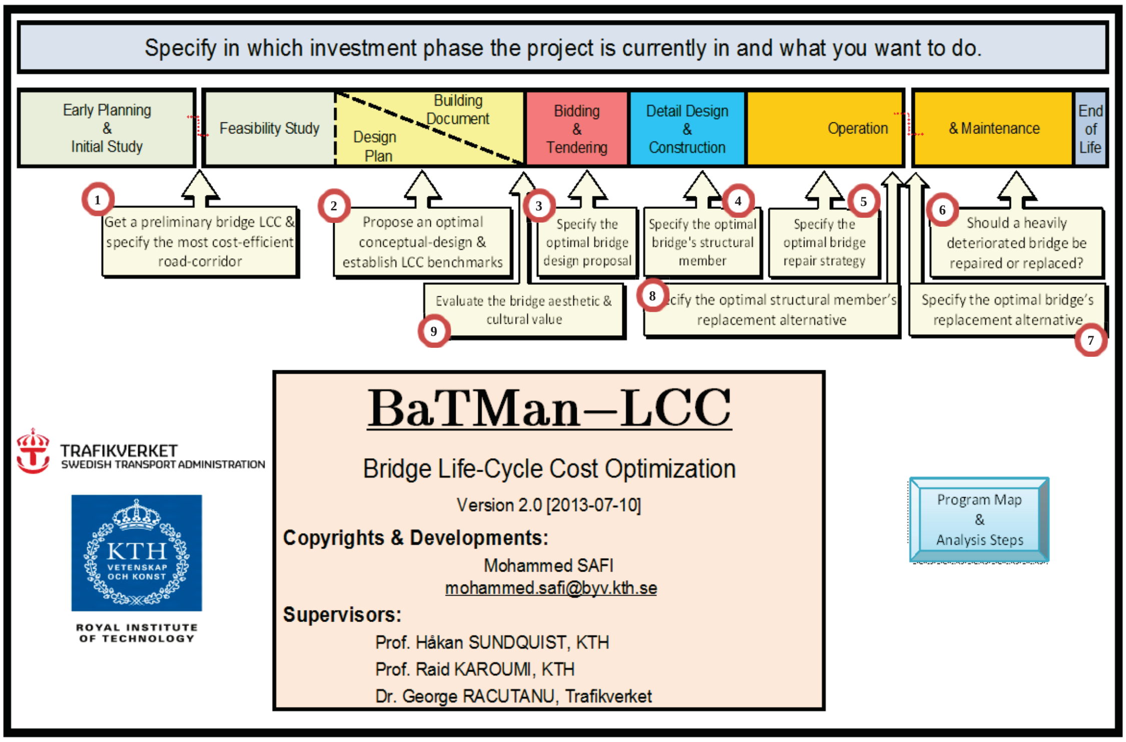


Figure 20 BaTMan-LCC front-page

BaTMan-LCC is a user-friendly tool that requires no sophisticated data input by the user. As shown in the front-page, the user is first requested to specify the current investment phase of the project and what he/she wants to do. After choosing the right LCCA application, the program will direct the user to an input window. The results of the LCCA and the related sensitivity analysis (like those presented in the case studies included in the appended papers) will be automatically generated and presented in different windows based on the inserted input data. BaTMan itself should be developed to accommodate the LCCA applications included in BaTMan-LCC. Thus, the LCCA applications will be integrated parts of BaTMan rather than BaTMan-LCC being a separate stand-alone tool. Doing this will permit automatic data extraction and maximal online-use.

The current version of the program supports 8 eight LCCA applications for bridges in different investment phases, as shown in Figure 20. Another application the program supports is evaluation of the bridges' aesthetic merits (Application 9 in Figure 20). A user manual, guidelines and flowcharts are included in the program. The section below presents the analytical steps included in BaTMan-LCC for the application of LCCA within the design-plan and building-document phases (Application 2 in Figure 20).

5.2 Design-Plan and Building-Document Phases

After specifying the road/rail corridor to be constructed, brief information on the bridges to be constructed in the corridor will be available, including their locations, approximate lengths, heights and widths. During the design-plan and building-document phases, several bridge proposals might offer technically feasible solutions for each location. The bridge procurer will seek here to determine the most cost-effective means to accomplish the project's objectives. Generally, a conceptual design for each bridge location will be prepared and attached to the tender documents. The use of D-B contract forms for bridge procurement is rapidly growing in Sweden. Although alternative designs are acceptable under D-B contracts, contractors sometimes hesitate to propose an alternative design to avoid risks of bid rejection. Thus, the conceptual design stated in the tender documents is a keystone for the entire project. Therefore, to switch fully to use of the lowest LCC bid (rather than the lowest INV bid) as the contract award criterion, and ensure that LCC-efficiency is considered by the contractors, they should be provided clear LCC-efficient benchmarks and guidelines in the tender documents. Bridge procurers are supposed to prepare these benchmarks during the design-plan phase and embed them in the tender documents as core specifications. Using BaTMan-LCC Application 2, a bridge-procurer could follow the analysis steps presented in Figure 21 to propose an optimal conceptual design and establish such LCC-efficient benchmarks.

5.2.1 Analysis steps using BatMan-LCC

Figure 21 summarizes the analysis steps included in BaTMan-LCC for the application of LCCA in the preparation of LCC-efficient benchmarks. The analysis steps are further described below. Detailed information about this application and the others included in BatMan-LCC can be found in the BaTMan-LCC user manual.

