Life Cycle Assessment of Railway Bridges

Developing a LCA tool for evaluating Railway Bridges

LOREA GARCÍA SAN MARTÍN

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Preface

This Master Thesis was carried out at the Division of Structural Design and Bridges, at the Royal Institute of Technology (KTH) in Stockholm. The work was conducted under the supervision of Håkan Sundquist, with the inestimable advice and guidance of Guangli Du, to whom I want to thank for providing valuable comments and reviewing the final report. I would also like to thank the Urbanism Department at the Council of Vitoria-Gasteiz, for providing access to useful information of the bridge studied in this report, and to everyone who has help in any way to carry out this thesis.

Last, but not least, I would like to thank my parents, Agustín and Rosario, and my brother Alberto for their understanding, support and encouragement without which I could not be able to finish this thesis successfully.

Stockholm, May 2011

Lorea García San Martín

Abstract

The global understanding that natural resources and non renewable energy sources are not inexhaustible has been growing lately together with the increase of conscientiousness on the consequences that our demanding way of life has on the environment. Global warming, ozone layer depletion, the greenhouse effect or the acid rain, are some of these consequences, which may reach catastrophic levels if nothing is done to emend the actual situation. Lately, society is beginning to see sustainability not only as a needed requirement but as a distinctive value which has to be pursued by the different areas of society involved and responsible for a sustainable development such as public administration and companies, engineers and researchers. As a fundamental part of society, infrastructures have utmost importance in sustainable development. Even more when it comes to rail transport infrastructure, given the important role of rail transport in the development of a sustainable society. That is why engineers should make an effort to use all the tools available to choose the best structural design, which not only meets structural requirements, but has also a good performance for the environment. To do so, engineers must focus on using renewable sources or energy and materials, increasing the life of the existing infrastructures, making them more durable. When it comes to railway bridges, it is preferable to reuse and adapt existing structures than tear them down to build new ones.

In this line, environmental assessment methodologies provide an incredibly valuable tool for help decision-makers and engineers to identify and select the best alternative design regarding environmental issues. Therefore, it is important to count on a common basis and established criteria together with a systematic methodology in order to obtain reliable results to compare alternatives and make the right decisions. However, nowadays, there exists very little guidance to perform this kind of analysis, and an extensive variety of databases and methodologies non standardized, which leads to uncertainties when it comes to evaluate and compare the obtained results.

This thesis means to be a good guide for engineers, when performing a Life Cycle Assessment of a railway bridge, and to become a useful tool to compare several alternatives to identify the best option relating the environmental burdens involved. With this purpose, in order to know the state of the art of LCA methodology, it has been studied a wide range of existing literature and previous studies performed to analyze bridges and building materials. Finally, it has been developed an own methodology based on all the research done before, and

implemented in an Excel application program based on Visual Basic macros, which means to be easy to use with a simple user interface, and to provide reliable results. The application is useful for assessing, repair or improving existing bridges, where the amounts of materials and energy are known, but can also be helpful in the design phase to compare different alternatives. It also allows using different weighting methodologies according to several reference sources depending on the case of study.

The application is tested by carrying out a Life Cycle Assessment of a Spanish railway bridge located in the city center of Vitoria-Gasteiz, evaluating the different structures that conform the bridge system thorough all the stages of its life cycle identifying the most contributive parameters to the environmental impacts. The study was carried out over a 100 year time horizon. In the case of performing the LCA of this particular bridge, the contribution of the whole bridge is taken into consideration. When comparing two different bridges, the application has the option to compare them in the same basis, dividing by length and width of the bridge, which is a helpful tool if both bridges are not the same size. All stages of the life cycle were considered: the material stage, construction, the use and maintenance stage, and the end of life. The material stage includes the raw material extraction, production and distribution. The construction stage accounts the diesel, electricity and water consumption during construction activities. The use and maintenance stage covers the reparation and replacing operations. And the end of life covers several scenarios. In this case of study, in order not to interrupt the rail traffic, the bridge was constructed parallel to its final location, and then moved into the right place with hydraulic jacks. This leads to an important auxiliary structure with its own foundations, which has a significant contribution to the overall environmental impact. The scenario chosen for the end of life was based on similar actuation in other constructions in the proximities of the bridge, as the bridge is already in use. These assumptions were to recycle 70 % of the concrete and 90 % of the steel; all the wood used for formwork was disposed as landfill.

The results obtained, weighted according to the US Environmental Protection Agency, shows that the main contributor to the environmental impacts is the material phase, with the 64 % of the total weighted results with concrete and steel production as principal factors, followed by timber production. These processes account great amounts of CO_2 emissions, which makes essential to focus on reducing the impact of the material processes by optimizing the processes but mainly by reusing materials from other constructions as much as it may be possible. The maintenance activities have some importance due to the frequency of the track replacement, assumed to be once every 25 years. While construction does not imply great burdens for the environment, the end of life causes the 33 % of the overall bridge impact. This is due to the timber formwork disposal as landfill and to a lesser extent because of the recycling of the steel. The timber disposal increases widely the eutrophication effect, and will be easy to be reused in further constructions. Regarding the different parts of the bridge structure, the auxiliary structure has an important contribution with the 61 % of the overall weighted impact. As it is a concrete bridge, both the substructure and

superstructure has similar contribution. The substructure has a slightly higher impact with the 21 % and the superstructure the 15 %. Rail structure and transport have very little contribution.

Keywords: Life Cycle Assessment, LCA, Railway Bridges, Environmental impact assessment, pre-stressed concrete bridges.

Contents

Chapter 1

Introduction

1.1 Goals of the project

Three are the main objectives of this thesis. The first objective is to gather all the existing literature and methodologies and study in depth and analyze all the published documents and past research on Life Cycle Assessment methodologies, in order to get conclusions and unify all existing approaches. By knowing the state of the art on LCA, the best practices and methods for railway bridges are identify, trying to use the latest breakthroughs to develop an own useful model and implement a useful tool that can be used for assessing railway bridges. With this same purpose, the already existing studies on building materials and bridges are investigate in order to learn from their conclusions and extrapolate them to the assessment of railway bridges. All the existing standards and normative regarding Life Cycle Assessment and sustainable construction are taken into consideration too.

The second objective is to develop a model and methodology based in all the previous research done on the topic, for evaluating the environmental impacts of railway bridges thorough its lifetime. The model will be able to identify the critical aspects of the life cycle or the parameters of the bridge that contributes the most to the environmental impact. It also will be able to compare two different bridge structures, with the same basis, dividing by length and width if the sizes are different, and will allow choosing the best alternative, using different weighting methodologies and reference sources. This model is then implemented in an Excel application tool, with the help of Visual Basic, and provided with an easy user interface which shows the results in a graphical format. The model and application aim to serve as a valuable tool for engineers and a point of starting for further developments and improvements.

The third objective is to apply the model to an existing railway bridge. In this case a Spanish railway bridge is assessed thorough its lifetime, and the different parts of the bridge structure are evaluated to identify the main contributors to the environmental impact. This study may serve in the future as a reference for choosing the best alternatives in posterior improvements to the bridge structure.

In brief, this thesis seeks to provide guidance and a useful tool, to carry out Life Cycle Assessment of railway bridges, facilitating the work for designers and engineers and, as a consequence of this, promote the use of Life Cycle methodologies in railway bridges construction.

1.2 Outline and Structure

This thesis is structured into six chapters. This first chapter means to be a global introduction to sustainability in infrastructures and environmental assessment needs, and provide an overview of the aim and framework for the later research.

Second chapter describes the Life Cycle Assessment methodology and the standard families ISO 14040. It is the result of an extensive research of all the different existing approaches and methodologies, and describes the state of the art of Life Cycle Assessment. It lays the foundations for developing the railway bridges LCA tool, which will be implemented in Excel and Visual Basic macros.

Third chapter highlights the environmental issues of construction materials and activities. It gives an overview of the European policies regarding Construction materials and activities, and analyzes the most important previous studies and research on LCA on building materials and bridge structures.

In the forth chapter, the Life Cycle model is described together with the implemented Excel application tool. It describes the framework and scope of the model and its main characteristics, such as the boundaries and data sources and uncertainties. It also explains the different parameters included in the model and the graphical user interface of the program.

Chapter five includes the case of study: the Life Cycle Assessment of the Spanish railway bridge “Puente de Castilla”. It describes the bridge structural system, the construction processes, maintenance and end of life scenarios. This chapter summarizes the results obtained with the Excel application and interprets those results according to the goal and scope defined before to get the main conclusions of the study.

Last chapter gathers the conclusions for the research on LCA, the development of the Excel tool and the application to the case of study. And lay the basis for further research regarding Life Cycle Assessment of railway bridges and further improvements for the developed EXCEL application.

1.3 Railway Infrastructures

1.3.1 European Railway and Sustainable Development

Lately, globalization has lead to a strong increase of the transportation activities. According to the Community of European Railway and Infrastructure Companies (CER) and the International Union of Railways (UIC), since 1970 freight transportation has increased by 185 % and transport of people by 145 % in the European Union. Since 1970, at the same time that traffic transportation increased, there has been an increase of the greenhouse gas emissions of the 70 %. The evidence shows that transport sector is one of the main contributors to global warming and greenhouse gas emissions due to the usage of fossil fuels. Transport causes more than the 25 % of the EU CO_2 emissions and it is responsible for more than the 30 % of the total European energy consumption, most of it is due to the road traffic. The drop in travel volumes due to the economic crisis has decreased this emission statistics in many countries, but for the long term the increase of greenhouse gas emissions will continue growing. As an attempt to reduce the catastrophic consequences of the climate change, the European Union agreed to reduce by 50 % the global emissions before 2050.

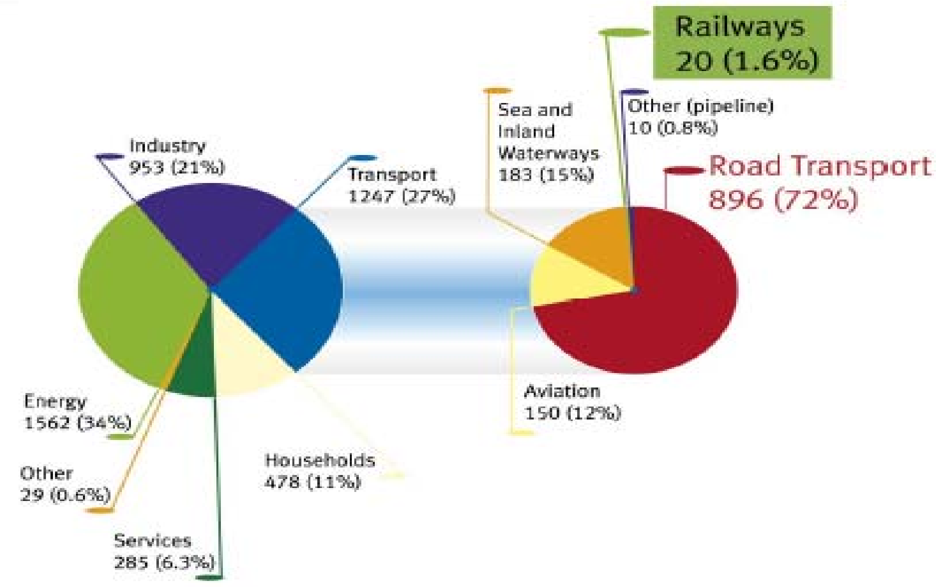


Figure 1: CO_2 emissions by sector and transport mode (UIC, 2007)

Rail traffic means a real efficient way of achieving this goal. It is the transport mode with the lowest specific CO_2 emissions. Furthermore, the rail sector has agreed on cutting its levels of emissions by 30 % since 1990. It is, in fact, the only transport mode that has decreased its CO_2 emissions.

