Public defense:

Life-Cycle Costing
Applications and Implementations in Bridge Investment and Management

Candidate: Mohammed Safi
Chairman: Prof. Johan Silfwerbrand, KTH
Opponent: Prof. Jan-Eric Nilsson, VTI
Evaluation Committee: Prof. Anne Landin, LTH
Prof. Lennart Elfgren, LTU
Prof. Hans Lind, KTH
Supervisors: Prof. Håkan Sundquist
Prof. Raid Karoumi
Background

- Selection from multiple alternatives
- Conventional financial costing
- Maximize efficiency, sustainability and ensure the optimum use of taxpayers’ money
- LCCA has great saving potential
Aim

• Enhance 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.

• Develop convenient parameters and techniques for evaluating other life-cycle aspects of bridges, such as, user costs, environmental impacts and aesthetic values.
Thesis Contents

• Part I: Extended Summary

1) Introduction
2) LCCA and BMSs
3) LCCA Applications and Obstacles
4) LCCA for Railway Bridges: a Case Study
5) BaTMan-LCC Tool
6) Conclusions

• Part II: Appendices

1) Appended 5 Papers
2) Appendix A: LCCA Tools
3) Appendix B: BSMs’ LCPs
Scope

- The scope of life-cycle costing
- Mainly focuses on project-level decisions
- Some results and conclusions are object-specific
- Trafikverket’s established procurement
- Records from BaTMan
- Values of general parameters, such as the discount rate and willingness-to-pay-extra for aesthetic merit and environmental impact
Bridge **Life-Cycle Cost: LCC**

- The time value of money, discount rate

- Life-Cycle Costing/Life-Cycle Cost Analysis (LCCA)
Important to Acknowledge

- The objective of LCCA is the minimization of the bridges’ LCC not only the LCM costs.

- Not necessarily the most LCC-efficient alternative is the one associated with the least LCM cost or the longest life-span.

- The most LCC-efficient option is the one associated with the lowest equivalent annual cost (EAC), i.e. annual INV and LCM costs over the proposed bridge’s life-span.

- It is the function of the design standards and the qualification requirements to minimize the LCM costs of the bridges.
LCCA Applications for Bridges

Decision on whether or not to undertake the project

Whole-life costing & LCCA

Early Planning & Initial Study

Feasibility Study

Building Doc. Design Plan

Bidding & Tendering

Detail Design & Construction

Operation & Maintenance

End of Life

Tender documents
Contract
Inauguration

Demolition

Get a preliminary bridge LCC & specify the most cost-efficient road corridor

Propose an optimal conceptual design and establish LCC benchmarks

Specify the optimal bridge structural member

Specify the optimal repair strategy

Specify the optimal structural member replacement alternative

Specify the optimal bridge design proposal

Specify the optimal bridge replacement alternative

Should a heavily deteriorated bridge be repaired or replaced?

The Potential Net Saving of the various LCCA Applications

Idea

Division of Structural Engineering and Bridges

28 July, 2015
Use of Bridge Management Systems to Implement LCCA for

Bridge Investment
- Procurement of New Bridges
- Building Doc. Design Plan
- Bidding & Tendering
- Detail Design & Construction
- Operation & Maintenance
- End of Life

Bridge Management
- Management of Existing Bridges
- Procurement of the most cost-efficient bridge
- Life-cycle cost
- Environment
- Life-cycle cost
- User Cost
- Aesthetics
- Life-cycle Assessment
- The most environmentally friendly conceptual design
- Net Saving
- Opportunity Loss
- Life-Cycle Cost
- Added-Value LCPS for the various BMS
- LCC & User Costs
- Lifespan
- Should a bridge be repaired or replaced?
- What is the most cost-efficient repair strategy?
- State-of-the-Art
- State-of-the-Practice

Research
Structure & Contributions

Paper I
Should a bridge be repaired or replaced?

Paper II
Procurement of the most cost-efficient bridge
Life-cycle cost

Paper III
LCC & User Costs
Lifespan
What is the most cost-efficient repair strategy?