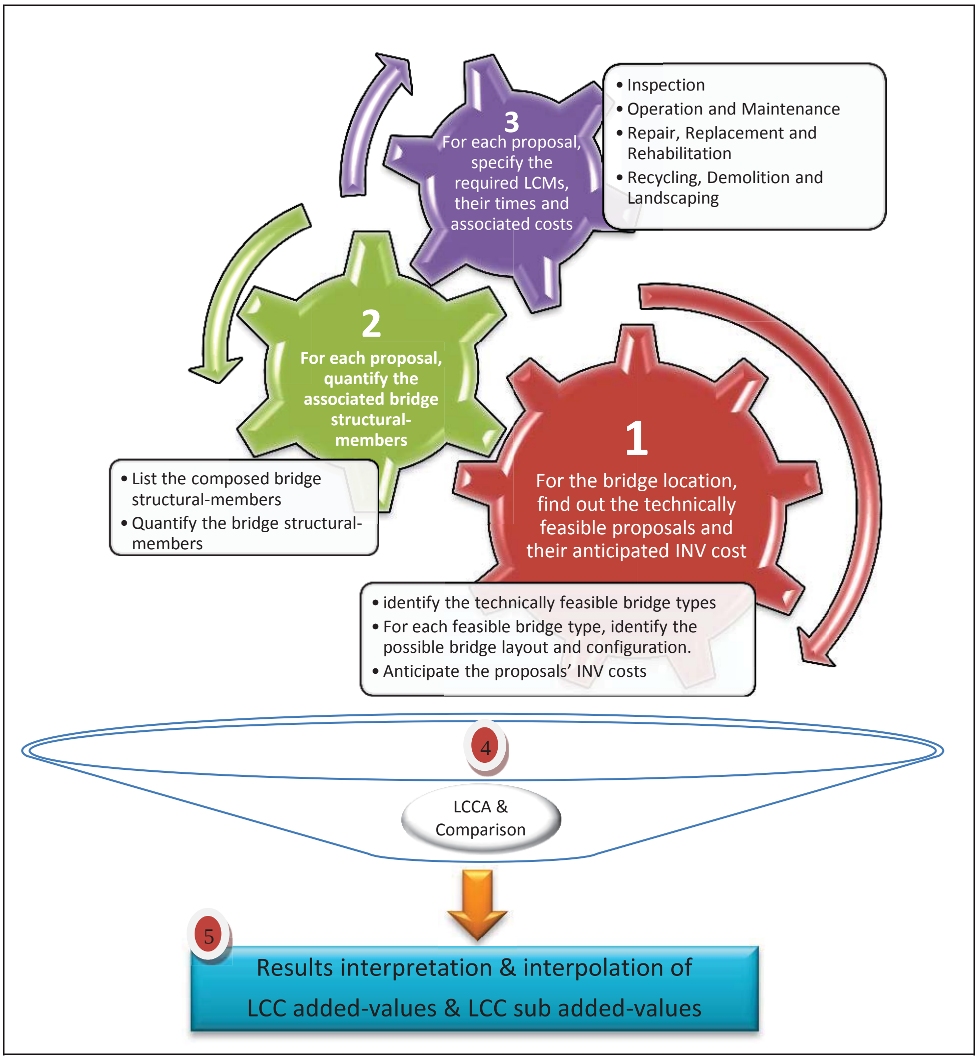


Figure 21. Steps for preparing LCC-efficient benchmarks

Step 1: Identify the technically feasible proposals for the bridge location

As discussed above, BaTMan-LCC includes a database providing information on all bridges in Sweden, including their numbers, construction material, spans lengths, etc. A user can choose a bridge type and the program will show the total number of similar existing bridges, their maximum and average span lengths, and the 95th percentile of the span length (assuming that the span lengths are normally distributed). The user can select a number of similar bridges to see more information, detailed drawings and pictures of them in BaTMan. The program also provides charts that schematically present user-friendly conclusions generated from the embedded related data that the user can refer to in order to facilitate the following sub-steps.

- Identify the technically feasible bridge types
- For each technically feasible bridge type, identify the maximum span length and possible configurations.
- Inspect detailed information on similar bridges in BaTMan, if necessary
- List the technically feasible options and their configurations

Step 2: For each technically feasible proposal, check the quantified bill of quantities and assess the initial investment cost

BaTMan-LCC incorporates automatically implemented equations for assessing the quantities of the various BSMs composing bridges of various types and designs, formulated from intensive reviews of numerous as-built drawings of various types of existing bridges. BaTMan-LCC will assess the quantities of the various BSMs required for each proposal, based on available parameters such as the proposed bridge type, construction material, total length, total width and number of spans. The user can check the quantities predicted by BaTMan-LCC and modify them if he has better information. The sub-steps included in this step are as follows:

- Insert the configuration of each proposal and confirm its recommended life-span
- Check the quantities of the BSMs required for each proposal
- Assess the proposal anticipated initial investment cost and verify the accuracy of the predictions

For assessment of the anticipated INV costs of the various feasible proposals BaTMan-LCC includes cost records, in SEK/m2, related to 2509 existing bridges in Sweden. The user can choose up to seven levels of details to get more precise unit costs, as shown in Figure 22. The unit costs are connected to the chosen construction year since they are inflation-adjusted. The user can also choose the predictions' confidence level and the program will show the related prediction boundaries. An upper limit, lower limit and forecast values are presented for each level, as also shown in Figure 22. After specifying appropriate unit costs, the program will calculate the anticipated INV cost for each proposal by multiplying the unit cost by the total bridge area.

