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2018

SBRI+ HELP MANUAL

LIFECYCLE ANALYSIS TOOL

ECCS, ISISE, UC-DEC

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1. ABOUT ECCS

1.1. Aims and Objectives

The **European Convention for Constructional Steelwork (ECCS)** is an international federation of national steelwork associations established in 1955.

The aim of **ECCS** is to promote the use of steelwork in the construction sector by the development of standards and promotional information. It also helps to influence decision makers through the management of working committees, publications, conferences, and by active representation on European and International Committees dealing with standardization, research and development and education.

ECCS brings together all the stakeholder of the Steel Construction Industry: Steel Producers, Steel Fabricators, Steel Stockholders, Suppliers of the Construction Sector, Designers (Architects and Engineers) and the Academic and R&D world through an international network of construction representatives, steel producers, and technical centres. Its Headquarters are located in Brussels, Belgium.

1.2. Membership

ECCS has the following categories of membership:
- **Full Members**, consisting of European national associations active in the field of steel construction;
- **International Members**, consisting of non-European national associations or other non-European organisations active in the field of steel construction;
- **Supporting Members**, consisting of International associations which represent raw material suppliers or other organisations concerned with or related to the use of structural steel and related building materials;
- **Associate Members**, consisting of European organisations that operate as Technical Institutions or Independent Promotion Organisations with interests in constructional steelwork and its application to the Construction market;
- **Individual Members**, consisting of anyone interested in subjects regarding Steel Construction and in supporting the Association's objectives;
- **Company Members**, consisting of any company interested in subjects regarding Steel Construction and in supporting the Association's objectives;

Individual membership is open worldwide to all architects, engineers or anyone interested in steel construction subjects and in supporting the ECCS's objectives. Individual Members are part of a large international network and benefit from various services:
- An annual subscription to "Steel Construction, *Design and Research*" in paper and electronic format (otherwise available at 170€ per year),
- Free access to Wiley Online,
- 20% discount on ECCS publications,
- Access to exclusive information via the ECCS homepage "MEMBER AREA",
- ECCS newsletter, [link em ECCS newsletter – enviar e-mail para itools@steelconstruct.com, assunto *Subscribe to Newsletter*]
- Supply of news for potential inclusion in Steel Construction,
- ECCS conferences at reduced prices:

- NSCC 2012: Nordic Steel Construction Conference, 10% discount for ECCS Individual Members;
- ICSA 2013: 2nd International Conference on Structures and Architecture, 10% discount for ECCS Individual Members;
- Eurosteel 2014: 7th European Conference on Steel and Composite Structures, 10% discount for ECCS Individual Members;

All this is available for an annual fee of 148 €/year and all are welcome to apply for membership.
Make your registration now and you will receive for free the last issue of 2010 and the 4 issues of 2011 of the Journal "Steel Construction".
Take advantage of this offer and join the ECCS as an Individual Member. You can apply by completing the ONLINE MEMBERSHIP FORM.

Note: To subscribe to ECCS newsletter, click here. [link em here – enviar e-mail para itools@steelconstruct.com, assunto *Subscribe to Newsletter*]

1.3. ECCS Steel Construction Platform

ECCS manages a Steel Construction Platform for collection and supply of information relevant for the steel construction sector and for internal management of the ECCS activities.

- Database of EPDs (Environmental Product Declarations),
- Database of Certified Steelwork Companies,
- R&D projects in the steel construction sector,

1.4. STEEL CONSTRUCTION: Design & Research

The journal "Steel Construction, *Design and Research*" is the official journal of ECCS and is published quarterly in cooperation with Ernst & Sohn (a Wiley company). ***Steel Construction*** brings together in one journal all the various aspects of steel construction. In the interest of "construction without depletion", it skillfully combines steel with other forms of construction using concrete, glass, cables and membranes to form integrated steelwork systems. This journal is aimed at all structural engineers, architects, and other professionals working in the field of steel construction, whether active in research or practice.

1.5. Technical guidance on the use of the Eurocodes

ECCS publishes guidance on the use of the Structural Eurocodes. The **ECCS Eurocode Design Manuals** offer detailed information on the application of the various parts of Eurocodes 3 (Steel Structures), 4 (Steel-concrete composite structures) and 8 (Seismic design of steel and composite structures) in a design oriented approach that includes numerous design examples.

The following **ECCS Eurocode Design Manuals** are available or in preparation:

- Design of Steel Structures – Eurocode 3, part 1-1,
- Fire Design of Steel Structures – Eurocode 1, part 1.2 and Eurocode 3, part 1.2,
- Design of Plated Structures – Eurocode 3, part 1-5,
- Fatigue Design of Steel Structures – Eurocode 3, part 1-9 and part 1-10,
- Design of Cold-Formed Steel Structures – Eurocode 3, part 1-3,

- Design of Connections in Steel and Composite Structures – Eurocode 3, part 1.8 and Eurocode 4, part 1-1,
- Design of Composite Structures, Eurocode 4, part 1-1,
- Fire Design of Composite Structures, Eurocode 4, part 1.2,
- Design of Steel Structures for Buildings in Seismic Areas, Eurocode 8, part 1.

ECCS also publishes extensive background guidance on all aspects relevant for steel construction. All this can be easily found in the **ECCS Online Bookstore**.

1.6. ECCS Academy

ECCS runs short training courses (1 day to 3 days) on specific topics related to steel construction with a special focus on the Eurocodes, using the ECCS Eurocode Design Manuals as base material. ECCS ensures the quality of the courses through an ECCS QUALITY LABEL. ECCS provides certificates of attendance to each participant, in cooperation with the Course Organizer. Further information is available here.

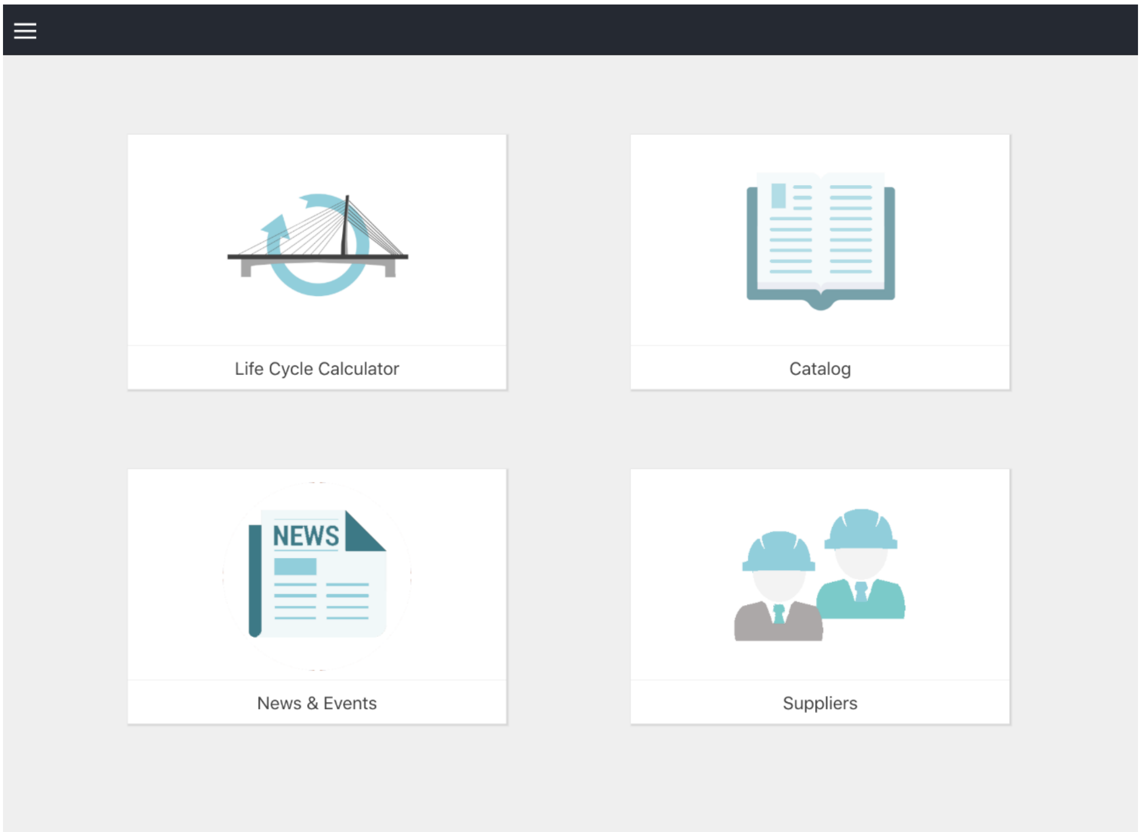
2. USING THE APPLICATION

2.1. Scope

The aim of this tool is to provide means to assess and compare the sustainability of different bridge types, in the early stages of design, implementing a holistic Lifecycle analysis methodology. The sustainability assessment is undertaken in accordance with the most recent European standard from CEN TC350 and ISO standards 14040 and 14044. The overall Lifecycle analysis incorporates three major sub-analyses: Lifecycle Environmental Assessment (LCA), Lifecycle Cost Analysis (LCC) and Lifecycle Social Analysis (LCS), at the different stages of the bridge's service life.

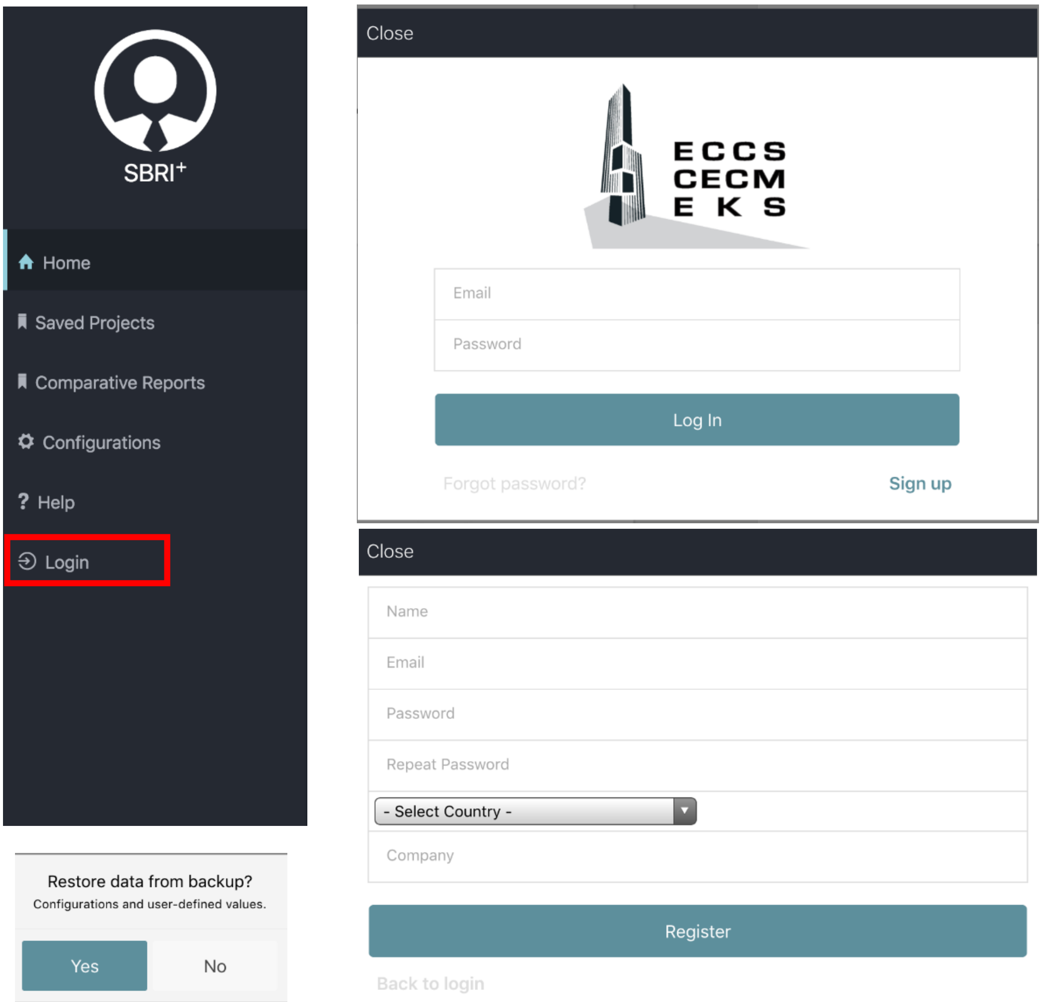
With the aim of simplifying the routine task of picking between common alternatives, the tool is organized by subgrouping projects into three representative bridge types: Type A – Crossings of motorway, Type B – Big motorway bridges and Type C – Small and medium motorway bridges.

The tool features three essential modules. The first one allows for the computation of Lifecycle Analysis for a single bridge alone - given parameters and data on the bridge properties. The second module enables users to run a Multi-criteria analysis when choosing between different elements/alternatives within the same bridge design type. Comparison of the Lifecycle Analysis of different bridge types can be performed by using the third module - Comparative Lifecycle Analysis.

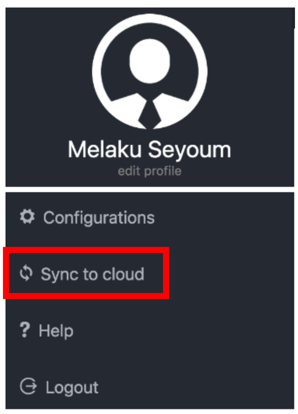


2.1. Registration, Login and Data Synchronization

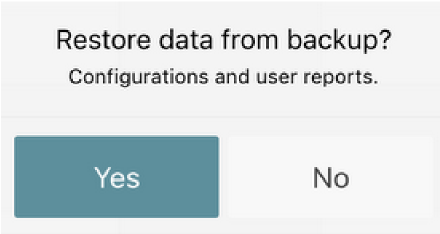
This utility is used to store the default configurations and user-defined values in a user's personal account while using the software. Users can easily access this feature by tapping on the options button (≡ triple bars on the top left) and selecting "Login". New users can create new accounts by tapping on the "Sign up" button.



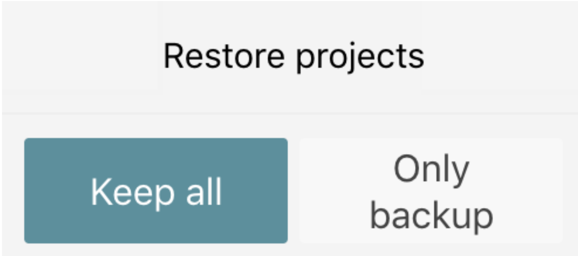
Up on successful creation of an account, users are able to synchronize projects and settings/configurations to the cloud. The user's provided name will show at the top of the main options window. An additional "Sync to cloud" button is activated upon a successful login.



Note: Data is automatically synchronized if internet connection is active at the time of saving a project. However, in the event of no connection while working on a project, a user can later manually sync his/her data by pressing the "sync to cloud" button while connected to the internet.



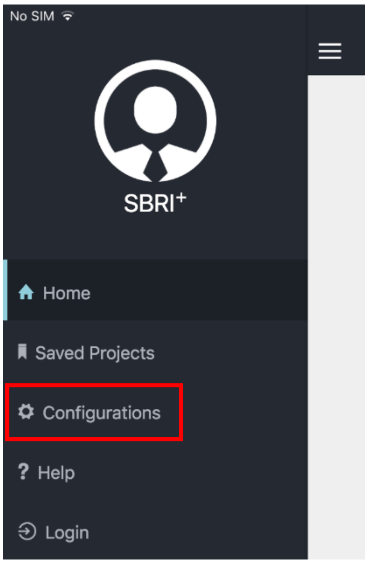
When a user logs in, the program asks if the user wants to load/restore data from their personal backup. Choosing to restore a backup, a popup follows giving the user two possible options to choose from.



The user can pick "only backup", if he/she wants to wipe all saved contents in the app and restore the previously backed up data. Alternatively, the user can choose "Keep all", if he/she wants to append the previously backed up data to whatever data is currently stored in the app.

2.2. Configurations

The default inputs are set in the configurations panel. Different details regarding the project settings, calculation options, databases, traffic, transport data, and construction and demolition details can be stored to make the entry of inputs user friendly. This inputs can later be changed in the particular project files in different windows/panels of the app.

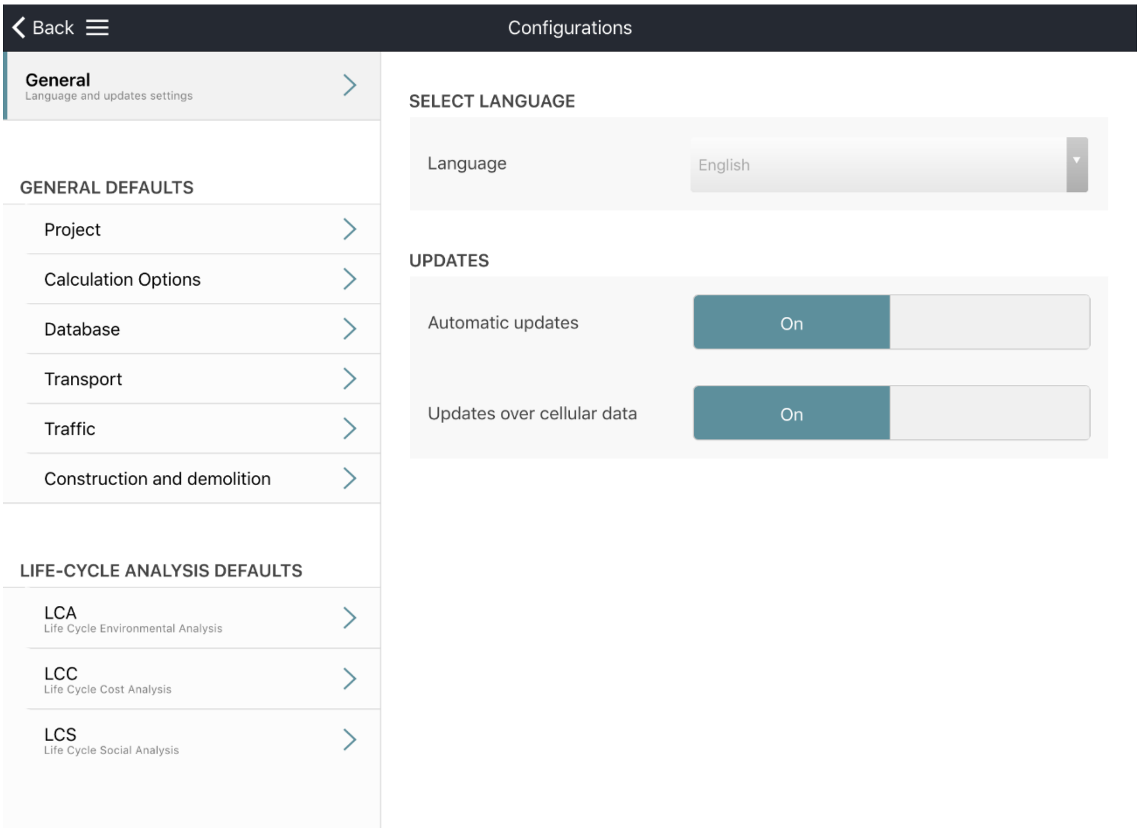


To access the configurations, start by tapping on the options button (☰ triple bars on the top left) and select "configurations". New users can create new accounts by tapping on the "Sign up" button.

Up on successful creation of an account, users are asked if they want to load/restore data from their personal backup.

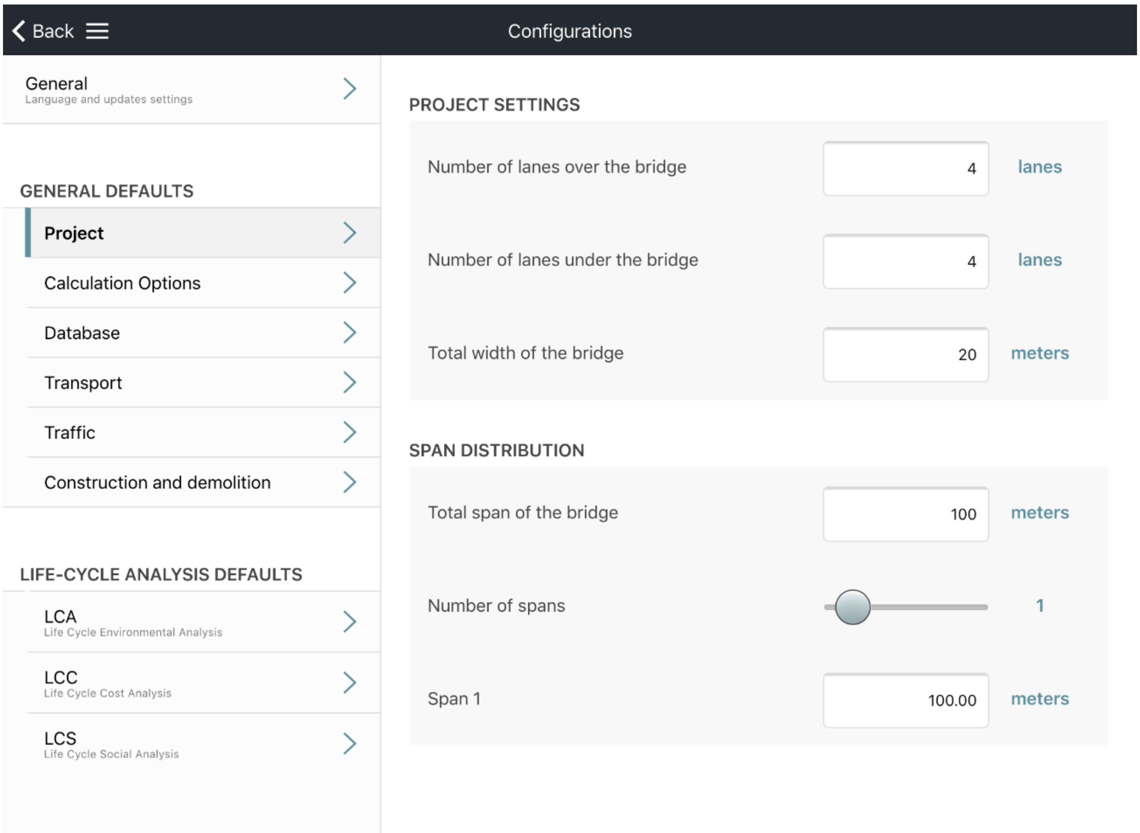
2.2.1. General

Language selection and options to enable/disable automatic updates "only on Wi-Fi" or "over cellular data" can be accessed here.



2.2.2. Project data

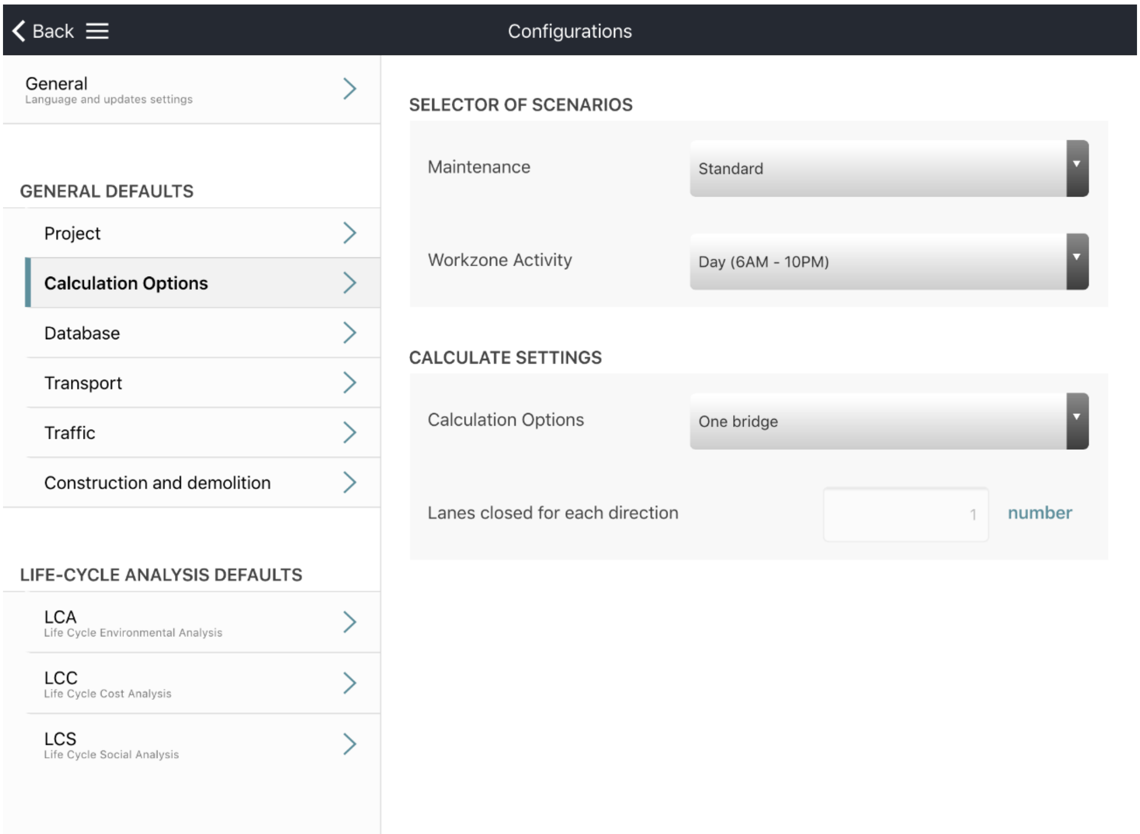
Default project settings such as the bridge length, span distribution, number of traffic lanes over and under the bridge, etc. can be stored here. This is handy in enabling faster input of bridge parameters for the analysis involving repetitive tasks carried out for a single bridge of varying particulars.



2.2.3. Calculation options

The main parameters defining the analysis type, maintenance scenarios, and operation situations are set here.

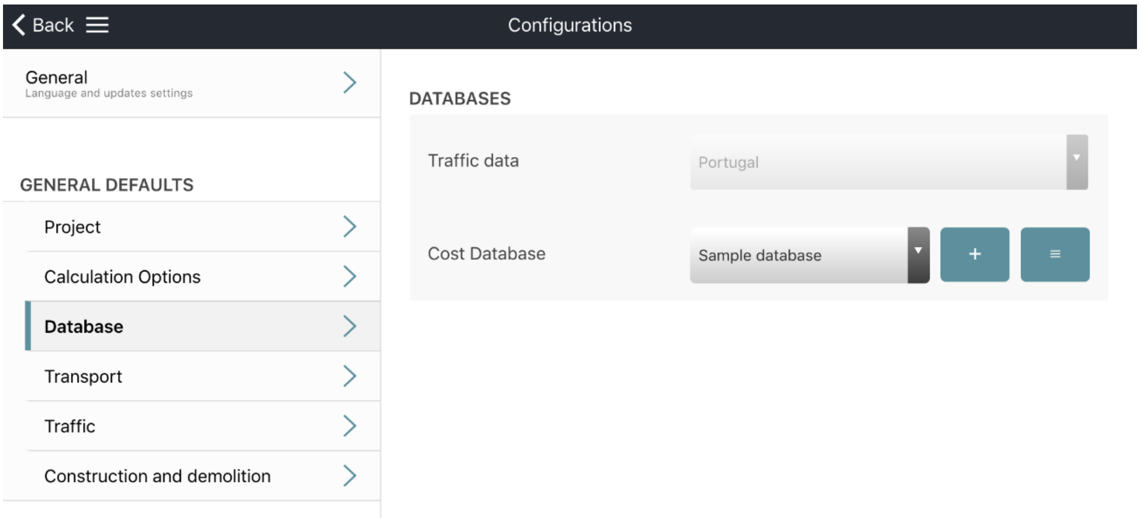
- Maintenance scenarios: “Standard”, “Lack of Money”, and “Prolonged Life”.
- Work zone activity: “Day work” or “Night work”.
- In case of situations where there are two different bridges for traffic in the opposite directions, an option to specify if input data came from one of the bridges or from both is included in the calculation options.
- The number of lanes closed for traffic on bridges under maintenance can be specified here. Note: This is limited to a single lane, in the current version of the software.



