Appendix (A)

LCCA for Bridges: Tools and Involved Techniques

This appendix presents all LCCA tools and techniques employed in the appended papers. Detail information about the proper way of applying these tools could be found in the appended papers.

Notations

a_{ACE}	The general aesthetic demand non dimensional factor,%
a_{EI}	The environmental willingness-to-extra-pay factor, %
$A_{t,r}$	The annuity factor
C_{ACC}	Accident cost
C_{AINV}^{R}	The anticipated INV cost of the reference proposal, proposal R which is the most LCC-efficient proposal promoted in the pre-LCCA process.
$CEAM^{X}$	The cost equivalent of the aesthetic merit of proposal X
$CEEI^{X,R}$	The cost equivalent of the environmental impact of proposal X during the life-span of proposal R
C_F	Average cost per fatal accident
C_I	Average cost per serious injury accident
C_{INV}^{X}	The initial investment cost of proposal X that is offered in a contractor bid
C_P	Future cash flow expected to fall due periodically every p years during the service life-span L
C_{TDC}	Traffic delay cost
C_{VOC}	Vehicle operating cost
C_n	Sum of all cash flows in year n
C_o	Future cash flow expected to fall due every year during the service life-span L
EAC_{AINV}^{R}	The equivalent annual cost of the anticipated initial investment cost of proposal R
EAC_{LCM}^{X}	The equivalent annual cost of the life-cycle measures cost associated with proposal X
j	The number of items to be considered during the aesthetics evaluation process
k_{AES}^{X}	The aesthetic coefficient of proposal X
k_{EI}^{X}	The environmental impact coefficient of proposal X, %
$LCC_{AV}^{X,R}$	The life-cycle cost added-value of proposal X relative to proposal R
$LCC_{NE}^{X,R}$	The net equivalent life-cycle cost of proposal X where proposal R is the reference proposals in the evaluation process
L_D	Detour length
L_R	The life-span of proposal R
L_{min}	The life-span of the short lasting proposal
O_P	Average hourly operating cost for one passenger car
O_T	Average hourly operating cost for one truck
P_F	Average number of killed persons in bridge related accidents

P_I	Average number of injured persons in bridge related accidents
p_i	The numerical value given by an evaluator on a chosen scale to a considered item i during the aesthetics evaluation process
p_{imax}	The maximum numerical value that could be given by an evaluator on a chosen scale to a considered item i during the aesthetics evaluation process
r	Discount rate
r_{TG}	Traffic growth rate
sc_{sf}	The bridge-site-class scale factor, %
$USER_{AV}^{X,R}$	The user-cost added-value of proposal X relative to proposal R
V_D	Detour speed
$WTEP_{ACE}$	The willingness-to-extra-pay for the bridge aesthetics aspects
$WTEP_{EI}$	The willingness-to-extra-pay for the bridge environmental aspects
w_T	Hourly time value for one truck
w_i	The weight of importance for an item i during the aesthetics evaluation process
w_p	Hourly time value for one passenger car

1.1 Net Present Value Method

The time value of money is germane to LCCA since the costs included in the analysis are incurred at varying points in time. For LCCA, costs occasioned at different times must be converted to their value at a common point in time. The commonest method used to compare past, present and future cash flows with those of today is termed the Net Present Value method (NPV). Costs occur at different times, therefore it is necessary to use a discount rate in the calculations to reflect the "time value of money". This can be expressed as the NPV equation:

$$NPV = \sum_{n=0}^{L} \frac{C_n}{(1+r)^n} \quad \textbf{(1)}$$

Where:

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

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

$$NPV = C_o \cdot \frac{1-(1+r)^{-L}}{r} \quad \textbf{(2)}$$

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

$$NPV = C_p \cdot \frac{1-(1+r)^{-m \cdot p}}{(1+r)^p - 1} \quad \textbf{(3)}$$

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

$$m = TRUNC\left(\frac{L-1}{p}\right) \quad \textbf{(4)}$$

1.2 Equivalent Annual Cost Technique

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

$$EAC = NPV \cdot A_{t,r} = NPV \cdot \frac{r}{1-(1+r)^{-L}} \quad \textbf{(5)}$$

Where:

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

1.3 Net Saving and Opportunity Loss

The Net Saving (NS) and the Opportunity Loss (OL) are two different techniques developed to highlight the feasibility of the LCCA results from different angles. The NS is the amount of money that could be saved by implementing the most cost-efficient alternative compared with the implementation of the other alternative, while the OL is the amount of money that could be lost by implementing the least cost-efficient alternative compared with the implementation of most cost-efficient one.

When comparing two alternatives having an equal life-span, the NPV could be employed to specify the most cost-efficient alternative. In this case, the NS will be equal to the OL and could be calculated by subtracting the NPV of both alternatives from each other.