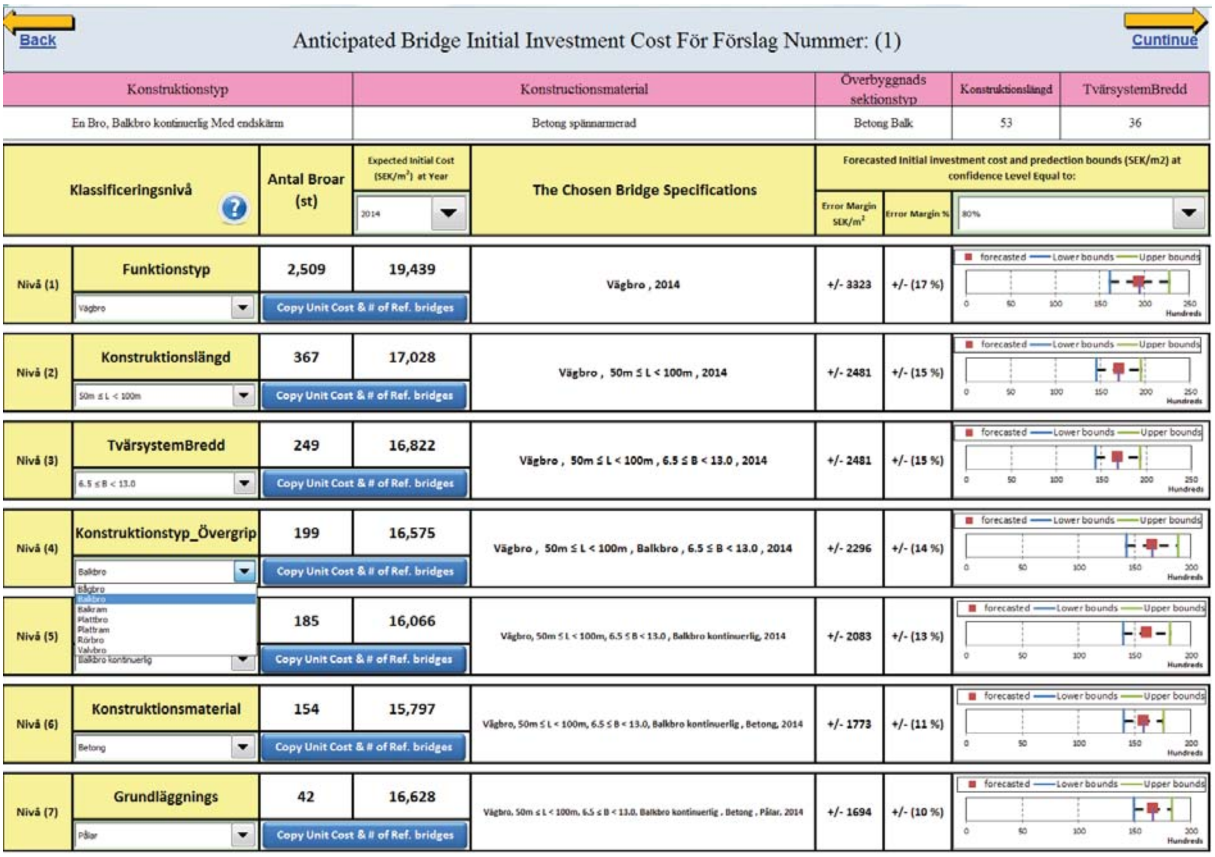


Figure 22. Assessment of proposals' INV costs using BaTMan-LCC

Step 3: Specify the required LCM and their associated costs for each technically feasible proposal

BaTMan-LCC includes manuals and tables clarifying the LCMs required for each of the bridge designs and types included in the BaTMan database. Recommended LCPs for the various BSMs comprising the various bridge types and designs are also included in the program, such as those listed in Appendix B. The costs of the various bridges' LCMs are extracted from the latest unit price list of BaTMan. The LCM that the user should specify are:

- Inspections (INS)
- Operation and Maintenance (O&M)
- Repair, Replacement and Rehabilitation (RRR)
- BaTMan's Standard Actions
- Recycling, Demolition and Landscaping (R,D&L)

BaTMan-LCC allows simultaneous LCCA comparison of up to five bridge designs for a given location. Figure 23 presents the window where the user can specify the LCMs that would typically be applied to the various BSMs comprising Design 1. As shown in the upper part of Figure 23, the user can choose to consider that these LCMs would be applied to the other proposals. Thus, LCMs do not necessarily need to be individually inserted for each proposal. Even if the same LCMs are applied in the analysis of all proposals the resulting NPVs will differ, since they would be applied to different numbers and quantities of BSMs in each design.

Typical unit-price lists for the LCMs associated with each BSM, published in BaTMan, are embedded in BaTMan-LCC. As shown in Figure 23, the user can apply up to four LCMs to each BSM comprising each proposed design. The user should choose the LCMs and the reference quantity they will be applied to from drop-down lists. To consider an action in the analysis, it should first be activated. Default values are provided in the program for the probability of the actions' necessities, their times, the percentage of the chosen reference quantity they will be applied to and the possible added fixed costs. However, the program allows users to modify those assumptions if more precise values are available.

