Guidelines to perform Life Cycle Analysis of bridges

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1 INTRODUCTION

The main purpose of these guidelines is to provide a general framework to conduct an integral Life Cycle Analysis (LCA) of bridges. These general guidelines will be used to perform the LCA of the case studies regarding bridges, within the scope of the COST Action C25 – Integrated approach to lifetime structural engineering.

Life cycle analysis of bridges comprehends the consideration of all stages over the life cycle of the bridge, from material production to demolition, through construction and use stages. In LCA several criteria can be evaluated. If environmental aspects are the major concern, then a life cycle environmental analysis can be performed. If the total cost of a bridge is the aim of the analysis, then a life cycle cost analysis fulfils that purpose. Each of these life cycle analysis has its own methodology, but many aspects are common to both analysis.

Nevertheless, if a sustainable assessment is the aim the analysis than the integration of several criteria into the same analysis is mandatory. Sustainability is a holistic concept with a multidimensional scope, aiming at integrating environmental, social and economic criteria (the triple bottom line) into the analysis.

Each stage, over the life cycle of the bridge, has its own characteristics and therefore generates different impacts. Bridges are often massive structures, using large quantities of materials. The production of materials and the construction stages of a bridge therefore contribute to a large share of environmental impacts and costs. However, other important impacts and costs are derived from the subsequent stages. During the operation stage, each time a maintenance or replacement operation is needed, besides the direct costs inherent to the maintenance of the bridge, the traffic over the bridge has to be conditioned and eventually one or more lanes are temporarily closed. This traffic interruption often provokes traffic congestion over and or under the bridge. The traffic congestion, apart from the increased risk of accidents, is responsible for an increase of emissions to air from fuel combustion. In the end-of-life of the structure, the demolition of the structure and the management of waste add another major share in terms of costs and environmental impacts.

In a life cycle analysis, the structural behaviour of the bridge over time is of major importance. The estimation of the service life of a bridge and the analysis of its global deterioration or the deterioration of its individual components is fundamental in order to predict the activities needed to maintain the bridge in its required condition over its service life and thus to quantify all the subsequent impacts and costs.

This report describes the general guidelines to perform a life cycle analysis of a bridge, aiming at the integration of the lifetime structural behaviour of the bridge with environmental, economic and social criteria. There is not a standard framework to conduct such an integral analysis, although there are methodologies for the assessment of the individual criteria. For instance, the framework to conduct a life cycle environmental analysis is specified in the ISO standards [1,2]. Life cycle cost analysis is a common procedure and standards [3] and manuals are available in the literature giving guidance to perform such analyses. The assessment of life cycle social impacts is probably the less developed methodology, and for which little guidance can be found in the literature. This is mainly due to the difficulty in defining the indicators to characterise social impacts. Nevertheless, the life cycle assessment of all these criteria share a basic framework. In these guidelines the basic framework to conduct the integral assessment is the methodology defined in ISO standards for life cycle environmental analysis. According to the methodological framework established by ISO, a life cycle environmental analysis is performed in four steps:

1st step: Goal and scope definition;
2nd step: Inventory analysis;
3rd step: Impact assessment; and
4th step: Interpretation.

Each of these steps will be adapted in these guidelines in order to include the other criteria in the life cycle analysis. The methodology defined in the ISO standards is not a pure sequential procedure, in fact, it is a highly iterative framework and the need to revise and reiterate previous steps may arise at any stage.

Taking into consideration the above framework, the main steps to conduct an integral life cycle analysis are represented in Figure 1. Each step will be detailed, separately, over this report. At this stage, the interpretation step, as well as all the subsequent steps, are not included.

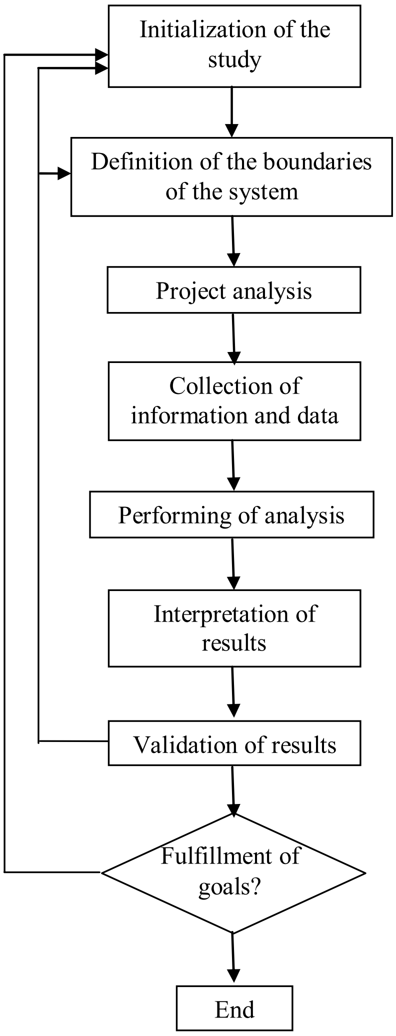

Figure 1. *General approach for life cycle analysis*

The first step of the analysis entails the definition of the goal(s) and scope of the integral analysis. In this step, definitions are made and assumptions are taken regarding the analysis of all the criteria involved. The second step comprehends the collection of all the data needed in order to conduct the analysis in relation to the scope of the analysis defined in the previous step. The analyses are performed in the 3rd step. Several types of analysis may be performed depending of the chosen criteria and the goal of the study. Care must be taken in order to avoid double counting of indicators. Finally, the combination of the results is made on the last step of the analysis, the interpretation step, where several criteria may be weighted and aggregated in order to provide a single result.

As already referred this procedure is highly iterative and, at any stage, it may be necessary to go back and redefine a previous step in order to have a consistent analysis.

The report is divided into 5 parts. Part A entails the definition of parameters and the description of global assumptions, which are needed for the remaining parts. Part B focuses on the lifetime structural behaviour of a bridge. In this part general methods for the assessment of the service life and of the condition of the bridge are introduced, followed by a description of some degradation models for different types of bridges. The environmental assessment of the bridge over its life cycle is described in Part C. In this section a list of the main indicators for the environmental assessment of bridges is introduced followed by a description of the general framework for the life cycle environmental analysis. Part D regards life cycle economic analysis. Life cycle costs are divided into agency costs and users' costs. While the former addresses the costs by the owner or operator of the bridge, the latter relates to direct costs of the users of the bridge. Finally, in Part E a short description of the case studies is provided. These case studies will be analysed following the guidance in these guidelines. However, each case study will have to make the necessary adaptation of this general framework in order fulfil the aims and goals of each case.

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Part A – Definition of global parameters

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1 INTRODUCTION

The object of these guidelines is a bridge. However, in a life cycle analysis, not only the object is assessed but also the way it is produced, constructed, maintained and decommissioned. Hereafter, the term bridge will be replaced by “bridge system” or simply “system”, taking into account that the definition of a “bridge system” comprises the bridge (object), the bridge site, the bridge production and construction, the bridge use and maintenance, and the bridge demolition.

The 1st step in a life cycle analysis, according to ISO framework [1], entails the following definitions:

- definition of the goal and scope of the analysis;
- definition of the functional unit;
- definition of the system’s boundaries.

This set of definitions is needed in order to enable a clear structure of the analysis and to allow a good understanding of its results.

The goal of the study should clearly specify what is to be done, what are the reasons to conduct it and what is the intended use of the results.