Paper IV
Net Saving
Opportunity Loss
Life-Cycle Cost
Added-Value LCPS for the various BSMs

Paper V
State-of-the-Art
State-of-the-Practice

Early Planning...
& Initial Study
Feasibility Study
Building Doc.
Design Plan
Bidding & Tendering
Detail Design & Construction
Operation & Maintenance
End of Life

28 July, 2015
BaTMan & WebHybris

BaTMan är ett hjälpmedel för effektiv förvaltning av broar, tunnelar och andra typer av byggnadsväx

Nyare rapporter

- Ny rapportssammanfattning
  
  28 July, 2015

Division of Structural Engineering and Bridges
LCCA for Management of Existing Bridges
**Bridge Management: Paper I & III**

**Repair or replace a heavily deteriorated bridge?**

<table>
<thead>
<tr>
<th>Road Bridges</th>
<th>Railway Bridges</th>
</tr>
</thead>
</table>

An action is required within a 3 years period, CC2

An immediate action is required, CC3

---

28 July, 2015

Division of Structural Engineering and Bridges
**Strategies Formulation**

**Strategy A:** Immediately repair the bridge

- Repair Cost
- User Cost
- Extended Residual Service after Repair
- Annual O&M Cost after Repair
- Today
- The Current Bridge Service Life

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

- Renewal Cost
- User Cost
- Residual Service Life without Action
- Current Annual O&M Cost
- Annual O&M Cost after Renewal
- Today
- The New Bridge Service Life

**Sensitivity analysis:**

1. Discount rate
2. The INV cost of a new bridge
3. Residual service life extension after repair
4. Residual service life without action
5. Actual service life of a new bridge
6. Long- and short-term planning of the repair
7. User cost inclusion
Repair or replace a bridge structural-member?

An action is required within a 3 years, CC2

Vårbyvägen Bridge [1-813-1]
The surfacing of the bridge deck is CC 2, 3 years
The bridge deck, CC 0

Parameters affecting the analysis, Sensitivity analysis:

1. Discount rate
2. The INV cost of the various strategies
3. User cost inclusion
4. Residual service life without action
5. Dominating structural member residual service life
6. Impact of the various strategies on the residual service life extension
LCCA for
Procurement of New Bridges
Important Principals in Procurement within Public Agencies

“The Swedish Transport Administration is an authority and by law must endeavor to procure goods, services and contracts in competition”

To ensure credibility and transparency
Bridge Investment & Management from a LCCA Perspective

- The main difference lies in the procurement method/contract type
- Fixed target strategy in management but not usually fixed in investment, particularly under D-B
- The lowest bid and no consistent LCC guidelines
- Trafikverek’s goal is: 50% D-B by 2018
- A new award criterion under D-B: lowest LCC bid
There are several improper ways to employ the concept of the lowest LCC bid as the contract award criterion under D-B.

The optimal way is for procurers to establish consistent LCC-efficient benchmarks and guidelines then clearly present them as core specification in the tender documents.
Comprehensive Approach:

1. A preliminary LCCA
2. Monetary LCC-efficient benchmarks
3. Bid evaluation criteria: lowest LCC bid
## Case Study
### The Karlsnäs Bridge 2013

<table>
<thead>
<tr>
<th>Proposal No.</th>
<th>Description</th>
<th>Cross-Section Details</th>
<th>Outlines &amp; Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>One bridge, two steel boxes (Trafikverket’s conceptual design)</td>
<td><img src="image1.png" alt="Diagram 1" /></td>
<td>5 Spans 4x60m + 2x40m Superstructure depth: 2.3m</td>
</tr>
<tr>
<td>2</td>
<td>Two bridges, two steel I beams per bridge</td>
<td><img src="image2.png" alt="Diagram 2" /></td>
<td>5 Spans 4x60m + 2x40m Superstructure depth: Haunch beam Max. 3.2m Min. 1.8m</td>
</tr>
<tr>
<td>3</td>
<td>Two bridges, one prestressed concrete box per bridge</td>
<td><img src="image3.png" alt="Diagram 3" /></td>
<td>7 Spans 5x50m + 2x35m Superstructure depth: Haunch beam Max. 2.8m Min. 1.6m</td>
</tr>
<tr>
<td>4</td>
<td>One bridge, two prestressed concrete boxes</td>
<td><img src="image4.png" alt="Diagram 4" /></td>
<td>7 Spans 5x50m + 2x35m Superstructure depth: Haunch beam Max. 2.8m Min. 1.6m</td>
</tr>
<tr>
<td>5</td>
<td>One bridge, one integral-cantilever concrete box</td>
<td><img src="image5.png" alt="Diagram 5" /></td>
<td>4 Spans 2x100m + 2x60m Superstructure depth: Haunch beam Max. 6.5m Min. 2.3m</td>
</tr>
</tbody>
</table>
### LCCA Results