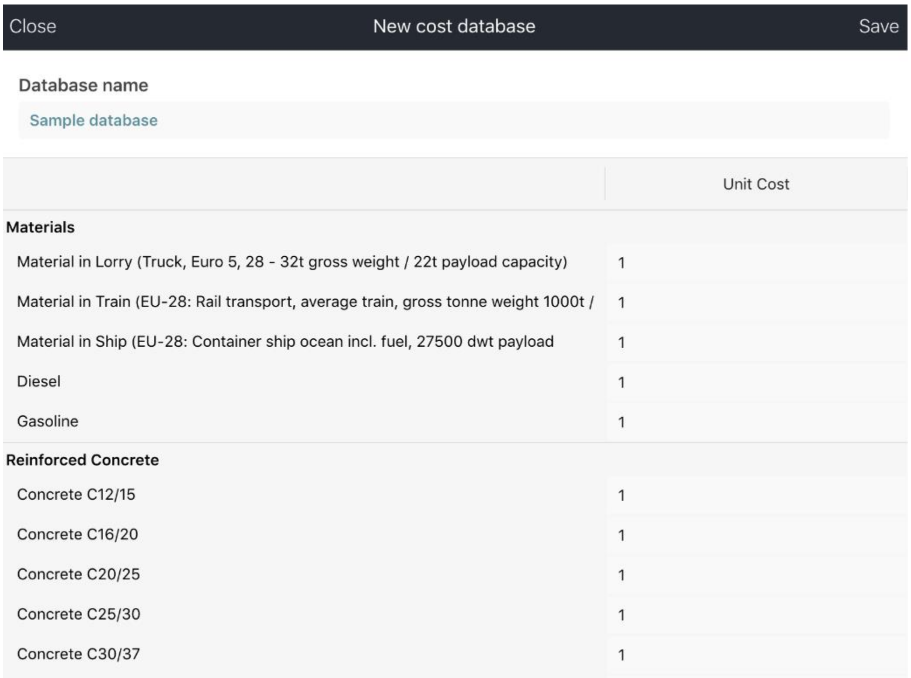
2.2.4. Databases

Traffic and cost databases can be created and/or selected in this panel. Traffic data related to the number, type and distribution of traffic over the hours of the day can be selected using the dropdown for traffic data.

Note: The traffic data is disable for now for lack of data from other sources.

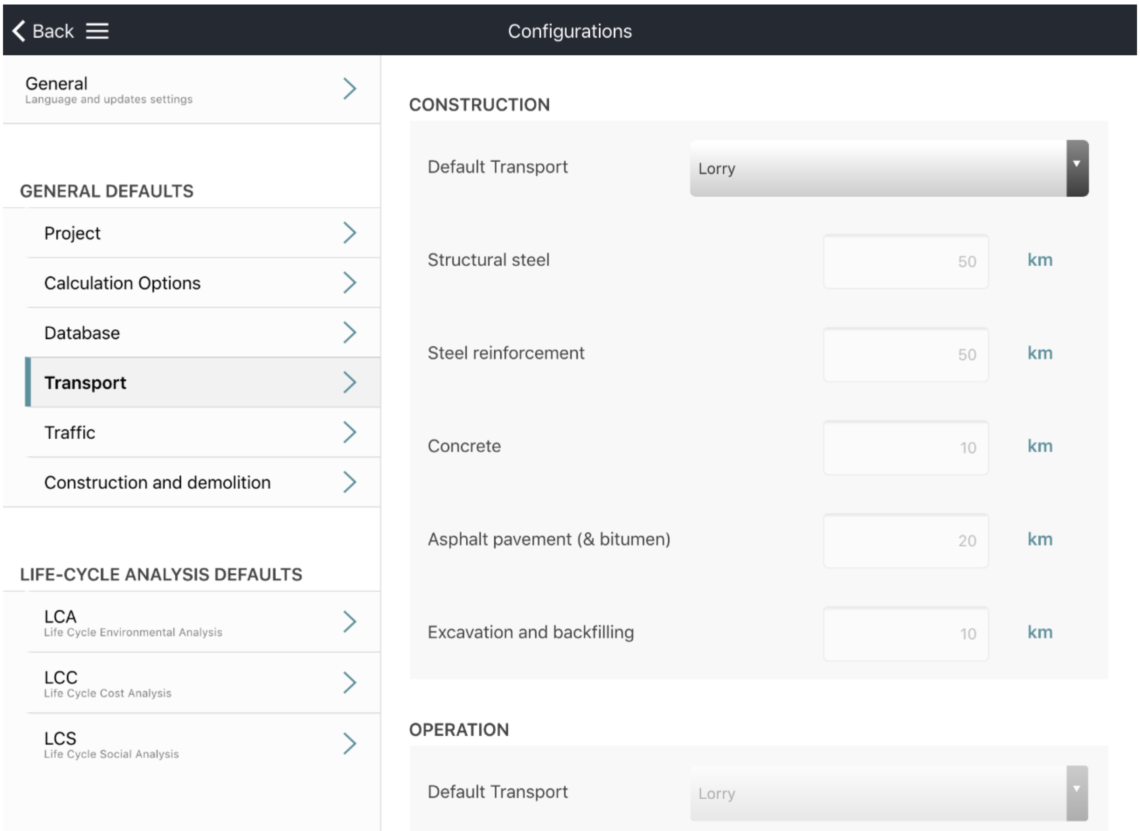


Likewise, a database of construction material, and execution costs can be defined (by tapping on the + button) or edited/modified (by tapping on the triple bars) in the costs database.



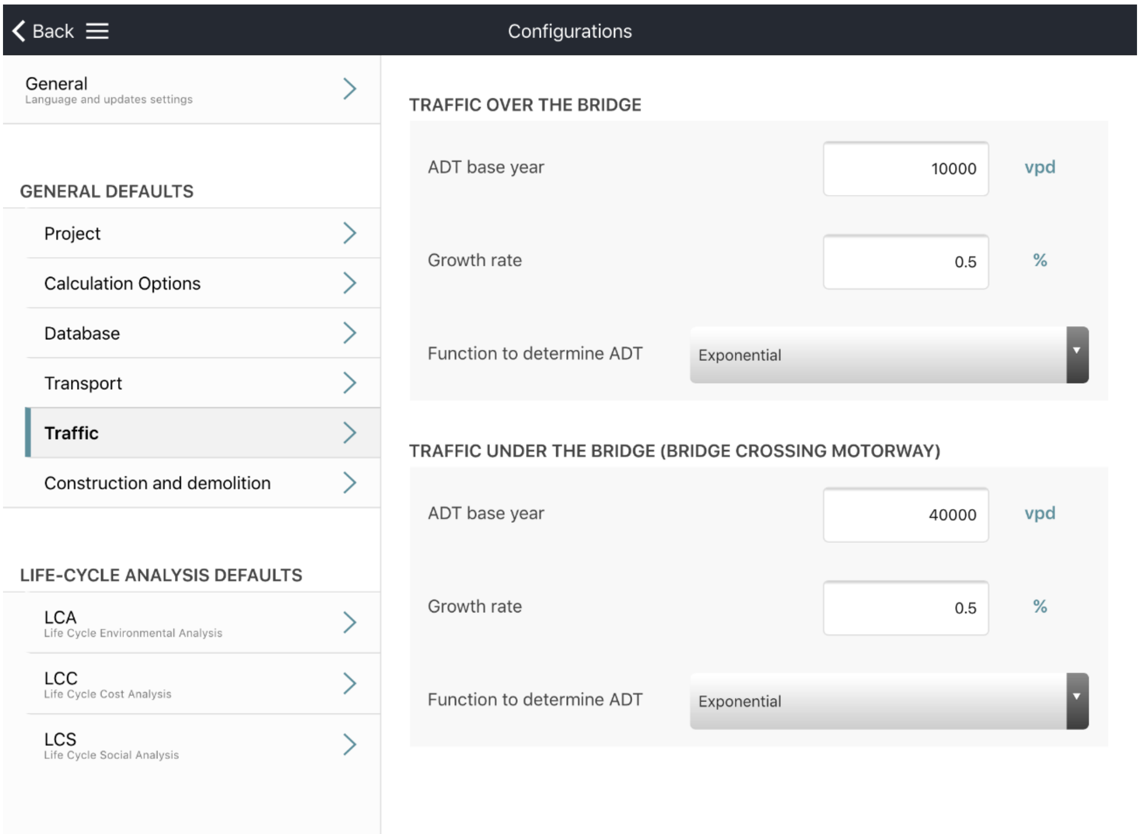
2.2.5. Transport of materials

The means of transport and the approximate distances of transport can be defined for different materials at different stages in the lifecycle of the bridge.



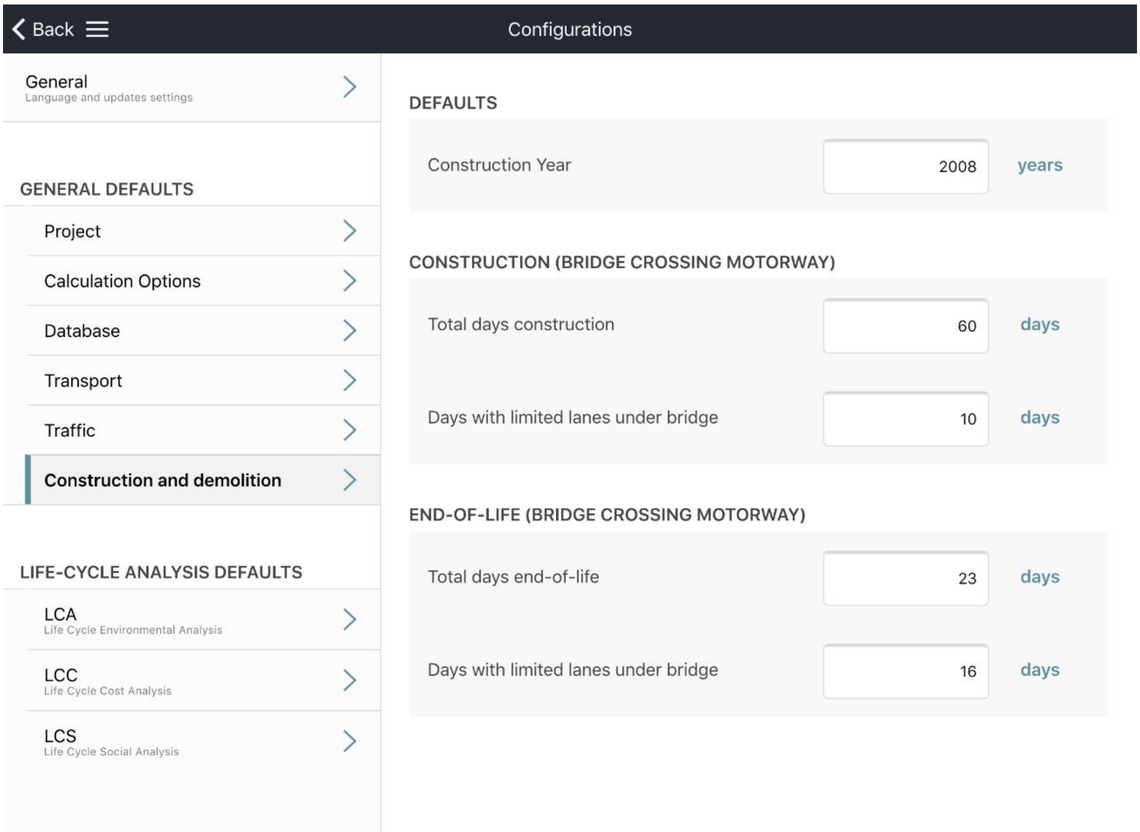
2.2.6. Traffic

Average daily traffic over and under the bridge on the base year and expected traffic at the end of the service life of the bridge (For linear growth) or growth rate (For exponential growth) can be defined in this panel.



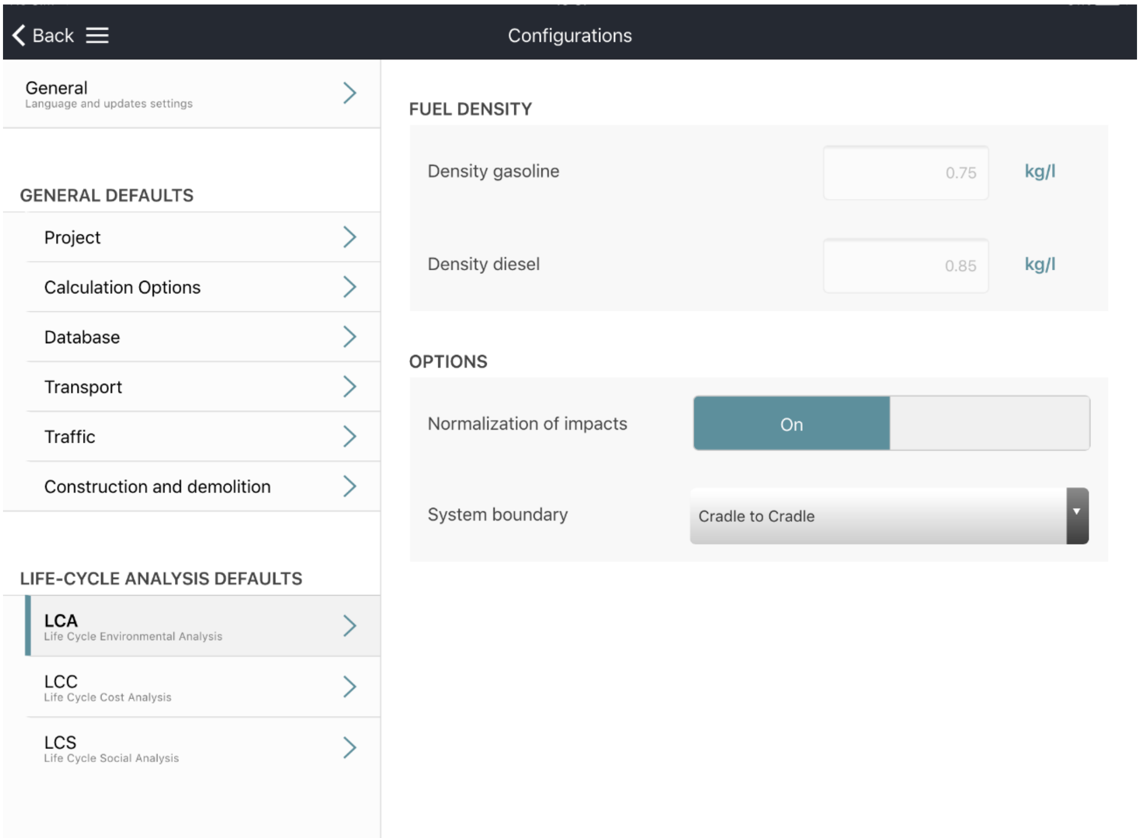
2.2.7. Construction and Demolition

For bridges crossing an existing motorway, the construction and demolition processes will impose restrictions in the traffic under the bridge. Data pertinent to these processes is to be defined in this panel.



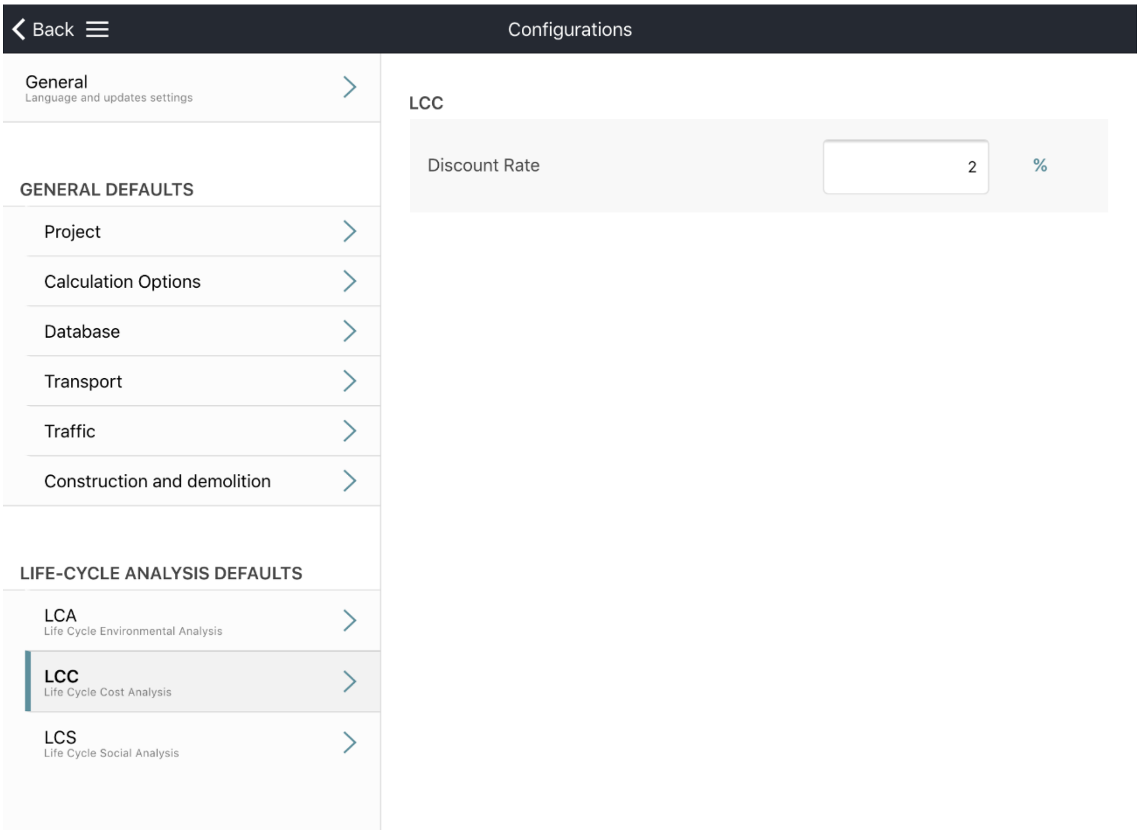
2.2.8. Lifecycle Environmental Analysis

Fuel density and system boundary can be defined here. Note: System boundary is currently limited to cradle to cradle. The use of normalization factors can be toggled as well.



2.2.9. Lifecycle Cost Analysis

The discount rate to be used in determining the present net value of costs can be fixed here.

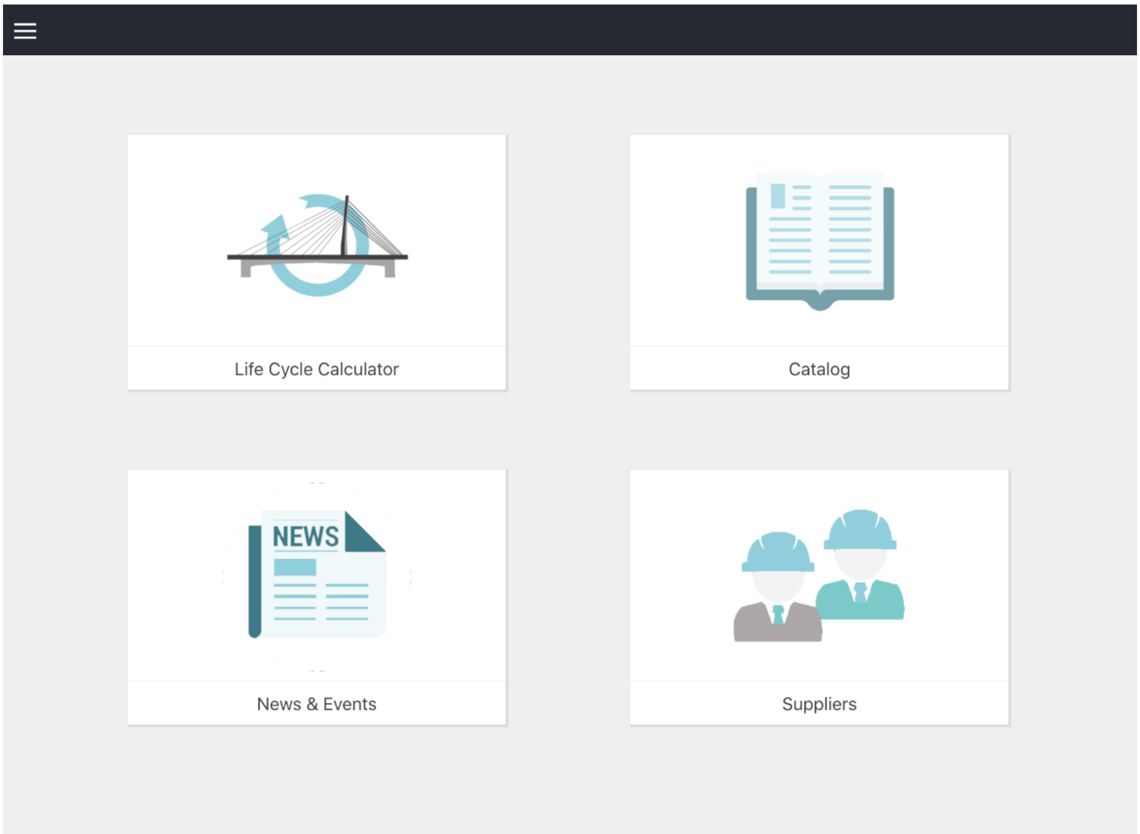


2.2.10. Lifecycle Social Analysis

As the inputs for the social costs are based on Portuguese data, static/constant coefficients and database values have been used! As a result, no options are outlined in this section of the app. Further databases and customizations will be included in future versions of the application.

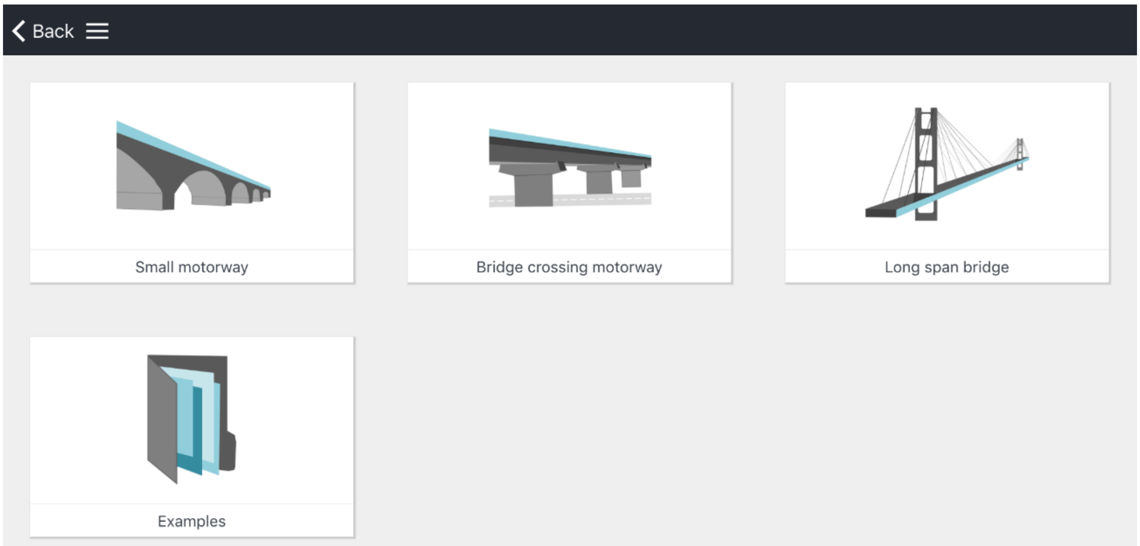
2.3. Home Interface

The main user interface can be reached by tapping on the home button from the options (triple bars). This window contains four destinations: the lifecycle calculator, catalog of materials, news and events, and suppliers' details.