Nowadays it has over 6 % of passenger and 10 % of the freight transport market share and still contributes with less than the 3 % of the CO_2 emissions of the transport sector in the EU, including the electricity production. The emissions generated by a single person when traveling long distances by train are minimal compared with the emissions generated by traveling the same distance by car or even by plan. Rail transport plays an important role by reducing the greenhouse gas emissions per passenger and Km, but also reduces the big demand of energy that the transport sector has, that is limiting its growth and creates dependence with non-renewable sources of energy.

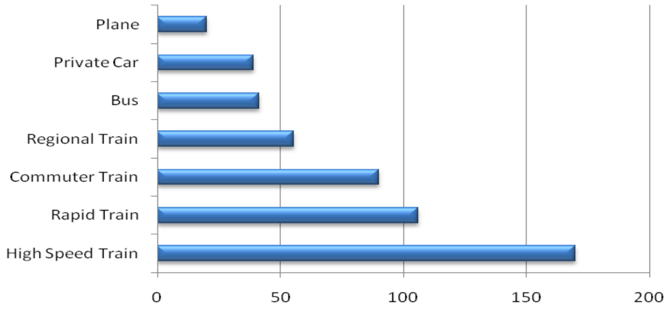


Figure 2: Passenger-Km carried per unit of energy (UIC: Unit of energy: Kg equivalent of petrol)

Most of the emissions caused by the rail transport are due to the electricity production. It is interesting to look at the sources of that electricity, and the differences between the European countries. In Figure 3 we can see that in Spain there are several kinds of energy used, with coal as main source, whereas in Sweden the whole energy source is the hydropower. It is remarkable that using renewable energy, rail transport can be close to the zero CO_2 emission goal.

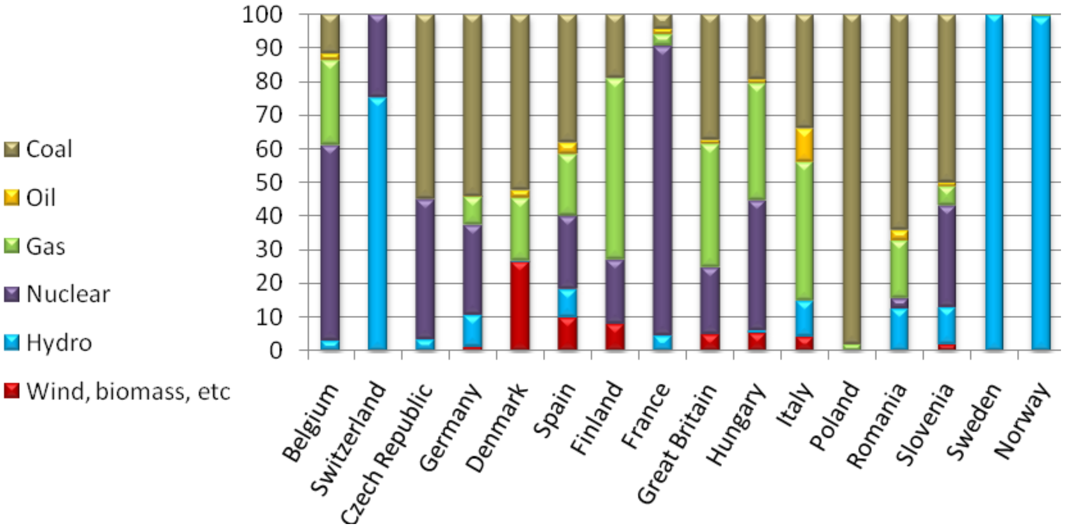


Figure 3: Electricity sources for railways in some European countries (UIC rail energy project)

Although the advantages of the rail transport are already proved and commonly known, it is less common to analyze the energy used to produce the materials required to built the railway infrastructure, or in the construction or even during the maintenance of that infrastructure. In order to make the rail the most efficient way of transport it has to be taken into account also the life cycle of the railway infrastructure and try to reduce the environmental impact over all process.

Chester et al., (2009) performed a clarifying life cycle assessment to analyze the impacts on the environment of several transportation modes. The study analyzed the energy consumption together with the greenhouse gas, SO_2, NO_x and CO emissions not only due to the use of each transportation mode, but also due to the transportation infrastructure. As the use of the transportation was the most contributive phase, they concluded that fuel consumption was the main cause of environmental impact. The results showed that, even though the active operation was the main cause of energy consumption and emissions, it was significantly lower than for the rest of the studied means of transport. The construction and maintenance of the infrastructure were nearly as much contributive to these impacts as the use phase (Chester and Horvath, 2009).

In this line of argument, Stripple and Uppenberg (2010) performed the first environmental product declaration (EPDs) of rail transportation and railway system of the Bothnia Line. This study revealed the importance of the infrastructure when it comes to study the environmental impacts of a rail system.

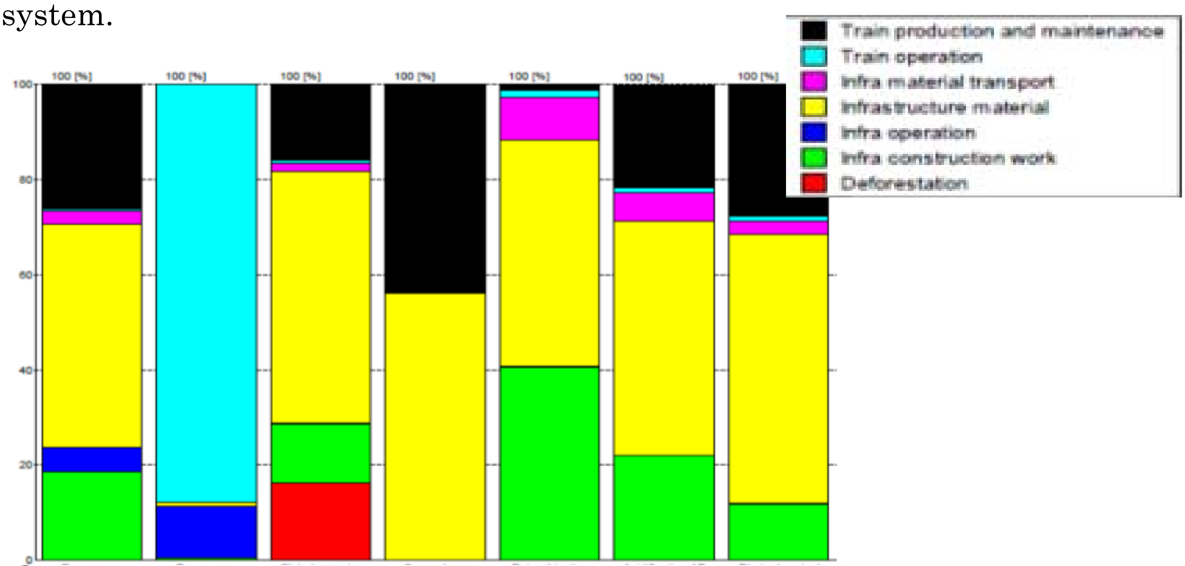


Figure 4: Impact distribution of passenger rail transport at the Bothnia Line (Stripple and Uppenberg, 2010).

1.3.2 European Railway Infrastructure: Bridges

As we have seen before, the rail transportation of people and freight is fundamental to reduce the impact of the transport sector on the environment. A good and reliable railway network is therefore needed for a sustainable development in Europe. Bridges constitute an important part of the railway infrastructure. A survey performed in 2004 by the European Railway Bridge Demography, showed an overview of the actual European railway network. The main findings of the survey were that the predominant type of bridge is the masonry arch bridge, followed by the metallic and concrete bridges, and a small number of composite bridges. It is remarkable that only the 5 % of the railway bridges in Europe are over 40 meters. This is a consequence of the old infrastructure, where the majority of the bridges are arch bridges with less than 10 meters of span built more than 100 years ago (European Railway Bridge Demography, 2004).

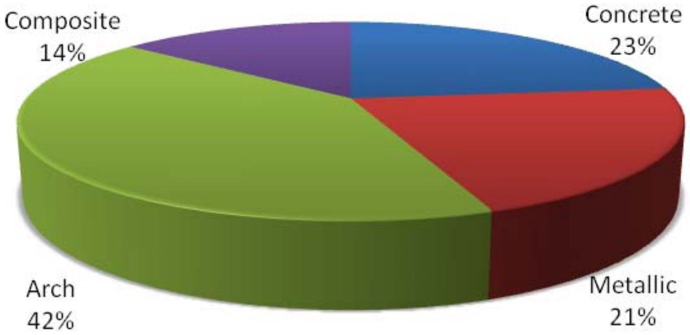


Figure 5: Types of Railway Bridges in Europe (European Railway Bridge Demography, 2004)

With the increase of the number of high-speed lines all over Europe, it has become an important necessity to rebuild and repair parts of the old European railway infrastructure. As it is shown in the Figure 6, barely the 11 % of the railway bridges are less than 20 years old, while the 35 % are over 100 years old. Many bridges have to be removed in order to fill the requirements of the high-speed networks. Moreover, it has become an increasing necessity to have straight railway lines to achieve higher speeds. In the graphic below it is shown the ages of the European bridges by type. An important fact shown in the graphic is that the bridges with more than 100 years are mostly masonry arch bridges, which are being replaced gradually. The concrete bridges were the most used 50 to 20 years ago, and as the new technologies and new materials are being improved, the composite bridges are being the best solution lately (European Railway Bridge Demography, 2004).

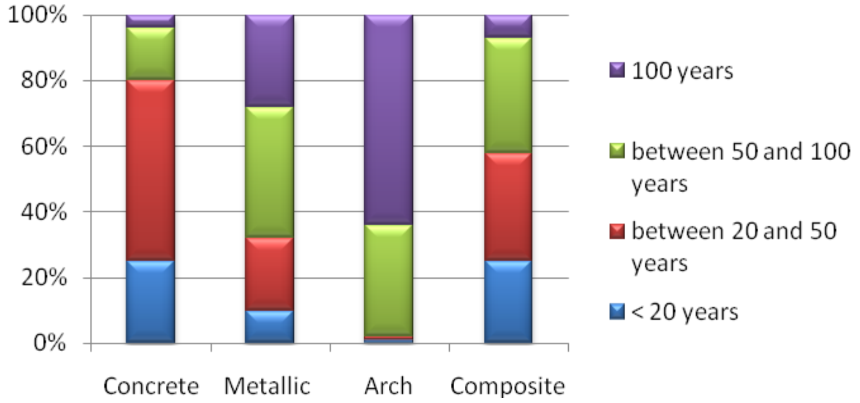


Figure 6: Age of Railway Bridges by Type (European Railway Bridge Demography, 2004)

A good sustainable practice is to rebuild the existing bridges and adequate them to the new lines and requirements. Maintaining and upgrading an existing bridge costs less both economical and environmental impact than tearing it down and build a new one instead. In this line, the process of rebuilding can be assessed with tools like the one presented in this thesis, to get the best solution regarding environmental issues.

1.4 Sustainable Development

1.4.1 Towards Sustainable Development

Sustainability has its origins in the late 70s. A great uncontrolled growth of industrial society after the Second World War, lead to a emerging awareness of the environmental impacts and the need to develop means and tools for slowing down the rate of damage that was being caused. In Goodland's words, "the need for sustainability arose from the recognition that the profligate, extravagant, and inequitable nature of current patterns of development, when projected into the not-too-distant future, lead to biophysical impossibilities" (Goodland, 1995). Is in 1987, with the Brundtland Commission report "Our common future", when the concept of sustainability was finally adopted.