#### Proposal Number

<table>
<thead>
<tr>
<th>Proposal Number</th>
<th>INV Cost</th>
<th>LCM Cost NPV, r=2%</th>
<th>LCM Cost NPV, r=4%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>169.94</td>
<td>31.23</td>
<td>19.33</td>
</tr>
<tr>
<td>(2)</td>
<td>110.13</td>
<td>28.16</td>
<td>14.79</td>
</tr>
<tr>
<td>(3)</td>
<td>116.96</td>
<td>28.17</td>
<td>13.58</td>
</tr>
<tr>
<td>(4)</td>
<td>124.20</td>
<td>15.86</td>
<td>13.61</td>
</tr>
<tr>
<td>(5)</td>
<td>115.55</td>
<td>33.65</td>
<td>14.79</td>
</tr>
</tbody>
</table>

![Graph showing LCM Cost NPV and INV Cost](image)
Impact of varying the discount rate on the proposals’ LCC
LCC added-values computed at indicated discount rates (SEK)

<table>
<thead>
<tr>
<th>LCC added-values, Million SEK</th>
<th>0%</th>
<th>2%</th>
<th>4%</th>
<th>6%</th>
<th>8%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposal (1)</td>
<td>14.65</td>
<td>5.48</td>
<td>2.27</td>
<td>-1.54</td>
<td>-0.74</td>
</tr>
<tr>
<td>Proposal (2)</td>
<td>38.44</td>
<td>14.16</td>
<td>5.75</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Proposal (3)</td>
<td>8.77</td>
<td>3.06</td>
<td>1.21</td>
<td>-2.02</td>
<td>-0.97</td>
</tr>
<tr>
<td>Proposal (4)</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.02</td>
<td>-2.54</td>
<td>-1.23</td>
</tr>
<tr>
<td>Proposal (5)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-2.57</td>
<td>-1.26</td>
</tr>
</tbody>
</table>

Division of Structural Engineering and Bridges
Structural-members’ LCC added-values at a discount rate of 4%

To maintain contractors’ freedom in D-B tendering processes and allow consideration of innovative/different designs.

<table>
<thead>
<tr>
<th>Bridge structural-member</th>
<th>Unit</th>
<th>LCC sub added-value</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Unit LCM cost</td>
<td>Fixed Cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(K SEK/Unit)</td>
<td>(K SEK)</td>
<td></td>
</tr>
<tr>
<td>Bearings number</td>
<td>set</td>
<td>7.0</td>
<td>54.4</td>
<td></td>
</tr>
<tr>
<td>Expansion joint length</td>
<td>m</td>
<td>5.8</td>
<td>156.4</td>
<td></td>
</tr>
<tr>
<td>Edge beam length</td>
<td>m</td>
<td>1.6</td>
<td>108.3</td>
<td></td>
</tr>
<tr>
<td>Painted area</td>
<td>m²</td>
<td>0.4</td>
<td>85.3</td>
<td></td>
</tr>
<tr>
<td>Parapets’ length</td>
<td>m</td>
<td>1.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Paved area</td>
<td>m²</td>
<td>0.5</td>
<td>462.0</td>
<td></td>
</tr>
<tr>
<td>Drainage system points</td>
<td>set</td>
<td>32.7</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Slopes and cones area</td>
<td>m²</td>
<td>0.4</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Superstructure area</td>
<td>m²</td>
<td>0.2</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Total bridge area</td>
<td>m²</td>
<td>0.6</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>
Procurement of the Karlsnäs Bridge

- The LCC added-values and BSM’s LCC added-values had been stated in the tender documents.
- 5 Contractors had participated, all of them are Proposal 3
- The contract was awarded to the lowest LCC bid, with an INV cost of 115 million SEK.
- Trafikverket has saved 57 million SEK
Paper V: Holistic Approach

Bridge LCC

- Agency cost: INV & LCM
- User Cost
- Society Cost
  - Aesthetical & Cultural Effects
  - Environmental Impact (LCA)
Holistic Approach

- The **lowest Net Equivalent LCC bid** should be the criterion used to identify the most sustainable bridge proposal and select the D-B contractor offering it.

- The approach combines LCC Added-Value analysis with other novel techniques that make proposals’ aesthetic merit and environmental impact commensurable,

- Thereby enabling agencies to establish **Monetary Benchmarks** concerning those aspects in an early planning phase and embed them in the tender documents as core specifications.
WTP & WTPE

• In economics, the willingness-to-pay (WTP) is the maximum amount a person would be willing to pay in order to receive a good or avoid something undesired.