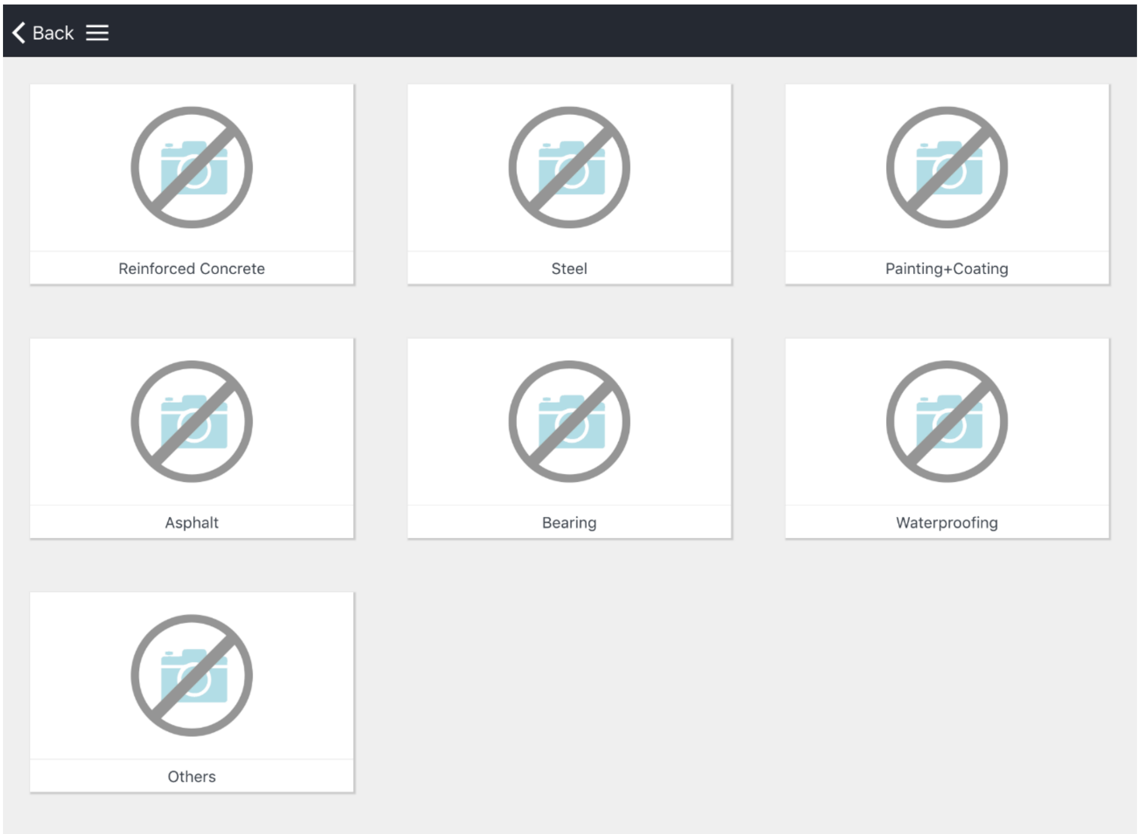
2.3.1. Lifecycle calculator

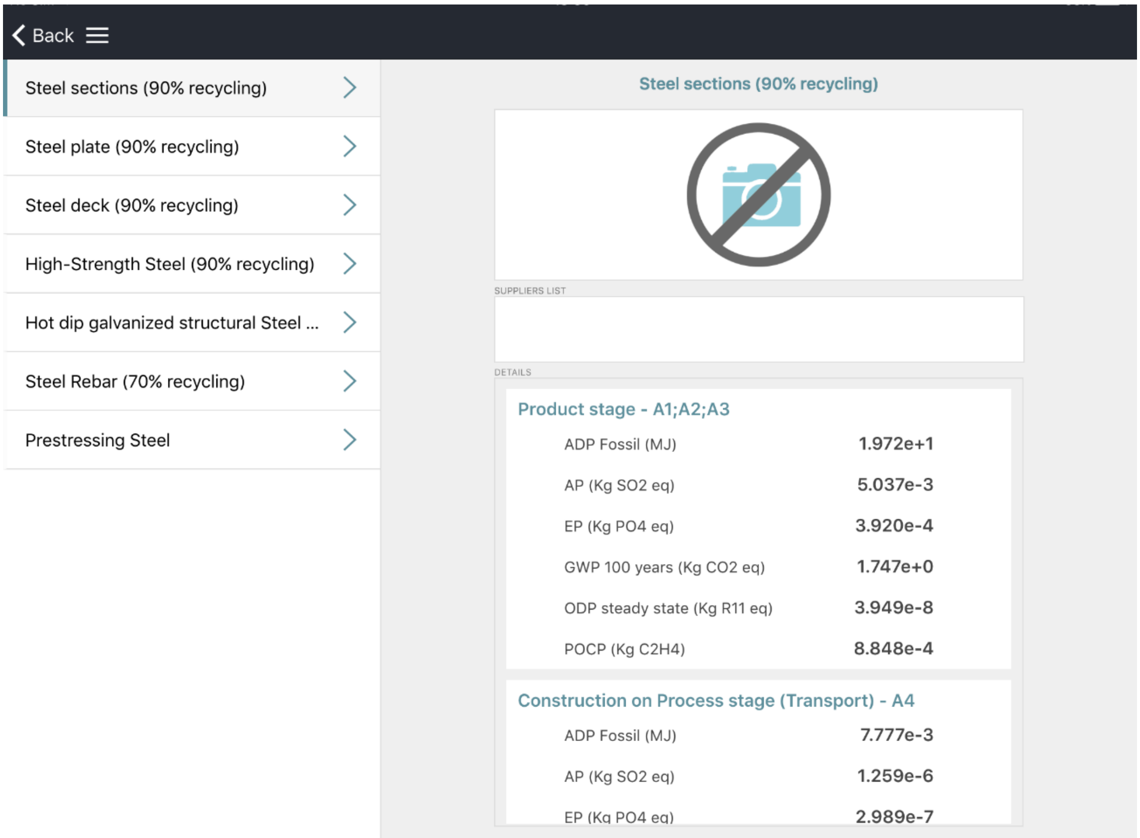
Tapping Lifecycle calculator in the home screen takes users to the main calculation tools. The following interface presents the three main tasks: Lifecycle analysis, comparative lifecycle analysis and multi-criteria analysis.



2.3.2. Catalog

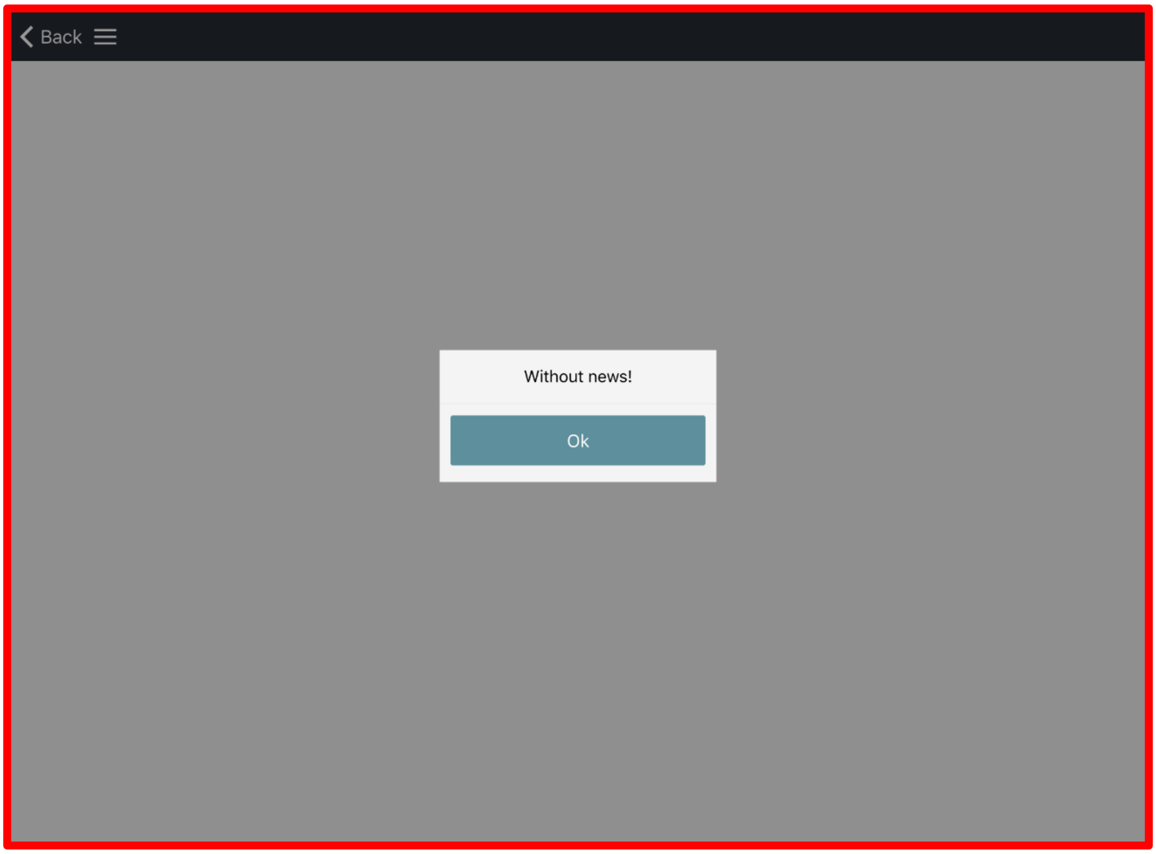
This window shows materials in different categories and their respective environmental impacts at the different lifecycle stages.





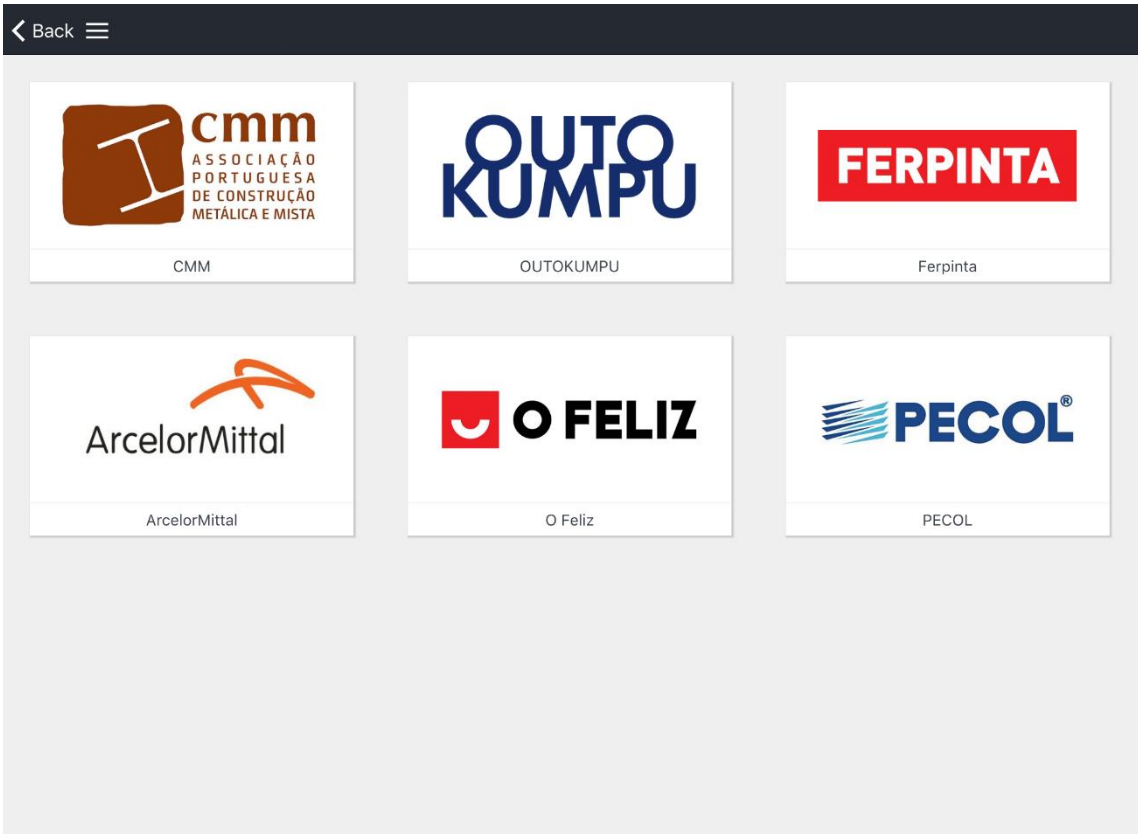
2.3.3. News and Events

News and events will be shared/broadcast here.



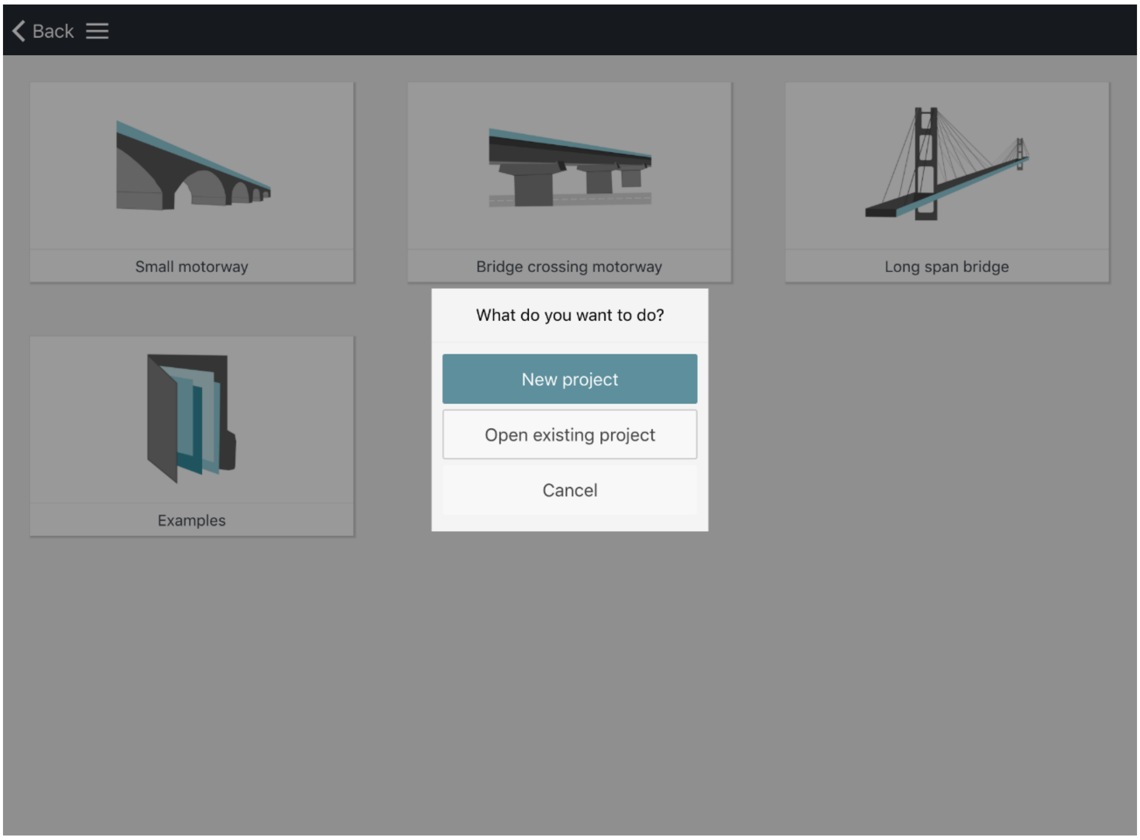
2.3.4. Suppliers

A list of suppliers and related details are presented in this section.



2.4. Lifecycle Analysis Procedure

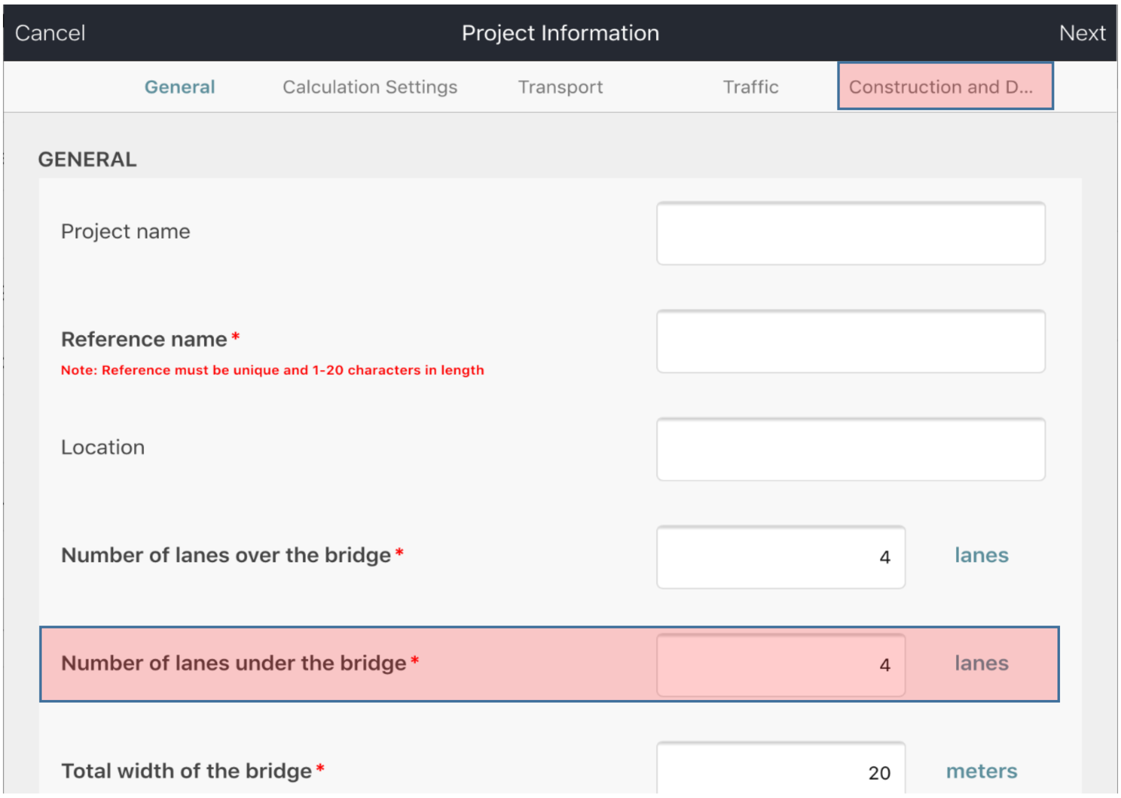
Once in the lifecycle calculator window, select the type of bridge (small motorway, bridge crossing a motorway or long span bridge), and you will be prompted to decide if you want to create a new project or load an existing project, if there exists at least one saved project. Select "new project" and you will be taken to the project window.



The project information will immediately pop up. [The same window can later be activated to edit inputs by tapping on the "clipboard" icon located next to the options icon at the top of the screen.] This window consists 4 or 5 tabs depending on the type of project, i.e., construction and demolition details will be added for bridges with traffic underneath. (See the tabs and texts highlighted in the figure below.)

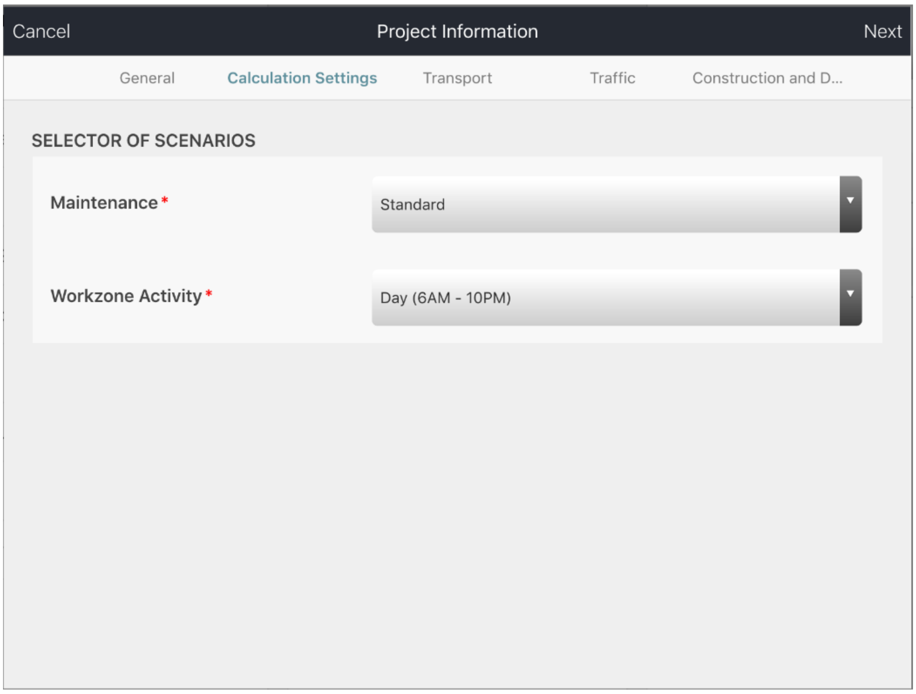
I. Start by filling in the reference name in the general tab. The reference name should have a unique value and shall not exceed 20 characters in size. [e.g. A1.1] You may specify the project name and bridge location (not mandatory).

   Also, input the number and distribution of spans, width of the bridge, number of lanes on the bridge, the number of lanes on the motorway under the bridge (Only if the bridge is a motorway crossing bridge. Otherwise, selecting a small motorway bridge the options highlighted in the following figure won't show.)

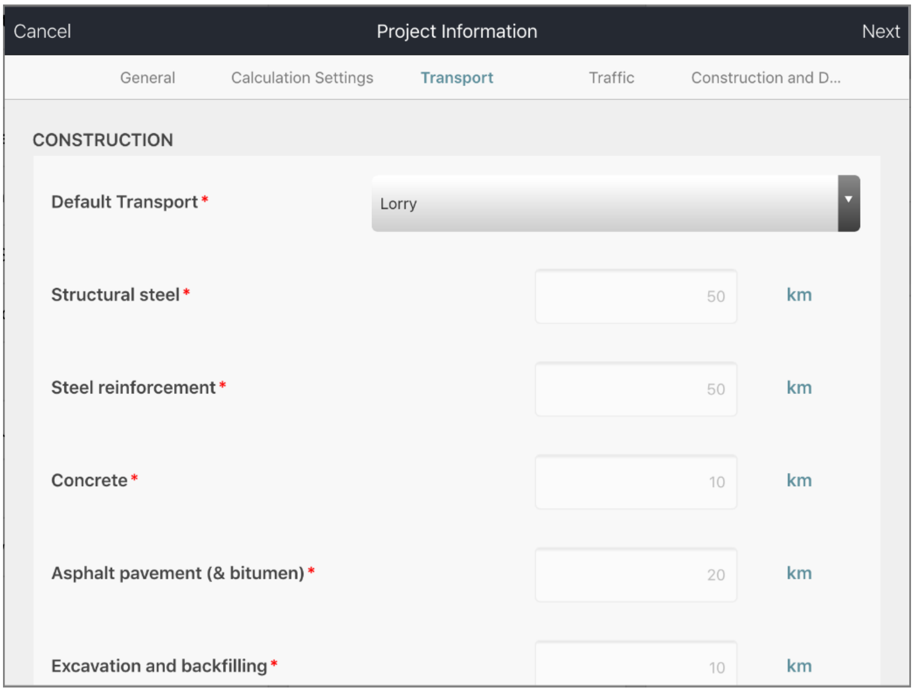


Note that the default values have been brought to this window from your configurations to help facilitate the process. The text-boxes (text-fields) marked by **BOLD** text and an asterisk mark (*) are mandatory inputs.

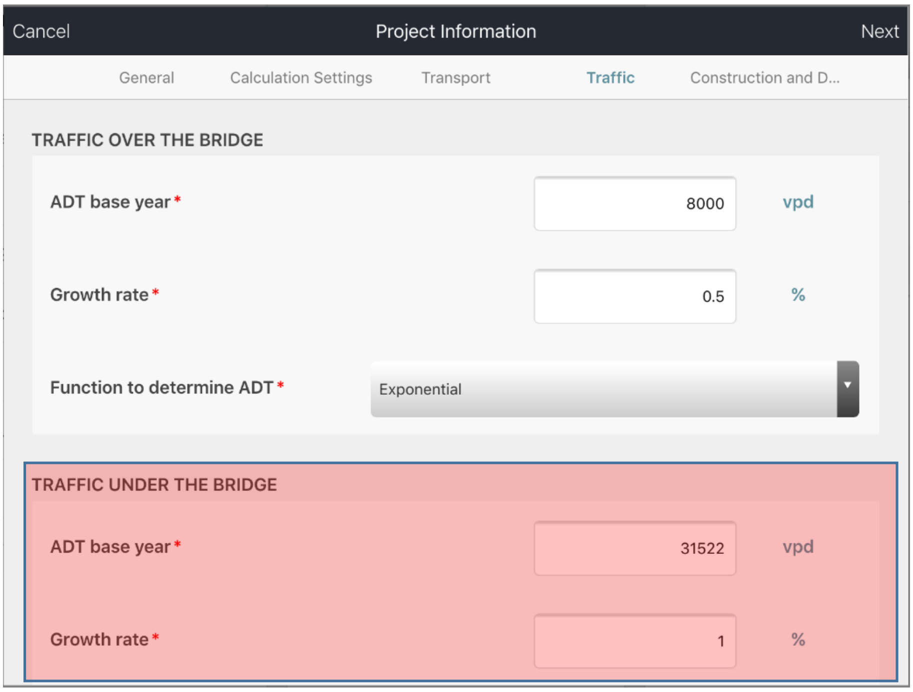
II. Select the calculation settings that suit your project.



III. Adjust the material transport schemes for your project.
Note: The distances of material transportation can't be altered in the current version of the app.

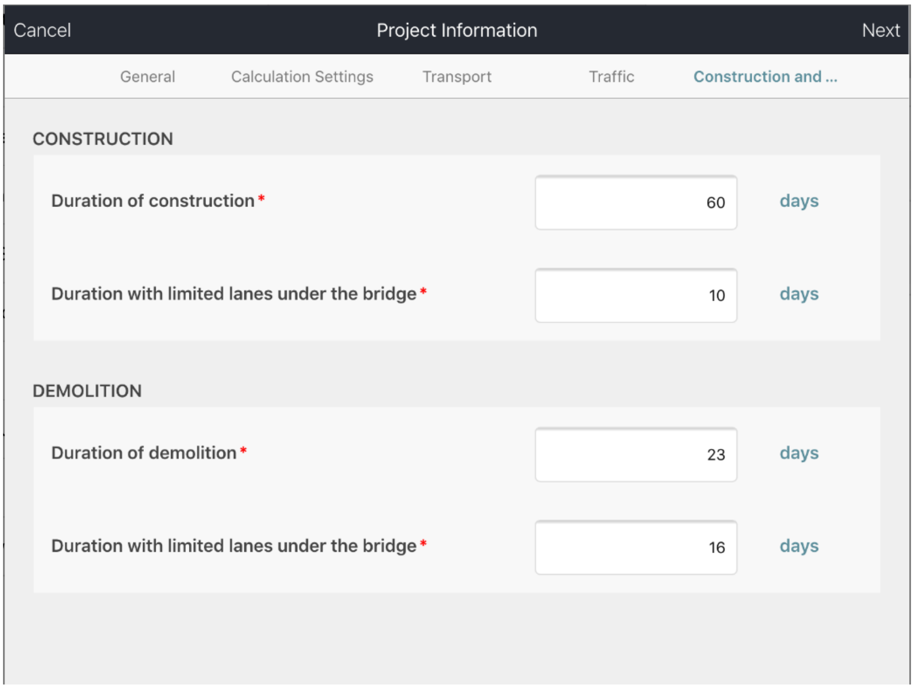


IV. Enter/modify the average daily traffic over the bridge (for bridges with no traffic underneath) or the traffic both over and under the bridge (in case of motorway crossing bridges). The highlighted portion of the panel will display in the latter case only.



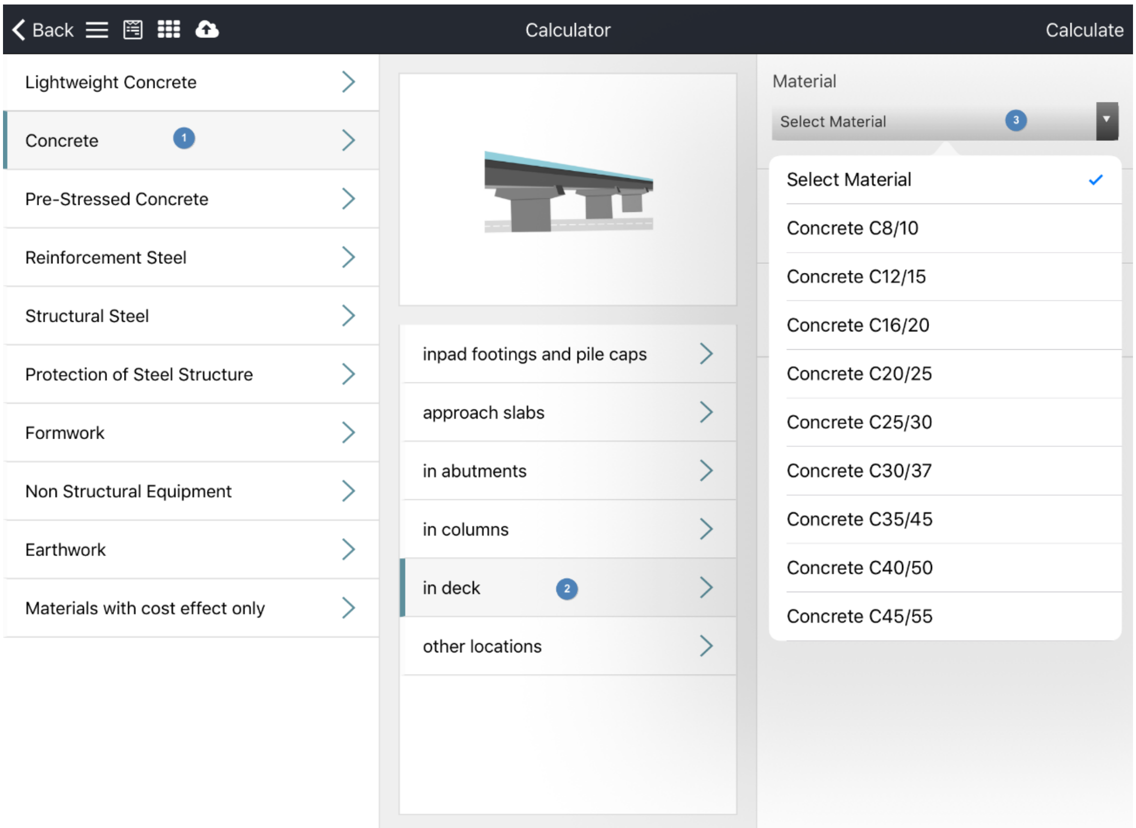
V. Specify details regarding the construction and demolition periods.