In 1992, in the Rio de Janeiro Conference, The United Nations Environmental Program adopted sustainability as the principal goal for the future development of our society, and was established as the main task for 21st century (UNEP, 1992). In 2002, the World Summit for Sustainable Development took place in Johannesburg. Several governments and companies' leaders gathered to discuss the latest breakthroughs and lay the foundations of a common plan to confront the challenge of a sustainable development. Some of the main goals were to promote the tendency to change unsustainable production and consumption habits, and reduce the impacts on human health and environment through a life cycle approach. Three main aspects were remarked as the baseline towards this sustainable development: economic growth, ecological balance and social progress (WBCSD, 2003). A particularly important event for sustainability was the adoption in 1997 of the Kyoto protocol, which set the basis for the reduction of greenhouse gas emissions related to sustainable development.

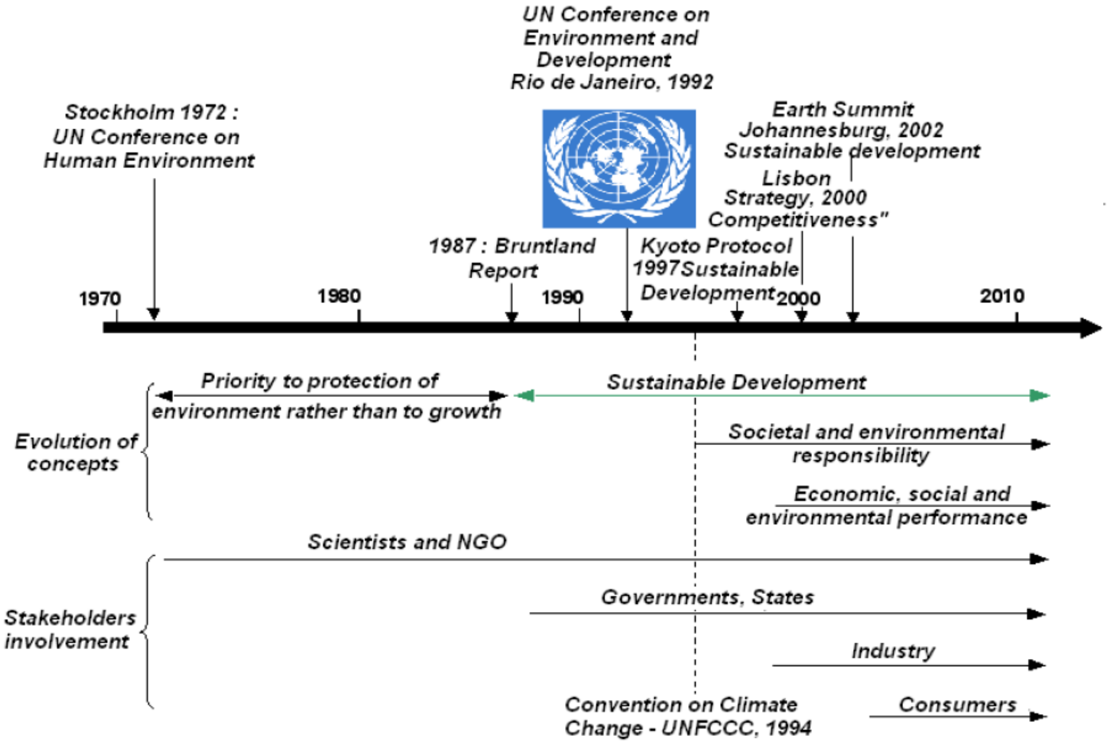


Figure 7: Chronology of the concept of sustainability (CEN, 2010)

1.4.2 EcoDesign Strategies through Life Cycle

Quoted from the earlier Brundtland Report in 1987, "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

The commitment to a sustainable development by all sectors of society requires applying this line of thoughts to every step of a projects life, especially to the design step. A good design and planning can lead to an environmentally friendly project, reducing the energy and resources consumption. This must be an important challenge for today's engineers, on who resides the chance to drive the progress towards a sustainable world. The Ecodesign is a recent concept and techniques for a structured product development. This concept remarks the need of environmental management and control policies, within the companies and organizations.

Ecodesign is focus on studying the entire life cycle of either the existing products, in order to identify critical aspects of their performance and change them, or in an early stage, of the products that about to be produced in order to save ulterior environmental and socioeconomically costs. To identify this critical parts of the product's life that needs improvement, methodologies like the Life Cycle Assessment have become a valuable tool. Either with environmental, economical (White, et.al, 1996 and Norris, 2001) or social (O´Brian M., et.al, 1996 and Norris, et.al, 2005) purposes, any assessment method must consider the whole life cycle of the studied system. Life Cycle approach has turned out to be fundamental for a sustainable designing.

Along this line of thinking, Figure 8 shows in a graphical way the eight ecodesign strategies that can be carried out for this purpose and the life cycle stage that the changes have an improvement effect.

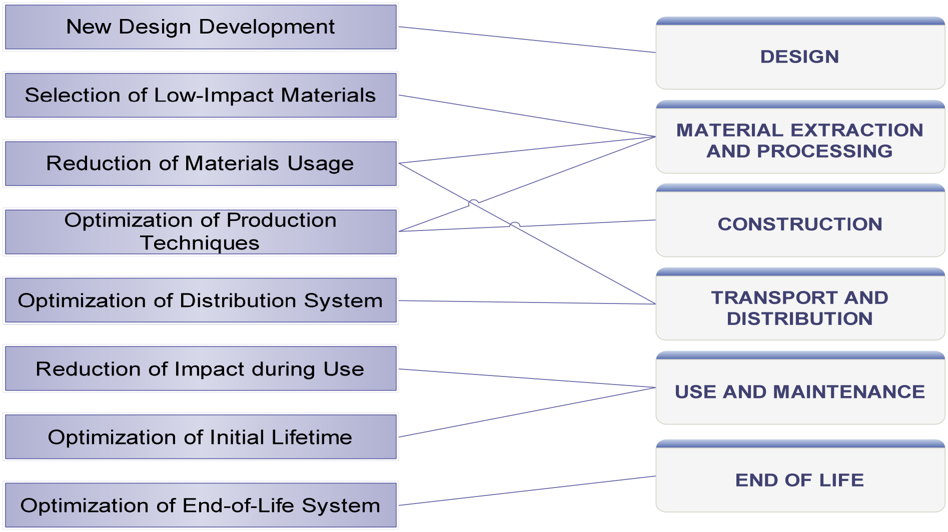


Figure 8: Relation between ecodesign strategies and product life cycle

With a good environmental management, companies can benefit their selves, not only because of the obvious energy and resources consumption decreasing or the reduce of environmental fines, but also with a good eco-friendly marketing that, in a society where the environmental issues are more and more taken into consideration. A good environmental management is a key factor in corporative strategies, and lays the foundations for a competitive growth were a better and sustainable future is the main goal (Hart, 1997).

Although sustainable development requires the implication of all areas of society, engineers have a critical responsibility in this process. As principal involved agents, engineers must assume their duties and apply these environmental concepts to a better design in their projects.

1.4.3 Sustainable Construction

The building sector is one of the main contributors to the total resources and energy consumption in Europe, waste generation and greenhouse gas emissions. The term sustainable construction has a special meaning for engineers and developers, whose duty is to create new environmentally friendly constructions taking into consideration all the aspects mentioned above. To achieve this goal, sustainable construction is part of the European policy, and there are several standards and normative to regulate and assess the processes and materials related to the building sector, and will be described in later chapters.

Sustainable construction, does not only mean to design and construct new buildings and infrastructures with a good environmental performance, it also means to analyze old existing constructions and identify the aspects that needs to be changed in order to achieve sustainable goals. For assessing these existing structures, the engineers should consider the use of new materials or processes better for the environment than the existing ones, trying to reduce the impact caused by demolishing or waste disposal. It is important too, to create structures that need less maintenance operations during their lifetimes, in order to reduce the energy or resource consumption, and extend the service life, avoiding having to replace the whole structure in short time.

1.4.4 Green Engineering and Infrastructures design

The engineers commitment to sustainable design was the main goal of the IEEE-USA annual meeting of 2008, entitled “Green Engineering: A Push Toward Sustainability”. In the conference, Buck stated that “Green Business is Good Business”, and explained that the wills of every company to increase its economic profits is not against a sustainable practices. She remarked that “by making your business green, you can pre-empt government regulation, avoid long-run costs, live up to your customer's expectations, and improve your employee expectations and retention rates.” (Buck, 2008). In this line of thoughts, in order to pursue a sustainable development, civil engineers and architects can use technology improvements to solve environmental related problems, and apply concepts and tools like the Life Cycle Analysis to study the environmental impacts of their designs. As a fundamental pillar of society, civil infrastructures must be designed from their very early steps, to a future-oriented development, which should be accomplished by all parties involved: international traffic associations, ministries of transport, civil engineering departments, construction companies and producers of road construction materials (Gschösser, 2008). As Kelly Burnell et al. remarked in the APWA conference in 2009, aspects like the energy consumption, the use of friendly materials, the reduce of the needed maintenance and reparations and a good waste management have to be taken care while designing infrastructures like bridges.

In the case of bridge infrastructures, in the CEN/TC25 workshop, they propose the main goals that bridge design should pursue. These goals are described in the following table.

BRIDGES	Sustainable development	Using existing lines and crossings
	Security of use	Operational requirements for dimensions of bridges, clearances, etc., no disruption of traffic by maintenance and repair
	Safety	Load carrying capacity, resistance to accidental situations, seismic resistance and, in some circumstances, fire safety.
	Durability	Reduction of maintenance costs, enhancement of residual life

Figure 9: Proposal of growth drivers in bridge design (CEN/TC250 Chairman's Advisory Panel (CAP) "Assessment")

In order to apply this line of thoughts, and design sustainable bridges, there are few tools or standardized procedures to follow, but there exists some studies in the literature that can be used as a basis for developing a common tool. There also exist many studies that evaluate the performance of most of the building materials, and can be useful in future studies in the field of infrastructures. Is in the design phase were the whole life of the bridge must be evaluated. The materials, construction processes, maintenance and service use, and the end of life management must be considered in this early stage. Here is where tools like the LCA are useful, and are beginning to be widely used by companies with environmental policies.

In this review, some examples of Life Cycle Assessment for bridge infrastructures are going to be described, with the main purpose to help giving perspective and allow developing an own methodology applicable to railway bridges. In this line, the research and use of new materials like fiber reinforced polymer can be a crucial factor (APWA, 2009). The figure illustrates the importance of civil engineers on the sustainability of infrastructures, and the areas were this influence is bigger.