• Extending this concept, we propose here a novel parameter, willingness-to-pay-extra (WTPE), the maximum extra amount a person would be willing to pay to receive a good that is better than another in terms of a specific attribute.

• This is not meant to imply that designs of great aesthetic merit or more environmental friendly are necessarily more expensive than ugly substitutes, or vice versa.
Case Study

A wildlife crossing bridge over the European route E6 in Gothenburg, 2015.

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Elevation and Cross-Section</th>
<th>Similar Existing Bridges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concrete beam bridge with integrated breast wall (Trafikverket’s conceptual design)</td>
<td><img src="image1.png" alt="Concrete Beam Bridge Diagram" /></td>
<td><img src="image2.png" alt="Concrete Beam Bridge Image" /></td>
</tr>
<tr>
<td>2</td>
<td>Steel I-beam bridge composite with concrete slab with integrated breast wall</td>
<td><img src="image3.png" alt="Steel I-beam Bridge Diagram" /></td>
<td><img src="image4.png" alt="Steel I-beam Bridge Image" /></td>
</tr>
<tr>
<td>3</td>
<td>Two steel pipe-arch culverts</td>
<td><img src="image5.png" alt="Pipe-Arch Culvert Diagram" /></td>
<td><img src="image6.png" alt="Pipe-Arch Culvert Image" /></td>
</tr>
</tbody>
</table>
Life-cycle aspects’ contributions and net equivalent LCC costs of Proposals

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticipated INV &amp; TCP cost</td>
<td>33.07</td>
<td>36.08</td>
<td>19.79</td>
</tr>
<tr>
<td>LCC added-value</td>
<td>-1.13</td>
<td>1.11</td>
<td>0.00</td>
</tr>
<tr>
<td>User cost added-value</td>
<td>2.10</td>
<td>-0.54</td>
<td>0.00</td>
</tr>
<tr>
<td>CEEM</td>
<td>-1.06</td>
<td>0.26</td>
<td>-1.83</td>
</tr>
<tr>
<td>CEEI</td>
<td>2.74</td>
<td>2.45</td>
<td>2.01</td>
</tr>
<tr>
<td>The net equivalent LCC</td>
<td>35.72</td>
<td>39.35</td>
<td>19.97</td>
</tr>
</tbody>
</table>
Network-level Benefits of LCCA Considering Trafikverket’s Bridges

If improper decisions are taken for 50% of Trafikverket's bridges, the agency might lose (or could otherwise save):

- **Paper I, III**
  - Road bridges: 75 million SEK each year
  - Railway bridges: 65 million SEK each year

- **Paper IV:**
  - 8 million SEK per year

- **Paper II and V:**
  - 340 million SEK per year

*Total of 488 million SEK each year?!*
Conclusions

• Undoubtedly, LCCA can be feasibly and fruitfully applied in both bridge management and bridge investment.

• The most expensive bridge proposal is not necessarily the most environmentally friendly, beautiful or LCC-efficient, and vice versa. Costs, aesthetic merit and environmental concerns could be complementary in bridge design.

• The greatest saving potential in bridge procurement could be achieved by allowing more proposals to be considered.

• D-Bs together with the lowest LCC bid affords greater opportunities to consider LCC aspects in bridge procurement than traditional contracts and the lowest bid criterion.

• The sensitivity analysis is, NS and OL parameters are important that allows decision-makers to evaluate their confidence in the optimality of their chosen solution and estimate the consequences of their decisions.

• The discount rate is usually has a considerable impact on the LCCA, but this does not hinder the implementation of the proposed applications and.
Proposals for Further Research

- Standard LCC sub added-values
- Technically feasible bridge-designs
- LCCA curves for the various bridge locations
- Effect of repairs on the residual service life
- Network-level LCCA
Practical Implementation

Specify in which bridge investment phase are you now & What do you want to do

1. Propose an optimal conceptual design
2. Decide whether to repair or to renew a bridge
3. Get a preliminary bridge LCC & specify the most cost-effective road's corridor

BaTMan-LCC

Bridge Life-Cycle Cost Optimization

Version 1 [2012-07-10]

Developer:
Mohammed SAFI, PhD Student, KTH
mohammed.safi@byv.kth.se

Supervisors:
Prof. Håkan SUNDQUIST, KTH
Prof. Raid KAROUUI, KTH
Dr. George RACUTANU, Trafikverket

Program Map & Analysis Steps
BaTMan-LCC Course
Thank You!
Questions?