Note: This option is available only for projects initiated in motorway crossing bridges.

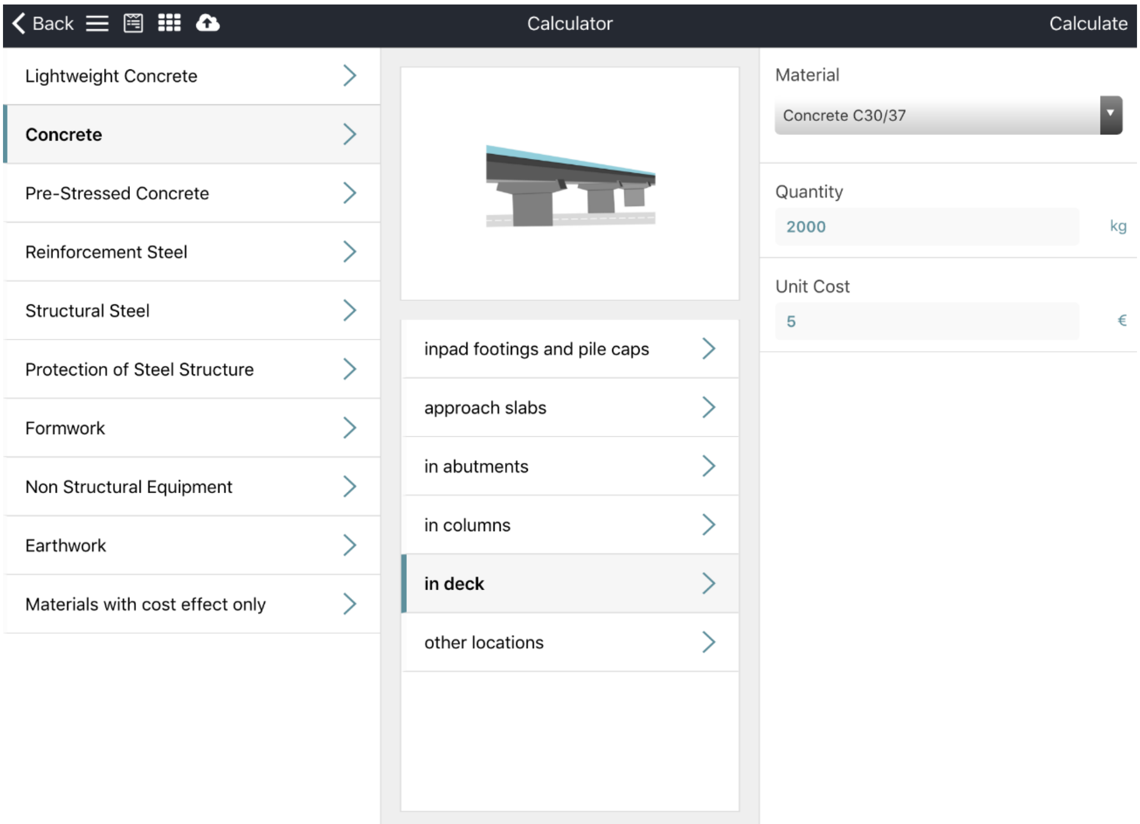


VI. Input the quantity and unit cost of each construction material in the bridge.

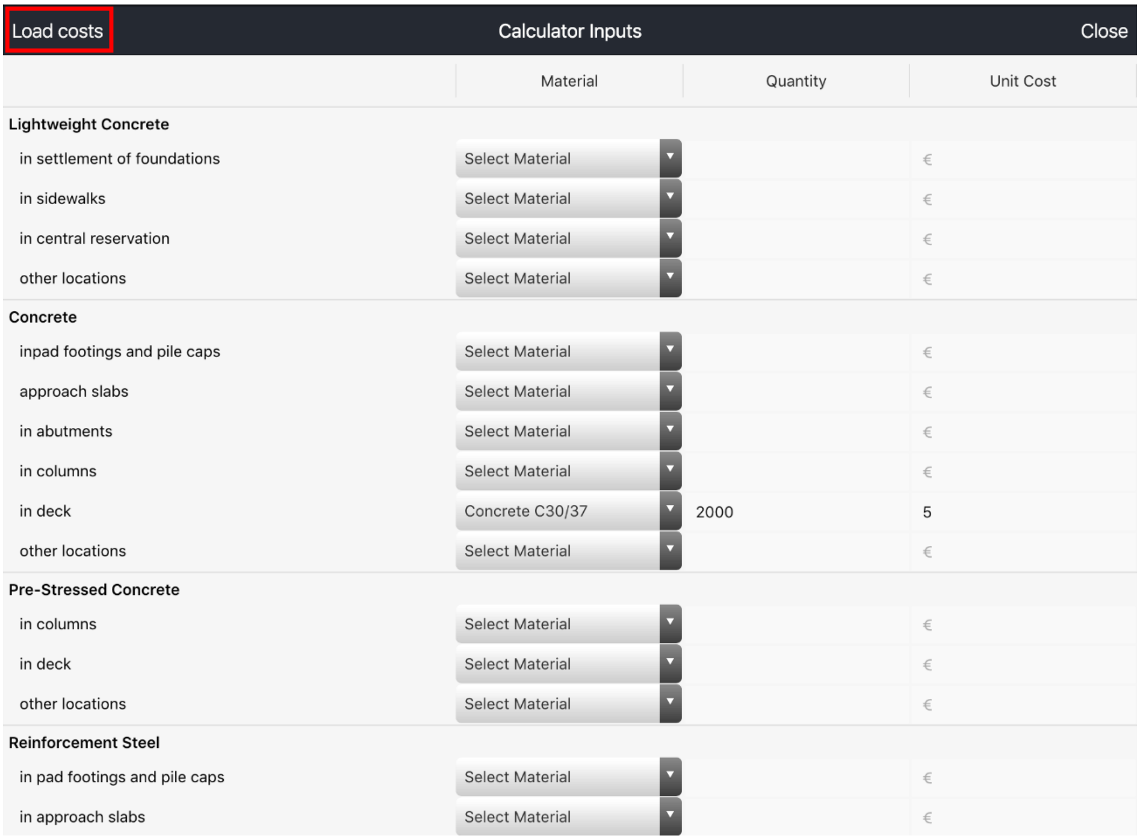
Start by selecting the material group in the left most panel ❶. Select the part of the bridge where the material is used in the middle panel ❷. In the right most panel ❸, Select the material grade/type, input the quantity and unit cost.



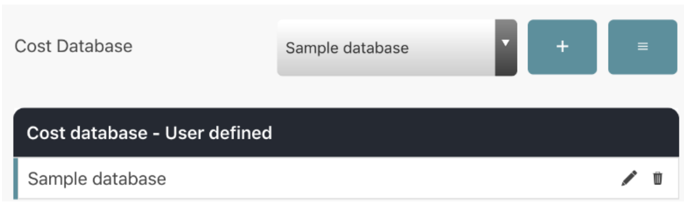
An example is given here for 2000kg (converted from 0.833m^3 volume) of C30/37 grade concrete, with a fictitious unit cost of 5EUR/kg in the deck.



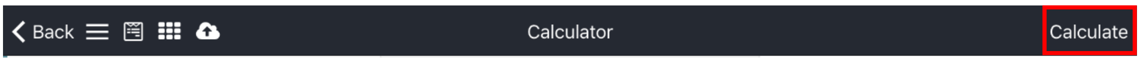
The inputs can be made/created or accessed for modification in the extended/detailed view by tapping on the grid icon ( ). Notice that you can use the "load costs" button to automatically import respective unit costs for the materials that have a non-empty quantity field.



Users can create/save/edit different user costs in the configurations panel. Configurations → databases → cost database (+ to Add) , ≡ → (to edit) or (to delete).

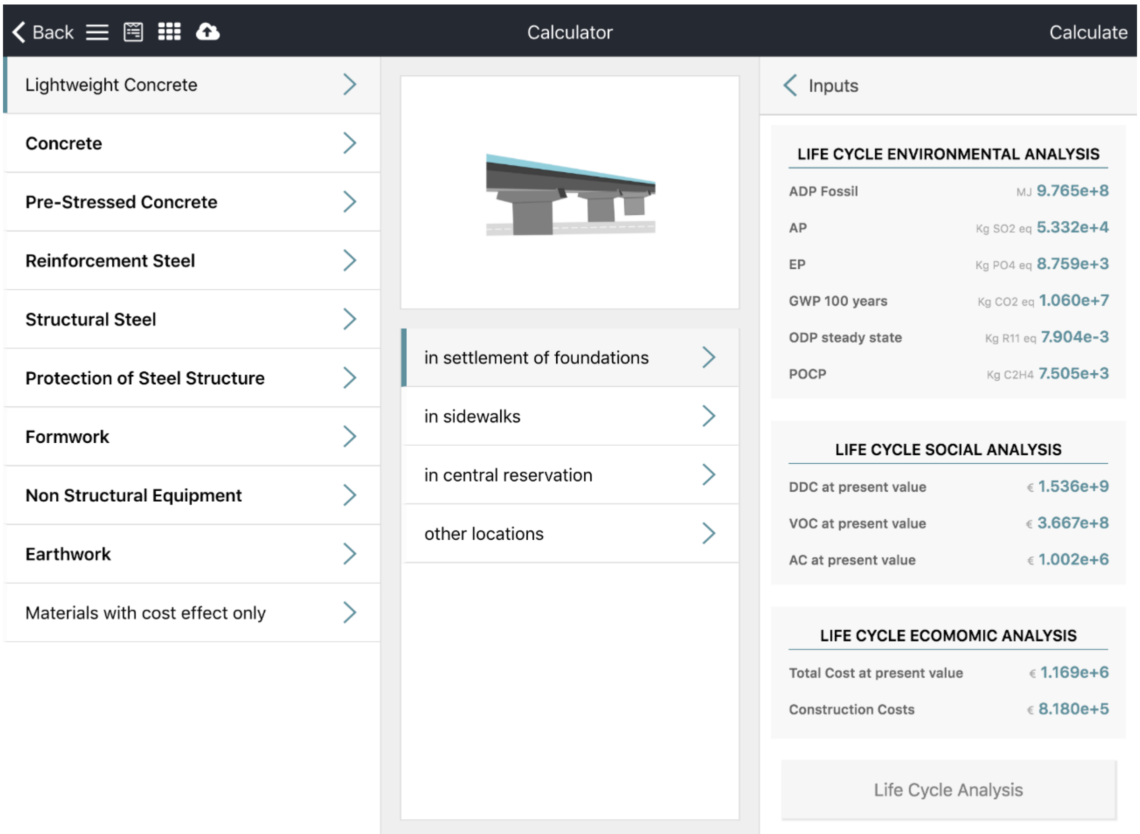


Once you have entered all necessary details, tap on calculate to do the lifecycle analysis.



2.5. Lifecycle Analysis Results

Once a successful input of necessary details is completed, tapping the "calculate" button will start the lifecycle analysis and a summary of the results will be presented on the right most side of the same screen. This summary presents the aggregate LCA, LCS and LCC in a brief form.



After visual inspection of these results, the user has the possibility of editing the input Bills of Quantities by tapping on "< inputs" button at the top of the LCA results.

The detailed report of the analysis consists of the description of the bridge on top, followed by tabular and graphical presentation of the LCA, LCC and LCS results. The detailed report can be accessed by tapping on the "Lifecycle Analysis" button which is located just below the brief results. The contents of the detailed report are discussed in details and sample reports presented in the following sections.

Note: Tapping on parts of the charts in the detailed report will show the actual figures associated to that particular part of the chart. (Percentages of contribution in the LCA and costs in the LCC and LCS.)

2.5.1. Description of the Bridge

This section presents the bridge type, location, geometry, span distribution, traffic data and calculation assumptions. An excerpt from a sample report is shown in the figure below.

Life-Cycle Analysis Report

1. Description

General

Type of the bridge: Bridge crossing motorway
Reference name: A1
Project name: Composite and single span
Location: Germany

Bridge geometry and span distribution

Number of lanes over the bridge: 4
Number of lanes under the bridge: 4
Total width of the bridge: 20 m

Span Distribution

Total span of the bridge: 100 m
Number of spans: 1
Span distribution: 45.25m

Calculation Assumptions

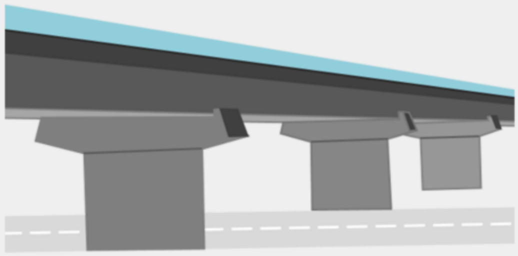
Base Year: 2008
Discount Rate: 2 %
Operation Scenario: Day (6AM - 10PM)
Maintenance Scenario: Standard

Traffic over the bridge

ADT base year: 5000 vpd
ADT last year: 10000 vpd
Function to determine ADT: Linear

Traffic under the bridge

ADT base year: 49485 vpd
Growth rate: 0.5 %
Function to determine ADT: Exponential



2.5.2. Initial Input Data

This section presents the bill of quantity and costs used in the calculation in a tabular form.

Life-Cycle Analysis Report Close

2. Initial data

Name	Material Type	Quantity	Unit cost
Concrete			
inpad footings and pile caps	Concrete C25/30	609600 kg	0.0323625
approach slabs	Concrete C16/20	53760 kg	0.031083333
in abutments	Concrete C30/37	1790880 kg	0.035195833
in deck	Concrete C35/45	346080	0.035195833

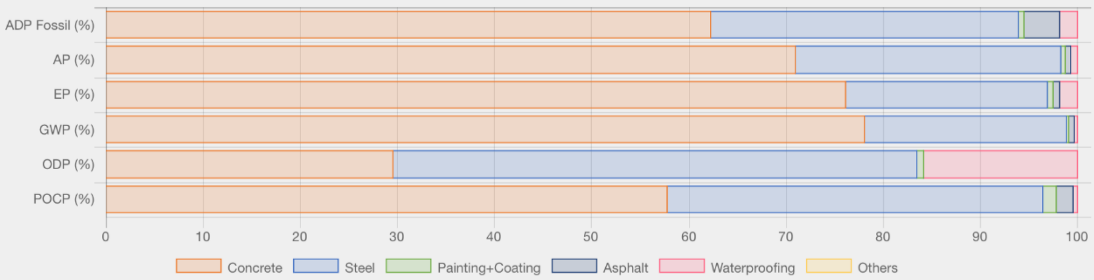
2.5.3. Lifecycle Environmental Analysis

2.5.3.1. Production Stage

3. Environmental

3.1 Stage Material Production

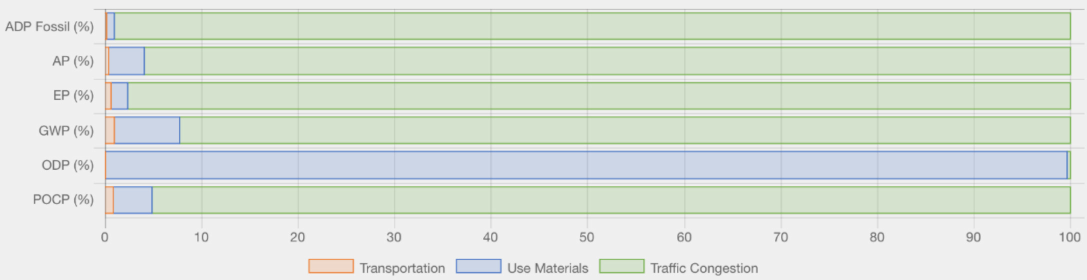
Production						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Concrete	3.251e+6	1.096e+3	1.201e+2	5.495e+5	1.768e-3	1.110e+2
Steel	1.653e+6	4.224e+2	3.280e+1	1.466e+5	3.230e-3	7.447e+1
Painting+Coating	3.483e+4	7.968e+0	9.212e-1	2.139e+3	3.902e-5	2.509e+0
Asphalt	1.897e+5	8.844e+0	1.112e+0	3.788e+3	3.181e-9	3.354e+0
Waterproofing	9.414e+4	9.844e+0	2.906e+0	2.272e+3	9.464e-4	9.167e-1
Others	0	0	0	0	0	0
TOTAL	**5.222e+6**	**1.545e+3**	**1.579e+2**	**7.043e+5**	**5.983e-3**	**1.922e+2**



2.5.3.2. Construction Stage

3.2 Stage Construction

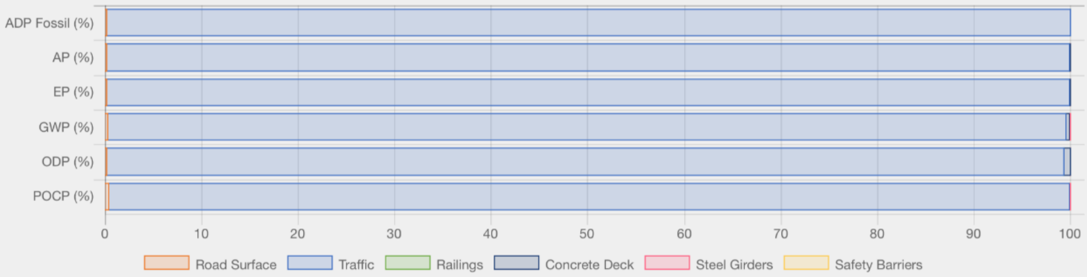
Construction						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Transportation	3.375e+4	5.465e+0	1.297e+0	2.448e+3	8.198e-10	-1.724e+0
Use Materials	2.024e+5	5.096e+1	4.136e+0	1.844e+4	2.498e-4	8.220e+0
Traffic Congestion	2.662e+7	1.358e+3	2.281e+2	2.514e+5	8.658e-7	1.946e+2
TOTAL	**2.686e+7**	**1.414e+3**	**2.335e+2**	**2.723e+5**	**2.507e-4**	**2.011e+2**



2.5.3.3. Operation Stage

3.3 Stage Operation

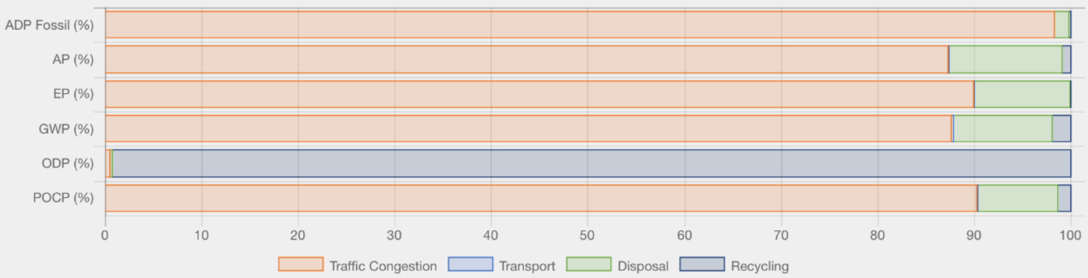
Operation						
Material	ADP fossil MJ	AP Kg SO_2 eq	EP Kg PO_4 eq	GWP Kg CO_2 eq	ODP Kg R_{11} eq	POCP Kg C_2H_4
Road Surface	9.526e+5	4.492e+1	5.728e+0	1.925e+4	1.601e-8	1.655e+1
Traffic	7.057e+8	3.657e+4	6.104e+3	7.015e+6	2.398e-5	5.223e+3
Railings	0	0	0	0	0	0
Concrete Deck	7.500e+4	3.737e+1	5.277e+0	2.486e+4	1.626e-7	1.643e+0
Steel Girders	7.758e+4	1.621e+1	7.874e-1	4.822e+3	8.992e-9	6.313e+0
Safety Barriers	0	0	0	0	0	0
TOTAL	**7.068e+8**	**3.667e+4**	**6.116e+3**	**7.064e+6**	**2.417e-5**	**5.248e+3**



2.5.3.4. End-of-life Stage

3.4 Stage End of Life

Stage End of Life						
Material	ADP fossil MJ	AP Kg SO_2 eq	EP Kg PO_4 eq	GWP Kg CO_2 eq	ODP Kg R_{11} eq	POCP Kg C_2H_4
Traffic Congestion	2.346e+8	1.217e+4	2.030e+3	2.337e+6	7.987e-6	1.737e+3
Transport	6.503e+4	1.053e+1	2.499e+0	4.718e+3	1.580e-9	-3.321e+0
Disposal	3.547e+6	1.635e+3	2.224e+2	2.741e+5	2.686e-6	1.571e+2
Recycling	-5.397e+5	-1.222e+2	-3.373e+0	-5.157e+4	1.635e-3	-2.730e+1
TOTAL	**2.377e+8**	**1.369e+4**	**2.252e+3**	**2.564e+6**	**1.646e-3**	**1.864e+3**



2.5.3.5. Aggregate Results

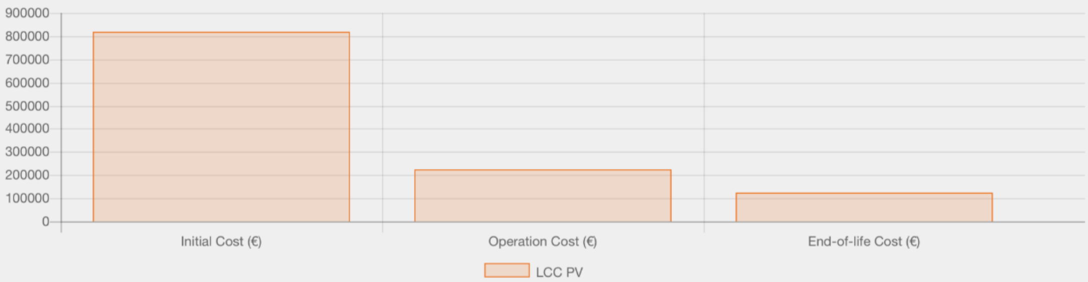
3.5 Aggregate Results

Aggregate						
Material	ADP fossil MJ	AP Kg SO_2 eq	EP Kg PO_4 eq	GWP Kg CO_2 eq	ODP Kg R_{11} eq	POCP Kg C_2H_4
Production	5.222e+6	1.545e+3	1.579e+2	7.043e+5	5.983e-3	1.922e+2
Construction	2.686e+7	1.414e+3	2.335e+2	2.723e+5	2.507e-4	2.011e+2
Operation	7.068e+8	3.667e+4	6.116e+3	7.064e+6	2.417e-5	5.248e+3
End-Of-Life	2.377e+8	1.369e+4	2.252e+3	2.564e+6	1.646e-3	1.864e+3
TOTAL	**9.765e+8**	**5.332e+4**	**8.759e+3**	**1.060e+7**	**7.904e-3**	**7.505e+3**

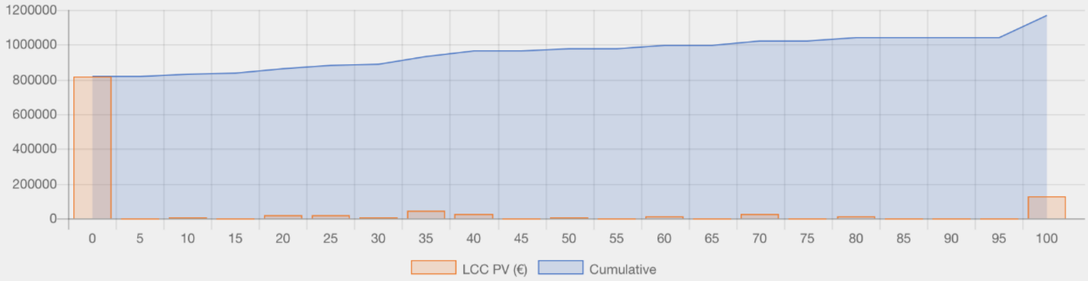
2.5.4. Lifecycle Cost Analysis

4. Economic

Summary		
	LCC PV €	LCC PV €/m2
Initial Cost	8.180e+5	4.090e+2
Operation Cost	2.261e+5	1.130e+2
End-of-life Cost	1.252e+5	6.262e+1
TOTAL	**1.169e+6**	**5.847e+2**



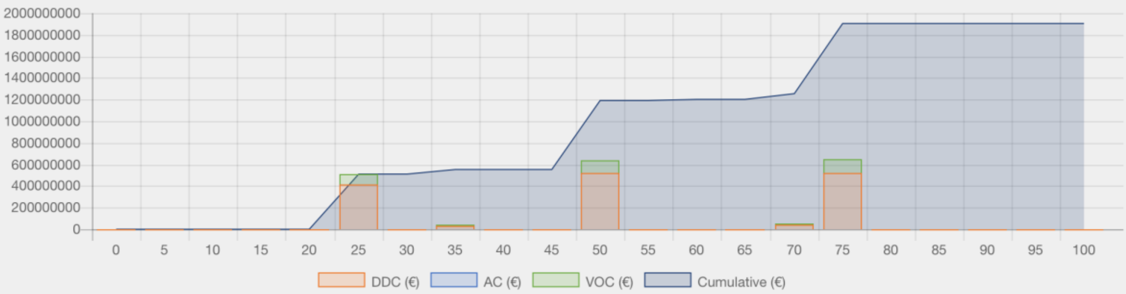
Year	LCC PV €	Cumulative €
0	8.180e+5	8.180e+5
1	3.775e+2	8.184e+5
2	3.700e+2	8.187e+5
3	3.628e+2	8.191e+5
98	5.529e+1	1.044e+6
99	5.421e+1	1.044e+6
100	1.252e+5	1.169e+6



2.5.5. Lifecycle Social Analysis

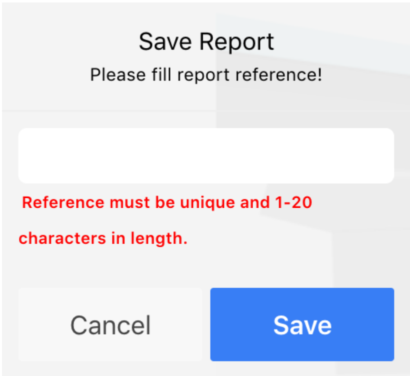
5. Social

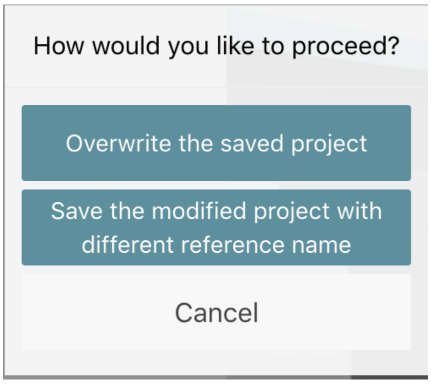
Year	DDC €	VOC €	AC €
0	1.552e+6	1.495e+6	7.065e+3
5	0	0	0
10	1.620e+3	2.402e+3	1.745e+1
15	0	0	0
20	7.878e+3	1.167e+4	8.457e+1
25	4.114e+8	9.893e+7	2.744e+5
30	1.315e+3	1.947e+3	1.407e+1
35	3.611e+7	8.564e+6	2.352e+4
40	6.966e+3	1.031e+4	7.432e+1
45	0	0	0
50	5.162e+8	1.203e+8	3.269e+5
55	0	0	0
60	1.724e+6	3.987e+5	1.112e+3
65	5.752e+1	8.503e+1	6.091e-1
70	4.393e+7	9.924e+6	2.677e+4
75	5.238e+8	1.267e+8	3.411e+5
80	4.210e+3	6.219e+3	4.440e+1
85	0	0	0
90	6.207e+2	9.164e+2	6.527e+0
95	1.631e+6	3.866e+5	1.037e+3
100	0	0	0
TOTAL	**1.536e+9**	**3.667e+8**	**1.002e+6**



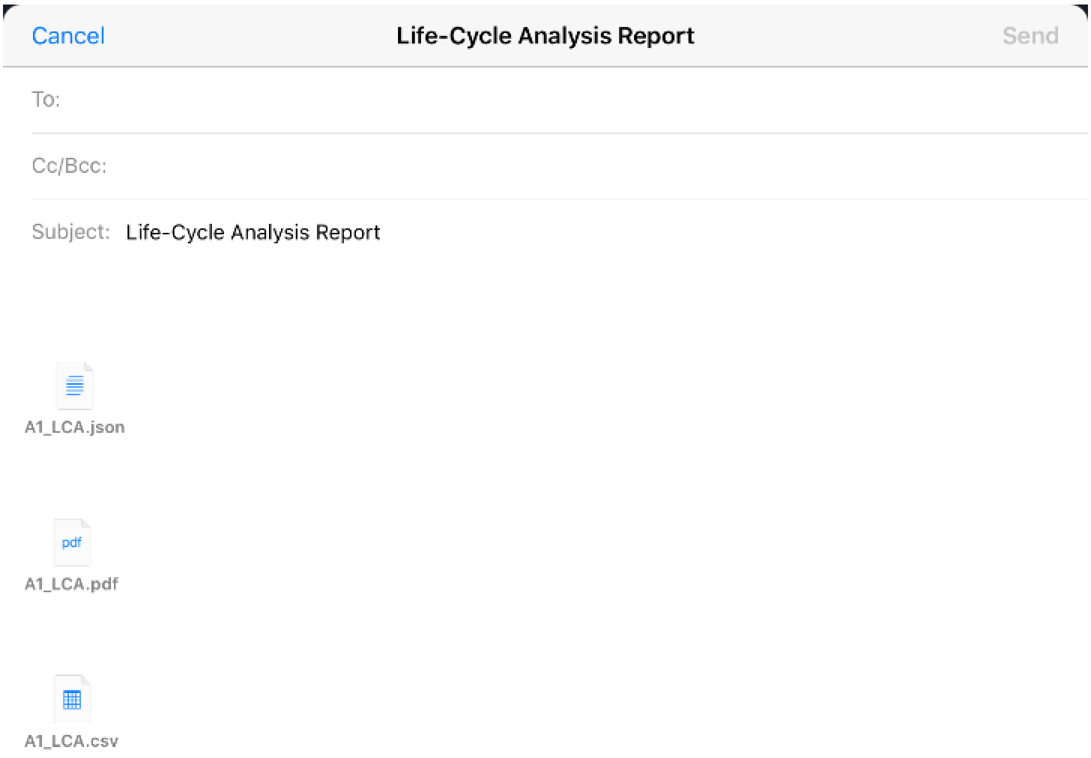
2.5.6. Saving, Printing and Exporting the LCA Report

Users can print, email/export and save the report by using the three buttons on the left side of the top bar, respectively. By tapping on the "Save project's report" button, users will be prompted to specify a unique reference name to their report. In the event that a user wants to save one of the pre-installed example projects or a modification of an existing project, the user will be prompted by a dialogue box asking if the user wants to overwrite the existing project or save it with a new name.