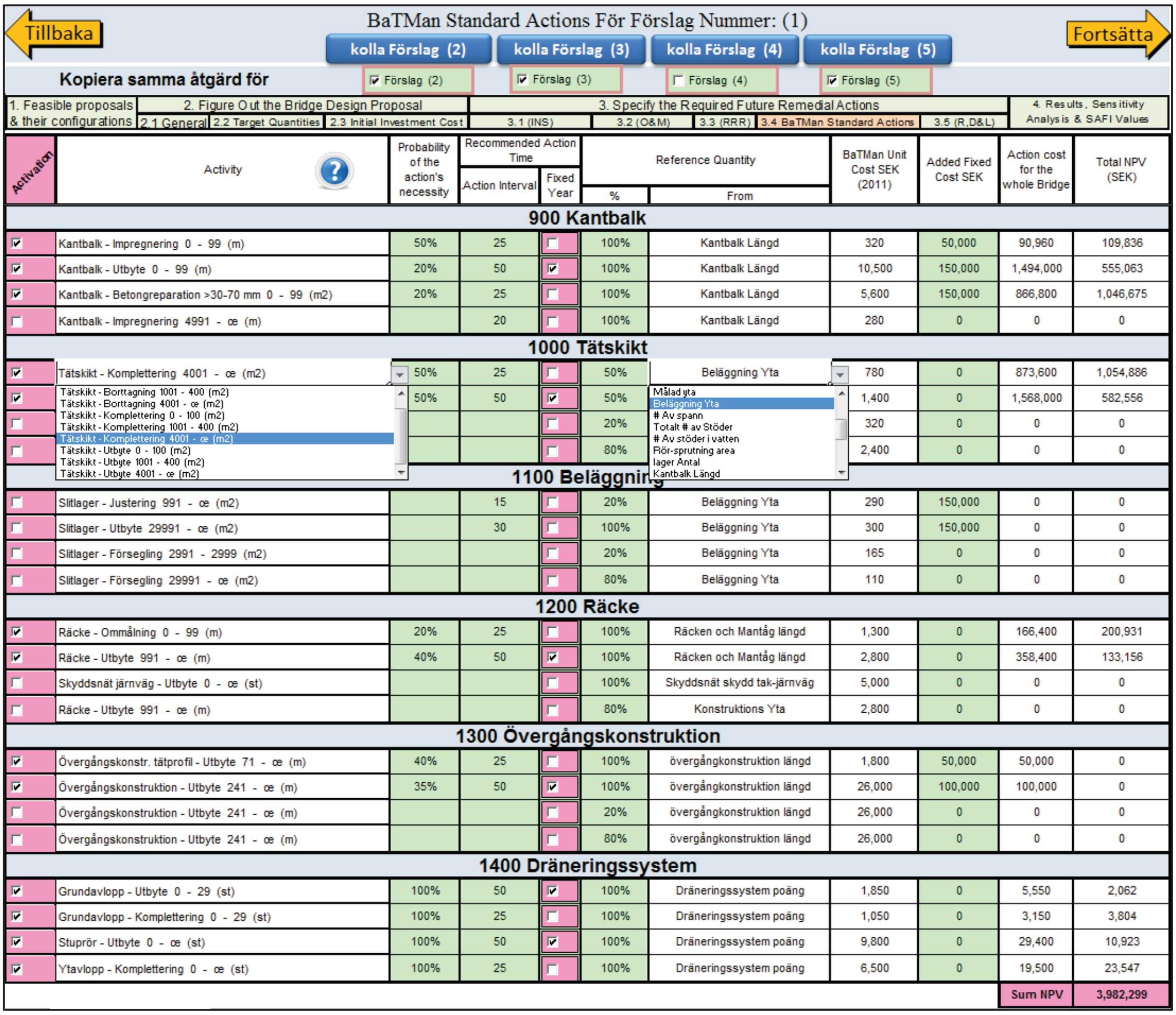


Figure 23. BaTMan-LCC window for specifying the LCM required for the various BSMs

Step 4: LCCA results and conclusion

After completing steps 2 and 3 for all feasible proposals chosen in step 1, the program will calculate the LCC associated with each proposal. The LCCA techniques and tools presented in Appendix A are employed in BaTMan-LCC in this step, which allows the user to check the following:

- The life-cycle cost (LCC) associated with each proposal
- The sensitivity of the LCC to variation in the discount rate
- The cost-effectiveness rankings of the proposals at different discount rates
- The life-cycle cost-effectiveness of each proposal (conceptual design)
- The Net saving (NS) at various discount rates

They also allow comparison of the proposals' LCC efficiency and associated NS, at selected discount rates.

Step 5: Interpolation of results and generation of LCC-efficient benchmarks

Two main tables, presenting results of the analysis, are generated in this step. The first summarizes the technically feasible proposals and their LCC added-values. The second table consists of the LCC sub added-values associated with various BSMs. The user should perform the following sub-steps before printing out the LCCA summary and conclusion.

- Specify the reference proposal and the discount rate
- Check the other proposals' LCC added-values
- Check the BSM's sub added-values
- Print out a technical report

Along with the two main tables, the final report generated using BaTMan-LCC for a LCCA process will include five tables that clarify:

- The various technically feasible proposals, their bridge types, construction materials and layouts
- The BSMs and the bill of quantity associated with each proposal
- The anticipated INV cost of each proposal, the total number of similar existing bridges, the prediction boundaries and the confidence level
- Cost-effectiveness rankings of the proposals, LCCA conclusion, and LCC, NS and OL comparisons of the proposals
- A table clarifying the LCMs considered for the BSMs comprising each of the proposed designs

The report will also include two charts depicting:

- The impact of varying the discount rate on the proposals' cost-effectiveness rankings
- The INV and LCM costs of each proposal

5.3 Implementation within Trafikverket as an Example

BaTMan-LCC (mainly Applications 2 and 6; Figure 20) has been employed in several real projects by both the bridge investment and bridge management divisions of Trafikverket. The LCCA results and saving potentials of those two applications were clearly presented to several specialists within Trafikverket. In September 2012, a high level decision was taken to implement BaTMan-LCC's Application 2 in Trafikverket's investment division. The implementation included the stipulation that LCCs of at least three proposals should be compared before procuring any bridge, regardless of its size. Subsequently, in November 2012, an intensive course was provided for 10 bridge specialists, chosen from staff based at Trafikverket offices all over Sweden, who are considered to be super-users. These super-users were each given a portable version of the program and they will train their colleagues in its use. A future target is to integrate the BaTMan-LCC program into BaTMan to facilitate maximization of its implementation and allow automatic data extraction.

In March 2013, an initial course was provided for around 20 bridge managers based in Trafikverket's bridge management division. The course mainly focused on Application 6 in BaTMan-LCC. To continue the program's implementation within Trafikverket's bridge management division an intensive course is planned for the beginning of 2014.