When comparing two alternatives having unequal life-span, the EAC could be employed to specify the most cost-efficient alternative. Hence, the NS and the OL could be presented in two ways. Firstly, they could be presented as an annual saving/loss during the life-span of the alternative that will be implemented. This could be computed by subtracting the EAC of both alternatives from each other. The implemented alternative when computing the NS is the most cost-efficient alternative while the implemented alternative when computing the OL is not the most cost-efficient alternative.

Secondly, the NS and the OL could be presented as a total saving/loss amount during the life-span of the alternative that will be implemented. This can be calculated by converting the annual NS/OL to a present value. Equation 6 and 7 respectively present the present value of the NS and the OL in case of comparing two alternatives A and B, where alternative B is the most cost-efficient alternative.

$$NS = (EAC_A - EAC_B) \cdot \frac{1-(1+r)^{-L_B}}{r} \quad \textbf{(6)}$$

$$OL = (EAC_A - EAC_B) \cdot \frac{1-(1+r)^{-L_A}}{r} \quad \textbf{(7)}$$

1.4 Holistic Approach to Sustainable Bridge Procurement

Equation (9) presents the criteria for which the contractor's bids are supposed to be evaluated under the D-B contract forms. Hence the lowest combined bid would be awarded the contract.

$$LCC_{NE}^{X,R} = C_{INV}^{X} + LCC_{AV}^{X,R} + USER_{AV}^{X,R} + CEAM^{X} + CEEI^{X,R} \quad \textbf{(8)}$$

Where,

$LCC_{NE}^{X,R}$	The net equivalent life-cycle cost of proposal X where proposal R is the reference proposals in the evaluation process
C_{INV}^{X}	The initial investment cost of proposal X that is offered in a contractor bid
$LCC_{AV}^{X,R}$	The life-cycle cost added-value of proposal X relative to proposal R
$USER_{AV}^{X,R}$	The user-cost added-value of proposal X relative to proposal R
$CEAM^{X}$	The cost equivalent of the aesthetic merit of proposal X
$CEEI^{X,R}$	The cost equivalent of the environmental impact of proposal X during the life-span of proposal R

1.4.1 LCC Added-Value Technique

If a proposal (R) is considered to be the reference proposal in the tender documents in which it is given an LCC added-value equal to zero, the LCC added-value for a proposal (X) can be calculated using equation (8), considering that proposal (R) and (X) have unequal life-spans and are associated with unequal LCM costs:

$$LCC_{AV}^{X,R} = \left((EAC_{LCM}^{X} - EAC_{LCM}^{R}) \cdot \frac{1-(1+r)^{-L_{min}}}{r} \right) \mp \left(\frac{EAC_{AINV}^{R}}{(1+r)^{L_{min}}} \cdot \frac{1-(1+r)^{-|L_R - L_X|}}{r} \right) \quad \textbf{(9)}$$

The second part of equation (8) will have a positive sign if $L_X < L_R$ and vice versa.

The first part of equation (8) is simply the NPV of the LCM cost difference between the reference proposal and the compared proposal during the life-span of the short lasting proposal. The second term in this equation is the NPV of the cost equivalent of the life-span difference between the compared proposals, where:

EAC_{LCM}^{X}	The equivalent annual cost of the life-cycle measures cost associated with proposal X
r	The discount rate
L_{min}	The life-span of the short lasting proposal
EAC_{AINV}^{R}	The equivalent annual cost of the anticipated initial investment cost of proposal R
L_R	The life-span of proposal R

1.4.2 User-Cost

To count for the life-span difference between the various alternatives, the user-cost of the various alternatives should be computed considering the life-span of the reference proposal (R). The EAC of the user-cost of the reference proposal EAC_{USER}^{R} should be stated in the tender documents. Hence, a contractor could use equation (10) to compute the user-cost added-value of a proposal (X) relative to the user-cost added-value of the reference proposals which is always equal to zero.

$$USER_{AV}^{X,R} = (EAC_{USER}^{X} - EAC_{USER}^{R}) \cdot \frac{1-(1+r)^{-L_R}}{r} \quad \textbf{(10)}$$

1.4.3 Bridge Aesthetics and Cultural Values

The aesthetics WTEP could be a proportion of the anticipated INV cost of the most LCC-efficient proposal promoted in the pre-LCCA process. Two non-dimensional factors are included in computing this proportion; the general aesthetic demand factor and the bridge-site-class scale factor, seen in equation (11).

$$WTEP_{ACE} = C_{AINV}^{R} \cdot a_{ACE} \cdot sc_{sf} \quad \textbf{(11)}$$

Where,

$WTEP_{ACE}$	The willingness-to-extra-pay for the bridge aesthetics aspects
C_{AINV}^{R}	The anticipated INV cost of the reference proposal, proposal R which is the most LCC-efficient proposal promoted in the pre-LCCA process.
a_{ACE}	The general aesthetic demand non dimensional factor,%
sc_{sf}	The bridge-site-class scale factor, %

After the receipt of the contractors' bids, an individual aesthetic coefficient could be computed for each proposal. Hence, the cost equivalent of aesthetics merit (CEAM) of a proposal (X) could be computed by equation (12), where the k_{AES}^{X} is the aesthetic coefficient of proposal X.