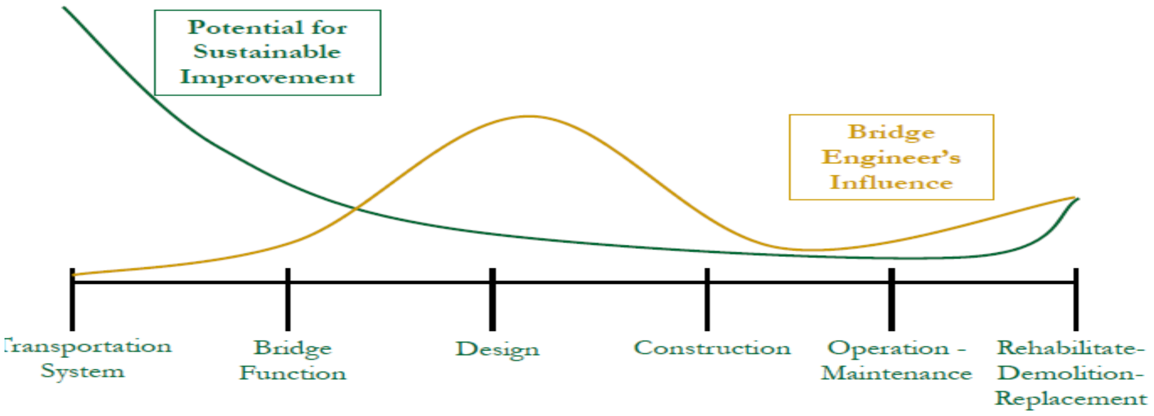


Figure 10: Engineer's area of influence in the Bridge Project Life (APWA Conference, 2009)

Chapter 2

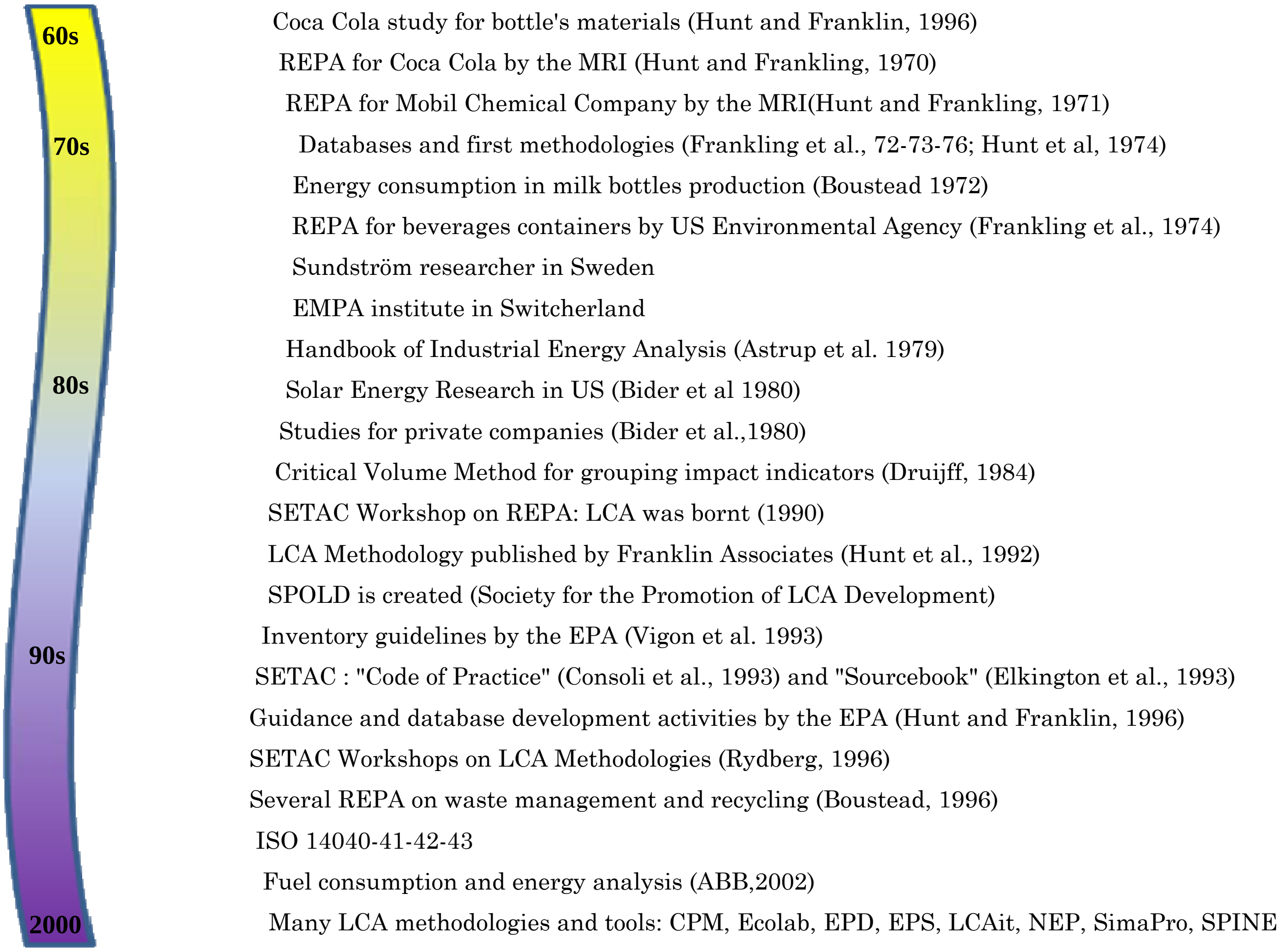
Life Cycle Assessment

2.1 Introduction of the LCA

2.1.1 Background

Life Cycle Assessment (LCA) is a systematic method developed to evaluate and interpret the potential environmental aspects and potential impacts that is going to be caused by the whole life of a product or activity studied. To analyze those impacts it is necessary to consider all phases that the evaluated product goes through. These phases are the raw material extracting, the construction or production phase, the maintenance and use of the product, the end-of-life treatment, the recycling of the materials and the final disposal. In a Life Cycle Assessment, the studied product is evaluated by the address and quantification of aspects such as energy consumption, renewable or non-renewable resources, emissions to the atmosphere, water waste and contamination, etc, to assess environmental impacts as for example acidification or ecotoxicity. These impacts are analyzed and considered in order to identify stages of industrial processes that require environmental improvements, to compare different processes or alternative products. It is therefore important to take into account not only the constructive phases and use, but also the recycle, waste treatment and final end of the product (“from cradle to grave”).

The development of the Life Cycle Assessment began in the 70’s. Due to the petrol crisis there was a strong need to reduce the energy consumption by the industrial companies, which represented a restraint in their economical growth. Within the idea of decreasing the energy, there was a change in the studies point of view and to make the analysis more accurate they began taking into account raw material consumption and later the disposal of the product in the end of its life. The first study made in this context was made by Coca-Cola on 1969 in order to decrease the resources consumption and therefore reduce the emissions to the environment. This study was carried out by Hunt and Frankling, and it was called the Resources and Environmental Profile Analysis (ERPA). Its main goals were to choose for the bottle the best material between glass and plastic, the end of life alternatives and whether they should have internal or external bottle production. Contrary to all thoughts, the plastic bottle turned out to be the most efficient choice. This fact leaded the scientific community to develop a methodology and go into standardization process. In the 70's, the evaluation of the impact in the global warming and other environmental issues where included in those studies and a methodology is starting to be use. Later, in the 80's, this methodology will be developed and consolidate. During those decades, many other studies were made in both Europe and USA. In 1979 the Society of Environmental Toxicology and Chemistry is founded (SETAC). SETAC was the most important organization in the development of a unified method. They made several studies and research on LCA, and publish the first international code for the practice of Life Cycle Assessment on the 90's. It is in 1992 that appeared the first European project in the "Eco-labels", in order to aware the consumers and promote the production of sustainable products. After some other publications on the topic by several companies and organization, the International Organization for Standardization (ISO) publishes the ISO 14000 family on environmental management that includes the standards about Life Cycle Assessment. The methodology adopted is based on the one that was originally set by SETAC.



Coca Cola study for bottle's materials (Hunt and Franklin, 1996)
REPA for Coca Cola by the MRI (Hunt and Frankling, 1970)
REPA for Mobil Chemical Company by the MRI(Hunt and Frankling, 1971)
Databases and first methodologies (Frankling et al., 72-73-76; Hunt et al, 1974)
Energy consumption in milk bottles production (Boustead 1972)
REPA for beverages containers by US Environmental Agency (Frankling et al., 1974)
Sundström researcher in Sweden
EMPA institute in Switcherland
Handbook of Industrial Energy Analysis (Astrup et al. 1979)
Solar Energy Research in US (Bider et al 1980)
Studies for private companies (Bider et al.,1980)
Critical Volume Method for grouping impact indicators (Druijff, 1984)
SETAC Workshop on REPA: LCA was bornt (1990)
LCA Methodology published by Franklin Associates (Hunt et al., 1992)
SPOLD is created (Society for the Promotion of LCA Development)
Inventory guidelines by the EPA (Vigon et al. 1993)
SETAC : "Code of Practice" (Consoli et al., 1993) and "Sourcebook" (Elkington et al., 1993)
Guidance and database development activities by the EPA (Hunt and Franklin, 1996)
SETAC Workshops on LCA Methodologies (Rydberg, 1996)
Several REPA on waste management and recycling (Boustead, 1996)
ISO 14040-41-42-43
Fuel consumption and energy analysis (ABB,2002)
Many LCA methodologies and tools: CPM, Ecolab, EPD, EPS, LCAit, NEP, SimaPro, SPINE

Figure 11: History of the LCA

Although the ISO 14040 standards were a step forward towards the systematization of the LCA, there are still several different techniques and databases of material emissions that can be used for an LCA, and it may lead to contradictory results when comparing two studies in the same product with similar conditions. It is therefore a main goal in the closest future to develop a unified a standardized database to use in LCA inventory, and adopt one common technique to follow within the LCA phases to avoid non accurate results when comparing different studies.

2.1.1 LCA Description

A life cycle assessment has to take into account all phases of the product or process life. In the study of an infrastructure construction, the LCA must include the assessment of the different phases of the products life, including the raw material extraction, manufacture and distribution, the use and maintenance and finally the disposal, including the recycling and transportation phase.

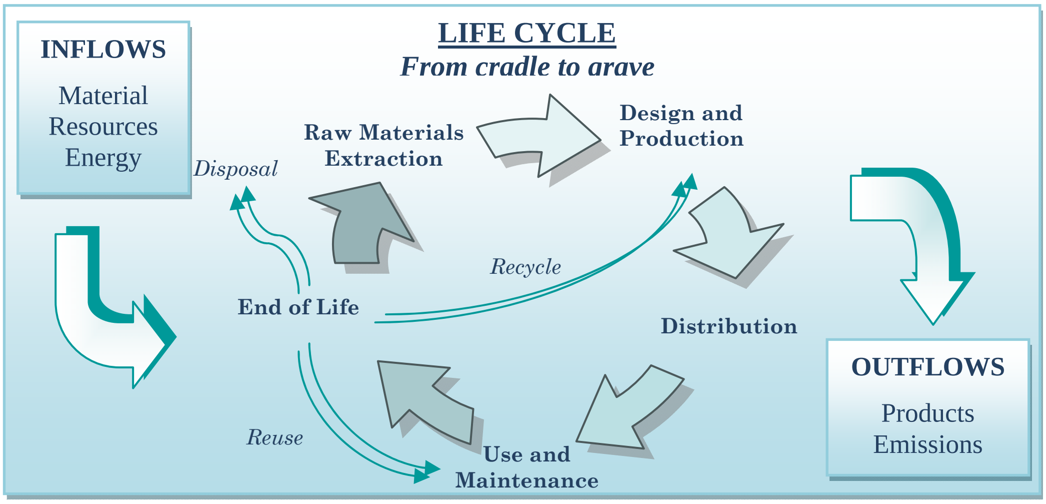


Figure 12: Life Cycle Assessment: From the cradle to the grave

In the product phase, the main materials used in the construction must be analyzed. The study of all materials used would be long and expensive, so it is important to select the bounders of the study to get an accurate study with the minimum coast of time and resources. In order to choose the more relevant materials for the LCA, not only the material with the highest quantities must be included, but also the ones that, even in small quantities, may have a big environmental impact or energy waste in production. One main factor to analyze is the transportation of products, materials or people. The environmental impact of the transport depends on not only the distance and the fuel used, but also on the weight of the transported load, and of course on the main of transport used. In the construction phase, it is of the utmost importance to consider the use of energy, and the kind of energy used in the construction and in the transportation. To analyze the use phase, the energy consumption and the maintenance operations are studied. It is remarkable that the constructive solutions and materials chosen in the construction phase will determine the subsequent maintenance operations. In the disposal phase, it is studied what is going to happen with the materials when the use phase is over. In this phase are analyzed the demolition processes, recycling or disposal of the non-recycling materials. The transportation of the waste materials is studied in this phase. A good waste management policy is vital for reducing the environmental impacts of the life of the infrastructure.