The definition of the scope of the analysis establishes the main characteristics of the LCA study, and addresses issues such as criteria, temporal, geographical and technology average in relation to the goal of the study.

The aims and scope of the analysis may vary from case to case. In general terms the analysis may have a comparative purpose or a descriptive purpose. In a comparative analysis, two or more types of bridges may be compared in terms of materials, structural systems, construction processes, maintenance strategies, etc. In a descriptive case, a bridge life cycle can be analysed in order to evaluate which stages are more critical in terms of cost and/or environmental burdens.

A life cycle analysis relates the impacts to a specific system function. A system can only be compared on the basis of a similar function. Based on the system function it is possible to define the functional unit. The functional unit is a key element of LCA which has to be clearly defined. The functional unit is a measure of the function or functions of the studied system and it provides a reference to which the inputs and outputs can be related. Also, the durability or the duration of the function provided by the system should be taken into account. This enables comparison of two essential different systems. For example, 1 kg of steel is not comparable to 1m^3 of concrete. However, if the functional unit is a steel column, made of 200 kg of steel, designed to support a load of 10 kN for a period of 10 years, than a comparison to a similar column made of concrete and fulfilling the same function is therefore possible.

A system may provide one specific function or fulfil more than one function. If a system fulfils just one function the selection of the function step is fairly straightforward. A bridge is a system which fulfils mainly one specific function [2]: “bridges provide a passage over a gap without closing the way beneath”. However, a bridge can also fulfil other functions, e.g. aesthetics. In this case, the system may be defined by its primary function and all the other functions taken as facultative [3].

An example of a functional unit of a bridge system may be “a bridge designed for a service life of 100 years, for a maximum hourly traffic of 1000 vehicles”.

Once the functional unit is defined, the next step will be to define the boundaries of the system. According to the aim of the study, boundaries should be established in order to identify the extent to which unit processes are included or excluded in the LCA study.

Considering a life cycle of a bridge the main unit processes are illustrated in Figure 1.

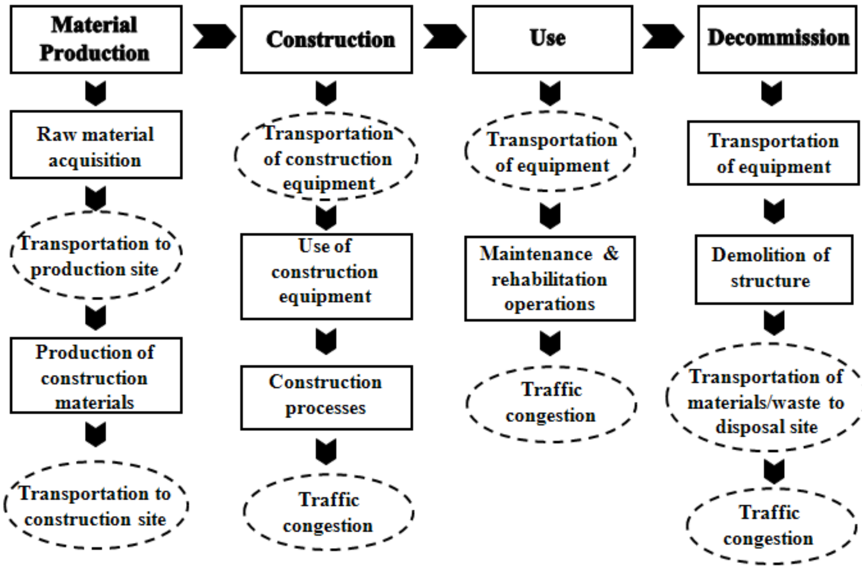

Figure 1. *Boundaries of the life cycle analysis*

The scheme represented in Figure 1 is only an example, some unit processes may be excluded and others included, depending of the aim and scope of the analysis.

There are no general rules to be used in the definition of the system boundaries, although some rules of thumb are used to assist in boundary setting [4]:

- some sources can be excluded simply because the associated flows are negligible to the final results,
- some desirable aspects of assessment may not actually be feasible, which is why some sources are excluded,
- non-negligible flows associated with some sources are sometimes poorly known (lack of reliable models, or uncontrolled variables such as the transport mode of occupants) and thus tool developers prefer to exclude the flows so that the more controlled environmental effects of the variants studied can be more favourably revealed,
- when decision-makers dealing with a building are unable to modify some causes of impact, these are often excluded from the assessment,
- some processes can be considered as being external to the life cycle of the building as they belong to other systems (e.g.: the final disposal of some wastes),
- the cost of the assessment should also be taken into account, as it increases in proportion to the exhaustiveness of sources; in some applications, a limit to the cost of the assessment is a criterion which can cause the limits of the system to be restricted.

2 COLLECTION OF GENERAL DATA

Once the boundaries of the system are defined, the inventory step takes place. In this step, data is collected in order to allow the quantification of the impacts in the following stage of the analysis. Data is collected in regard of the unit processes included in the system boundary (see Figure 1) and in regard of the scope of the analysis. That is, if environmental and economic criteria are included in the scope of the analysis, then data should be collected in order to allow the quantification of both criteria, in each unit process over the life cycle.

Two main sources of data are usually available: data collected from the project and data obtained from specific databases.

The project usually provides useful data in regard of several criteria, namely:

i) the bill of materials, which allows to quantity the mass of each material;
ii) the costs of the materials;
iii) construction information, including the process itself of construction, time needed for the construction, associated costs, etc;
iv) traffic information and forecasts;
v) in case an Environmental Impact Assessment study was carried out, it provides very important data in regard of environmental, cost and also social criteria.

Data can also be obtained from databases:

i) for the environmental analysis, the environmental profiles of materials and assemblies can be obtained from specific databases (e.g. Ecoinvent [5])
ii) for the economic analysis, unit prices for materials and processes can be obtained from cost databases; etc.

Other sources of information include Environmental Product Declarations (EPDs), Eco-labels, and general literature.

The data required for a life cycle analysis of a bridge is summarized in Table 1.

Table 1. Collection of data

General data	Bill of materials Description of construction processes Service life of the structure Maintenance plan End-of-life plan Traffic data
Environmental data	Inputs for each unit process: - Energy - Materials - Water Outputs for each unit process: - Emissions to air, water, soil - Waste
Economic data	Costs of materials Costs of construction processes (equipment, man-power, etc) Cost of maintenance Cost of demolition

The quality of the data collected has a major influence on the outcome of the analysis. A life cycle analysis based on data with poor quality cannot provide results of better quality. A proper evaluation of data quality is thus very important in a life cycle study. Some rules to check data quality are [6]:

i) collection of data from specific sites versus general data;
ii) being measured, calculated or estimated;
iii) measure the variability of data values;
iv) check the completeness of data;
v) check the representativeness of data;
vi) check the consistency of data, etc.

In the step of data collection, there are two major problems to deal with. One problem regards the fact that in a life cycle analysis it is practically impossible to include all the unit processes and related data over a system's life. Thus, clear rules must be taken in order to exclude some unit processes. The other problem refers to the allocation.

The main reason for the cut-off problem arises from the lack of data, in combination of lack of time and money, for a particular unit process. Cutting off processes can influence the analysis and therefore it should be avoided as much as possible. When this is not possible, estimations can be made either by the consideration of a similar process or by comparing a process for which data is lacking with a similar process for which data is available and justify whether cutting off is or is not reasonable. If, however, estimations are not possible, the processes for which data are lacking should be considered with a zero value, and a justification of it should be made.