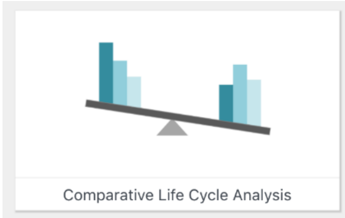


The report can also be exported by email. When a user requests this task, the app automatically generates a PDF version of the report along with the inputs and outputs in CSV format.



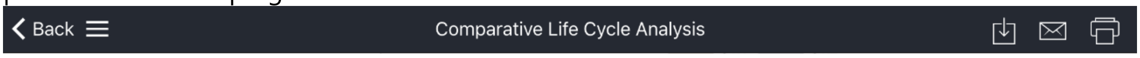
2.6. Comparative Lifecycle Analysis and Multi-Criteria Analysis

2.6.1. Comparative Lifecycle Analysis



The comparative lifecycle analysis tool can be accessed in the Lifecycle calculator panel. With this tool, users will be able to quantitatively compare the performance of two or more bridges. In order to be able to run this form of analysis, there needs to be two or more saved projects in the app.

Comparative analysis can be saved, emailed/exported and printed from the top right menu.

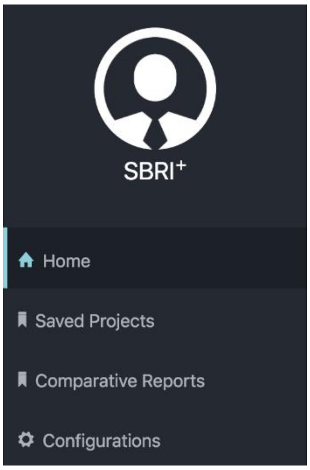


2.6.2. Multi-Criteria Analysis

This part will be completed in the next version of this document.

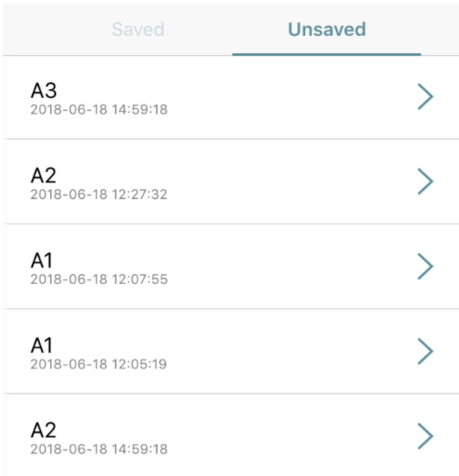
2.7. General Use

2.7.1. Managing Project Files



Saved Projects and reports can be accessed from the "Saved Projects" and "Comparative Reports" panels that are located in the main options drawer (Triple bars).

Saved projects are those projects manually saved by the user. The application also automatically saves the user inputs at certain intervals to avoid a complete loss of inputting progress due to unforeseen issues such as interrupting phone calls. However, these automatically saved versions of users' documents are saved in a different folder.



The automatically saved versions of the project files can be accessed when opening a project file. When opting to do an LCA, users are prompted if they want to create a new project or open existing projects. Choosing "Open existing projects", users will have access to both saved (manually saved) and unsaved (automatically saved) projects. In addition to the Reference names, these automatically saved projects can be further filtered based on the saved time stamp on each project.

Within the same panel, users have the possibilities of loading/opening and deleting a selected unsaved project.

3. Lifecycle Analysis Examples

A lifecycle analysis was done on selected bridges in Europe in the framework of the SBRI+ project. The outputs of these analyses is included in the SBRI+ application in the Examples folder located inside the Lifecycle calculator module. Eight different examples are provided in the application.

Out of the eight examples, three are presented below to illustrate the use of the app and the contents of the reports.

- Composite and single span A1
- Prestressed Concrete with two spans A2
- Composite with two spans A3
- Composite with three spans B
- Composite (multi-span) C1.1
- Concrete (multi-span) C1.2
- Composite and single span C2.1
- Concrete and single span C2.2

3.1. Example C1.1

1. Description

General

Type of the bridge: Long span bridge
Reference name: C1.1
Project name: Composite (multi-span)
Location: Portugal

Bridge geometry and span distribution

Number of lanes over the bridge: 4
Total width of the bridge: 20 m

Span Distribution

Total span of the bridge: 100 m
Number of spans: 1
Span distribution: 100.00m

Calculation Assumptions

Base Year: 2008
Discount Rate: 2 %
Operation Scenario: Day (6AM - 10PM)
Maintenance Scenario: Standard

Traffic over the bridge

ADT base year: 11575 vpd
Growth rate: 0.5 %
Function to determine ADT: Exponential

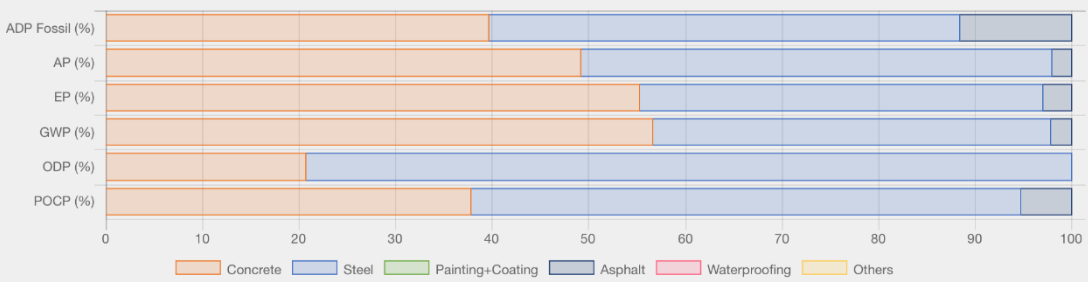
2. Initial data

Name	Material Type	Quantity	Unit cost
Lightweight Concrete			
other locations	Lightweight concrete	211200 kg	0.051181818
Concrete			
inpad footings and pile caps	Concrete C30/37	8126400 kg	0.050620833
in deck	Concrete C40/50	7428000 kg	0.044829167
other locations	Concrete C20/25	213600 kg	0.035275
Reinforcement Steel			
in deck	Reinforcement bars	371400 kg	1.05
other locations	Reinforcement bars	897600 kg	1.05
Structural Steel			
in longitudinal beams	Steel sections	1521000 kg	2.42
other locations	Steel plate	31655 kg	5.66
Formwork			
Reusable formwork	Formwork	1325 m2	40.86
In-situ formwork	Formwork	8395 m2	37.31
Non Structural Equipment			
Asphalt layer	Asphalt pavement	2146560 kg	0.076875
Expansion joints	Expansion joint	72 m	1167.43
Elastomeric bearings	Bearing elastomeric	40 un	2682.85
railings	Guardrail	637 m	51.26
safety barrier	Safety barrier	637 m	124.43
Earthwork			
Excavation	Excavation	6620000 kg	0.009985
Backfilling	Backfilling	3620000 kg	0.003695
Materials with cost effect only			
Others (Gross value)	Others	1 GV	304406.68
Others materials given in units of length	Other mat. given as length	620 m	163
Others materials given in units of area	Other mat. given as area	9850 m2	42.88
Others materials given in units of pieces	Other mat. given in pieces	108 un	21.66

3. Environmental

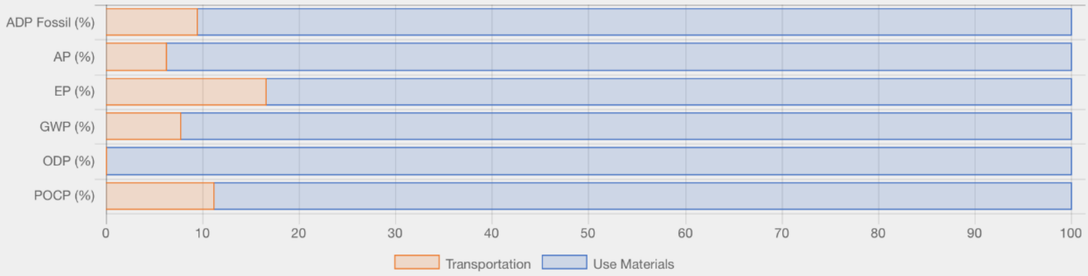
3.1 Stage Material Production

Production						
Material	ADP fossil MJ	AP Kg SO_2 eq	EP Kg PO_4 eq	GWP Kg CO_2 eq	ODP Kg R_{11} eq	POCP Kg C_2H_4
Concrete	2.504e+7	7.968e+3	8.094e+2	3.765e+6	1.566e-2	9.271e+2
Steel	3.090e+7	7.899e+3	6.130e+2	2.741e+6	6.006e-2	1.394e+3
Painting+Coating	0	0	0	0	0	0
Asphalt	7.320e+6	3.413e+2	4.293e+1	1.462e+5	1.228e-7	1.294e+2
Waterproofing	0	0	0	0	0	0
Others	0	0	0	0	0	0
TOTAL	**6.326e+7**	**1.621e+4**	**1.465e+3**	**6.652e+6**	**7.572e-2**	**2.450e+3**



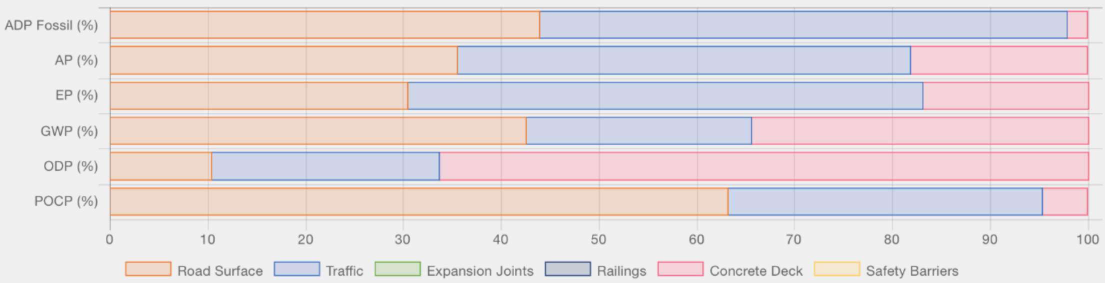
3.2 Stage Construction

Construction						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Transportation	2.674e+5	4.330e+1	1.028e+1	1.940e+4	6.495e-9	-1.366e+1
Use Materials	2.564e+6	6.532e+2	5.178e+1	2.312e+5	3.786e-3	1.091e+2
TOTAL	**2.831e+6**	**6.965e+2**	**6.206e+1**	**2.506e+5**	**3.786e-3**	**9.541e+1**



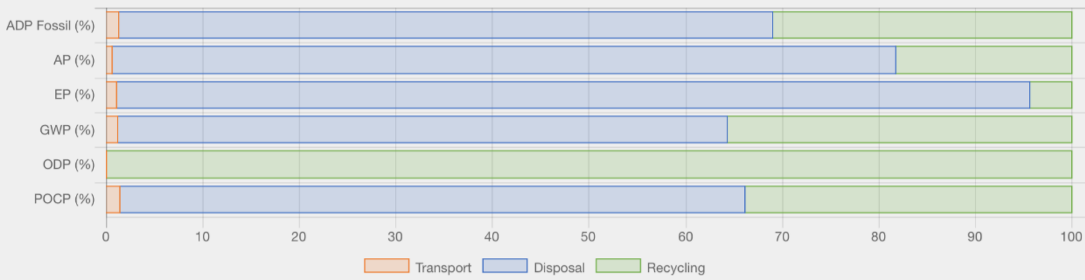
3.3 Stage Operation

Operation						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Road Surface	3.677e+7	1.734e+3	2.211e+2	7.430e+5	6.180e-7	6.387e+2
Traffic	4.520e+7	2.267e+3	3.832e+2	4.032e+5	1.400e-6	3.261e+2
Expansion Joints	0	0	0	0	0	0
Railings	0	0	0	0	0	0
Concrete Deck	1.775e+6	8.870e+2	1.226e+2	6.028e+5	3.969e-6	4.665e+1
Safety Barriers	0	0	0	0	0	0
TOTAL	**8.374e+7**	**4.887e+3**	**7.269e+2**	**1.749e+6**	**5.987e-6**	**1.011e+3**



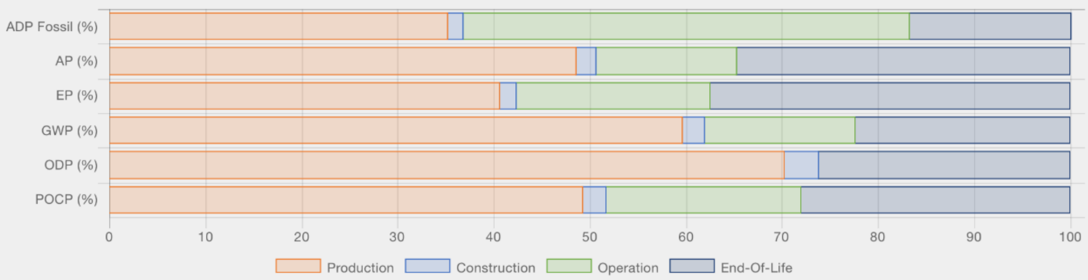
3.4 Stage End of Life

Stage End of Life						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Transport	3.822e+5	6.189e+1	1.469e+1	2.773e+4	9.285e-9	-1.952e+1
Disposal	2.045e+7	9.426e+3	1.282e+3	1.580e+6	1.548e-5	9.058e+2
Recycling	-9.343e+6	-2.116e+3	-5.840e+1	-8.927e+5	2.830e-2	-4.726e+2
TOTAL	**1.149e+7**	**7.372e+3**	**1.239e+3**	**7.154e+5**	**2.832e-2**	**4.136e+2**

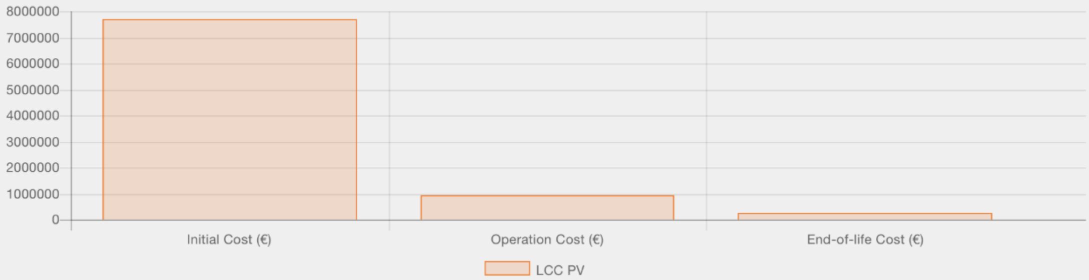


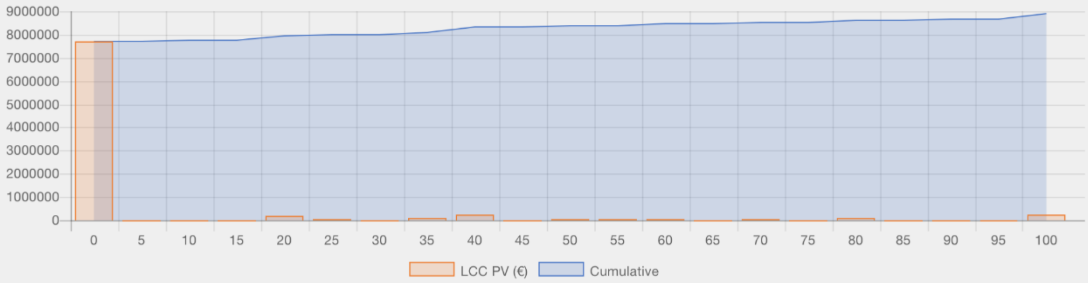
3.5 Aggregate Results

Aggregate						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Production	6.326e+7	1.621e+4	1.465e+3	6.652e+6	7.572e-2	2.450e+3
Construction	2.831e+6	6.965e+2	6.206e+1	2.506e+5	3.786e-3	9.541e+1
Operation	8.374e+7	4.887e+3	7.269e+2	1.749e+6	5.987e-6	1.011e+3
End-Of-Life	1.149e+7	7.372e+3	1.239e+3	7.154e+5	2.832e-2	4.136e+2
TOTAL	**1.613e+8**	**2.916e+4**	**3.493e+3**	**9.367e+6**	**1.078e-1**	**3.971e+3**



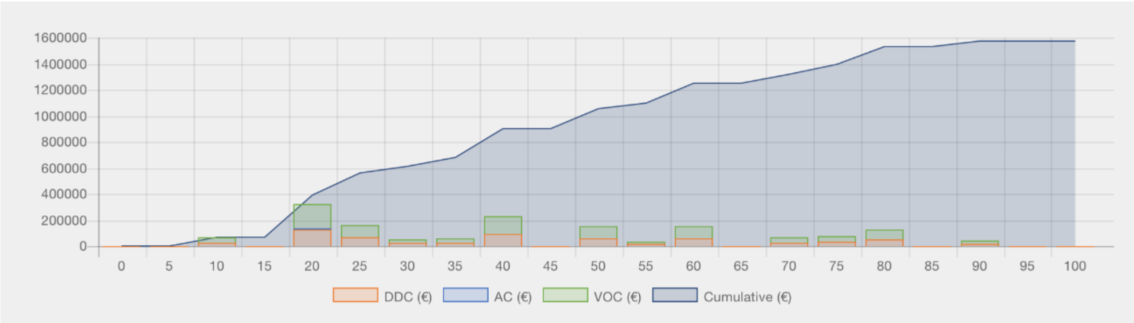
Summary		
	LCC PV €	LCC PV €/m2
Initial Cost	7.714e+6	6.918e+2
Operation Cost	9.472e+5	8.496e+1
End-of-life Cost	2.344e+5	2.102e+1
TOTAL	**8.895e+6**	**7.978e+2**





5. Social

Year	DDC €	VOC €	AC €
0	0	0	0
5	0	0	0
10	2.811e+4	4.156e+4	2.979e+2
15	0	0	0
20	1.306e+5	1.929e+5	1.380e+3
25	6.659e+4	9.838e+4	7.031e+2
30	2.128e+4	3.144e+4	2.245e+2
35	2.542e+4	3.753e+4	2.676e+2
40	9.193e+4	1.357e+5	9.672e+2
45	0	0	0
50	6.199e+4	9.147e+4	6.503e+2
55	1.437e+4	2.120e+4	1.505e+2
60	6.144e+4	9.063e+4	6.431e+2
65	7.364e+2	1.086e+3	7.691e+0
70	2.777e+4	4.093e+4	2.897e+2
75	3.226e+4	4.753e+4	3.359e+2
80	5.290e+4	7.795e+4	5.508e+2
85	0	0	0
90	1.811e+4	2.667e+4	1.879e+2
95	0	0	0
100	0	0	0
TOTAL	**6.335e+5**	**9.350e+5**	**6.657e+3**


1600000
1400000
1200000
1000000
800000
600000
400000
200000
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
DDC (€)
AC (€)
VOC (€)
Cumulative (€)

3.2. Example C1.2

1. Description

General

Type of the bridge: Long span bridge
Reference name: C1.2
Project name: Concrete (multi-span)
Location: Portugal

Bridge geometry and span distribution

Number of lanes over the bridge: 4
Total width of the bridge: 20 m

Span Distribution

Total span of the bridge: 100 m
Number of spans: 1
Span distribution: 100.00m

Calculation Assumptions

Base Year: 2008
Discount Rate: 2 %
Operation Scenario: Day (6AM - 10PM)
Maintenance Scenario: Standard

Traffic over the bridge

ADT base year: 11575 vpd
Growth rate: 0.5 %
Function to determine ADT: Exponential

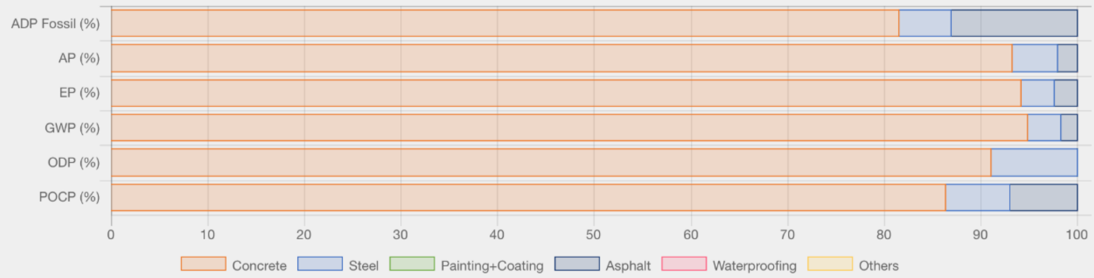
2. Initial data

Name	Material Type	Quantity	Unit cost
Lightweight Concrete			
other locations	Lightweight concrete	99000 kg	0.051182
Concrete			
inpad footings and pile caps	Concrete C30/37	18943200 kg	0.050621
in deck	Concrete C35/45	16917600 kg	0.067425
other locations	Concrete C12/15	458400 kg	0.052283
Reinforcement Steel			
in columns	Prestressing Steel	170107.03 kg	3.88
in deck	Reinforcement bars	511481.7 kg	1.05
other locations	Reinforcement bars	1210090.3 kg	1.05
Formwork			
Reusable formwork	Formwork	18161 m2	53.07
In-situ formwork	Formwork	12387 m2	37.31
Non Structural Equipment			
Asphalt layer	Asphalt pavement	1827456 kg	0.076875
Expansion joints	Expansion joint	74 m	4694.63
Elastomeric bearings	Bearing elastomeric	44 un	6040.21
railings	Guardrail	691 m	51.26
safety barrier	Safety barrier	1323 m	54.29
Earthwork			
Excavation	Excavation	22154000 kg	0.009985
Backfilling	Backfilling	5692000 kg	0.003695
Materials with cost effect only			
Others (Gross value)	Others	1 GV	892355.52
Others materials given in units of length	Other mat. given as length	691 m	163
Others materials given in units of area	Other mat. given as area	5847 m2	6.13
Others materials given in units of pieces	Other mat. given in pieces	1 un	19243.68

3. Environmental

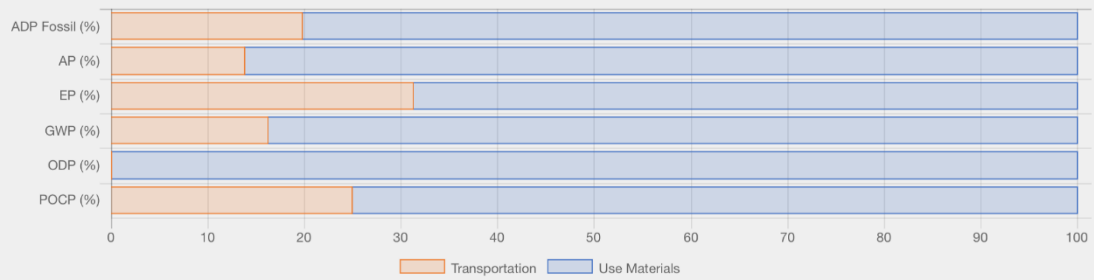
3.1 Stage Material Production

Production						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Concrete	3.875e+7	1.324e+4	1.446e+3	6.703e+6	2.125e-2	1.358e+3
Steel	2.570e+6	6.690e+2	5.295e+1	2.362e+5	2.097e-3	1.038e+2
Painting+Coating	0	0	0	0	0	0
Asphalt	6.232e+6	2.906e+2	3.655e+1	1.244e+5	1.045e-7	1.102e+2
Waterproofing	0	0	0	0	0	0
Others	0	0	0	0	0	0
TOTAL	**4.755e+7**	**1.420e+4**	**1.536e+3**	**7.063e+6**	**2.335e-2**	**1.572e+3**