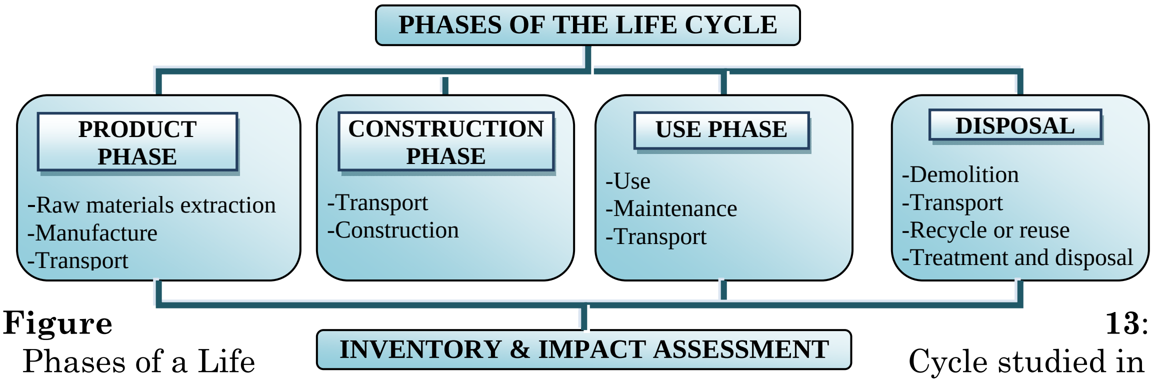


Figure 13: Phases of a Life Cycle studied in a LCA

2.2 LCA Methodology

2.2.1 ISO14040 Standards

Overview

The ISO 14040 standards are included in the ISO 14000 family on environmental management. The whole 14000 standards provides management tools for organizations to manage their environmental aspects and assess their environmental policies even obtaining economic benefits by reducing raw materials, energy consumption, waste generation and by improving process efficiency and using recoverable resources. ISO 14040 provides the general methodology and describes the principles for a life cycle assessment (LCA) study and for life cycle inventory (LCI). However, it does not describe a particular technique for the individual phases of the LCA.

In 1997, the International Organization for Standardization published the first edition to the ISO 14040:1997. After that, the standards 14041:1998, 14042:2000 and 14043:2000 where published. ISO 14041 describes the Inventory Analysis phase, ISO 14042 the Impact Assessment phase and finally the ISO 14043 provides guidance to make the interpretation of the whole Life Cycle Assessment. The subsequent second edition of the ISO 14040 with the ISO 14044:2006 replaces all of them, and are currently in effect. In this moment there are in process to be published the standards ISO 14047, ISO 14048, ISO 14049 that will complement the ISO standard series 14040. The standards ISO 14047 will contain illustrative examples of how to apply the ISO 14042 (LCIA); in the same way, ISO 14049 will provide examples to apply the ISO 14041 (LCI); finally, the ISO 14048 will involve the data documentation format for developing an LCA.

ISO 14040 in Brief

These standards include a general description of the LCA, the main principles and phases, and a detailed methodological framework to perform the LCA. In this methodology it is included the following concepts:

- General requirements
- Goal and Scope
- Life cycle inventory analysis (LCI)
- Life cycle impact assessment (LCIA)
- Life cycle interpretation

In the standards, we can also find advice for the reporting and for carry out a critical review, showing the limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements.
Originally, in the methodology proposed by SETAC, there were five differentiated stages, goal definition, inventory, classification, valuation and improvement. In the ISO standards, just four stages are included, goal definition, inventory analysis, impact assessment and interpretation. The improvement is no longer a stand-alone phase, as considered influence for all the other stages, and another methodological stage is introduced, the life cycle interpretation, which interacts with all the other stages.

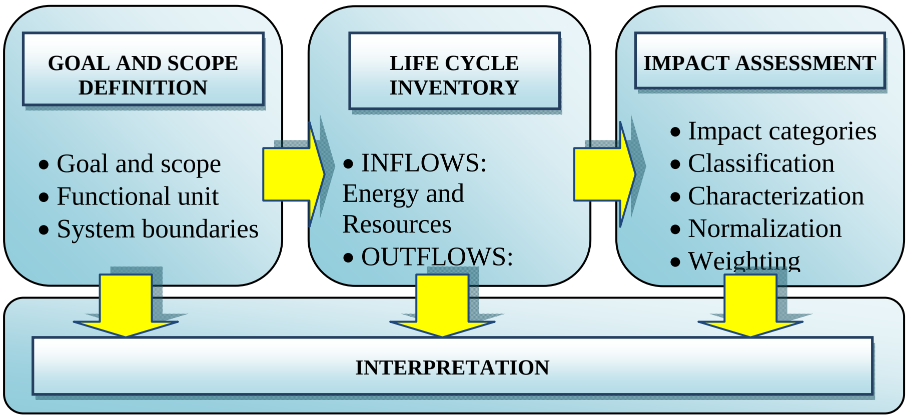


Figure 14: Phases of a Life Cycle Assessment

2.2.2 Goal and Scope Definition

The first stage is the goal and scope definition. In this stage the goal of the study is describe in detail, and the considered boundaries and hypothesis of the study are given. The goal of the study must include the reasons for carrying out the study and it must be detailed and concrete. The entire study is going to be influenced by the goal and the intended use of the study. The depth and complexity of the study may differ considerably depending on the goal of the assessment. An LCA study can be done for various reasons or different objectives. For instance, the aim of the study may be to compare the environmental aspects of two different products, services or processes. Other studies, however, may have the goal to determinate the stages of the life cycle that contribute more to certain impacts.

The scope of an LCA is determined by the aim of the study and its definition must provide the context in which the study is made, including the system boundaries and the approximations that need to be taken. The model and process layout is defined here. It also must provide a detailed description of the studied product including the processes, materials or products needed and the units considered in the model. Time scale and functional units have to be established also in this stage. The functional units are the units that all system data will be referred to, both inputs and output flows, and they provide as well, the reference to compare LCA from different studies and ensure its comparability. This unit can be either physical or functional. A physical type of unit may be the characteristics of the product studied. A functional type unit would, on the other hand provide information of the quantities of material required to fulfill an objective (i.e. 50 years of good product behavior). The scope definition must include the data requirements and the assumptions that are going to be made, mentioning the limitations of the study. The boundaries chosen in the study are defined by the processes that are going to be included. Normally are excluded from the studied the stages, processes or materials of product life that are not going to be significant in the results. All of these factors will condition the accuracy of the results obtained and has to be considered in the interpretation phase.

2.2.3 Life Cycle Inventory (LCI)

In the inventory analysis stage (LCI), the life cycle inventories are made by estimating the different material and energy flows during the lifetime. In order to obtain the main results of the environmental impacts from a life cycle assessment, it is necessary to obtain first the life cycle inventory. It is the longest and complex phase and the result of the LCI is a database where are included, in detail, all energy and resources used in the whole life of the studied product (in-flows) and their emissions to the environment (outflows), calculated per functional unit.

The first thing that has to be done to develop a life cycle inventory is to determine and create a system with all the input flows of each process or phases studied in the life cycle considering the boundaries established in the goal and scope definition stage. In the Figure 7 above shows an example of these phases and sub-phases that are studied in a life cycle inventory. The outputs will be the emissions to the environment, the energy consumption, the materials used and the waste generated in every process of the cycle. This output flows must be calculated for each unit process and for the functional unit of the system. It is remarkable that, depending on the boundaries chosen for the model, the results found may differ. A good criterion for selecting the main parameters and system boundaries is therefore fundamental.

The picture shows the different phases and parameters that must be analyzed in a product's life and therefore included in the inventory. This box tree allows developing successfully the inventory phase, considering each item that contributes to the inflow data.