The allocation problem may arise from two different situations [7]:

i) the process in question delivers more than one useful product, and thus allocation procedures are required to determine which inputs and outputs are attributable to the system under assessment;

ii) the process or product in question is part of recycling loop, and thus an allocation procedure is needed in order to allocate the burdens of the initial production on the successive products or processes.

Allocation procedures can be based on (i) technical/natural causality; (ii) physical quantities; (iii) economic value; (iv) social causality; and (v) arbitrary numbers. The choice of the allocation procedure should be careful and transparent, as the results of the analysis can be significantly influenced by the choice of method.

3 DEFINITION OF LIFE CYCLE SCENARIOS

Due to the long time span of bridges, the assessment of some stages over the bridge's life is based on scenarios. That is often the case for the use and demolition stages, where scenarios are defined either for the maintenance of the bridge and for the deconstruction of the bridge.

Regarding the maintenance of the structure scenarios are needed to indicate the long term behaviour of the bridge. These scenarios should indicate the maintenance cycles (frequency and duration), repair and replacement schedules. A short example of a maintenance plan, for a bridge with a service life of 100 years, is illustrated in Table 2.

Table 2. Maintenance plan of a bridge

Maintenance activity	*Unit Cost*	*Start year*	*End year*	*Frequency*
Inspection of the bridge	10 €/m	6	96	6
Painting of the steel structure	150 €/m^2	30	90	30
Cleaning of expansion joints	10 €/m	1	99	1
New top layer of asphalt	35 €/m^2	5	95	5
(...)				

Also the duration of the maintenance activities is necessary to be estimated in order to assess the impacts due to the traffic congestion on users of the bridge and on the environment.

The maintenance plans are defined based on the engineering experience or on historical data of similar bridges. Although, considering an integrated approach, the maintenance strategy can be based on the input from degradation models.

In what concerns the end-of-life of the structure, again scenarios are needed to indicate how the structure will be demolished and what will be the final destination of the related construction waste, either sending them to recycling, to landfill, etc. In Table 3, a short example of a demolition plan of a bridge is illustrated.

Table 3. Demolition of the bridge

Structural component	*End-of-life scenario*
Steel beams	To be recycled in a recycling plant situated 100 km from the site of demolition (road transportation)
Concrete slab of the deck	To be sent to landfill situated 50 km from the site of demolition (road transportation)
Concrete from the abutments	To be sent to a sorting plant for disassembly, situated 10 km from the site of demolition. The reinforcement steel is to be sent for recycling (100 km by road transportation) and concrete waste sent to

	landfill (50 km by road transportation)
(...)	

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Part B – Life cycle performance analysis

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1 LCA OF MAINTENANCE AND REPAIR

Description of a method to be used in case studies of bridges.The calculations are carried out by an Excel worksheet. Three tables are worked out:

1) Analysis Table
2) Data table of maintenance systems
3) Data table of repair systems

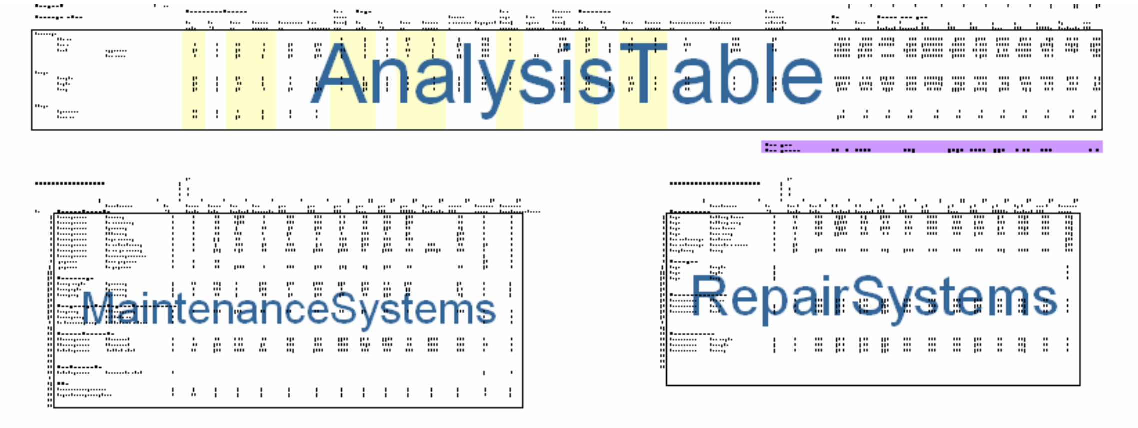

Figure 1. *Layout of the LCA analysis*

The table of maintenance systems contains data of all optional maintenance and protection methods, such as coatings, water proofing of deck and other maintenance and protection methods. The table contains the data of costs and environmental loadings of maintenance systems in given units. Also the reference service lives and the relative rate of degradation of substructure (as a result of protection) are given in the table.

The table of repair systems contains all the optional repair and renovation systems of concrete and steel structures. The data on costs, environmental loadings and service lives of repair and renovation systems are given. The service lives are determined based on degradation models.

The analysis table contains data on the environmental loadings of parts of the bridge through the analysis period. Only the main parts of the bridge are considered. As an example the following break-down could be used: (1) abutments, (2) columns, (3) deck, upper surface, (4) deck, bottom surface, (5) main girders, (6) tie girders, (7) pavement, (8) expansion joint devices etc. The table contains necessary data for calculating the environmental loadings from maintenance, repair and renovation actions. To be able to calculate the environmental loadings of actions the following data is necessary: (1) system code (referring to the data table of maintenance systems and data table of repair and renovation systems). (2) quantity of action in given unit, (3) coefficient of exposure (referring to the reference service life in the data tables of systems), (4) coefficient of maintenance system for determination of service life (for repair and renovation systems only), (5) service life of the system, (6) times of sequential application of the system, etc. The service life of the original structure before any repairs or renovations is also determined using degradation models. Some of these data is input manually, some is obtained from the data tables of systems. When all the necessary data is gathered the environmental loadings are determined by the analysis table. The total loadings are determined by summing up the total loadings of each part of the bridge. The annual loadings are determined by dividing the total loadings by the analysis period.

The analysis period should be selected so that it is longer than the lifetime of bridge before the first renovation. When doing so the annual environmental loadings depend only little on the analysis period and they approach to constant values when lengthening the analysis period.

2 SERVICE LIFE PREDICTION

Service life of structures is the period for which the structures are to be used for its intended purpose. It is related to the structural performance. Figure 2 shows schematically the evolution of the structural performance along the service life comparing the available performance of the structure (structural health) and the required performance criteria (performance levels).