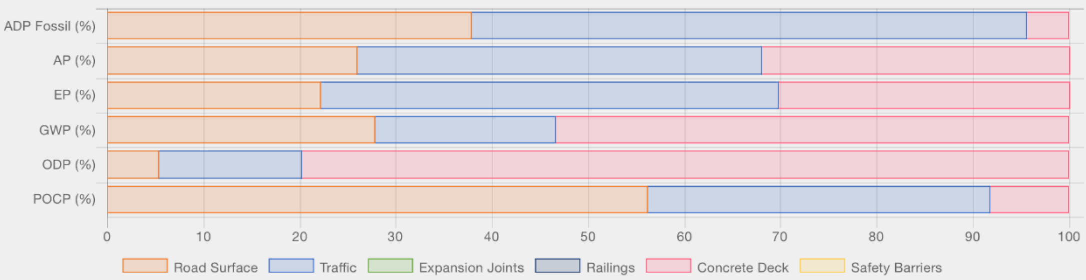
3.2 Stage Construction

Construction						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Transportation	3.852e+5	6.238e+1	1.480e+1	2.794e+4	9.357e-9	-1.967e+1
Use Materials	1.566e+6	3.918e+2	3.260e+1	1.450e+5	1.167e-3	5.921e+1
TOTAL	**1.951e+6**	**4.542e+2**	**4.740e+1**	**1.730e+5**	**1.167e-3**	**3.953e+1**



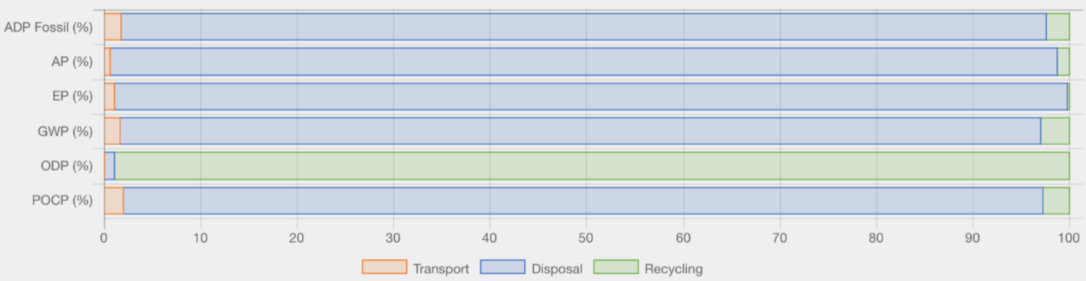
3.3 Stage Operation

Operation						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Road Surface	3.130e+7	1.476e+3	1.882e+2	6.326e+5	5.261e-7	5.437e+2
Traffic	4.785e+7	2.400e+3	4.057e+2	4.268e+5	1.482e-6	3.452e+2
Expansion Joints	0	0	0	0	0	0
Railings	0	0	0	0	0	0
Concrete Deck	3.666e+6	1.827e+3	2.580e+2	1.215e+6	7.948e-6	8.032e+1
Safety Barriers	0	0	0	0	0	0
TOTAL	**8.282e+7**	**5.702e+3**	**8.519e+2**	**2.275e+6**	**9.956e-6**	**9.692e+2**



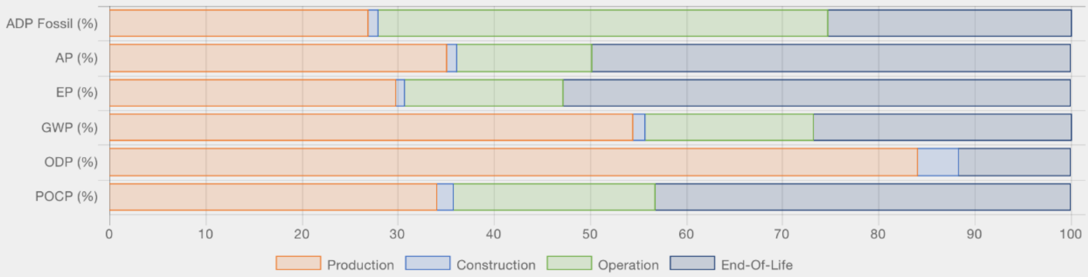
3.4 Stage End of Life

Stage End of Life						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Transport	7.590e+5	1.229e+2	2.917e+1	5.506e+4	1.844e-8	-3.877e+1
Disposal	4.303e+7	1.983e+4	2.698e+3	3.326e+6	3.258e-5	1.906e+3
Recycling	-1.064e+6	-2.410e+2	-6.651e+0	-1.017e+5	3.224e-3	-5.383e+1
TOTAL	**4.272e+7**	**1.972e+4**	**2.721e+3**	**3.279e+6**	**3.256e-3**	**1.813e+3**



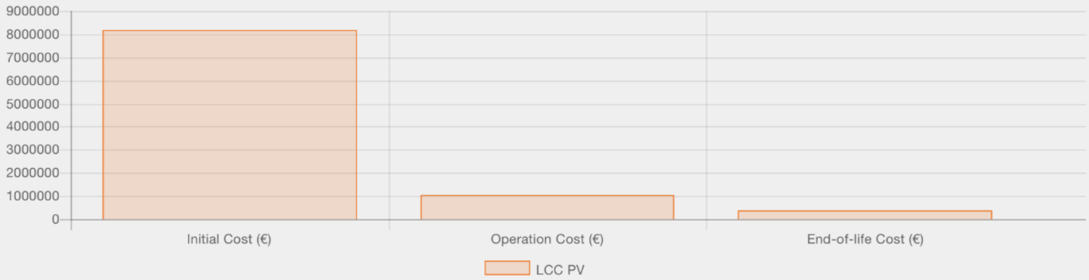
3.5 Aggregate Results

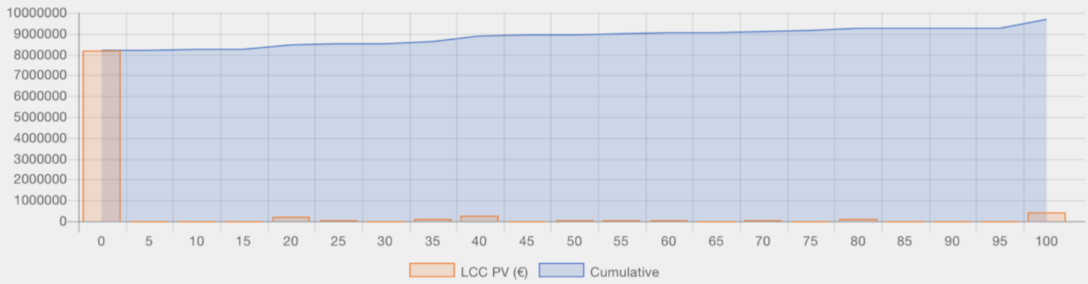
Aggregate						
Material	**ADP fossil** MJ	**AP** Kg SO_2 eq	**EP** Kg PO_4 eq	**GWP** Kg CO_2 eq	**ODP** Kg R_{11} eq	**POCP** Kg C_2H_4
Production	4.755e+7	1.420e+4	1.536e+3	7.063e+6	2.335e-2	1.572e+3
Construction	1.951e+6	4.542e+2	4.740e+1	1.730e+5	1.167e-3	3.953e+1
Operation	8.282e+7	5.702e+3	8.519e+2	2.275e+6	9.956e-6	9.692e+2
End-Of-Life	4.272e+7	1.972e+4	2.721e+3	3.279e+6	3.256e-3	1.813e+3
TOTAL	**1.750e+8**	**4.008e+4**	**5.156e+3**	**1.279e+7**	**2.778e-2**	**4.394e+3**



4. Economic

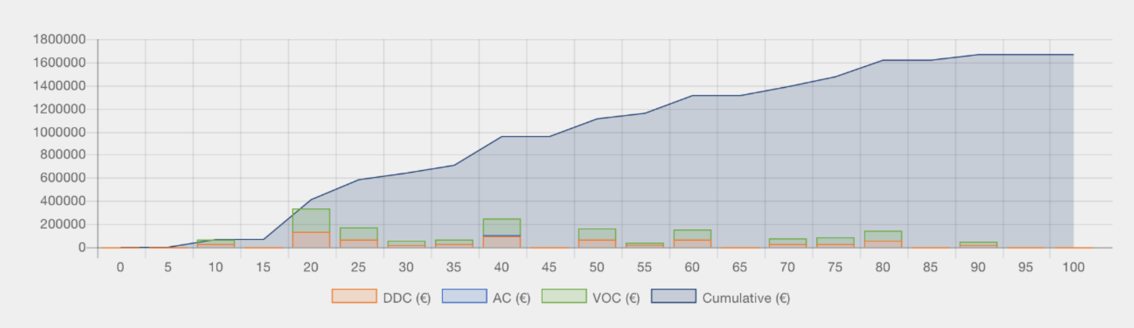
Summary		
	LCC PV €	**LCC PV** €/m2
Initial Cost	8.209e+6	7.180e+2
Operation Cost	1.073e+6	9.385e+1
End-of-life Cost	4.038e+5	3.532e+1
TOTAL	**9.686e+6**	**8.472e+2**





5. Social

Year	DDC €	VOC €	AC €
0	0	0	0
5	0	0	0
10	2.884e+4	4.264e+4	3.056e+2
15	0	0	0
20	1.361e+5	2.011e+5	1.439e+3
25	6.965e+4	1.029e+5	7.353e+2
30	2.183e+4	3.225e+4	2.303e+2
35	2.796e+4	4.128e+4	2.944e+2
40	1.004e+5	1.482e+5	1.056e+3
45	0	0	0
50	6.357e+4	9.380e+4	6.669e+2
55	1.581e+4	2.332e+4	1.656e+2
60	6.327e+4	9.333e+4	6.623e+2
65	1.529e+3	2.255e+3	1.597e+1
70	2.964e+4	4.369e+4	3.093e+2
75	3.308e+4	4.874e+4	3.445e+2
80	5.771e+4	8.503e+4	6.008e+2
85	0	0	0
90	1.923e+4	2.832e+4	1.995e+2
95	0	0	0
100	0	0	0
TOTAL	**6.686e+5**	**9.869e+5**	**7.025e+3**

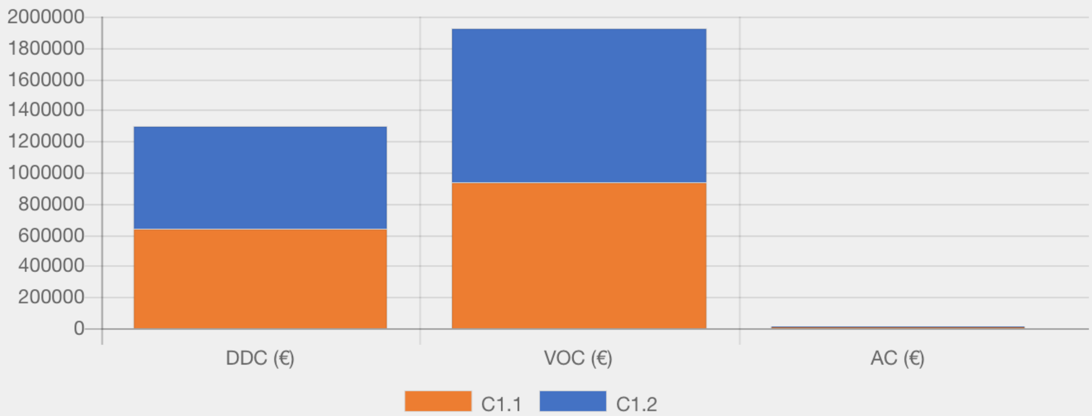


3.3. Comparison between C1.1 vs C1.2

Comparative Life-Cycle Analysis Report

1. Social

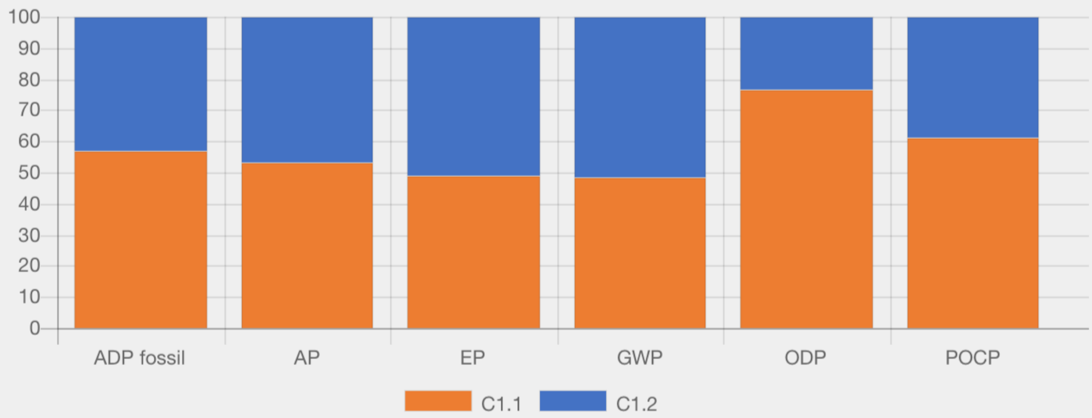
Impact Category	DDC €	VOC €	AC €
C1.1	6.335e+5	9.350e+5	6.657e+3
C1.2	6.686e+5	9.869e+5	7.025e+3
Δ (C1.1, C1.2)	-5.544e-2	-5.543e-2	-5.539e-2



2. Environmental

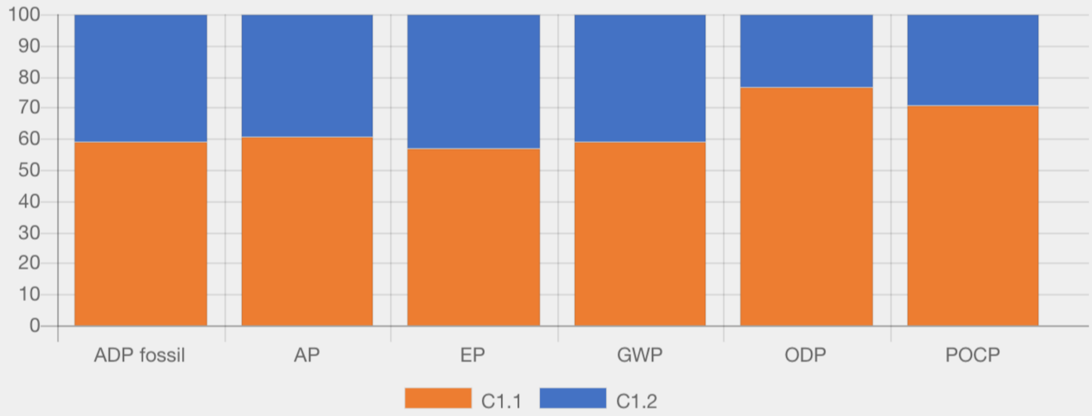
2.1 Stage Material Production

Production						
Impact Category	**ADP fossil** MJ	**AP** Kg SO^2 eq	**EP** Kg PO^4 eq	**GWP** Kg CO^2 eq	**ODP** Kg R^{11} eq	**POCP** Kg C^2H^4
C1.1	6.326e+7	1.621e+4	1.465e+3	6.652e+6	7.572e-2	2.450e+3
C1.2	4.755e+7	1.420e+4	1.536e+3	7.063e+6	2.335e-2	1.572e+3
Δ (C1.1, C1.2)	2.482e-1	1.237e-1	-4.793e-2	-6.177e-2	6.916e-1	3.585e-1



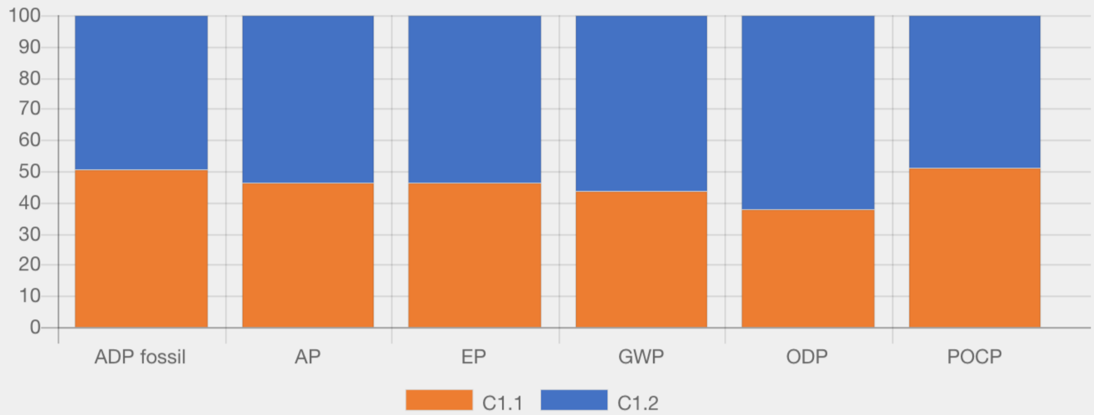
2.2 Stage Construction

Construction						
Impact Category	**ADP fossil** MJ	**AP** Kg SO^2 eq	**EP** Kg PO^4 eq	**GWP** Kg CO^2 eq	**ODP** Kg R^{11} eq	**POCP** Kg C^2H^4
C1.1	2.831e+6	6.965e+2	6.206e+1	2.506e+5	3.786e-3	9.541e+1
C1.2	1.951e+6	4.542e+2	4.740e+1	1.730e+5	1.167e-3	3.953e+1
Δ (C1.1, C1.2)	3.109e-1	3.478e-1	2.362e-1	3.096e-1	6.918e-1	5.857e-1



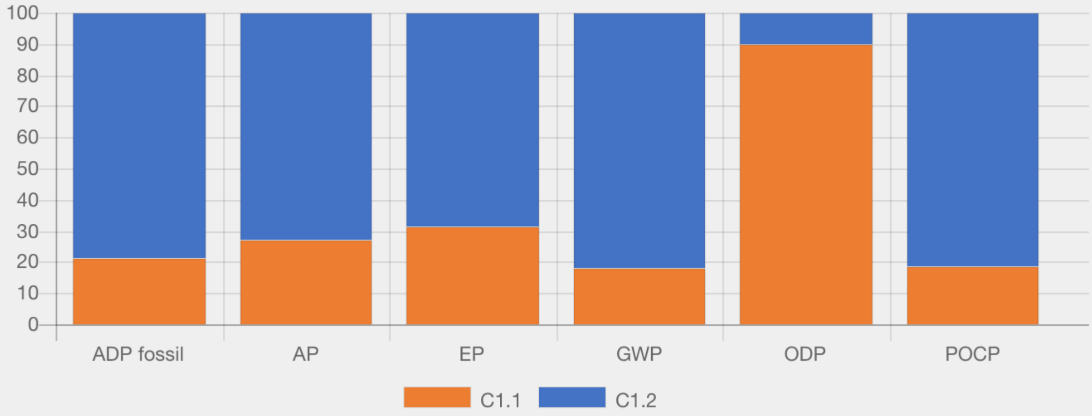
2.3 Stage Operation

Operation						
Impact Category	**ADP fossil** MJ	**AP** Kg SO^2 eq	**EP** Kg PO^4 eq	**GWP** Kg CO^2 eq	**ODP** Kg R^{11} eq	**POCP** Kg C^2H^4
C1.1	8.374e+7	4.887e+3	7.269e+2	1.749e+6	5.987e-6	1.011e+3
C1.2	8.282e+7	5.702e+3	8.519e+2	2.275e+6	9.956e-6	9.692e+2
Δ (C1.1, C1.2)	1.101e-2	-1.667e-1	-1.720e-1	-3.005e-1	-6.629e-1	4.168e-2



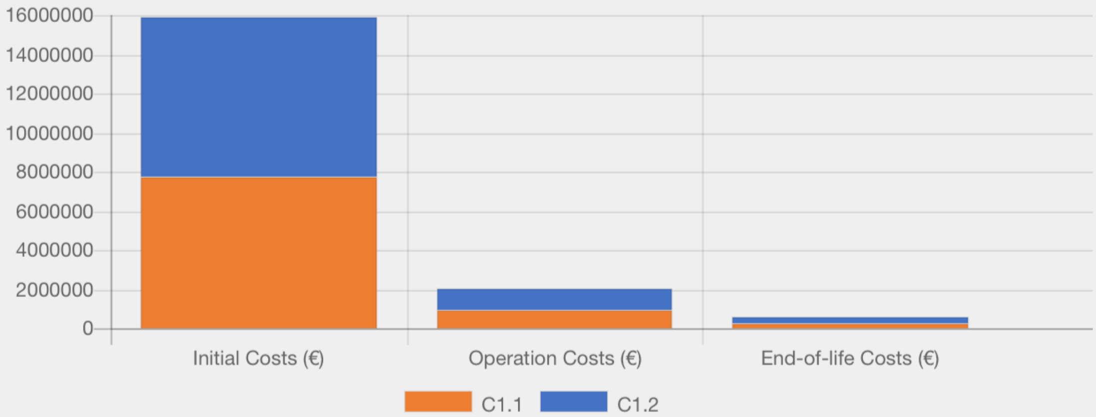
2.4 Stage End of Life

End of Life						
Impact Category	**ADP fossil** MJ	**AP** Kg SO^2 eq	**EP** Kg PO^4 eq	**GWP** Kg CO^2 eq	**ODP** Kg R^{11} eq	**POCP** Kg C^2H^4
C1.1	1.149e+7	7.372e+3	1.239e+3	7.154e+5	2.832e-2	4.136e+2
C1.2	4.272e+7	1.972e+4	2.721e+3	3.279e+6	3.256e-3	1.813e+3
Δ (C1.1, C1.2)	-2.719e+0	-1.675e+0	-1.197e+0	-3.583e+0	8.850e-1	-3.384e+0



3. Economic

Resume			
	Initial Cost €	**Operation Costs** €	**End-of-life Costs** €
C1.1	7.714e+6	9.472e+5	2.344e+5
C1.2	8.209e+6	1.073e+6	4.038e+5
Δ (C1.1, C1.2)	-6.415e-2	-1.328e-1	-7.229e-1



4. TECHNICAL BACKGROUND OF THE CALCULATOR

4.1. INTRODUCTION

4.1.1. General

Sustainability requires lifecycle thinking. In the context of sustainable construction, the design of a bridge goes beyond the traditional requirements of safety and initial costs. It comprises all lifecycle stages of the bridge, from raw material production to the bridge's demolition [1]. This implies the prediction of the structural behavior of the bridge over its lifespan, the estimation of bridge maintenance and repair, etc. Moreover, non-traditional aspects of the environment, economy, and society shall be considered together with traditional ones and currently, most engineers are rarely prepared for these new requirements.

Lifecycle analyses are usually time-consuming and thus costly and the lack of data is a problem often encountered. In addition, the benefits brought by a sustainability perspective are often perceived only in the long-term, which makes its effective implementation difficult to promote. Moreover, lifecycle methodologies have been developed for the analysis of simple products. The application of such approaches to more complex systems, like a construction system, entails specific problems that need to be addressed in order to make them feasible [1]. In light of this, extensive data regarding Lifecycle Cost Analysis (LCC), Lifecycle Environmental Assessment (LCA) and Lifecycle Performance (LCP) for all the lifecycle stages of bridges were collected in the SBRI research project. The database forms then the basis for the detailed investigations on LCC, LCA, and LCP. Focus is given to the Lifecycle Performance in regard to different degradation processes in composite bridges. As bridges are designed to cover a lifespan of more than 100 years, inspections and maintenance actions need to be given a special focus. The analysis of complete case studies aims at possible comparisons and improvements by variations.

4.1.2. Framework of the SBRI-Tool

The aim of this tool is to provide means to assess and compare the sustainability of different bridge types, in the early stages of design, implementing a holistic Lifecycle analysis methodology. This would help select the best option by considering the pros and cons of each alternative in the construction, operation and end-of-life stages of the bridge's life – contrary to comparing mere initial construction costs.

The sustainability assessment is undertaken in accordance with the most recent European standard CEN TC350 and ISO standards 14040 [2] and 14044 [3]. The overall Lifecycle analysis incorporates three major sub-analyses: Lifecycle Environmental Assessment (LCA), Lifecycle Cost Analysis (LCC) and Lifecycle Social Analysis (LCS), at the different stages of the bridge's service life. Steel-concrete composite bridges are currently built in a lot of various situations with various possible designs. With the aim of simplifying the routine task of picking between common alternatives, the tool is organized by subgrouping projects into three representative bridge types: Type A – Crossings of motorway, Type B – Big motorway bridges and Type C – Small and medium motorway bridges.

The tool features three essential modules. The first one allows for the computation of Lifecycle Analysis for a single bridge alone - given parameters and data on the bridge properties. The second module enables users to run a Multi-criteria analysis when choosing between different elements/alternatives within the same bridge design type. Comparison of the Lifecycle Analysis of different bridge types can be performed by using the third module - Comparative Lifecycle Analysis.

4.1.3. Goals and Scope

The current situation in the European bridge market is dominated by concrete bridges. Steel and steel-composite bridges only represent an interesting alternative if additional criteria count such as e.g. aesthetics, construction time or reduced overall weight. That is because the choice of orders is mostly made according to minimum initial construction costs only. However, with rising traffic volume and increasing vehicle gross weight, this approach does no longer seem to be adequate, especially considering that bridges are in general long-living structures where the lifecycle is planned for more than 100 years.

Therefore, a new holistic approach was investigated by combining analyses of Lifecycle Environmental Assessment (LCA), Lifecycle Costs (LCC) and Lifecycle Performance (LCP). For steel-composite bridges, innovative solutions were analyzed to give alternatives to concrete bridges. Throughout the project, the approach is applied to three realistic types of bridges and a multitude of variants which represent the standard situations of steel-composite road bridges identified according to the span length and bridge functionality. The analyses of these examples as case studies mainly aim to familiarize the users with the application of the method and also allow comparisons and improvements.

4.2. SUSTAINABILITY BY LIFECYCLE ANALYSIS OF BRIDGES

4.2.1. General Definitions

The traditional design of a bridge is based on the requirements of codes and rules that have been developed for that purpose. These requirements are related to the safety of the structure and usually include rules for resistance, durability, and serviceability. In this approach, the initial safety of the structure, according to the requirements of the Structural Eurocodes, is assumed to be fulfilled. In addition, it is assumed that major failure of the bridge does not occur over the time span of the analysis (100 years). Such an approach is limited in a lifecycle analysis, though. Bridges start to deteriorate immediately after they enter into service. The rate of deterioration depends on many factors for different types of bridges. In order to keep the bridge above some condition, maintenance and rehabilitation actions are required.

Looking at bridges from the point of view of sustainability, not only the construction stage must be taken into account but the entire lifecycle of 100 years. These long-living structures are facing different degradation processes throughout the years. Degradation can be divided into several processes as among which fatigue, corrosion of steel girders and carbonation having an impact on various details. The structural function of the details, and therefore the structure itself, can be preserved and improved by maintenance and/or renewal actions concerning defects discovered during inspections.

Each time an intervention to the bridge is needed, it implies environmental and economic impacts that need to be considered in a lifecycle analysis. Hence, the lifecycle environmental and economic analyses of bridges are directly dependent on the lifetime structural performance and this relationship is addressed by integrating the structural performance of the bridge over its lifespan as illustrated in Figure 1.