6 Conclusions

6.1 General Conclusion

This thesis presents attempts to improve the current state-of the-practice of LCCA in bridge procurement and maintenance. A comprehensive framework demonstrating the possible applications of LCCA for these purposes has been introduced. The thesis highlights the feasibility of implementing LCCA in bridge engineering and its potential for improving the associated processes. All appended papers treat BMSs and LCCA as strongly interrelated, complementary tools. The thesis discusses the need for a BMS with a cradle-to-grave, integrated and comprehensive LCCA program that assists decision-makers at all levels and during all phases to select the most cost-efficient option. The thesis introduces the bridge stock in Sweden and the Swedish Bridge and Tunnel Management System (BaTMan). The contributions of the appended papers can be summarized in the following points. For more detailed conclusions the reader is referred to the appended papers.

- Papers I, III and IV support the implementation of LCCA in bridge management. Paper I and III introduce a comprehensive approach supported with detailed case studies. The approach demonstrates how an agency could apply its BMS to support a decision on whether a heavily deteriorated road bridge should be repaired or replaced considering LCC and user costs. Paper IV includes a case study illustrating how an agency could benefit from its BMS to support a decision on whether to repair or replace a deteriorated superstructure of an existing road bridge considering LCC and user costs. The papers provide valuable insights into the various parameters affecting LCCA results. They also introduce and employ new LCCA parameters, Net Saving (NS) and Opportunity Loss (OL), which are particularly useful for comparing alternatives with differing life-spans.

In addition to the case studies presented in Papers I and III, this thesis includes a detailed case study demonstrating how the LCCA application considered in those papers could be implemented in the management of railway bridges.

- Papers II and V support the implementation of LCCA in bridge investment. Paper II introduces a novel procurement approach supported with a practical case study. The approach illustrates how an agency could benefit from its BMS to procure the most cost-efficient bridge design through a fair D-B tendering process. Paper II also introduces and employs a new parameter, “LCC Added-Value”. Paper V introduces a holistic procurement approach intended to enable procurement of the most “sustainable” (advantageous in life-cycle terms) bridge under D-Bs. The approach combines LCC Added-Value analysis with other new techniques that make bridges’ aesthetic merits and environmental impact commensurable. The case studies included in Papers II and V illustrate the practical implementation of the proposed approaches and techniques, address the roles of both contractors and the agencies in such procurement approaches, provide valuable insights into the various bridge aspects and address shortcomings that require further attention.

In addition to the techniques and parameters introduced in Papers II and V, Appendix B includes recommended life-cycle plans (LCPs) for the various bridge structural-members (BSMs) used in the various types of new Swedish bridges. This appendix is intended to formulate foundations of an intensive database that is essential for procuring the most cost-efficient bridge design under D-Bs.

6.2 Benefits of LCCA for Bridges

As an example, this section presents a rough assessment of LCCA saving potential considering Trafikverket’s bridge stock and the bridges that would be procured by Trafikverket in the coming decade. The benefit of LCCA for larger agencies would be even greater.

6.2.1 BaTMan-LCC Application 2

In the project considered in the case study presented in Paper II, based on a real discount rate of 2%, Trafikverket has saved 57.4 million SEK, equivalent to 8,494 SEK/m^2 of the bridge area. This NS comprises 54.9 million SEK as direct INV savings and 2.5 million SEK as LCC savings. In the coming decade Trafikverket is expected to build an average bridge area of 80,000 m^2 per year, equivalent to 280 bridges per year. If sub-optimal decisions are taken for 50% of Trafikverket's new bridges, the agency might lose 340 million SEK per year on average: 325 million SEK per year as direct INV losses and 15 million SEK per year as LCC losses through more than necessary LCM costs.

6.2.2 BaTMan-LCC Application 6

Trafikverket’s road bridges

Among Trafikverket's stock of road bridges, 6,268 (with a total area of 619,944 m^2) are older than 70 years. Based on the LCCA results of the case study included in Paper I, the annual OL is equal to 241 SEK/m^2 of the total bridge area per year, and these losses will continue for 20 years. Thus, if sub-optimal decisions are taken for 50% of Trafikverket's old bridges, the agency might lose 74.7 million SEK each year and 1.49 billion SEK during the coming 20 years.

Trafikverket’s railway bridges

Trafikverket is currently responsible for 400 railway bridges similar to the bridge considered in the case-study included in the extended summary of this thesis: older than 50 years and condition class (CC) 3 (requiring immediate action). The total area of those 400 bridges is 60,500 m^2. The LCCA presented for that case study showed that Trafikverket could save, on average, money equivalent to 1,089 SEK/m^2/year. Thus, if sub-optimal decisions are taken for

50% of those 400 bridges, the agency might lose (or could otherwise save) 65 million SEK each year and 1.64 billion SEK during the coming 25 years.

6.3 Summarizing Discussion

Undoubtedly, LCCA can be feasibly and fruitfully applied in both bridge management and bridge investment. It is not easy to draw general conclusions from an LCCA of a specific bridge because the results are strongly dependent on the input. One of the key components of an LCCA is the incorporation of uncertainty into the analysis. Therefore, the sensitivity analysis is an important step that allows decision-makers to evaluate their confidence in the optimality of their chosen solution. The NS and OL parameters should be valuable in this context, since they will enable decision-makers to estimate the consequences of their decisions, and this will promote forward thinking. Generally if the NS is considerable, variation of the included parameters will not substantially influence the final decision and vice versa. The discount rate usually has a considerable impact on the LCCA, but not on the final decision.