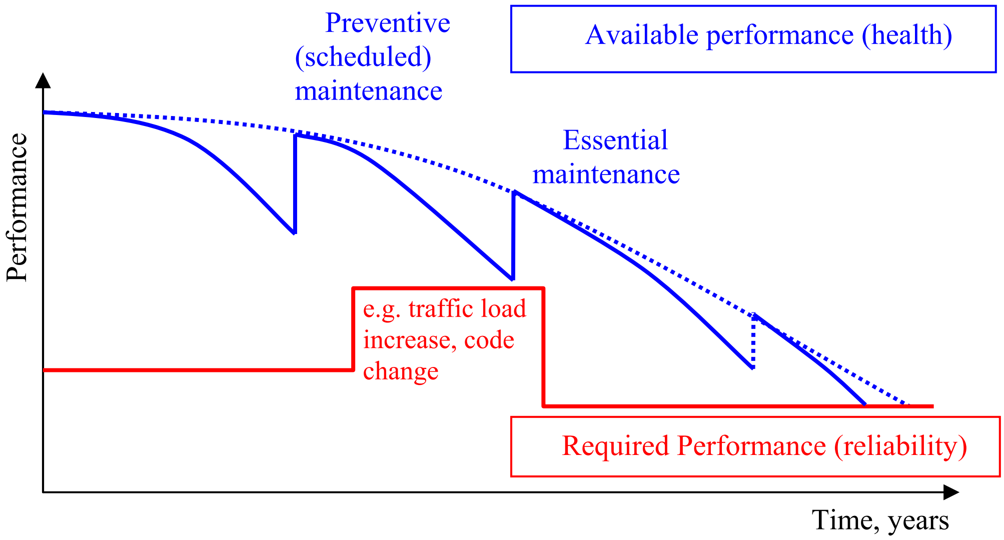

Figure 2. *Time dependent performance of structures*

Available performance is mainly influenced by load-dependent degradation processes like fatigue, by material specific degradation processes like corrosion or carbonation and by material and structural components ageing. Available performance can be estimated during design and construction if the basic requirements concerning resistance, serviceability, durability and execution given in the structural design codes are met. Furthermore, it can be controlled during the service life adopting adequate management of inspection and maintenance plans.

Required performance of the structure can be established in three levels (ISO 13822, 2001 in FiB, 2002): the safety performance level, which provides appropriate safety for the users in normal conditions, the continued performance level, which provides continued function for special structures like key bridges, hospitals or communication buildings under exceptional events like natural catastrophes or terrorist attack, and the level of special performance requirements imposed by the owner and related to property protection, economical loss or serviceability.

Actions on structures that do not depend on human decisions – such as service loads, wind, snow and earthquakes - have intensities that vary with time. Increasing the lifetime of a structure therefore increases the probability that, in a given time frame, the intensity of one of these actions will exceed the value assumed in the design. In order to work on a rational base, a conventional "design working life" for different types of structures must therefore be defined.

Design working life of structures is the period for which the structures are to be used for its intended purpose with anticipated maintenance but without major repair (Gulvanessian, 2001). Therefore, service life can be normally confounded with design working life, becoming a matter of convention. If no other requirement exists, it is assumed that he design working life of civil structures, including bridges is given by the EN1990 (CEN, 2001). This eurocode stipulates that the structure shall be designed for the indicative design working life given in Table 1. This specified working life is obviously independent of the type of material used in construction and actually increases with the importance of the structure. Nevertheless those values, being indicative, may be modified by the National Annexes of the EN1990.

Table 1. Indicative design working life *T*d (CEN, 2001)

Design working life category	Design working life *T*d (years)	Examples
1	10	Temporary structures
2	10 to 25	Replaceable structural parts
3	15 to 30	Agricultural and similar structures
4	50	Building structures and common structures
5	100	Monumental building structures, bridges and other civil engineering structures

If structures undergo regular maintenance they generally have longer lives than those in the table, which are to be intended only as a reference for the time dependent safety evaluations. According to EN1990 (CEN, 2001) structures shall be designed such that deterioration over its design working life does not impair the performance of the structure below that intended (see Fig. 1), having due regard to its environment and the anticipated level of maintenance. In order to achieve such durable structures following should be taken into account (CEN, 2001):

- intended and future use of the structure
- required performance criteria
- expected environmental influences
- composition, properties and performance of materials and components
- choice of a structural system
- shape of members and structural detailing, and buildability
- quality of workmanship and level of control
- particular protective measures
- maintenance during the intended life

3 DEGRADATION MODELS FOR CONCRETE

The most frequent types of degradation for concrete bridge structures are the following:

- carbonation and corrosion of reinforcement on concrete surfaces
- chloride penetration and corrosion of reinforcement on concrete surfaces
- carbonation and corrosion of reinforcement at cracks
- chloride penetration and corrosion of reinforcement at cracks
- frost attack on concrete

Two sets of degradation models for concrete structures are recommended:

1. "Proposed European models". In: Lay, S. & Schiessl, P. 2003. Service life models. Instructions on methodology and application of models for prediction of residual service life for classified environmental loads and types of structures in Europe. EC, FP5: Growth. RDT Project: Life cycle management of concrete infrastructures for improved sustainability: LIFECON Deliverable D3.2. 169 p. http://lifecon.vtt.fi/

2. “Finnish bridge models”. In: Vesikari, E. 2003. Statistical condition management and financial optimisation in lifetime management of structures. Part 1: Markov Chain based LCC Analysis. Part 2: Reference structure models for prediction of degradation. EC, FP5: Growth. RDT Project: Life cycle management of concrete infrastructures for improved sustainability: LIFECON Deliverable D2.2. 115 p http://lifecon.vtt.fi/

The “proposed European models” were developed during European Community projects “Duracrete”, “Lifecon” etc. The advantage of these models is the large agreement and acceptance of these models. Also the following instructions are based on these models:

- Model Code for Service Life Design. 2006. fib Bulletin 34.110 p.
- Vägledning för livslängdsdimensionering av betongkonstruktioner (Instructions for service life dimensioning of concrete structures). 2006. Swedish Concrete Society. Report 12.

The drawback of these models is that they do not include models for corrosion at cracks. Also the model for frost attack is hardly usable. So also the interaction between frost attack and corrosion processes (including carbonation and chloride penetration) is not considered in these models.

Another drawback in these models is that the use of them calls for testing of concrete. For example the model of carbonation requires testing of the carbonation resistance and the model of chloride penetration calls for testing the chloride migration coefficient. However, there are available test data that can be used for rough evaluation of these parameters based on standard concrete parameters, such as the w/c ratio and the cement type.

The Finnish bridge models were developed based on laboratory tests, field tests and computer simulation. They include models for all degradation types mentioned above. They consider also the interaction between frost attack and corrosion (including carbonation and chloride penetration). The models were used in the project level life cycle management system for bridges in Finland. The drawback of these models is that they were developed on national bases and, so, are not widely used in other countries.

In the Finnish bridge models reference degradation rates are determined at four reference environmental conditions:

- moisture burden 0 and chloride burden 0,
- moisture burden 0 and chloride burden 1,
- moisture burden 1 and chloride burden 0, and
- moisture burden 1 and chloride burden 1.

The final degradation rate is interpolated between the reference rates by knowing the real moisture burden and the real chloride burden.

Which ever degradation models are used the calculations become rather complicated. That is why it is proposed that the models are programmed on a worksheet in an easily adaptable form by an expert. So, not everybody has to be well-versed with the models. The result service life can be obtained simply by inserting key parameters of concrete, structure and the environmental burden. The key parameters of concrete and the structure would be:

- Concrete w/c
- Concrete nominal strength
- Cement type
- Concrete air content
- Concrete cover
- Diameter of reinforcement
- Crack width

The classification of the environmental burden relating to moisture and chlorides depends on the selected set of models.

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Part C – Life cycle environmental analysis

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1 LIFE CYCLE IMPACT ASSESSMENT METHODOLOGY

The life cycle impact assessment methodology proposed for the analysis of the case studies is the CML methodology [1]. There are several reasons for this choice:

- It is a well documented approach and with scientific recognition;
- It is based on state-of-art developments;
- It is an European methodology;
- It is a problem oriented approach, that is, indicators are defined at “mid-point level”.