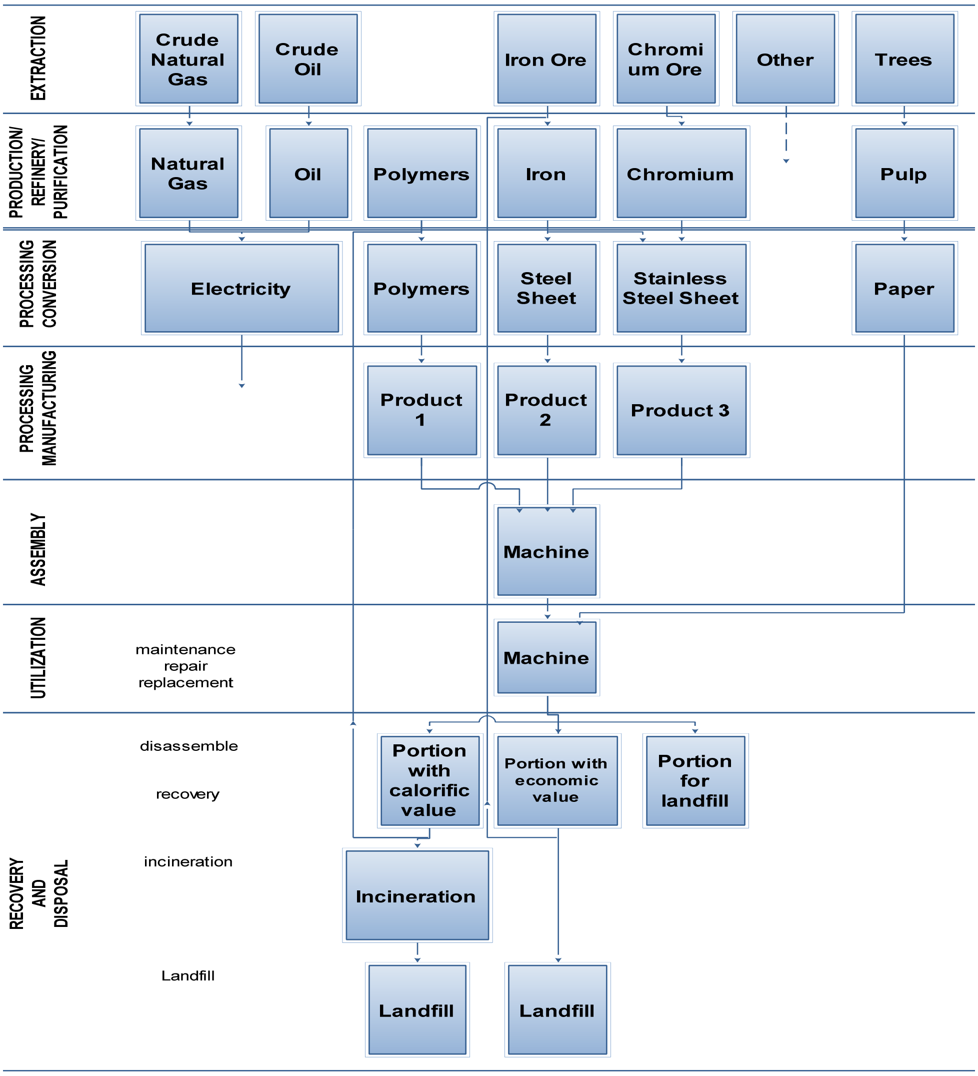
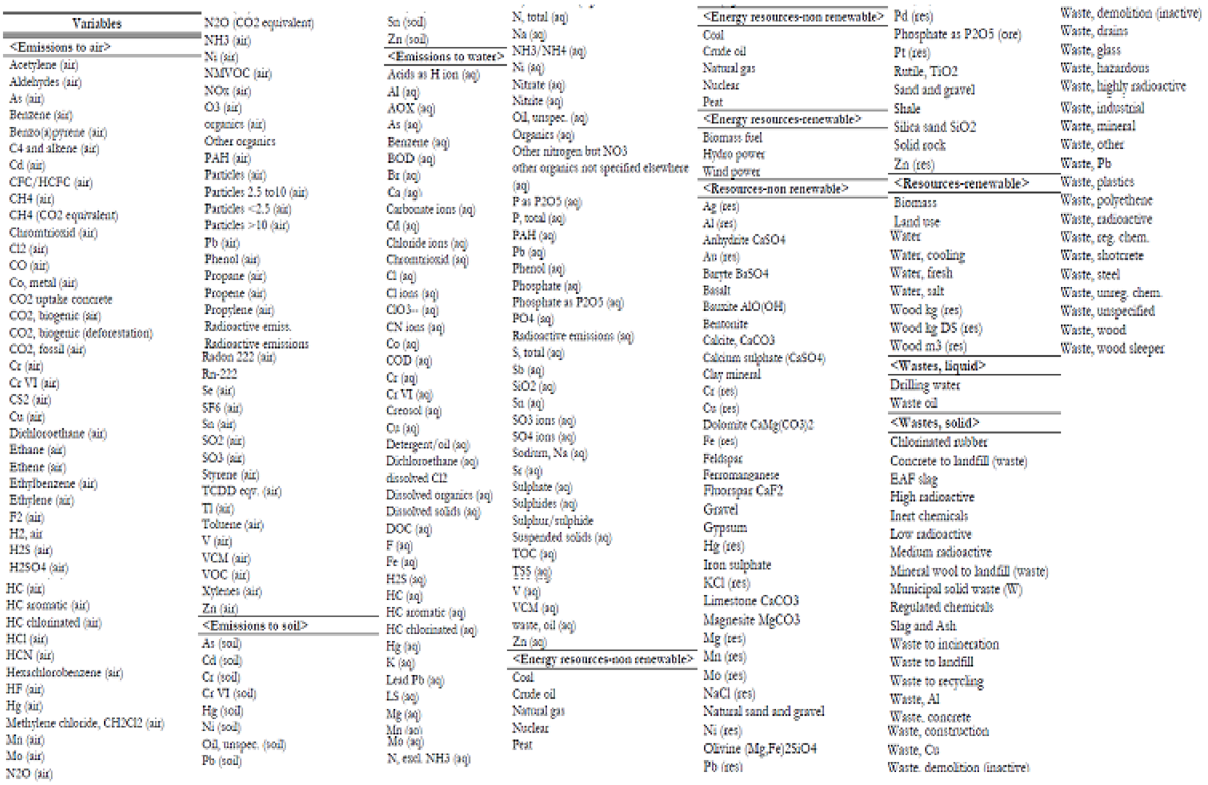


Figure 15: Example of a product process tree proposed by NTNU (modify by the author)

Regarding the energy consumption attached to each part of the life cycle of the product, 70 to 90 percent of the environmental impacts are due to the energy use in manufacturing the product, comparing with the little energy consumption in the extraction of the raw materials, the distribution or the energy related to the machinery used. Commonly, in a LCA the energy consumption considered for the calculations is directly related to the products manufacture and production and the raw material extraction, but is not so common to include the energy consumption invested in the machinery production, transportation or use, or in the generation of the sources of energy. However, most of the existing inventories contemplate these factors in their databases of the materials and processes, and give the environmental loads of the materials from grave to gate considering most of the mentioned energy consumption sources.

There are different approaches to calculate a life cycle inventory and to estimate the contribution of each material or process to the impacts on the environment. There are different theories, for instance, in considering the contribution of recycled or reuse materials as a negative factor, in order to show, that they are not only not increasing the impacts of the studied product but also reducing its contribution to the potential damage to the environment. There exists many databases where the data to calculate the output flows can be found. These databases include data for specific processes, technology and materials. It is important to choose a good source of data to build the LCI, because it will influence the quality of the results obtained. Several companies make this inventory databases and they all have its own values or parameters. These values may vary due to variations in measurements, differences on the circumstances or materials involved, etc. For instance, there may be high variability in the CO, methane or HC emissions between different plants, conditions, etc. However, the accuracy of the parameter depends on the substance measured. In general, SO_2, NOx or CO_2 measurements have more precision than others. The list below is an example of the most important parameters that should be included in a very detailed the inventory.



Variables

<Emissions to air>
Acetylene (air)
Aldehydes (air)
As (air)
Benzene (air)
Benzo(a)pyrene (air)
C4 and alkene (air)
Cd (air)
CFC/HCFC (air)
CH4 (air)
CH4 (CO2 equivalent)
Chromtrioxid (air)
Cl2 (air)
CO (air)
Co, metal (air)
CO2 uptake concrete
CO2, biogenic (air)
CO2, biogenic (deforestation)
CO2, fossil (air)
Cr (air)
Cr VI (air)
CS2 (air)
Cu (air)
Dichloroethane (air)
Ethane (air)
Ethene (air)
Ethylbenzene (air)
Ethylene (air)
F2 (air)
H2, air
H2S (air)
H2SO4 (air)
HC (air)
HC aromatic (air)
HC chlorinated (air)
HCl (air)
HCN (air)
Hexachlorobenzene (air)
HF (air)
Hg (air)
Methylene chloride, CH2Cl2 (air)
Mn (air)
Mo (air)
N2O (air)
N2O (CO2 equivalent)
NH3 (air)
Ni (air)
NMVOC (air)
NOx (air)
O3 (air)
organics (air)
Other organics
PAH (air)
Particles (air)
Particles 2.5 to10 (air)
Particles <2.5 (air)
Particles >10 (air)
Pb (air)
Phenol (air)
Propane (air)
Propene (air)
Propylene (air)
Radioactive emiss.
Radioactive emissions
Radon 222 (air)
Rn-222
Se (air)
SF6 (air)
Sn (air)
SO2 (air)
SO3 (air)
Styrene (air)
TCDD eqv. (air)
Tl (air)
Toluene (air)
V (air)
VCM (air)
VOC (air)
Xylenes (air)
Zn (air)

<Emissions to soil>
As (soil)
Cd (soil)
Cr (soil)
Cr VI (soil)
Hg (soil)
Ni (soil)
Oil, unspec. (soil)
Pb (soil)
Sn (soil)
Zn (soil)

<Emissions to water>
Acids as H ion (aq)
Al (aq)
AOX (aq)
As (aq)
Benzene (aq)
BOD (aq)
Br (aq)
Ca (aq)
Carbonate ions (aq)
Cd (aq)
Chloride ions (aq)
Chromtrioxid (aq)
Cl (aq)
Cl ions (aq)
ClO3-- (aq)
CN ions (aq)
Co (aq)
COD (aq)
Cr (aq)
Cr VI (aq)
Creosol (aq)
Cu (aq)
Detergent/oil (aq)
Dichloroethane (aq)
dissolved Cl2
Dissolved organics (aq)
Dissolved solids (aq)
DOC (aq)
F (aq)
Fe (aq)
H2S (aq)
HC (aq)
HC aromatic (aq)
HC chlorinated (aq)
Hg (aq)
K (aq)
Lead Pb (aq)
LS (aq)
Mg (aq)
Mn (aq)
Mo (aq)
N, excl. NH3 (aq)
N, total (aq)
Na (aq)
NH3/NH4 (aq)
Ni (aq)
Nitrate (aq)
Nitrite (aq)
Oil, unspec. (aq)
Organics (aq)
Other nitrogen but NO3
other organics not specified elsewhere (aq)
P as P2O5 (aq)
P, total (aq)
PAH (aq)
Pb (aq)
Phenol (aq)
Phosphate (aq)
Phosphate as P2O5 (aq)
PO4 (aq)
Radioactive emissions (aq)
S, total (aq)
Sb (aq)
SiO2 (aq)
Sn (aq)
SO3 ions (aq)
SO4 ions (aq)
Sodium, Na (aq)
Sr (aq)
Sulphate (aq)
Sulphides (aq)
Sulphur/sulphide
Suspended solids (aq)
TOC (aq)
TSS (aq)
V (aq)
VCM (aq)
waste, oil (aq)
Zn (aq)

<Energy resources-non renewable>
Coal
Crude oil
Natural gas
Nuclear
Peat

<Energy resources-non renewable>
Coal
Crude oil
Natural gas
Nuclear
Peat

<Energy resources-renewable>
Biomass fuel
Hydro power
Wind power

<Resources-non renewable>
Ag (res)
Al (res)
Anhydrite CaSO4
Au (res)
Baryte BaSO4
Basalt
Bauxite AlO(OH)
Bentonite
Calcite, CaCO3
Calcium sulphate (CaSO4)
Clay mineral
Cr (res)
Cu (res)
Dolomite CaMg(CO3)2
Fe (res)
Feldspar
Ferromanganese
Fluorspar CaF2
Gravel
Gypsum
Hg (res)
Iron sulphate
KCl (res)
Limestone CaCO3
Magnesite MgCO3
Mg (res)
Mn (res)
Mo (res)
NaCl (res)
Natural sand and gravel
Ni (res)
Olivine (Mg,Fe)2SiO4
Pb (res)
Pd (res)
Phosphate as P2O5 (ore)
Pt (res)
Rutile, TiO2
Sand and gravel
Shale
Silica sand SiO2
Solid rock
Zn (res)

<Resources-renewable>
Biomass
Land use
Water
Water, cooling
Water, fresh
Water, salt
Wood kg (res)
Wood kg DS (res)
Wood m3 (res)

<Wastes, liquid>
Drilling water
Waste oil

<Wastes, solid>
Chlorinated rubber
Concrete to landfill (waste)
EAF slag
High radioactive
Inert chemicals
Low radioactive
Medium radioactive
Mineral wool to landfill (waste)
Municipal solid waste (W)
Regulated chemicals
Slag and Ash
Waste to incineration
Waste to landfill
Waste to recycling
Waste, Al
Waste, concrete
Waste, construction
Waste, Cu
Waste, demolition (inactive)
Waste, demolition (inactive)
Waste, drains
Waste, glass
Waste, hazardous
Waste, highly radioactive
Waste, industrial
Waste, mineral
Waste, other
Waste, Pb
Waste, plastics
Waste, polyethene
Waste, radioactive
Waste, reg. chem.
Waste, shotcrete
Waste, steel
Waste, unreg. chem.
Waste, unspecified
Waste, wood
Waste, wood sleeper

Figure 16: Most important outflow parameters for a LCI

Another aspect to take into account when dealing with accuracy is the waste materials. Although the amount of waste is well known, there usually is high uncertainty in the composition of these wastes.

However, due to the small contribution of many of these parameters to the potential impacts that are being studied in the impact assessment stage, such as the acidification or global warming for instance, just some of them are relevant for the purpose of the study, therefore, the others are usually neglected to simplify the study.