Since implementation of LCCA in bridge investment involves adjusting the established procurement procedures, it is more difficult than implementing it in bridge management. In bridge management, the major factor affecting LCCA results is the impact a repair strategy could have on the residual service-life of the target BSMs and the bridge as a whole. However, the sensitivity analysis can robustly address the impact of varying that parameter on the final decision. The major uncertainties that could affect LCC Added-Values of designs considered in bridge procurement are the quantities and associated LCCs of the BSMs comprising the designs. This presents a potential obstacle to the rational formulation of tenders, which could be overcome by supporting the tender documents with properly assessed LCC sub added-values. The anticipated INV costs of the various proposals could also affect the LCCA, but they would only affect the LCC added-values if the considered proposals have differing life-spans.

Based on LCCA results of several case-studies, at a real discount rate of 2% the LCM cost of a bridge design generally represents 20% to 40% of the total LCC, depending on the quantities of BSMs and LCPs involved. Thus, the LCM costs of the various feasible bridge designs for a certain location could generally differ by up to 20%. On the other hand, the INV costs of the feasible bridge designs could differ by up to 50%. Hence, the largest NS in bridge procurement could be achieved by broadening the scope to consider (in LCC terms) more varied proposals. Therefore, further research efforts to improve analysis of feasible proposals will be more beneficial than efforts to improve assessment of the associated LCM costs.

The analysis included in Paper V emphasizes that the most expensive bridge design is not necessarily the most environmentally friendly, beautiful or LCC-efficient proposal and vice versa. In addition, costs, aesthetic values and environmental concerns could be complementary in bridge design.

6.4 Proposals for Further Research

Standard LCC sub added-values

In order to unify and ease procurement of the most LCC-efficient bridge design through use of LCC Added-Value analysis, standard comprehensive lists of LCC sub-added values for the various BSMs are highly important. These could be developed by establishing appropriate LCPs for the various BSMs comprising each of the bridge types in Trafikverket's (or any other agency's) bridge stock. Rigorous statistical analysis of intensive, reliable historic bridge repair records can generate LCPs that should be generally reliable. The LCPs should cover not only all BSMs, but also their different types and qualities, as well as their structural elements. The lists should also cover variations due to the diverse factors that can affect BSMs' deterioration rates (and hence the type, timing and costs of the LCMs required). Those factors could include the ADT volume, freeze-thaw cycles at the bridge's location, humidity, applications of deicing chemicals, etc. Appendix B in this thesis provides an initial step toward that objective. In addition, research efforts to develop robust, legally acceptable ways for including the generated LCC sub added-values in tender documents are highly important.

Technically feasible bridge-designs

The most important step in a LCCA used to facilitate the optimal procurement of bridges based on LCC Added-Values is the first step, in which an array of technically feasible proposals and their possible layouts is evaluated. Convenient techniques that could ease that step, and the estimation of considered proposals' LCCs by precisely quantifying the associated BSMs and other quantities, are highly important. The Building Information Modelling (BIM) that is currently being implemented within Trafikverket could significantly ease that work by providing access to 3D models and comprehensive bills of quantities for existing bridges.

LCCA curves for the various bridge locations

In an early planning phase, simplified curves depicting LCCs of the types of bridges that could be feasibly constructed in specific locations would be highly valuable for preliminary decision-making. These could be developed after completing the previous two further research proposals.

Effect of repairs on the residual service life

The main factor affecting results of BaTMan-LCC Application 6 is the effect a repair strategy could have on the residual service life of the targeted BSMs and (hence) the entire bridge. Thus, efforts to clarify these effects could improve the accuracy of LCCA in that respect.

Network-level LCCA

The case studies presented in this thesis and in Papers I and III illustrate how an agency could benefit from its BMS to support project-level decisions. Further research should be directed towards clarifying how a BMS with an integrated LCCA tool could support network-level decisions for prioritizing bridges for repair or replacement, taking into account OL and NS data generated by project-level analysis.

Bibliography

[1] AASHTO (2001), *Guidelines for Bridge Management Systems*, American Association of State Highway and Transportation Officials, AASHTO, Washington, D.C.

[2] Abdel-Al-Rahim, I. & Johnston, D. (1993). Estimating bridge related traffic accidents and costs. *Transportation Research Board*.

[3] Ahlroth, Sofia, and Göran Finnveden. "Ecovalue08–A new valuation set for environmental systems analysis tools." Journal of Cleaner Production 19, no. 17 (2011): pp. 1994-2003.

[4] Ahlroth, Sofia, Måns Nilsson, Göran Finnveden, Olof Hjelm, and Elisabeth Hochschorner. (2011) "Weighting and valuation in selected environmental systems analysis tools–suggestions for further developments." Journal of Cleaner Production 19, no. 2,pp145-156.

[5] Bakker, J., and Volwerk, J. (2007). Life-cycle cost tenders for infrastructure projects. *Life-Cycle Cost and Performance of Civil Infrastructure Systems-Cho*, D. Frangopol & A. Ang, eds., Taylor & Francis Group, London, ISBN 978-0-415-41356-5.

[6] BatMan Handbok Manual 2012, charter 06 Definitioner och begrepp.

[7] Berger, Markus, and Matthias Finkbeiner. "Correlation analysis of life cycle impact assessment indicators measuring resource use." *The International Journal of Life Cycle Assessment* 16, no. 1 (2011): 74-81.

[8] Bridge Aesthetics Sourcebook: Practical Ideas for Short-and Medium-Span Bridges 2010, American Association of State Highway and Transportation Officials-AASHTO.

[9] Carlsson Reich, Marcus. "Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC)." Journal of Cleaner Production13, no. 3 (2005): 253-263.

[10] Eamon, C., Jensen, E., Grace, N., and Shi, X. (2012). "Life-Cycle Cost Analysis of Alternative Reinforcement Materials for Bridge Superstructures Considering Cost and Maintenance Uncertainties." *J. Mater. Civ. Eng*., 24(4), 373–380.