Apart from these reasons, another particularity of this methodology is that it provides a list of impact assessment categories grouped into:

- Obligatory impact categories (Category indicators used in most LCAs)
- Additional impact categories (operational indicators exist, but are not often included in LCA studies)
- Other impact categories (no operational indicators available, therefore impossible to include quantitatively in LCA)

In case several methods are available for compulsory impact categories, a baseline indicator is selected, based on the principle of the best available practice. Baseline indicators are recommended for simplified studies. However, guidelines for inclusion of other methods and impact category indicators, in case of detailed studies and extended studies, are provided. For each baseline indicator, normalisation scores are calculated for the reference situations: the world in 1990, Europe in 1995 and the Netherlands in 1997.

2 SELECTION OF INDICATORS

The selection of indicators for the environmental impact categories should take into account the need to fully characterize the environmental burdens due to the system (in this case a bridge). For bridges, as well as for other construction related systems, many of the impacts are location specific. Traditional LCA does not address local impacts. In fact, all the loadings are aggregated, and thus impacts can only be calculated at a regional or global scale. Therefore, in order to adapt LCA to construction systems, the site-specific impacts must either be excluded from the system boundaries or separately inventoried and classified. In the case of ecologically sensitive area, the best alternative would be to combine LCA with another evaluation tool.

For the application in the case studies, a set of indicators for the impact categories were chosen, and are listed in the following paragraphs:

- *Depletion of abiotic resources*

This impact category is concerned with protection of human welfare, human health and ecosystem health. This impact category indicator is related to extraction of minerals and fossil fuels due to inputs in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation. The geographic scope of this indicator is at global scale.

- *Climate change*
  Climate change can result in adverse affects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air. The characterisation model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterisation factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission. The geographic scope of this indicator is at global scale.
- *Stratospheric Ozone depletion*
  Because of stratospheric ozone depletion, a larger fraction of UV-B radiation reaches the earth surface. This can have harmful effects upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. This category is output-related and at global scale. The characterisation model is developed by the World Meteorological Organisation (WMO) and defines ozone depletion potential of different gasses (kg CFC-11 equivalent/ kg emission). The geographic scope of this indicator is at global scale. The time span is infinity.
- *Human toxicity*
  This category concerns effects of toxic substances on the human environment. Health risks of exposure in the working environment are not included. Characterisation factors, Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance HTP's are expressed as 1,4-dichlorobenzene equivalents/ kg emission. The geographic scope of this indicator determines on the fate of a substance and can vary between local and global scale.
- *Terrestrial toxicity*
  This category indicator refers to impacts of toxic substances on terrestrial ecosystems, as a result of emissions of toxic substances to air, water and soil. Eco-toxicity Potential (FAETP) is calculated with USES-LCA, describing fate, exposure and effects of toxic substances. The time horizon is infinite Characterisation factors are expressed as 1,4-dichlorobenzene equivalents/kg emission. The indicator applies at global/continental/ regional and local scale.
- *Photo-oxidant formation*
  Photo-oxidant formation is the formation of reactive substances (mainly ozone) which are injurious to human health and ecosystems and which also may damage crops. This problem is also indicated as "summer smog". Winter smog is outside the scope of this category. Photochemical Ozone Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents/kg emission. The time span is 5 days and the geographical scale varies between local and continental scale.
- *Acidification*
  Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification Potentials (AP) for emissions to air are calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. AP is expressed as kg SO2 equivalents/ kg emission. The time span is eternity and the geographical scale varies between local scale and continental scale.
- *Eutrophication*
  Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water and soil. Nutrification potential (NP) is based on the stoichiometric procedure of Heijungs (1992), and expressed as kg PO4 equivalents/ kg emission. Fate and exposure is not in-

cluded, time span is eternity, and the geographical scale varies between local and continental scale.

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Part D – Life cycle cost analysis

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1 LIFE CYCLE IMPACT ASSESSMENT METHODOLOGY

In Sweden, the National Road Administration has developed a detailed program for the maintenance of bridges and tunnels, BaTMan (Bridge and Tunnel Management). This system includes about 27000 bridges and is not only used by the NRA, but also the Swedish National Railway Administration and a large number of cities and communities are using it. Within this system it is possible to search for maintenance operations, costs, pictures of damaged details etc, which gives the users an important and efficient tool in order to control and estimate the maintenance of their bridges.

However, the system has only been used since 2004, which gives us a great picture of the recent maintenance, but it is therefore difficult to get a total picture of the maintenance needed for a total life cycle analysis. Older inspections and maintenance operations are added to the system continuously, but it will of course take some time before that work is completed. Therefore, we are at this point relying on general information regarding the maintenance interval, received from a couple of bridge inspectors in the north of Sweden.

In the north of Sweden, the interval and costs in Table 1 can be used to describe the maintenance of a bridge, with a normal traffic intensity of approximately 25000 vehicles/day. The unit costs in table 1 are collected from one of the public documents at the BaTMan website (in Swedish) https://batman.vv.se [1].

Table 1. Some examples of maintenance activities of a Swedish bridge

Maintenance activity	*Unit Cost*	*Interval (years)*
Inspection of a concrete bridge	9 €/m	6
Inspection of a steel bridge	8 €/m	6
Inspection when diving needed	1600 €	6
Exchange of the edge beams	790 €/m	30
Exchange of the concrete deck	440 €/m^2	
Painting of bearings	670 €/un	30
Painting of the steel structure	150 €/m2	30
Cleaning of expansion joint	10 €/m	1
Exchange of rubber band	1500 €/m	10
Exchange of steel profile	24000 €/m	30

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Part E – Case studies

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1 INTEGRAL ABUTMENT BRIDGE

1.1 *Short description of the case study*

In this case study a comparative life cycle analysis between an integral composite bridge and a concrete bridge with expansion joints is proposed. The case study focuses on a composite bridge with two I-beam girders with a concrete deck and integral abutments [1], with a single span of 40 meters, see Figure 1. This bridge is compared with an alternative solution, consisted of a reinforced concrete bridge with two spans of 18 meters, a middle pier in the river and end screens at the end supports, see Figure 2.