Some of the principal studied emissions are CO_2, SO_2, NO_2, and VOC. The CO_2 is a transparent and with a lightly spicy smell gas which is heavier than the atmospheric air and it is toxic for the human beings in high concentrations. It is the main cause of the greenhouse effect. SO_2 and the NO_2 are the major causes for the acid rain. The NO_2 is involved too in the photochemical smog and the global warming, and it is toxic in high concentrations. The volatile organic compounds (VOC) are basically hydrogen and carbon composites and they mainly contribute to the photochemical smog. They are also called THC.

There are two kinds of databases that can be used. One kind of databases are the ones that offer the emissions and resource consumptions for the products already manufactured. Here there is display the data for products as steel or concrete bricks already produced for example. In this data there is always included the environmental cost of the process of manufacture and transportation in what is call from “cradle to gate” assessment, which consist in a partial life cycle assessment of the aggregated material, from the raw material extraction to the moment when the product leaves the industry.

It may be a good choice when the goal of the life cycle assessment is to find a general solution and it is not required to get extremely accurate results. On the other hand, it can be found databases that offer disaggregated data. These databases allow having more accurate results in the LCI, and they give the chance to adapt the data to different types of processes and products. They provide more transparency to the results obtained, that can be more reliable. However, it needs considerably more time and resources to create a life cycle inventory based on this kind of databases, and it may not be worth it. It will depend on the goals defined previously and the accuracy required in the results. One of the most common used databases is the Ecoinvent Database.

A preliminary evaluation study can be made now with the life cycle inventory created. This study will show the emissions and resource consumption from every step in the life cycle, and can be useful to get an overview to the general consumption of each part of the product life. This evaluation can provide an idea of which parts are susceptible to be changed or redesigned according to their contribution to the emissions and consumption before the next step which is the interpretation phase.

Existing LCI Databases

Many of the existing databases and inventories are private, and it is quite complicate to get good reliable values without them. Next table summarizes the main inventory databases existing for construction materials and processes (Thiebault, 2010).

DATABASE NAME	SCOPE	MANAGED BY
Environmental profile report for the European aluminum industry	Aluminum production and transformation processes	European aluminum association http://www.aluminium.org
Eco-profiles of the European plastics industry	Plastics products production	PlasticsEurope http://www.plasticseurope.org
Life Cycle Inventory of Portland Cement Concrete	Production of ready mixed, masonry, and precast concrete.	Portland cement association http://www.cement.org
Worldsteel Life Cycle Inventory	Steel products	IISI (International Iron and Steel Institute) http://www.worldsteel.org
Life cycle assessment of nickel products	Nickel products	Nickel institute http://www.nickelinstitute.org
European Reference Life Cycle Database (ELCD)	Energy, material production, systems, transport, end-of-life treatment	European Commission http://lct.jrc.ec.europa.eu
US NREL database	Global	US National Renewable Energy Laboratory (NREL) http://www.nrel.gov/lci/
JEMAI database	Global	Japan Environmental Management Association for Industry (JEMAI) http://www.jemai.or.jp/english
ProBas database	Energy, materials and products, transport, waste management	German federal environmental agency (Umweltbundesamt) http://www.probas.umweltbundesamt.de
SPINE@CPM database	Global	Chalmers CPM, Göteborg, Sweden http://www.cpm.chalmers.se
Ecoinvent	Energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services.	The Ecoinvent Centre, Switzerland http://www.ecoinvent.ch
ETH-ESU 96 Database	Energy: Electricity generation and related processes like transport, processing, waste treatment	ETH Zurich, Switzerland
BUWAL 250	Packaging materials (plastic, carton, paper, glass, tin plated steel, aluminum), energy, transport, waste treatments	Swiss Federal Office for the Environment (FOEN)
IDEMAT 2001	engineering materials (metals, alloys, plastics, wood), energy and transport	Delft Technical University, The Netherlands
European Database for Corrugated Board - Life Cycle Studies	Corrugated board (packaging) production	FEFCO (European Federation of Corrugated Board Manufacturers) http://www.fefco.org

Figure 17: LCI databases for construction materials and processes (Thiebault, 2010)

2.2.4 Life Cycle Impact Assessment (LCIA)

The Impact Assessment is the third stage of the Life Cycle Assessment. It is where the potential environmental impacts are estimated and classified, characterized, normalized and weighted. This stage will provide the main information for the next stage, where the interpretation of the whole LCA is made. In this stage, the results obtained in the inventory phase are analyzed. It is calculated the contribution to the studied impacts of each phase or process of the life cycle. This is achieved by studying the effect that the emissions and resources used on each stage of the product life have on each environmental potential impact studied. All of this data must be reduced to the equivalent unit of the most significant contributor substance to the impact categories that are being studied, and then be weighted to obtain one value for each process or component analyzed.

The methodology to use in the impact assessment phase of an LCA is not well defined yet in the standards, and there exist many different ways of carrying it out which are use currently. To develop a LCA, several categories of impacts exists that can be studied in a Life Cycle Assessment. There are as well many methods that can be used for this, regarding what impacts are wanted to be included in the study or the type of model used to characterize those impacts, and they usually differ in the databases used on the Life Cycle Inventory. However, the methodology used is similar for all of them. Some of the more common and more used methods used are for instance the Eco-indicator, Ecosystem Damage Potential (EDP), the Environmental Design of Industrial Products (EDIP), the IPCC or the IMPACT 2002+. One of the most used software to develop a Life Cycle Assessment is SimaPro. This software has several assessment methods with different characterization, normalization and weighting methodologies. Some of the methods used in SimaPro are the ECO-Indicator 99, Ecopoints 97 and CML baseline 2000, which are the more used ones; older versions of the CML and ECO-indicator, and some methods oriented to product design. In this chapter some of these LCIA methods will be described more in detail.

ISO 14042 recommends following a standard procedure to develop the LCA and defines the elements that are mandatory to include, and the ones that are optional. Following this method will help with the process, and allows considering each different element separately and will give transparency to the whole process.

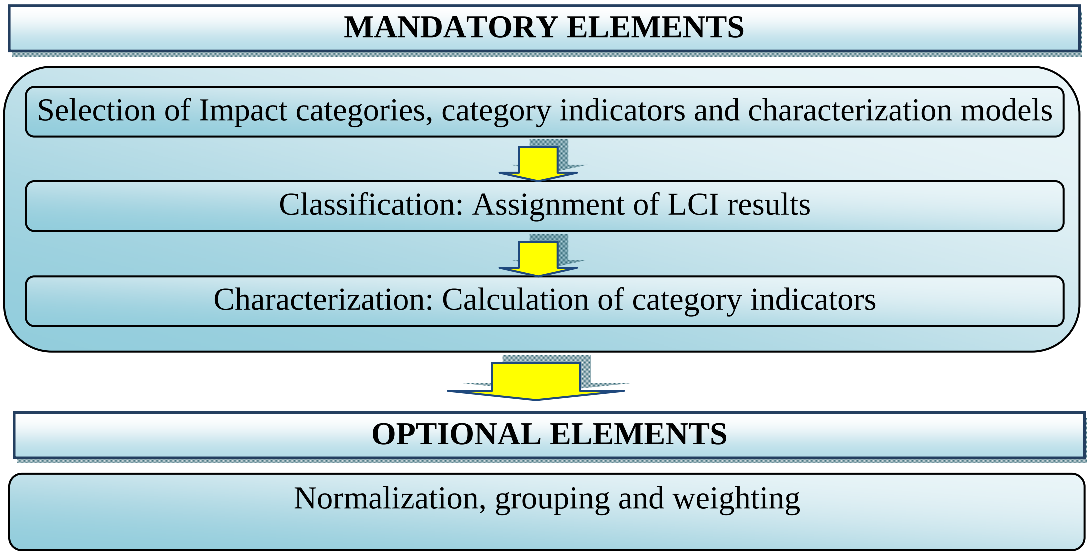


Figure 18: Recommended methodology to perform a LCA (ISO 14042)

Mandatory Elements for the LCIA

Selection of the impact categories

In this step, the impact categories and the characterization methods that are going to be use are chosen. The selection of the appropriate categories and methodology has to be done regarding the main goals that want to be achieved with the study (defined in the first stage of the LCA). According to the ISO standards for the LCIA, ISO 14042, the impact categories can be divided according to its area of impact into three main groups. These three categories would be the resources use, human health or ecological impact, which were described by Pennington et al. (2004) as Areas of Protection (AoP).

Another different approach is to divide them according to its environmental relevance (Guineé et al. 2001). The impact categories in this case, would be divided in baseline impact categories, study-specific impact categories or other impact categories. As it is shown in the figure 19, the baseline impact group includes the commonly studied impact categories, while the study-specific impact includes those impacts that are only included if the goal of study requires it. In the last group, there are all the rest impact categories that are not usually studied, but can be included in a very specific and complex study.

Group A Baseline Impact Categories	Group B Study-Specific Impact Categories	Group C Other Impact Categories
Depletion of abiotic resource	Land use – loss of life support function	Depletion of biotic resources
Land use – land competition	Land use – loss biodiversity	Desiccation
Climate change	Freshwater sediment ecotoxicity	Malodorous water
Stratospheric ozone depletion	Marine sediment ecotoxicity	Etc.
Human toxicity	Ionizing radiation	
Freshwater aquatic ecotoxicity	Malodorous air	
Marine aquatic ecotoxicity	Noise	
Terrestrial ecotoxicity	Waste heat	
Photo-oxidant formation	Casualties	
Acidification		
Eutrophication		

Figure 19: Groups of categories Impacts (Guinée et al., 2001)

Classification:

In this step of the LCIA, the different flows included in the inventory are assigned to each impact category and the impacts are quantified for each stage (Pennington et al., 2004). The table below shows some classifications for the LCI main flows for the more usually studied impact categories (SAIC, 2006).

Impact Category	Scale	Examples of LCI Data	Indicator
Abiotic Depletion	Global	Quantity of minerals used Quantity of fossil fuels used	ADP (Abiotic Depletion Potential)
Climate change	Global	Carbon Dioxide ($CO2$) Nitrogen Dioxide ($NO2$) Methane ($CH4$)	GWP (Global Warming potential)
Acidification	Local	Sulfur Oxides (SOX) Nitrogen Oxides (NOX) Ammonia ($NH4$)	AP (Acidification Potential)
Eutrophication	Local	Phosphate ($PO4$) Nitrogen Oxide (NO) Nitrogen Dioxide ($NO2$) Nitrates Ammonia ($NH4$)	EP (Eutrophication Potential)
Photo-oxidant formation	Local	Non-methane hydrocarbon (NMHC)	POCP (Photo-Oxidant Creation Pot.)
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs)	ODP (Ozone Depletion Potential)

Figure 20: Main impact categories (SAIC, 2006)

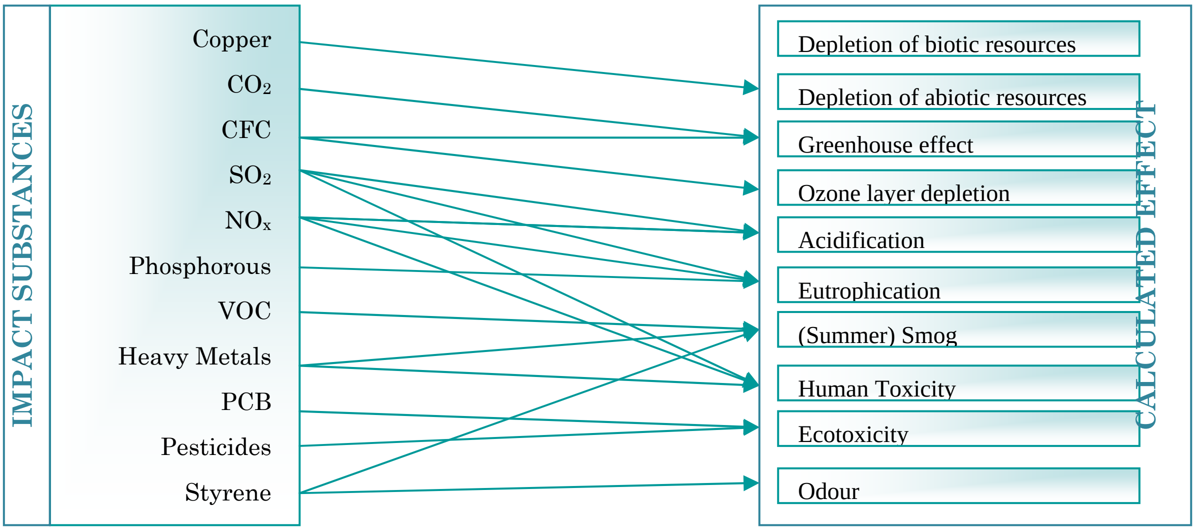


Figure 21: Classification in accordance with the Dutch LCA manual (Heijungs, 1992).