[11] Editors: Hunkeler D, Lichtenvort K, Rebitzer G, Lead authors: Ciroth A, Huppes G, Klöpffer W, Rudenauer I, Steen B, Swarr T (2008): Environmental Life Cycle Costing.

[12] Ehlen, M., BridgeLCC 2.0 Users Manual, Life-Cycle Costing Software for the Preliminary Design of Bridges, NIST GCR 03-853. http://www.bfrl.nist.gov/bridgelcc/UsersManual.pdf

[13] Elbehairy, H. (2007). *Bridge management system with integrated life cycle cost optimization.* PhD Thesis, University of Waterloo, Waterloo.

[14] Fischer, J. and Amekudzi, A. (2011). ”Quality of Life, Sustainable Civil Infrastructure, and Sustainable Development: Strategically Expanding Choice.” J. Urban Plann. Dev., 137(1), 39–48.

[15] Goedkoop M.J., Heijungs R, Huijbregts M., De Schryver A.;Struijs J., Van Zelm R, 2009. ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation.

[16] Göran Finnveden, Cecilia Håkansson, Maria Noring, 2013. A new set of valuation factors for LCA and LCC based on damage costs-Ecovalue 2012, The 6th International Conference on Life Cycle Management in Gothenburg, Sweden.

[17] Guangli Du & Raid Karoumi (2012), "Life cycle assessment framework for railway bridges: literature survey and critical issues." The Journal of Structure and Infrastructure Engineering, ahead-of-print: 1-18. DOI:10.1080/15732479.2012.749289

[18] Guangli Du & Raid Karoumi (2013). Life cycle assessment of a railway bridge: Comparison of two superstructure designs. Structure and Infrastructure Engineering. 9(11), pp. 1149-1160.

[19] Hallberg, D. & Racutanu, G. (2007). Development of the Swedish bridge management system by introducing a LMS concept. *Materials and Structures* (2007) 40:627–639

[20] Hammervold, Johanne, Marte Reenaas, and Helge Brattebø. (2013) "Environmental Life Cycle Assessment of Bridges." Journal of Bridge Engineering, 18(2), 153-161.

[21] Hawk, H. (2003). *NCHRP Report 483: Bridge Life-Cycle Cost Analysis.* TRB, National Research Board, Washington, D.C.

[22] Helsinki University of Technology TKK - Aalto University (2009), Structural Engineering and Building Technology Publications B. Espoo, TKK-R-BE3: *ETSI PROJECT (Stage 2): Bridge Life Cycle Optimisation.*

[23] Helsinki University of Technology. (2007). ETSI Project (Stage 1): Bridge life cycle optimisation. Department of Civil and Environmental Engineering.

[24] Henriksen, C., Ladefoged, L. & Thaulow, N. (1996). Concrete specifications for new bridges. *Bridge Management 3*, E & FN Spon, 124-137.

[25] Huang, R. Y. (2006). A performance-based bridge LCCA model using visual inspection inventory data. *Construction Management and Economics* 24, No. 10, 1069-1081.

[26] Ingvarsson, H. & Westerberg, B. (1986). *Operation and maintenance of bridges and other bearing structures: State-of-the-art report and R&M needs.* Swedish Road and Traffic Research. Swedish Transport Research Board.

[27] ISO 14040 (2006). Environmental management – life-cycle assessment – principles and framework. Geneva: International Organization for Standardization.

[28] ISO15686-5. (2008). *Building and constructed assets-service-life planning. Part 5: Life-cycle costing.* Stockholm: Swedish Standard Institute.

[29] Keoleian, G.A., Kendall, A., Dettling, J.E., Smith, V.M., Chandler, R.F., Lepech, M.D., & Li, V.C. (2005). Life cycle modeling of concrete bridge design: Comparison of engineered cementitious composite link slabs and conventional steel expansion joints. Journal of Infrastructure Systems ASCE, 11(1), 51–60.

[30] Kicherer, Andreas, Stefan Schaltegger, Heinrich Tschochohei, and Beatriz Ferreira Pozo. Eco-efficiency. The International Journal of Life Cycle Assessment 12, no. 7 (2007): 537-543.

[31] Leeming M. G. (1993). The application of life cycle costing to bridges. *Thomas Telford , Bridge Management 2*.

[32] Lim, Seong-Rin, Donghee Park, and Jong Moon Park. Environmental and economic feasibility study of a total wastewater treatment network system. Journal of Environmental Management 88, no. 3 (2008): 564-575.

[33] Markow, M. and Hyman, W. (2009). *NCHRP Synthesis 397: Bridge Management Systems for Transportation Agency Decision Making.* TRB, Transportation Research Board, Washington, D.C.

[34] Mattsson, H. & Sundquist, H. (2007). The Real Service Life of Road Bridges. *Proceedings of the Institution of Civil Engineering, Bridge Engineering*, 160 (BE4), 173-179.

[35] Mattsson, H. (2008). Integrated Bridge Maintenance: Evaluation of a pilot project and future perspectives. Doctoral thesis ISSN 1103-4270, Structural Engineering and Bridges Division, KTH Royal institute of Technology, Sweden.

[36] Mirzaei, Adey, Klatter, Kong. IABMAS 2012, The IABMAS Bridge Management Bridge Management

[37] Mohammed Safi (2009), Bridge Life Cycle Cost Optimization: Analysis, Evaluation and Implementation, Master's Thesis 278, ISSN 1103-4297, Structural Engineering and Bridges Division, KTH Royal institute of Technology, Sweden.

[38] Nakamura, Shinichiro, and Yasushi Kondo. Hybrid LCC of Appliances with Different Energy Efficiency (10 pp). The International Journal of Life Cycle Assessment 11, no. 5 (2006): 305-314.