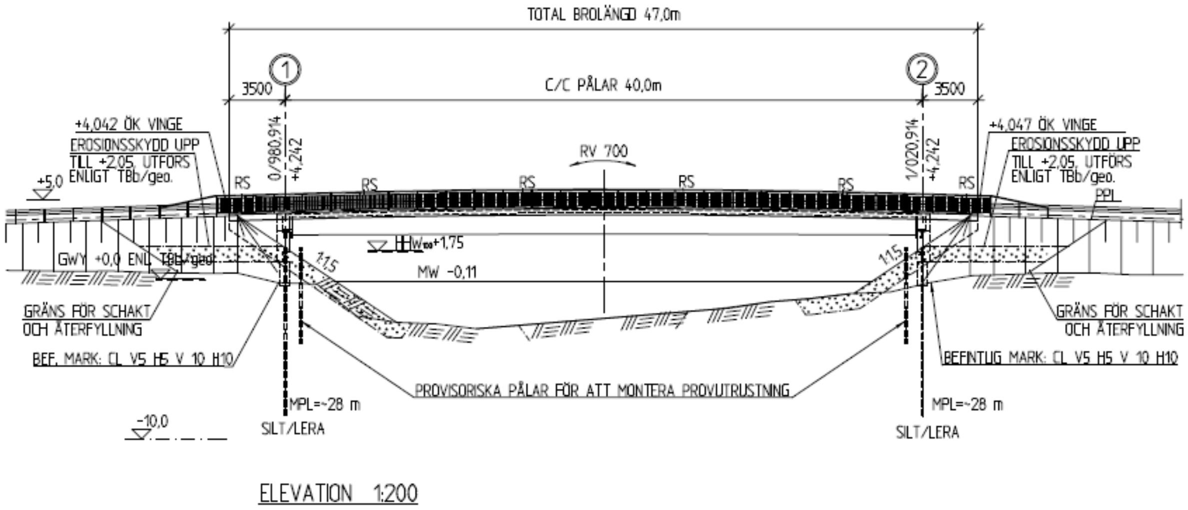

Figure 1. *Elevation plan of the integral abutment bridge*

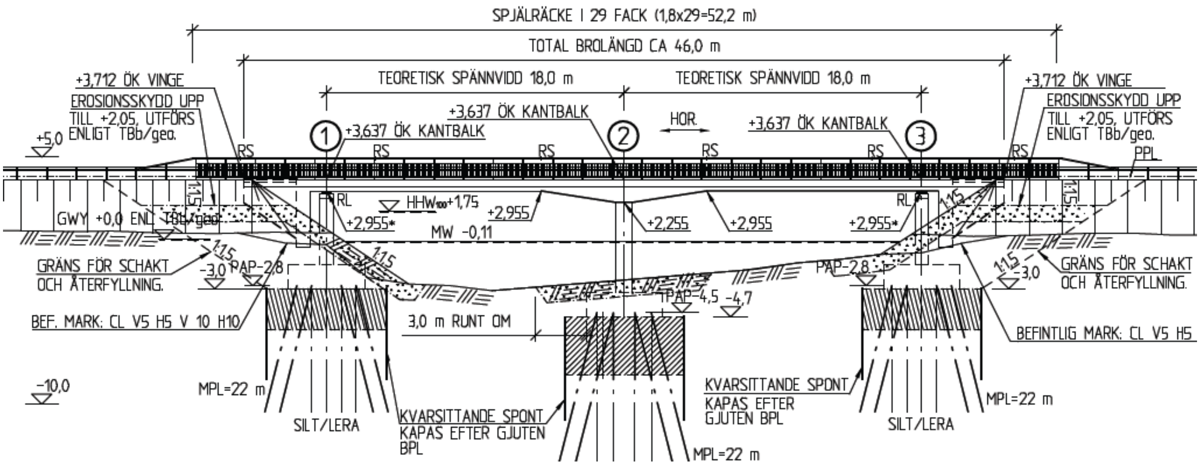

Figure 2. Elevation plan of the concrete bridge

Tables 1 and 2 shows the bills of materials used in each bridge.

Table 1. Bill of materials of the integral bridge

Material	*Quantity*	*Unit*
Concrete Grade C40/50	108.5	m^3
Reinforcement Grade B500	6.3	ton
Steel Grade S355 (web) & S460 (flanges)	41.4	ton
Steel piles (170x10) Grade S440	13.9	ton
Steel pipes (600x1.6) Grade S355	0.6	ton
Shear studs (22)	1000	un
Paint (Epoxy and Polyurethane)	300.0	m^2
Polystyrene	1.5	m^2

Table 2. Bill of materials of the reinforced concrete bridge

Material	*Quantity*	*Unit*
Concrete Structure, Grade C35/45	429	m^3
Concrete Piles ,Grade C50/60	103	m^3
Reinforcement, Grade B500 B	50	ton
Bearings:		
- TOBE FR-E 2000	2	un
- TOBE FR-A 2000	2	un
- TOBE FR-F 4000	2	un
Expansion joints (Maurer D90B)	5	m
Steel sheet piling	103	ton

During the operation stage of the bridge the maintenance plan, represented in Tables 3 and 4, was estimated according to current Swedish practice in the northern part of the country.

Table 3. Maintenance plan of the integral bridge

Maintenance activity	*Unit Cost*	*Start year*	*End year*	*Frequency*
Inspection of the bridge	320 €	6	96	6
Painting of the steel structure	37 800 €	30	90	30
Exchange of the edge beams	51 320 €	30	90	30

Table 4. Maintenance plan of the concrete bridge

Maintenance activity	*Unit Cost*	*Start year*	*End year*	*Frequency*
Inspection of the bridge	375 €	6	96	6
Exchange of the edge beams	60 710 €	30	90	30
Painting of bearings	1 260 €	30	90	30
Expansion joints:				
Cleaning of joint	100 €	1	99	1

Exchange of rubber band	2 625 €	10	90	10
Exchange of steel profile	11 025 €	20	80	20

1.2 *Life Cycle Analysis*

A life cycle analysis of a bridge encompasses all the stages from material production to end-of-life stage. In this cost analysis, however, due to lack of information, the costs related to the end-of-life stage, the disposal costs, are not considered. Thus, in Figure 3, the boundary of the system under analysis is indicated by the dashed line.

In this life cycle cost analysis two types of costs are going to be considered, the costs incurred by the owner/operator of the bridge over the study period (agency costs), and the costs incurred by direct users of the structure (user costs). The time period of the analysis is 120 years and the base year of the analysis is 2008.

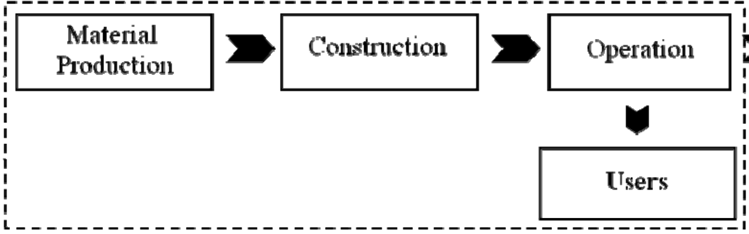

Figure 3. *System boundary of the life cycle cost analysis*

The environmental Life Cycle Analysis (LCA) in this paper follows the guidelines of ISO standards for LCA [4,5] and it is performed according to the Eco-indicator methodology [6] and the SimaPro software program [7]. The object of assessment, the functional unit, is a bridge designed for a service life of 120 years.

An environmental life cycle analysis entails the quantification of all environmental burdens from the production of the raw materials to the final destination of the products. For this case study, the processes included in the life cycle analysis of the composite bridge are represented in Figure 4.

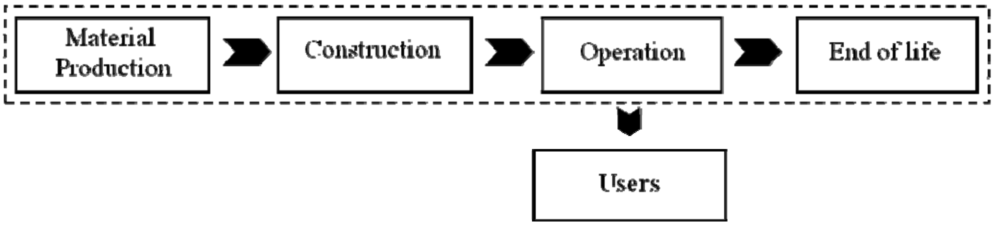

Figure 4. *System boundaries of the life cycle environmental analysis*

In Figure 5, the normalized results of the life cycle analysis are presented, according to the three damage categories and for each structural solution. In each column the results obtained for each life cycle stage are summed up. According to Figure 5, the composite bridge has a better environmental performance in every damage category.