$$CEAM^{X} = WTEP_{ACE} \cdot k_{AES}^{X} \quad \textbf{(12)}$$

The computation technique of the proposals' aesthetic coefficients presented in equation (6) is based on the idea that points are given to different items in a pre-established scheme. These points are given based on individual opinions of assigned evaluators. The number of items j to be considered could freely be chosen and each item can have a different weight of importance w_i. A comprehensive list consists of the items that will be evaluated and their weight factors should be a part of the aesthetics guidelines that are supposed to be attached with the tender documents. The evaluators rule is to give a numerical value or points p_i on a chosen scale to each considered item i.The weight values w_i in equation (13) consider how important an item i is in relation to the other items. The higher the value, the more important the item is. The points p_i indicate how well the requirements of an item i are fulfilled by a design under evaluation from the view point of an evaluator. Five values are accepted, namely -2, -1, 0, +1 and +2, corresponding: "poor", "modest", "medium", "good" and "excellent" attributes, respectively.

$$k_{ACE}^{X} = \frac{-\sum_{i=1}^{j} w_i \cdot p_i}{\sum_{i=1}^{j} w_i \cdot p_{imax}} \tag{13}$$

1.4.4 Bridge Environmental Impact

This environmental WTEP could be assigned as a percentage from the anticipated INV cost of the most LCC-efficient alternative that promoted in the pre-LCCA process, equation (14). Then, the different proposals could be measured on the environmental WTEP scale on which the environmentally-worst proposal is assigned the full amount of that WTEP. Accordingly, an individual environmental impact coefficient could be computed for the various alternatives. Hence, the CEEI of the various proposals could be computed using equation (15). In addition, assigning an environmental allowance boundary doesn't necessarily mean that the most environmental friendly bridge design is the most expensive one or vices versa. The case study included in this paper will highlight this point.

$$WTEP_{EI} = C_{AINV}^{R} \cdot a_{EI} \tag{14}$$

$$CEEI^{X,R} = WTEP_{EI} \cdot k_{EI}^{X} \tag{15}$$

Where,

$WTEP_{EI}$	The willingness-to-extra-pay for the bridge environmental aspects
a_{EI}	The environmental willingness-to-extra-pay factor, %
k_{EI}^{X}	The environmental impact coefficient of proposal X, %

The environmental WTEP factor in equation (14) defines the maximum amount of money, as a percentage from the anticipated INV cost of the most LCC-efficient proposal, an agency could extra pay for a more environmental friendly design alternative. The higher the value, the more the environmental aspects are appreciated. This parameter reflects the general policy of an organization, a government or a country.

1.5 Bridge User Cost

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

$$C_{User} = C_{TDC} + C_{VOC} + C_{ACC} \tag{16}$$

The costs should be calculated in a present value and added up for all foreseen LCM needs work-zone within the period studied.

1.5.1 Traffic delay cost

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

$$C_{TDC} = \sum_{t=0}^{L} T \cdot ADT_t \cdot N_t \cdot (r_T \cdot w_T + (1 - r_T) \cdot w_P) \cdot \frac{1}{(1+r)^t} \quad \textbf{(17)}$$

Where:

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

1.5.2 Vehicle operation cost

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

$$C_{VOC} = \sum_{t=0}^{L} T \cdot ADT_t \cdot N_t \cdot (r_T \cdot O_T + (1 - r_T) \cdot O_P) \cdot \frac{1}{(1+r)^t} \quad \textbf{(18)}$$

Where:

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

1.5.3 Accident cost

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

$$C_{VOC} = \sum_{t=0}^{L} T \cdot ADT_t \cdot N_t \cdot (A_n - A_a) \cdot \left((C_F \cdot P_F) + (C_I \cdot P_I)\right) \cdot \frac{1}{(1+r)^t} \quad \textbf{(19)}$$

Where:

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

1.5.4 Traffic growth rate

Due to factors such as population growth and economic prosperity, the volume of traffic on bridges may increase each year. The current or future *ADT*, based on the desired construction year, should be obtained from the traffic monitoring section. If the future *ADT* is not readily available, the following formula can be used. In bridge LCCA, it is recommended to consider the traffic growth within the first 40 years only since new routs or other solutions are usually implemented after 40 years to accommodate the increased volume of traffic.

$$ADT_t = ADT \cdot (1 + r_{TG})^{Year_t - Year_0} \quad \textbf{(20)}$$

Where:

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

1.6 Prediction interval and limits of prediction

For predicting the INV cost of new bridges based on cost records related to similar existing bridges, the method of least square could be employed to forecast the average cost. Equation 21 could be used to predict the prediction interval.

$$Predection\ interval = (a + bx_0) \pm t_{\alpha/2} \cdot S_e \cdot \sqrt{1 + \frac{1}{n} + \frac{(x_0 - \bar{x})^2}{\sum(x - \bar{x})^2}} \quad \textbf{(21)}$$