[39] Ozbay, K., Jawad, D., and Hussain, S. (2004). Life-Cycle Cost Analysis-State of the Practice versus State of the Art. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1864,* TRB, Washington, D.C., pp. 62–70.

[40] Patidar, V., Labi, S., Sinha, K., and Thompson, P. (2007). *NCHRP REPORT 590: Multi-Objective Optimization for Bridge Management Systems*, TRB, Transportation Research Board, Washington, D.C.

[41] Perera, O., Morton, B., and Perfrement, T. (2009). Life Cycle Costing in Sustainable Public Procurement: A Question of Value, *A white paper from the International Institute for Sustainable Development (IISD).*

[42] R. Helmerich, E. Niederleithinger, D. Streicher, H. Wiggenhauser, and D. Algernon (2008). Bridge Inspection and Condition Assessment in Europe. *Transportation Research Record: Journal of the Transportation Research Board, No. 2044*, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 31–38.

[43] Racutanu G. *The Real Service Life of Swedish Road Bridges – A case study*. TRITA-BKN Bulletin 59, Dept. of Structural Engineering, Royal Institute of Technology, Stockholm, PhD thesis, 2000.

[44] RTA Roads and Maritime Services records – Operations Directorate, Bridge Section (2003), *Bridge aesthetics: design guideline to improve the appearance of bridges in NSW*, Government Transport, Roads & Maritime Services, and Centre for Urban Design.

[45] Safi, M. (2012). LCC pplications for Bridges and Integration with BMS. Licentiate Thesis, Division of Structural Engineering and Bridges, KTH Royal Institute of Technology, Stockholm, Bulletin 111.

[46] Safi, M. (2013). Procurement of the most cost-efficient bridge through incorporating life cycle costing with Bridge Management Systems: case study of the Karlsnäs Bridge in Sweden, ASCE Journal of Bridge Engineering.

[47] Safi, M., Sundquist, H., Karoumi, R., and Racutanu, G. (2012). Development of the Swedish bridge management system by upgrading and expanding the use of LCC. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, DOI:10.1080/15732479.2012.682588.

[48] Safi, M., Sundquist, H., Karoumi, R., and Racutanu, G. (2012). Life-Cycle Cost Analysis Applications for Bridges and Integration with Bridge Management Systems, Case Study of Swedish Bridge and Tunnel Management System. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2292, 125-133, Transportation Research Board of the National Academies, Washington, D.C., DOI: 10.3141/2292-15.

[49] Shirolé, A. (2010). Bridge Management to the Year 2020 and Beyond, *Transportation Research Record: Journal of the Transportation Research Board, No. 2202*, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 159–164.

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

[51] So, K. K. L., Cheung, M. M. S. & Zhang, E. X. Q. (2009). Life-cycle cost management of concrete bridges. *Proceedings of the Institution of Civil Engineering, Bridge Engineering*, 162 (BE3), 103-117.

[52] Sundquist, H. & Karoumi, R. (2009). *Life cycle cost methodology and computer tool webLCC*. The Royal Institute of Technology, Structural Design and Bridges, Stockholm

[53] T. Hegazy, E. Elbeltagi, and H. El-Behairy (2004). Bridge Deck Management System with Integrated Life-Cycle Cost Optimization. *Transportation Research Record: Journal of the Transportation Research Board, No. 1866*, TRB, National Research Council, Washington, D.C., 2004, pp. 44–50.

[54] The State of New Jersey. (2001). *Road User Cost Manual*. Department of Transportation, New Jersey.

[55] The Swedish Road Administration, Publication for Bridge Encoding 2006, BaTMan – Koder för inspektion av byggnadsverk Publ 2006:61

[56] The Swedish Transport Administration (1996), Bridge Inspection Manual, *SRA publication 1996-036 (E) Borlange*, Sweden.

[57] Thiebault Vincent, Guangli Du, Raid Karoumi. "Design of railway bridges considering life-cycle assessment" Proceedings of the Institution of Civil Engineers (ICE)-Bridge Engineering, http://dx.doi.org/10.1680/bren.10.00054.

[58] Thomas D. Everett, Peter Weykamp, Harry A. Capers, William R. Cox, Thomas S. Drda, Lawrence Hummel, Paul Jensen, David A. Juntunen, Tod Kimball, Glenn A. Washe. 2008. Bridge Evaluation Quality Assurance in Europe. Federal Highway Administration, U.S. Department of Transportation, Report No. FHWA-PL-08-016.

[59] Thompson, P. D., J. J. Campbell, J. A. Duray, A. R. Marshall, W. E. Robert, J. Aldayuz, and K. F. Hurst. Integration of AASHTO's BRIDGEWare Products. In *Transportation Research Circular E-C049: 9th International Bridge Management Conference.* TRB, National Research Council, Washington, D.C., April 2003, pp. 85–95.

[60] Thompson, Paul D. (2004). Bridge Life-Cycle Costing in Integrated Environment of Design, Rating, and Management. *Transportation Research Record: Journal of the Transportation Research Board, No. 1866,* TRB, National Research Council, Washington, D.C., pp. 51–58.

[61] Troive, S. (1998). *Structural LCC design of concrete bridges.* PhD Thesis, KTH-The Royal Institute of Technology, Department of Structural Engineering, Stockholm.

[62] U.S. Department of Transportation Federal Highway Administration Office of Asset Management. August 2002: Life-Cycle Cost Analysis Primer.

[63] V. Patidar, S. Labi, K. Sinha and P. Thompson (2007). *NCHRP REPORT 590: Multi-Objective Optimization for Bridge Management Systems.* TRB, Transportation Research Board, Washington, D.C.

[64] Wedgwood, A. and Sansom, K. (2003), Willingness-to-pay surveys — A streamlined approach: Guidance notes for small town water services, WEDC, Loughborough University, UK.