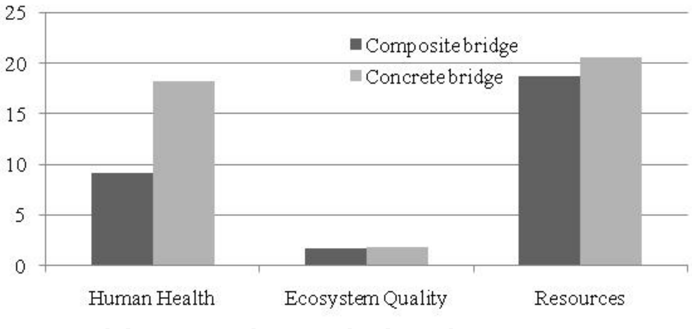

Figure 5. *Total damage analysis per bridge solution*

In Figure 6, the same results are represented but according to the respective life cycle stage and for each structural solution. In each column the normalized results obtained for each damage category are summed up.

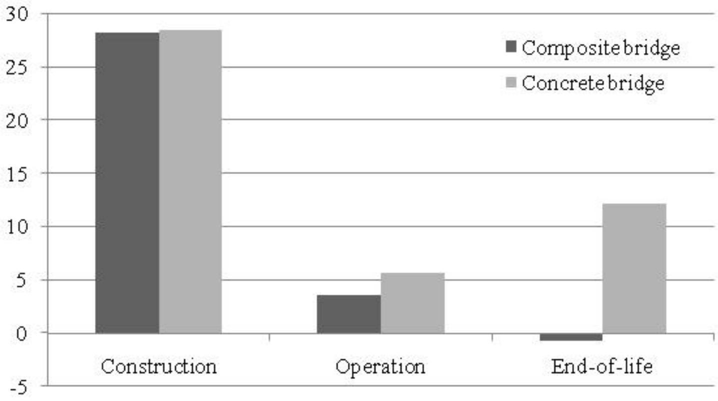

Figure 6. *Damage analysis per life cycle stage*

From Figure 6, it can be concluded that the construction stage has a major influence on the final result of the analysis. The end-of-life stage can also be important, particularly in the case of recyclable materials. In this case study the operation stage is not significant as many simplifications were assumed due to lack of data.

2 THREE-SPAN MOTORWAY VIADUCT

2.1 *Short description of the case study*

In this case study a life cycle analysis of a motorway bridge is proposed. The bridge, represented in the following picture, is a composite bridge with 3 spans: 19.15 m + 42.5 m + 19.15 m.

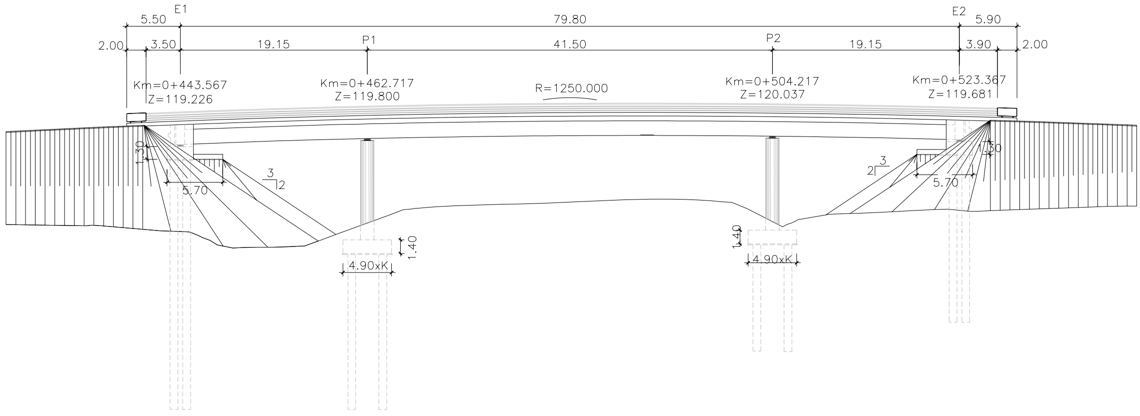

Figure 7. *Elevation view of bridge*

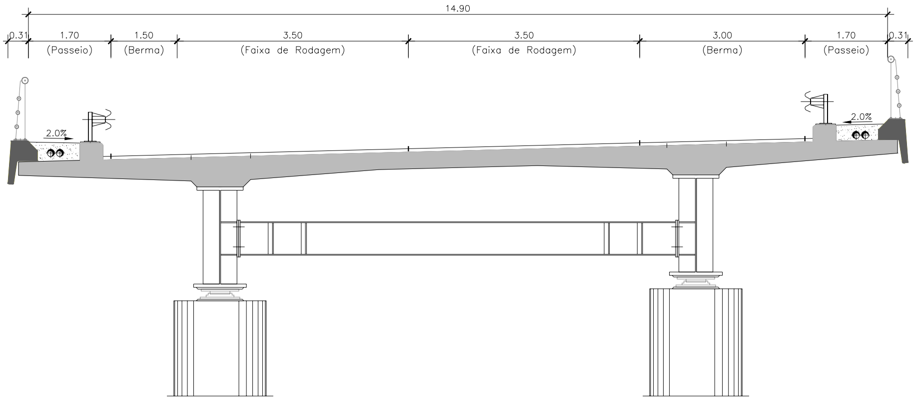

Figure 8. *Cross-section of the bridge (at the intermediate piers)*

The aims and goals of this study are:

- To estimate the structural performance of the bridge over the service life
- To assess the environmental performance of the structural system from the construction stage to demolition stage (including impacts on users)
- To assess the costs over the life cycle (including costs on users)
- To make sensitivity studies regarding different parameters
- Define strategies to combine different criteria in life cycle analysis
- To establish guidelines for the optimization of bridge design over its life cycle

Functional unit:

A composite motorway bridge, designed for a service life of 100 years, according to structural eurocodes.

Boundaries of the system:

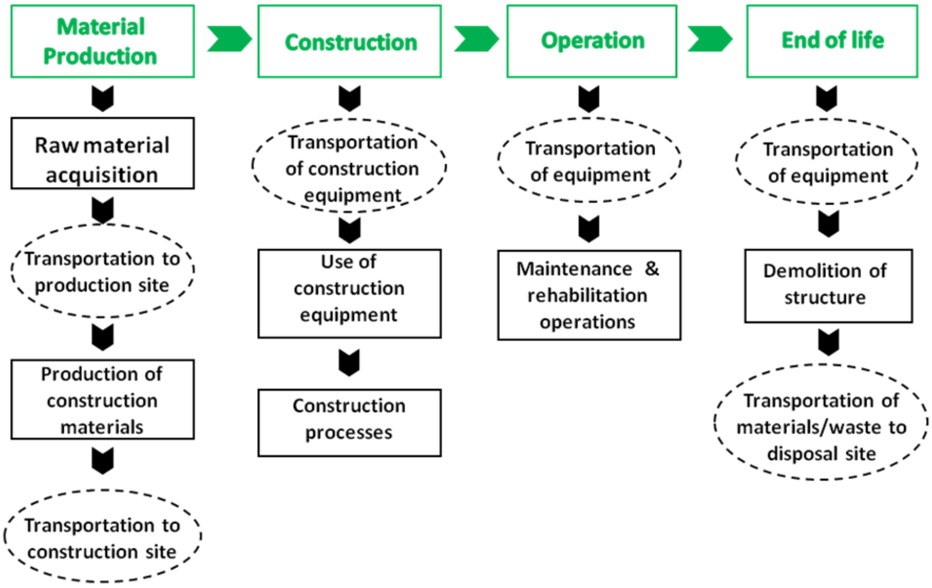

Figure 9. *System boundaries of the bridge*

Table 5. Bill of materials

Structural element	*Class/grade*	
Base of foundations	Concrete C16/20	26 m^3
Piles + Abutments + foundations of piers	Concrete C25/30	322 m^3
Piers	Concrete C30/37	60 m^3