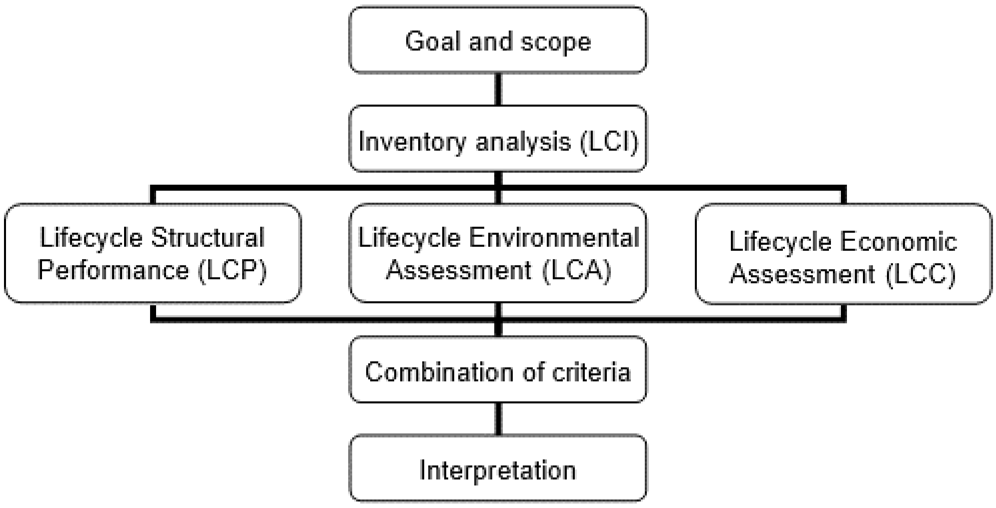


Figure 1: Flowchart of the Lifecycle Integral Analysis

The impact assessment stage of the three main categories is made separately for each criterion. The following step, the combination of criteria, depends on the aim of the analysis. If the aim of the analysis is to identify the improvement possibilities of the processes contributing to major impacts, then the structural, environmental and costs performances may be interpreted individually. On the other hand, if the aim of the analysis is to solve the decision-making problems, then the balance between the individual performances may be achieved by a multi-criteria decision analysis. It should be emphasized that a lifecycle analysis is not a decision-making approach; however, it can provide valuable information for decision-makers in the process of decision-making [1].

The lifecycle performance of steel-composite bridges is analyzed starting from the stage of production of raw materials, followed by construction, the operation of the bridge (including maintenance etc.) and until the demolition at the end-of-life. Under the participation of scientists, bridge owners, consultants, and industry as project partners the lifecycle performance of steel-composite bridges was analyzed in the SBRI project employing a holistic approach as described in the following.

An integral lifecycle approach for the assessment of motorway bridges was developed in the framework of this project. The aim of the approach is the lifecycle assessment of a bridge in the context of sustainable development and, in particular, in the context of sustainable construction. Therefore, the approach aims at balancing environmental and economic aspects.

Currently, there is not a standardized methodology providing guidance for an integral lifecycle analysis of a construction system [1]. The lifecycle environmental analysis has currently the most well established standardized framework, although there is still no generalized acceptable methodology in the scientific community. In a decreasing order of development follows the lifecycle economic analysis. For this reason, the development of the general framework for the integral lifecycle analysis was based on the standardized framework for Lifecycle Environmental Analysis (LCA), according to the series of ISO standards 14040 [2], with further adaptation in order to include economic criteria.

Therefore, the generalized framework proposed in this manual entails the four main steps of the ISO standard 14040 [2]: the goal and scope step; the inventory step; the impact assessment step; and the interpretation step. However, as already referred, each step of the analysis was adopted in order to allow the integration of economic aspects in the lifecycle analysis.

4.2.2. Holistic Approach

Lifecycle analysis which aims at sustainable bridge structures is divided into three main categories of consideration, see Figure 2. First, the environmental quality represents the analysis of emissions within the lifecycle assessment (LCA). The economic quality comprises costs occurring during the entire lifecycle (LCC) and is defined in the second category. The social and functional quality is involved as the third main category of lifecycle social analyses (LCS). Applying the holistic approach to the entire lifecycle of bridges, the influence of the outlined parameters to the structure and society is taken into account throughout the service life.

Figure 2: Holistic approach to lifecycle analyses.

The description of the lifecycle performance (LCP) of the structure and its details is the all-embracing condition to determine any inspection measurement during operation needed to guarantee a functional structure. The initial design and construction strongly interact with the inspection and repair measurements needed during the service life and the scenario at the end-of-life of bridges. Possible effects of degradation and renewal actions may lead to additional emissions (LCA), costs (LCC) and restricted social and functional quality (LCS).
The application of this holistic approach over the entire lifecycle is the basis for a shift from bridge designs based on construction costs to a sustainable design taking into account the advantages of steel-composite bridges such as construction time, durability and exploration of material properties in an efficient way.

4.2.3. Lifecycle Performance

The evaluation of lifecycle performance starts with the construction of the bridge including also material production. The operation phase starts when the bridge goes into service and this stage ends when the bridge reaches the end of its functionality – end-of-life. Lifecycle Performance concerns both: a) various degradation processes as among which carbonation (initiation of corrosion of concrete rebars), corrosion of steel girders and fatigue and b) the corresponding inspection and maintenance intervals and methods.
The lifecycle performance of each bridge is mainly described by the performance of critical details. Therefore, a good knowledge of the behavior of the details during the entire lifespan of a bridge is essential for holistic analyses. Degradation can be divided into several processes. For bridges, fatigue, corrosion and carbonation are the processes that were investigated in the SBRI project, see Figure 3.

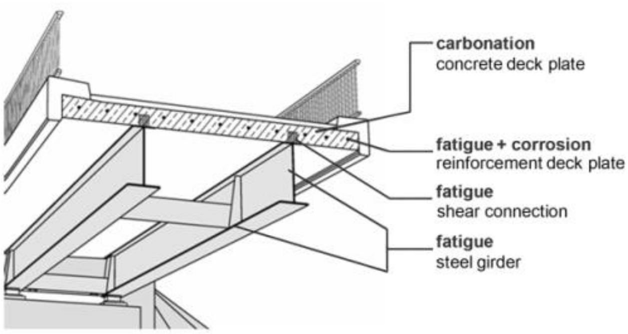


Figure 3: Degradation processes

Scheduling inspections and maintenance actions should be done based on a detailed description of the lifecycle performance of the affected details. Thus, lifecycle costs and emissions can be reduced. Intervals of bridge inspections can also be optimized by the knowledge of the adequate non-destructive testing methods to early detect defects. Knowing and being able to describe the lifecycle under deterioration processes of bridge details gives the possibility to optimize the structure in regard to sustainable aspects.

4.2.3.1. Fatigue behavior

Bridges are subject to traffic loading over a long lifespan. Traffic loading is recurrent and beyond that, due to increasing traffic volume, it must be calculated with an increased loading till the end of the lifecycle. Fatigue, therefore, cannot be neglected in bridges as it is one of the main degradation processes.

Various details can be affected by fatigue and cause deterioration of bridges. A classification by the severity of the induced damage can lead to the identification of the most critical details during the lifecycle. Literature shows that critical spots are not only located in steel but also in composite details. The transverse stiffener was selected as a typical detail in steel. Transverse stiffeners are used in both steel bridges and in composite bridges and are a common detail which faces crack problems due to fatigue. Post-weld treatment by high frequent hammering was found to improve that crucial resistance.

An effective shear connection in composite bridges is horizontally lying shear studs in combination with an omitted steel flange, e.g. for prefabricated composite bridge girders or connections of the concrete slab to the outer main girder in typical arch bridges. The existing degradation models for these details were analyzed and improved by results from own prototype tests in order to be included in the overall assessment.

4.2.3.2. Corrosion

A common problem found in composite bridges is corrosion attacks in the joint between the steel beam and the concrete deck. Rust stains may occur in the joint between the steel beam and the concrete deck and/or on the surface of the sealant in the areas where the sealant is used in the interface zone. Rust stains are caused by corrosion on the steel surface behind the sealant or by corroding binding wire. In the latter case, the stains have no direct influence on the condition of the steel beam. Once corrosion is noticed, a proper repair is needed in order to stop the process and avoid future major problems. To repair the corrosion problem in the joint between the steel beam and the concrete deck different methods can be used, such as the application of surface coatings or of elastic sealants to the joint.

4.2.3.3. Carbonation

Carbonation processes impact the reinforced concrete structure of composite bridges leading to degradation. Long-term durability of reinforced concrete (RC) structures has become one major concern in view of the vast amounts of money required to maintain the infrastructures in a serviceable state. Regarding the steel RC corrosion, resulting from chloride ingress and/or atmospheric carbonation, the traditional approach to the concrete design has been to follow deemed-to-satisfy rules which set requirements on mix-parameters, the thickness of the concrete cover, crack width limitations, etc. However, these requirements are no longer appropriate because of the complexity and the variety of the binders used today, and even stifle the designers who have nowadays numerous possibilities in terms of mix-design parameters (use of admixtures like superplasticizers, air-entraining agents, etc., and use of cement blended with supplementary cementitious materials like fly ash, slag, silica fume, etc.).

That is why a need is currently appearing for performance-based approaches [4] [5] in which the rules are associated with the performance to be achieved in terms of durability properties (i.e., porosity, permeability, etc.). Corrosion of the embedded reinforcement steel, resulting from atmospheric carbonation, is a matter of considerable concern which irreversibly affects the serviceability of RC structures. Most concrete structures are exposed to the action of CO2 which diffuses into the concrete cover, dissolves in the pore water, and reacts with the hydration compounds, causing a reduction in the pH-value which thus makes corrosion of the steel reinforcement possible [6]. This issue is particularly pronounced for cementitious materials with a low portlandite content (CH) since CH is the main supplier of alkaline buffering capacity. Therefore, an ordinary concrete (medium to high porosity) made of a binder with a large amount of supplementary cementitious materials is likely to be more sensitive to carbonation. This is why the quantification of the carbonation mechanism for these kinds of concrete is crucial, all the more since their use will drastically increase in the next decades to fulfill commitments related to the mitigation of the CO2 footprint.

The simplest and most effective way of enhancing service life (SL) of RC structures is to increase the length of the corrosion initiation period which is defined as the time required for the first layer of steel rebars to become depassivated. To make the prediction of this induction period possible, mathematical models can be used. Most of the time, a deterministic approach is adopted. Even if a deterministic approach can provide an acceptable assessment of the carbonation penetration for accelerated conditions, the predictions for durations of more than fifty years are very uncertain given that most input data of the model show a great variability which rejects any idea of absolute reliability.

4.2.4. Inspection and Maintenance Strategies

During the operation phase of a bridge, regular inspections are necessary to allow the continuous monitoring of the bridge condition, evaluation and eventual need for maintenance and rehabilitation actions. The definition and aim of each the types of inspections are:

- Routine inspection – visual observation to detect small damage that can be promptly repaired; The team is formed by one or two members of the maintenance staff with specific training;
- Principal inspection – detailed visual inspection with special means of access. The aim is the assessment of the bridge condition rating evolution, with the definition of potential repair/rehabilitation actions;
- Special inspection – detailed inspection when there is a need for a specific repair plan for the complete or partial rehabilitation of the bridge. Tests and laboratory analysis are also used to help evaluate damage conditions and allow recommendations for damage repairs.

The frequency assumed for each type of inspection for the standard scenario is shown in Table 1.

Table 1: Standard scenario - Inspection frequency and average occurrence.

Type of Inspection	Inspection frequency	Average occurrence during 100 years
Routine	annually	100
Principal	6 years	17
Special	2 in 100 years	2

Regarding maintenance during the operation stage, a list of maintenance strategies was compiled for different European countries [7]. Maintenance activities can be divided into categories regarding the intensity of maintenance. In this research three types of maintenance scenarios were considered:

- Standard – a scenario with a 100-year service life, according to the normal service life of bridges, for which there will be enough money to undergo all the necessary inspections and maintenance/repair actions;
- Lack of money – along the bridge lifecycle, there is not enough money to undergo the necessary maintenance/repair actions and the bridge will be critically deteriorated and with traffic restrictions on year 100. Inspection activity will have to be increased in the last years for the knowledge of the actual bridge condition, and also maintenance actions are introduced to extend the service life of some elements;
- Prolonged life – the decision of maintaining the bridge for an additional 30 years (130 years total and no more) is taken around year 80. After this year, inspection and maintenance actions are adapted to accomplish this service life extension.

Basic definitions for the three scenarios are described in the following chapters.

4.2.4.1. Standard scenario

In the standard scenario, the types and inspection frequencies shown below are considered necessary to maintain the knowledge of the bridge condition and average service life of bridge elements. The frequency of maintenance/repair actions is considered essential in maintaining a good condition rating for the bridge. Regarding maintenance/repair, in the standard scenario, it is assumed that maintenance actions take place before the end of the average service life of the elements of the bridge. Structural elements are replaced when the average service life is reached. For the operation phase, it is assumed that the average service life for each structural or non-structural element of the bridge is the same for the standard, lack of money and prolonged life scenario, according to Table 2. Based on the average service life, a maintenance/repair works frequency was assumed.

Table 2: Average service life assumed for bridge elements (for the standard, lack of money and prolonged life scenarios).

Element	Average service life (years)
Superstructure concrete	100
Concrete edge beam	40
Safety barrier	40
Superstructure steel	100
Steel corrosion protection	35
Expansion Joints	40
Road surface	20
Water Proofing Layer	40

Metal cornice gutter	25
Elastomeric bearing	35
Railing	40

Table 3: Standard scenario - average maintenance/repair work frequency.

Element	Maintenance action	Standard maintenance frequency (years)
Superstructure concrete	Small area repairs	25
Concrete edge beam	Minor repairs	25
Safety barrier	Partial replacement	25
Steel corrosion protection	Repainting of corrosion protection	25
Expansion Joints	Partial replacement	10
Road surface	Minor repairs	10
Water Proofing Layer	No maintenance actions *	0
Metal cornice gutter	No maintenance actions *	0
Elastomeric bearings	Clean, painting, lubricating	20
Railing	Painting	20

(*) - Elements with no maintenance actions. Total replacement takes place when the element's service life is reached.

In the Annex – Table A1 (Design Manual I) summarizes data that were assumed for the definition of the standard scenario.

4.2.4.2. Lack of money scenario

In this scenario, it is assumed that in the early stages of the bridge, inspection actions will be less frequent, due to the lack of money, and as the estimated end of the bridge service life approaches, inspection actions are more frequent for evaluation of bridge condition rating and control of structural safety.
Repair actions are delayed and scheduled towards the end of the service life and new maintenance actions are introduced to extend the service life of some bridge elements, in order to delay or remove other maintenance actions.
Regarding the assumptions in the previous sections, the average service life for the bridge elements is the same for all scenarios but the assumed frequency for maintenance/repair actions is shown in Table 4.

Table 4: Lack of money scenario - average maintenance/repair work frequency.

Bridge Element	Maintenance action	Standard maintenance frequency (years)
Superstructure concrete	Small area repairs	50
Concrete edge beam	Minor repairs	50
Safety barrier	Partial replacement	20
Steel corrosion protection	Repainting of corrosion protection	25
Expansion Joints	Partial replacement	10
Road surface	Minor repairs	10
Water Proofing Layer	No maintenance actions *	0
Metal cornice gutter	No maintenance actions *	0

Elastomeric bearings	Clean, painting, lubricating	20
Railing	Painting	20

(*) - Elements with no maintenance actions. Total replacement takes place when the element's service life is reached.

In Annex A – Table A2 (Design Manual I) summarizes data that were assumed for the definition of the lack of money scenario.

4.2.4.3. Prolonged life scenario

In this scenario, the decision of maintaining the bridge for an additional 30 years (130 years of service life and no more), is made around year 80. Inspection and maintenance frequencies and actions are similar to the standard scenario up to year 80 except for the following elements: superstructure concrete, edge beams, safety barriers, and bearings. After this year, inspection and maintenance actions are adapted to accomplish the service life extension. Maintenance actions in some elements will be more frequent between year 115 and 130. It is also assumed that there will be no fatigue problems in the steel superstructure and therefore no strengthening actions will be considered.
The average service life for bridge elements is the same as the one considered for the standard and lack of money scenarios and the assumed frequency for maintenance/repair actions is shown in Table 5.

Table 5: Prolonged life scenario - average maintenance/repair work frequency.

Element	Maintenance action	Standard maintenance frequency (years)
Superstructure concrete	Small area repairs	25
Concrete edge beam	Minor repairs	40
Safety barrier	Partial replacement	20
Steel corrosion protection	Repainting of corrosion protection	25
Expansion Joints	Partial replacement	10
Road surface	Minor repairs	10
Water Proofing Layer	No maintenance actions *	0
Metal cornice gutter	No maintenance actions *	0
Elastomeric bearings	Clean, painting, lubricating	25
Railing	Painting	20

(*) - Elements with no maintenance actions. Total replacement takes place when the element's service life is reached.

In Annex A – Table A3 (Design Manual I) summarizes data that were assumed for the definition of the prolonged life scenario.

4.3. LIFECYCLE ENVIRONMENTAL ANALYSIS (LCA)

4.3.1. General

The framework for Lifecycle Environmental Analysis (LCA) adopted in this project is according to ISO standards 14040 [2] and 14044 [3]. These standards specify the general framework, principles, and requirements for conducting and reporting lifecycle assessment studies. According to these standards, the lifecycle assessment shall include (i) definition of goal and scope, (ii) inventory analysis, (iii) impact assessment, (iv) normalization and weighting, and (v) interpretation of results. The step of normalization and weighting is considered to be optional in ISO standards and will not be addressed in the lifecycle environmental analysis. Thus, the complete flowchart for the environmental lifecycle analysis is detailed in Figure 4.

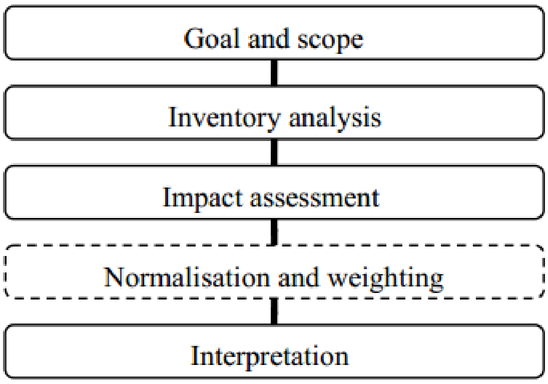


Figure 4: Scheme of the environmental lifecycle analysis

Sustainability requires lifecycle thinking. In the context of sustainable construction, the design of a bridge goes beyond the traditional requirements of safety and initial costs. It comprehends the lifecycle of the bridge, from raw material acquisition to the bridge's decommissioning [1]. This implies the prediction of the structural behavior of the bridge over its lifespan, the estimation of bridge maintenance and repair, etc. Moreover, non-traditional aspects of environment, economy, and society shall be considered together with traditional ones and currently, most engineers are not prepared for these new requirements.

Lifecycle analyses are usually time-consuming and thus costly, and the lack of data is a problem often encountered. In addition, the benefits brought by a sustainable perspective are often perceived only in the long-term, which makes its effective implementation difficult to promote.

Finally, lifecycle methodologies have been developed for the analysis of simple products. The application of such approaches to more complex systems, like a construction system, entails specific problems that need to be addressed in order to make them feasible [1].

4.3.2. Goal and Scope of the LCA

The goal of the LCA is to evaluate the environmental performance of composite motorway bridges over their lifecycle. The period of analysis is assumed to be 100 years. The lifecycle analysis will highlight main advantages and disadvantages of this kind of structures and will allow providing recommendations for further improvements.

The system boundaries determine which unit process shall be included within the LCA [2]. Several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience.

The system boundary adopted in this project is introduced in Figure 5. All stages of the complete lifecycle of the bridges, from raw material extraction until end-of-life procedures, are included. Furthermore, the transportation of materials are also within the system boundary.

When the composite bridge is built (assuming that the motorway is under service) or it goes under repair, traffic congestion results from delays over the construction work zone. This construction-related delay results in additional fuel consumption and related emissions. The effects of traffic congestion were also taken into account in the LCA.

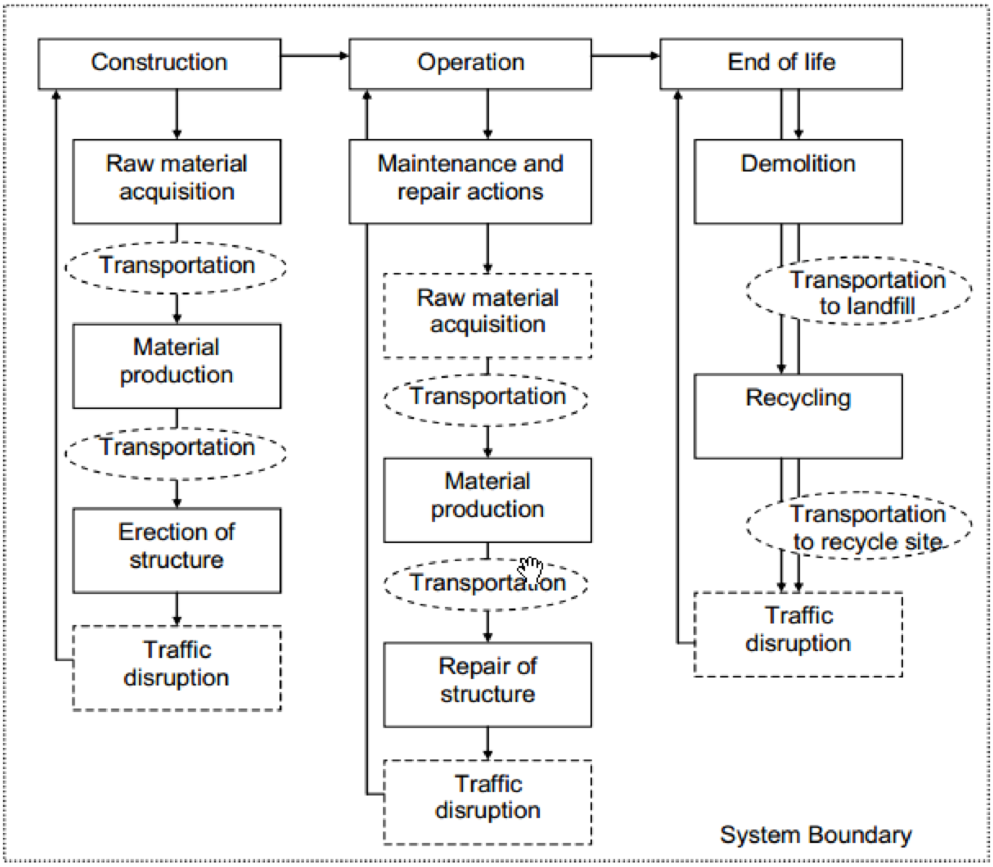


Figure 5: System boundary of the LCA

4.3.3. Methodology for Impact Assessment

The impact assessment stage of an LCA is aimed at evaluating the significance of potential environmental impacts using the results of the lifecycle inventory analysis. In general, this process involves associating inventory data with specific environmental impact categories, and is made in two parts (i) mandatory elements, such as selection of environmental indicators and classification; and (ii) optional elements, such as normalization, ranking, grouping, and weighting.

The classification implies a previous selection of appropriate impact categories, according to the goal of the study, and the assignment of inventory results to the chosen impact categories. Characterization factors are then used representing the relative contribution of an inventory result (mi) to the impact category indicator result, as expressed by the following equation:

$$impact_{cat} = \sum_i m_i \times charact\_factor_{cat.i} \quad (1)$$

The environmental indicators adopted in the lifecycle approach are listed in Table 6.

Table 6: Environmental indicators for LCA

Indicator		Unit	Timescale
Global Warming Potential	GWP	Kg CO_2 eq.	100 years
Acidification Potential	AP	Kg SO_2 eq.	∞
Eutrophication Potential	EP	Kg PO_4 eq.	∞
Photo Ozone Creation Potential	POCP	Kg C_2H_4 eq.	-
Ozone Depletion Potential	ODP	Kg CFC eq.	∞
Abiotic Depletion Potential	ADP	Kg Sb eq.	-

4.3.4. Environmental Indicators

4.3.4.1. Global Warming Potential (GWP)

The global warming indicator measures the impact of human emissions on the radiative forcing of the atmosphere. GWPs are defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas [8]. For the definition of GWPs, the reference gas is carbon dioxide (CO_2).

4.3.4.2. Ozone Depletion Potential (ODP)

An ozone depletion indicator is derived from several properties of a gas, which include its stability to reach the stratosphere and the amount of bromine or chlorine the gas carries. These properties are then compared to CFC-11 (although CFC-11 is now banned by the Montreal Protocol in industrialized nations, it is still manufactured in many developing economies). The properties of each gas are then compared to the properties of CFC-11 and converted into CFC-11 equivalents. Then the individual equivalents are added together for the overall ozone depletion indicator score, which represents the total quantity of ozone-depleting gases released.

4.3.4.3. Photochemical Ozone Creation Potential (POCP)

Photo-oxidants may be formed in the troposphere under the influence of ultraviolet light, through photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) [9]. This chemical reaction is "non-linear," meaning that sometimes the NO_x concentration will drive the reaction, and other times, it's the VOC that drive the reaction. Various indicators take low, average and high NOx concentrations to calculate an overall score. Photochemical ozone creation potentials assess various emission scenarios for VOCs. Therefore, the photochemical ozone creation potential of a VOC (POCP) is given by the ratio between the change in ozone concentration due to a change in the emission of that VOC and the change in the ozone concentration due to a change in the emission of ethylene (C_2H_4) [9].

4.3.4.4. Acidification Potential (AP)

Acidification in one of the impact categories in which local sensitivity plays an important role. The characterization factors adopted in this work are based on the model RAINS-LCA, which takes fate, background depositions and effects into account [10]. Based on this model, Huijbregts [10] developed characterization factors for 44 regions in Europe and average European factors, by a weighted summation of the regional factors for each acidifying emission. This indicator is expressed in kg of SO2 equivalents.

4.3.4.5. Eutrophication Potential (EP)

The eutrophication indicator is given by the aggregation of the potential contribution of emissions of N, P and C (given in terms of chemical oxygen demand, COD) to biomass formation [9]. The Eutrophication Potential of substance i reflects its potential contribution to biomass formation. This indicator is expressed in kg of PO4 equivalents.

4.3.4.6. Abiotic Depletion Potential (ADP)

The indicator abiotic depletion aims to evaluate the environmental problem related to the decreasing availability of natural resources. By natural resources, it is understood the minerals and materials found in the earth, sea, or atmosphere and biota, that have not yet been industrially processed [11].

The model [11] adopted for abiotic depletion in this work, assumes that ultimate reserves and extraction rates together are the best way to represent the seriousness of resource depletion. This model is a global model based on ultimate reserves in the world combined with yearly depletion on a world level.

4.4. LIFECYCLE COST (LCC)

4.4.1. General

Lifecycle cost (LCC) is an economic evaluation method that takes account of all relevant costs over the defined time horizon (period of study), including adjusting for the time value of money. The total lifecycle costs include not only construction costs but also other costs such as design, maintenance and dismantlement which may represent a significant portion of the total lifecycle costs of a steel composite bridge as illustrated in Figure 6.