Deck	Concrete C35/45	363 m^3
Steel reinforcement	Steel A500	115134 kg
Structural steel (hot rolled sections)	Steel S355	8887 kg
Structural steel (welded plate sections)	Steel S355	165456 kg
Alkyd Paint	------	1535 l

2.2 *Preliminary analysis*

A preliminary life cycle environmental analysis was performed in order to assess the influence of the end-of-life stage. The results of this preliminary analysis are presented in the following paragraphs.

2.2.1 *Inventory analysis*

Data for construction materials, apart from steel, and transportation were obtained from Ecoinvent [6] database, which is included in SimaPro software. Data for the production of steel was obtained from the IISI database [7]. This case study includes two kinds of steel sections: hot rolled sections, for the bracing elements, and welded plate sections, for the main girders. In the IISI database, LCI data is calculated for products derived via the blast furnace/basic oxygen furnace route (based mainly on new raw materials) and/or the electric arc furnace route (mainly based on steel scrap). Data is available for several steel semi-finished products at the gate of the factory. However, it does not consider the necessary processes to obtain the finished products which usually take place in a fabrication shop. A typical fabrication shop involves detailing, filling, welding, surface preparation, surface protection and shipping. To fill this gap, data from the fabrication shop was collected directly from Martifer SA, a leading Portuguese steelwork fabricator [8]. It was assumed that both steel plate and hot rolled sections were produced via the primary route (BF route).

2.2.2 *Impact Assessment analysis*

The environmental life cycle analysis is performed according to the CML methodology [9] and the SimaPro [5] software program. The processes included in the life cycle analysis of the composite bridge are represented in Figure 3. According to the CML methodology, the Impact Assessment analysis comprehends 8 impact categories: abiotic depletion kg (Sb eq.), global warming (kg CO2 eq.), ozone layer depletion (kg CFC-11 eq.), human toxicity (kg 1,4-DB eq.), terrestrial ecotoxicity (kg 1,4-DB eq.), photochemical oxidation (kg C2H4), acidification (kg SO2 eq. and eutrophication (kg PO4--- eq.).

In order to assess the influence of the end-of-life stage in the overall result of the life cycle analysis, several scenarios were defined and analysed, according to Table 6.

Table 6. End-of-life scenarios

	End-of-life scenario
Base scenario	All the construction waste is to be sent to a landfill (50 km by road transportation)
Scenario 1 -Reuse	Steel structure is going to be reused (80%) (100 km by road transportation) and all the remaining construction waste is to be sent to a landfill (50 km by road transportation)
Scenario 2 - Recycling	Steel structure is going to be recycled (80%) (200 km by road transportation) and all the remaining construction waste is to be sent to a landfill (50 km by road transportation))

In Figure 10, the results of the life cycle analysis are shown for scenarios 1, 2 and the base scenario. From the graph, the influence of the end-of-life stage is clear observed. The results for the LCA considering the reuse of steel in the end-of-life stage are naturally better than for the recycling scenario, as the latter includes all the processes necessary to process steel scrap.

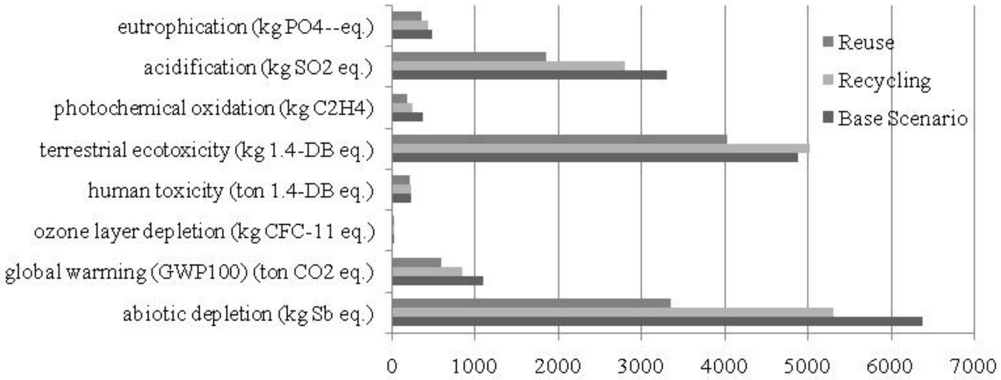

Figure 10. *Life cycle environmental analysis (Sce. 1 – recycling, Sce. 2 – reuse & Base scenario)*

In Figure 11, the results of the life cycle analysis for scenario 1 are presented by life cycle stage. This picture allows to conclude that the environmental burdens due to the operation stage, less than 2%, have little influence of the final result of the analysis. It should be noted, however, that the operation stage was very much simplified in this case study as the focus of the analysis was the last stage.

The end-of-life stage, on the other hand, has a major influence on the overall result of the life cycle analysis, about 15%.

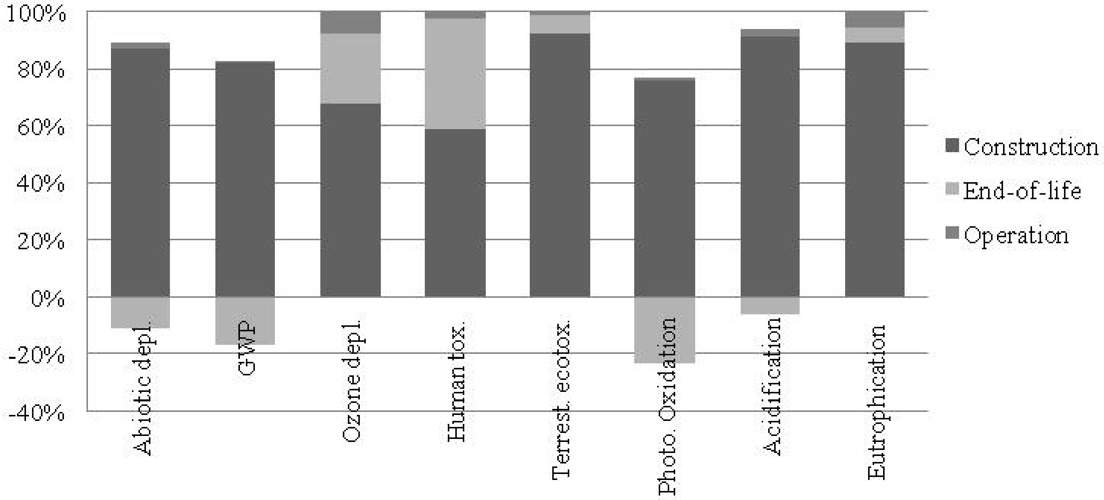

Figure 11. *Environmental analysis by stage*

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