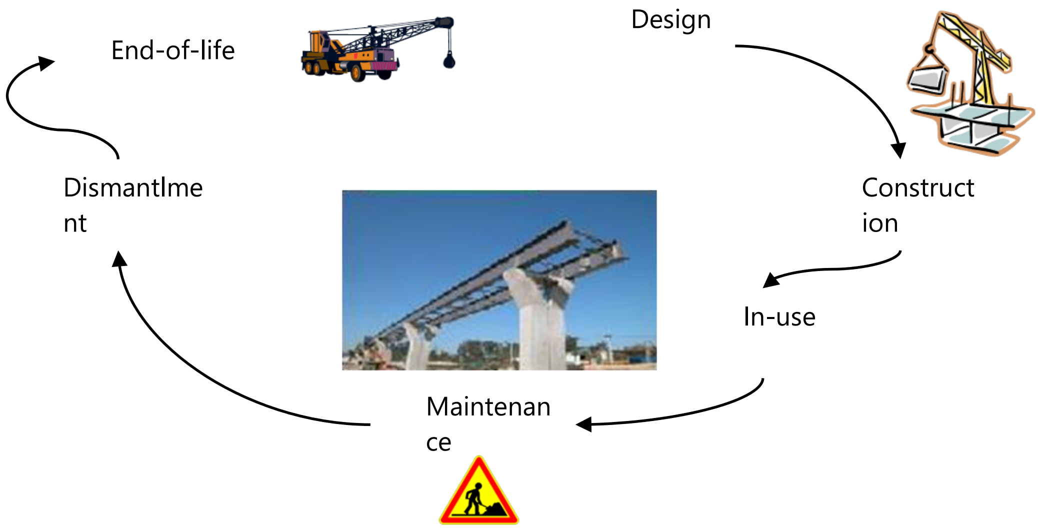


Figure 6: Lifecycle stages/costs from design to bridge end-of-life

The ISO 15686-5 methodology [6] defines the lifecycle costing as a technique which enables systematic economic evaluation of the lifecycle costs over the period of analysis. Figure 7 summarizes the concept of whole life and Lifecycle cost. In a whole life costing approach, the projected costs or benefits may include finance, business costs, income from land sale and user costs. One important motivation to use lifecycle cost analysis (LCC) is to balance the decrease of operation and maintenance costs with a possible increase of initial costs [7].

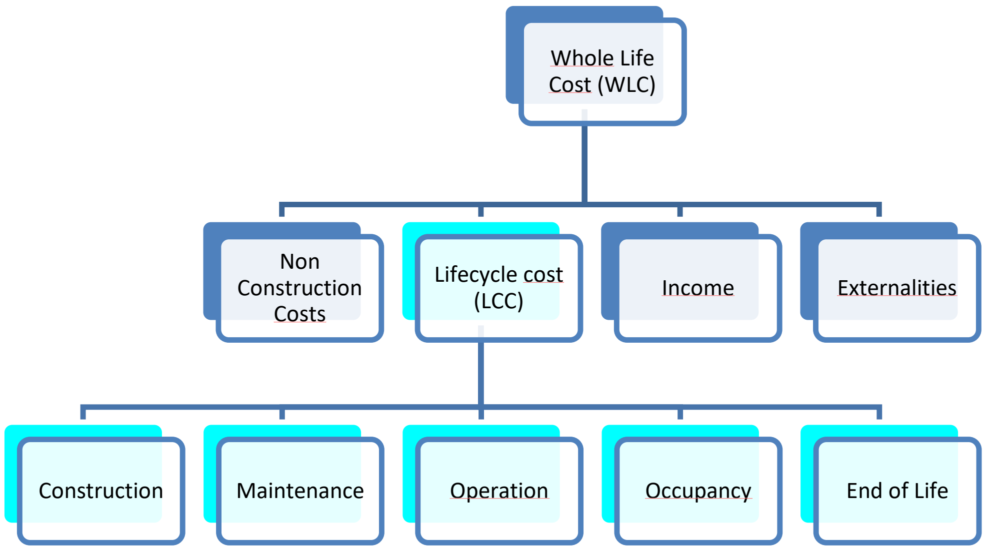


Figure 7: "Whole life costs" and "lifecycle costs" concept [6].

4.4.1.1. Construction stage

Expenses associated with steel-concrete composite bridge construction mainly include costs for (i) foundation, (ii) substructure with abutments, piles and bearings, (iii) superstructure with steel girder/box (for composite bridge), concrete deck and equipment (expansion joints, road surface, waterproofing layer, metal cornice gutter, railing and protection). It is noted that these costs should include all materials and work costs needed for each component as illustrated in Figure 8 to Figure 12.

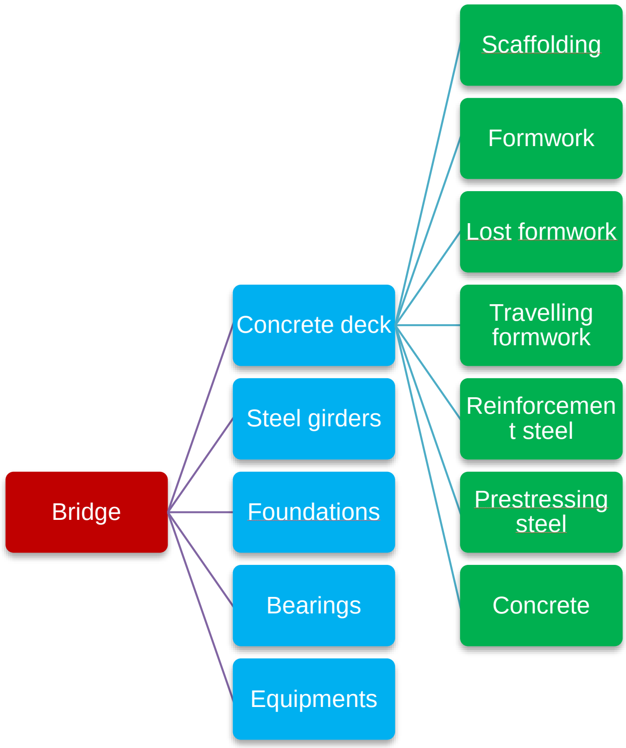


Figure 8: Concrete deck elements

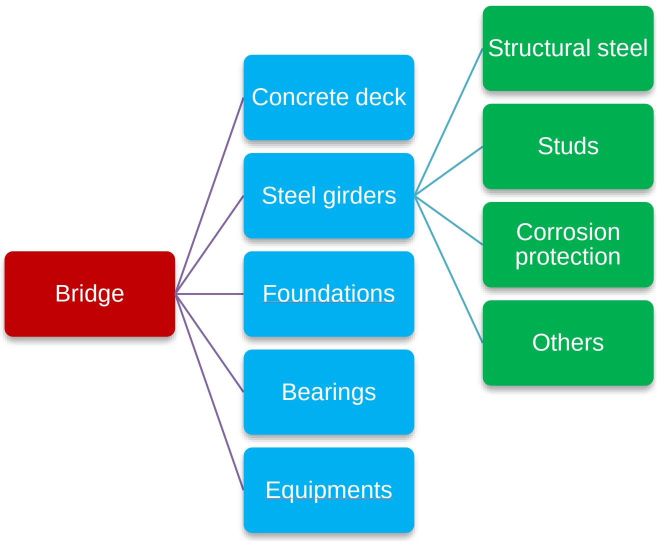


Figure 9: Steel girders elements

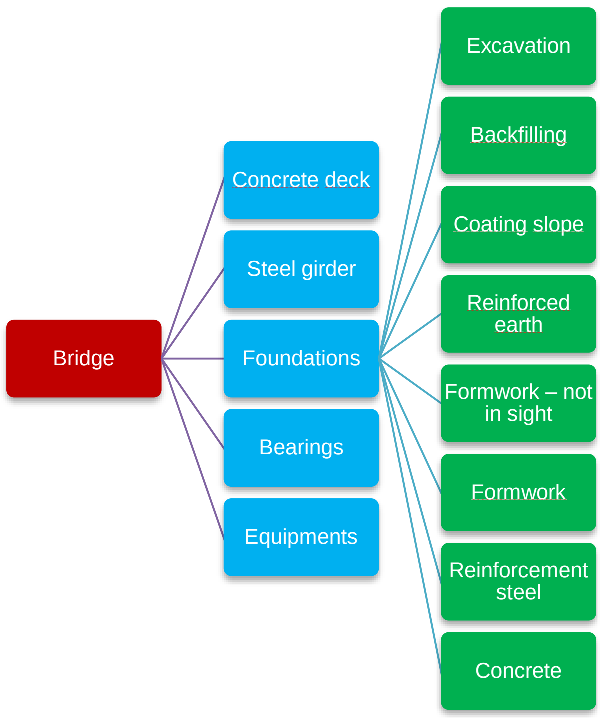


Figure 10: Foundation elements.

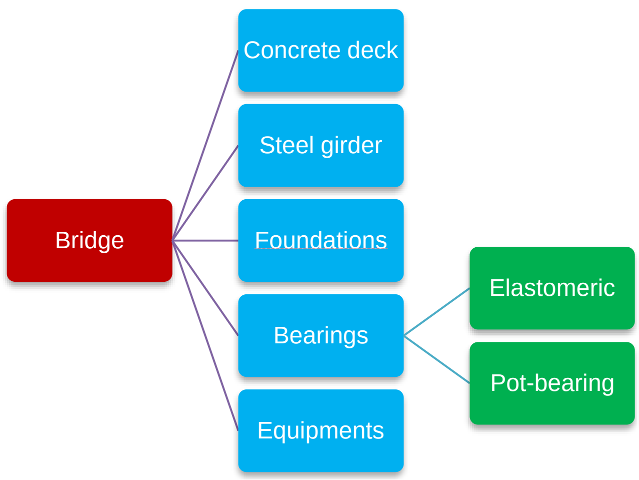


Figure 11: Bearing elements

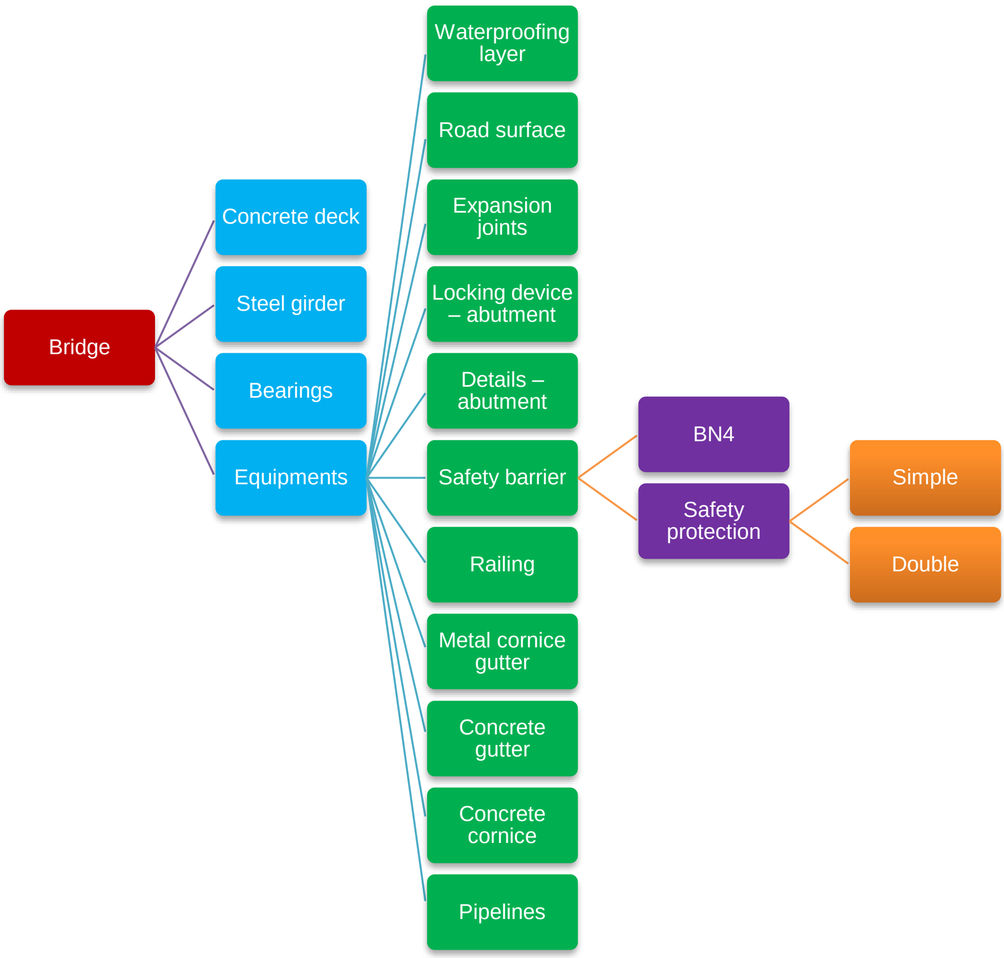


Figure 12: Detail of equipment

The different design solutions of a composite bridge are associated with different construction costs according to the type of materials used and the fabrication/erection process. [12] states that with the choice of the appropriate steel grade and concrete quality, the conditions for economic construction are provided. The use of steel in composite construction represents a great economic potential developed with the use of cost-effective construction techniques and advanced construction procedures. It is noted that most construction materials consume energy for production and transportation. This aspect is taken into account in [13] by multiplying all costs for materials for construction and repair with some factor due to energy consumption for manufacturing and transportation. The use of non-renewable materials is also considered by involving costs for reproducing or reusing materials when the structure is decommissioned.

4.4.1.2. Operation stage

All structures have to be inspected and maintained. In particular, bridge inspections are essential for the determination of intervention strategies. The time intervals between these measures depend on the type of bridge, the experience in the different countries, the economic resources available, the average daily traffic value, the use of de-icing salt and so on. Also, inspection strategies (intensities and frequencies of inspections) may be different in each country based on climate conditions and prioritization strategies proper to each country (Woodward 1997). The three basic types of inspection considered were discussed in section 2.4.
During the bridge operation stage, some maintenance activities are taken into account, the objective being that the bridge performance (associated with serviceability and safety concepts)

always remains above a minimum threshold. This point corresponds to the end of the service life if no other rehabilitation action is conducted.

4.4.1.3. End-of-life

In the end-of-life stage, it is assumed that the bridge is demolished and that the materials are sorted in the same place before being sent to their final destination. For steel-composite bridges, it is assumed that the steel structure is going to be reused. The remaining parts, which are generally concrete and bitumen materials, are cut down and transported to waste disposal areas. In this context, end-of-life costs should take into account the cost of bridge dismantlement (labor work, equipment, road warning signage), cost of transportation and cost for deposition of materials and/or revenue due to recycling of materials.
By considering all these costs in the decision process and ensuring performance constraints are satisfied, solutions that may be more expensive than others at the construction stage can finally be more attractive when considering the overall life service of the structure (Figure 13).

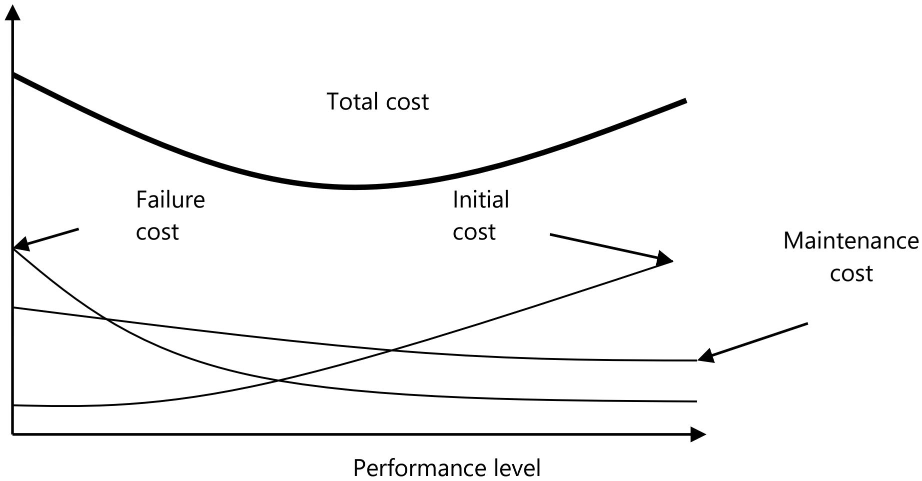


Figure 13: Schematic representation of lifecycle costs.

4.4.2. Economic Evaluation Method for LCC

Understanding the time value of money and the fact that the costs reflected in an LCC analysis are incurred at varying points in time, a need to convert all cost values into a value at a common point in time arises. Several methods exist to lead to LCC some of which are:

- the payback method, which determines the time required to return to the initial investment,
- the equivalent annual costs, which express the costs per year of owning and operating an asset over its entire lifespan,
- the internal rate of return, which is the discount rate at which the net present value of costs (negative cash flows) of the investment equals the net present value of the benefits (positive cash flows) of the investments,
- the net present value approach which directly applies discount factors to each year projected cash flow.

The net present value approach mentioned above is one of the most used methods to compare past and future cash flows with those of today. To make costs time-equivalent, the approach discounts them to a common point in time, the discount rate of money reflecting the investor's opportunity costs of money over time. The net present value can be calculated as follows:

$$NPV = \sum_{k=1}^{N} \frac{C_k}{(1+r)^k} \qquad (2)$$

NPV: lifecycle costs expressed as a present value,
K: year considered,
Ck: sum of all cash flows in year K,
r: discount rate,
N: number of actions to be considered during the service lifetime.

The yearly profile of one unit of money is shown for illustration in Figure 14. It is noted that a steep drop in the discounted costs is observed for high discount rate values. Also, it is shown that choosing r = 6 or 8% leads to a monetary value close to zero after sixty years.

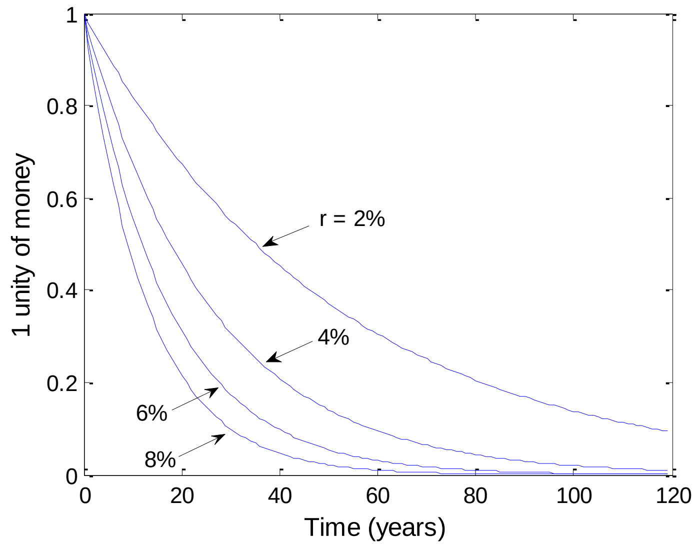


Figure 14: Profile of one unit of money for different values of r.

The value of the yearly discount rate used is crucial since the current worth of money (NPV) is highly sensitive to this parameter. Indeed, the higher the discount rate, the more importance is given to the near-present. Choosing a high discount rate may then promote management strategies with low initial costs and a costly end-of-life. Therefore, the choice of the discount rate is delicate and has to be in agreement with the time horizon. The discount rate is fixed at 2% in the LCCA performed in the SBRI-project for a 100-year service life.

4.5. LIFECYCLE SOCIAL ANALYSIS

The evaluation of the social criteria fully respects the boundary system of the integral analysis (see Figure 5). Social criteria enable us to quantify the impacts of the bridge on its direct users and surrounding population. Users of the bridge are all people traveling through the roads, beneath and above the bridge.

For the social Lifecycle analysis two types of indicators are considered: mandatory, those which are recommended to be always included in the Lifecycle analysis; and optional, those that can be included or not, depending on the aim of the analysis.

4.5.1. Mandatory indicators

Mandatory indicators aim to quantify the impacts due to any construction activity on the users of the bridge. In this case, three types of indicators are considered: driver's delay cost, vehicle operation cost, and road accident cost. Another impact could be included in this group, which is the impact on users due to detours. If for any specific reason, the traffic over and/or beneath the bridge has to be stopped for a certain period of time, then traffic needs to be diverted to an alternative road. In this case, the additional time spent by drivers and the additional length of road traveled can also be taken into consideration by the three indicators referred before. Thus in the LCS presented in this chapter, only the three basic indicators are considered.

4.5.2. Driver's delay cost

The cost of the time lost by a driver while traveling through a work zone is here denominated as Driver's Delay Cost (DDC). This cost is given by the difference between the cost of the time lost by a driver while traveling at normal speed and the time lost while traveling at a reduced speed due to construction works on the same length of the motorway.

4.5.2.1. Vehicle operation costs

A vehicle traveling through a work zone is subjected to delays. These construction-related delays result in additional costs for the owner of the vehicle. These additional costs are hereby denominated Vehicle Operating Costs (VOC). This cost is given by the difference between the cost of the operation of the vehicle while traveling at normal speed and the operation of the vehicle while traveling at a reduced speed due to construction works on the same length of the motorway.

4.5.2.2. Accident costs

Accident costs (AC) represent the additional costs due to a work zone in a road or motorway; thus, they are calculated by the difference between the cost of accidents in a length of motorway with no work activity and the cost of accidents in the same length when there is work activity.

4.5.2.3. Optional Indicators

Two indicators are here introduced as optional because its importance depends on the analyzed situation. These two indicators are hereby considered as optional as they differ from the other indicators. The first difference between these two impacts and the remaining is that, although they can be quantified over the Lifecycle of the bridge, there is no sense of adding their effects over that period of time. The other difference is that the two optional indicators have a strong subjective nature and this should be taken into account in its quantification.

The first indicator is noise, which may become important if the working place is located near a sensitive area and if the work is estimated to take place during the night. The other indicator is aesthetics. This indicator may be important if the bridge is intended to have an aesthetic function besides its normal function. Although, the aesthetics of a bridge should also be considered part of its conceptual design problem. However, in particular cases such as special types of bridges, bridges built in urban environments, etc., then the aesthetic value of the bridge may become an important criterion. These two indicators have some characteristics in common. They are not usually assessed based on a Lifecycle approach and they are both subjective, which implies another approach for their quantification and interpretation.

Noise

Noise can be defined as an undesirable sound thus implying that it has an adverse effect on human beings and their environment. Noise affects a large number of people and it is usually perceived as one of the major environmental problems. It can affect people in both physiological and psychological ways, interfering with basic activities such as sleep, rest, study and communication. Noise is associated with many human activities, but it is road, rail and air traffic noise that has the highest impact.

Aesthetics

The evaluation of aesthetics is commonly understood as a highly subjected issue. Aesthetics can be defined as (i) a set of principles concerned with the nature of beauty (especially in art), and (ii) the branch of philosophy which deals with questions of beauty and artistic taste. Different persons have different perceptions of beauty, and what is pleasant and acceptable to one might be offensive and unacceptable to others. Naturally, this makes the evaluation of aesthetics a highly subjective and often controversial issue.

4.5.3. User Costs

Contrary to the owner costs that are directly measurable costs, the user costs are indirect and hardly measurable. In the case of highway bridges, these costs are those incurred by the users due to maintenance operations of highway structure causing congestion or disruption of the normal traffic flow. These costs are not directly measurable but the traffic delays that lead to them can be measured. Traffic delay costs have, consequently, to be predicted on the basis of estimated delay and vehicle operation costs which include additional costs of fuel plus additional costs of vehicle maintenance. More details on the definitions of the user costs can be founded at [1]. These costs are briefly described below:

- Traffic delay costs resulting 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. These costs are influenced by many factors such as current and future traffic, bridge capacity, the timing, duration, and frequency of work-zone-induced capacity restrictions, and the unit costs for the delay.

- Vehicle operating costs due to the level of service loss caused by the maintenance operations on highway structures. The disruption of normal traffic causes speed reductions, an increase in fuel and oil consumptions, tire wear and vehicle maintenance. In particular, additional costs of fuel are due to the fact that its consumption is significantly higher in congested conditions. Besides, vehicle maintenance costs increase since these items need a faster replacement for vehicles traveling in congested conditions. Finally, the traffic disruption induced by maintenance works has a negative impact on road safety and consequently increases the accident rate on the road part affected by the works.

The current or future average daily traffic (ADT expressed in vehicles/day), based on the desired construction year, should be obtained from the traffic monitoring section. Due to factors such as population growth and economic prosperity, the volume of traffic on the bridge may increase each year and can be estimated:

$$ADT_t = ADT \times \left(1 + r_{tg}\right)^{year_t - year_0} \qquad (3)$$

ADTt is the average daily traffic to be used in the analysis at year t (vehicles/day),
rtg is the expected traffic growth rate,
yeart is the year in which the ADT is to be calculated,
year0 is the year in which the ADT is measured.

4.6. MULTICRITERIA ANALYSIS

Once different solutions are defined for the bridge, the final step of the approach is the comparison between different solutions. The lifecycle approach proposed in the scope of this project aimed at the integration of different criteria in the context of sustainability. To fulfill the aim of the proposed approach, outranking based methods are preferred to aggregating methods (or single criterion methods) because they involve weaker trade-offs, [14].

The method adopted in this research project is the Preference Ranking Organization Methodology of Enrichment Evaluation (PROMETHEE) developed by Brans [15] and further extended by Vincke and Brans [16]. PROMETHEE belongs to the family of outranking methods and although not being the most non-compensatory approach. PROMETHEE is a quite simple ranking method in conception and application compared with the other methods for multi-criteria analysis [17], [18]. One of the extensions of PROMETHEE (PROMETHEE II) enables a complete ranking of alternatives, while other approaches provide partial rankings including possible incomparability. PROMETHEE has a widespread use in decision-making situations varying from environmental management to business and financial management, medical applications, etc. A comprehensive review of PROMETHEE methodologies and applications is provided in [19].

4.6.1. PROMETHEE

In order to use PROMETHEE, it is necessary to provide additional information between the criteria and within each criterion, as described in the following paragraphs. Three main criteria were considered: environmental, economic and user costs. The environmental criteria considered in the analysis included abiotic depletion, acidification, eutrophication, global warming, ozone depletion, human toxicity, ecotoxicity and photo-oxidant formation. The economic criteria included construction cost, management costs, and end-of-life costs. For user costs, a single criterion was considered representing traffic delay costs, vehicle operation costs, and accident costs. Information between criteria is given by a set of weights (w_j = 1, 2,..., k) representing the relative importance of the different criteria. The higher the weighting factor the more important the criterion. It is up to the user to define the set of weighting factors to be assigned to each criterion. The information within each criterion, the preference structure, is based on pairwise comparisons. The deviation between the evaluations of two alternatives on a particular criterion is considered. For small deviations, the decision-maker allocates a small preference to the best alternative or possibly no preference if the deviation is negligible. The larger the deviation, the larger the preference.

For analysis, different scenarios are considered for the weighting of different criteria:

- Scenario 1 considered equal importance for the three main criteria: environmental, economic and user costs (1/1/1);
- Scenario 2 considered a higher importance to the environmental criterion in relation to economic and user costs (2/1/1);
- Scenario 3 considered a higher importance to the economic criterion in relation to environmental and user costs (1/2/1);
- Scenario 4 considered a higher importance to the user costs in relation to environmental and economic criteria (1/1/2).

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