Characterization:

The category indicators are calculated for each impact categories using characterization factors. These factors are used as coefficients that multiply each inventory flow and give to each flow its relative importance regarding the impact category that is being studied. The equations above show the procedure to obtain the potential impact indicators using the characterization factors (Brattebø et al., 2009):

$$e_{ij} = x_i * f_{ij}$$

$$d_k = \sum_{i=1,j=a}^{i=h,j=p} e_{ij} * c_{jk}$$

i = parameter studied of the system
j = item or contaminant emitted
k = impact category
e_{ij} = emissions of item j regarding i parameter
f_{ij} = emission of item j per unit of i parameter
x_i = amount of i parameter consumed
d_k = total potential impact in impact category k
c_{jk} = characterization factor that scales the emissions e_{ij} for each category k

Although nowadays exist several databases and literature where these characterization factors can be found, and all the LCA software packages have them already implemented in their system, the characterization factors are estimated with the characterization models. Some of the models used to calculate these factors are base in midpoints or endpoints, using the cause-effect chain proposed by Finnveden in 1996.

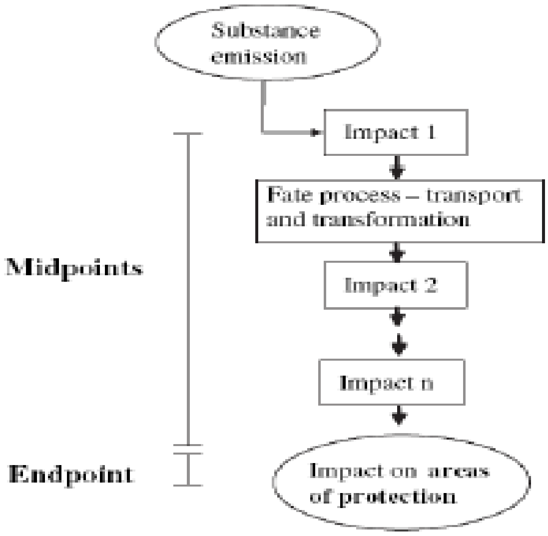


Figure 22: Cause-effect chain to present the concepts of midpoint and endpoint (Finnveden et al., 2009)

The midpoint approach models assess the impact categories regarding to the baseline impact categories (Guinée et al. 2001) and its impact to the environment, while the endpoint approach evaluates the damage caused to the Areas of Protection (AoPs) (Pennington et al., 2004; Finnveden et al., 2009). The endpoint methods should focus on the weighting strategies so the final result is accurate and reliable. This is a handicap for this approach because not all weighting methods for all impact categories are well established and developed yet, in addition to the subjectivity of the weighting factors that are somehow tied to moral and cultural issues.

Main Impact Categories and Characterization factors:

The impact categories that are going to be included in the study depend directly to the goal of the whole Life Cycle Assessment. Some of the main impact categories that are usually included in a Life Cycle Assessment are the greenhouse effect, the stratospheric ozone depletion, the acidification, eutrophication, toxicity, natural resources consumption, energy consumption, photochemical smog, solid or liquid waste generation, heavy metal emissions.

- Greenhouse Effect:

The greenhouse effect is the warming of the Earth's atmosphere due to an increase of gases like CO_2, usually emissions produced in the fossil fuel consumption, which prevent the heat to leave the Earth. This warming will lead to an increase on the temperature of the Earth with catastrophic results, such as the melting of the poles with the consequent increase of the sea levels or the desertification of many urbanized areas of the world and its effect in the agriculture and way of living. CO_2 emissions are usually taking as a reference to measure the greenhouse effect, as it is its main inducer. However, many other substances contribute to increase it, such as CH_4, N_2O, or even water vapor. Although water vapor has an important effect in the greenhouse effect, almost comparing with the CO_2, it is not usually taken into account due to its effect to prevent solar radiation to get to the Earth surface. This characteristic of the water vapor, which CO_2 does not have, equilibrates its contribution to the global warming. The effect of these substances on the global warming is measure by its ability to absorb radiation in comparison to the CO_2. These characteristics also depend on the frame time considered. For instance, according to Kyoto protocol, the global warming potential (GWP) of the CH_4 is 56 times the effect of CO_2 in 20 years time, but it decreases to 23 when comparing for 100 years. Kyoto protocol demands for the protocol signers to use the Intergovernmental Panel of Climate Change (IPCC) values for the GWP that are established for 100 years of frame time. The table below gathers the main substances normally considered as contributors to the global warming, and the characterization factors (IPCC; 1996, 2001).

Substance	IPCC 1996	IPCC 2001
CO_2	1	1
CH_4	21	23
N_2O	310	296
HFC-23	11700	12000
HFC-125	2800	3400
HFC-134a	1300	1300
HFC-143a	3800	4300
HFC-152a	140	120
HFC-227ea	2900	3500
HFC-236fa	6300	9400
PFCs(CF_4)	6500	5700
C_2F_6	9200	11900
SF_6	23900	22200

Figure 23: GWP characterization factors in kg eq. CO_2 by the Intergovernmental Panel of Climate Change (IPCC; 1996, 2001)

- Stratospheric Ozone Depletion:

The ozone, O_3, is found in the upper layers of the atmosphere and it absorbs most of the harmful radiation preventing ultraviolet rays from reaching the surface of the earth. On the last decades, the thickness of the ozone layer has been decreasing dangerously. This effect is due to the emission and accumulation in the atmosphere of certain chemicals such as chlorofluorocarbons (CFCs). These compounds are released into the atmosphere from foams and aerosol propellant vaporizers used and produced worldwide. Fortunately, many of the industrial countries have policies and laws against the use and manufacture of these kinds of products. The CFC_{11} is one of the principal causes to the stratospheric ozone layer depletion, and its impact is taken as reference to characterize the impact of each substance in the ozone destruction. The depletion capacity that a substance has always depends on the amounts of chlorine or bromine that the molecules have, but also depends on the time of live that the molecule has in the atmosphere before it is degraded. The table below shows some characterization factors for CFCs compounds by the U.S. Environmental Protection Agency.

Substance	Kg CFC-11 eq.
CFC-11	1
CFC-12	1
CFC-113	0,8
CFC-114	1
CFC-115	0,6

Figure 24: Potential stratospheric ozone depletion in kg eq. CFC_{11} (U.S. EPA)

- Acidification:

The acid rain is cause by the emissions of oxides mainly produced in the combustion of fossil fuels. These oxides are mainly base on sulfur and nitrogen such as SO_2 and NOx. This gasses when combined with the water in the atmosphere formed H_2SO_4 and HNO_3, which are the principal components of the acid rain. To characterize the impact of each studied substance on the acidification, it is considerate the ability that this substance has to form compounds taking hydrogen atoms from the air molecules. This ability is related to the one of the SO2, which is one of the main causes of the acid rain. The substances that are normally considered as contributors to this impact category are SO_2, SO_3, NOx, HCl, HNO3, H_2SO_4, H_3PO_4, HF, H_2S and NH_3. The characterization factors for the main contributors are show in the table below.

Substance	Kg SO_2 eq.
SOx	1
NH_3	1,88
NO_x	0,7

Figure 25: Acidification characterization factors in kg eq. SO_2 (Eco-indicator 95)

- Eutrophication:

The eutrophication is the process that occurs when the aquatic ecosystems are enriched with nutrients, mostly based on nitrogen or phosphorus. This is because of the waste of organic or mineral matter that is accumulated in those ecosystems, with the subsequent growth of plants in the water. This enrichment of nutrients is mainly due to the wastewaters and residual wastes that are thrown to the environment untreated. This nutrient increasing may seem to be a positive thing, but on the contrary, it leads to an important decrease on the oxygen levels in the water that makes difficult the life of animal species.

The main substances that cause the eutrophication are nitrogen and phosphorus compounds, and this is the reason why all the substances eutrophication potential is based on its contribution of phosphorus to the environment comparing to the contribution of the PO4.

Substance	Kg PO_4 eq.
PO_4	1
NH_3	0,33
NO_x	0,13
N	0,42
NO_3	0,10
P	3,06

Figure 26: Eutrophication characterization factors in kg eq. PO_4 (Eco-indicator95)

- Human And Eco-Toxicity:

The human toxicity is an important impact category. The toxicity of a substance for human health depends not only in the type of substance, but also in the quantities, the ways of administrating or the exposure time. As many product and processes includes hazardous and toxic substances nowadays, this has become an important subject to study in an LCA. Analogously, when these contaminators are thrown to the environment, either to the air, water or soil, even in small concentrations, can be increased to dangerous levels and become a hazard for the ecosystem.

Some LCIA methods base their toxicity assessment in the heavy metals like plumb or mercury, accumulations and wastes, some others take the particles emissions as main contributor to this impact. Nuclear radiation may also be included in the proximities of a nuclear plant. It is difficult though, to group all the toxic effects in one category, therefore there are two main categories, human health and eco-toxicity. However, there are also other divisions regarding to the level of danger that the toxicity represents and the time of effect. For instance, if the danger becomes with a short or long period of exposure or if the effect can be seen with small concentrations of product or there are needed high concentrations of it.

The substances normally included in these impact categories are heavy metals like cadmium, lead or mercury, NOx, SO_2, volatile organic compounds (VOC), chlorinated compounds, persistent organic pollutants (POP), and particulate matter (PM10).

- Resource Consumption:

The use of resources has become a relevant issue in the society nowadays. Many of the resources used are not renewable, or the renewable cycle is extremely slow (e.g. fossil fuels), and the consumption of this kind of resources is increasing constantly. The increased of individual consumption together with the growth of the Earth's population, and a barely inexistent resources management leads to an inevitable depletion of natural resources. In a LCA this depletion of resources is measured and weighted in relation to the scarcity of the resource and the rate of consumption. This means that if a resource exists abundantly in the environment, it is less important its consumption for the study. On the contrary, if it is highly and quick consumed it must be more important for this impact category. All of this makes it difficult to evaluate the impact of each factor, and it is needed to have a collected database about the resources for calculating their relevance on the study.

- Energy Consumption:

To perform an accurate assessment of the energy consumption in the whole life cycle, it must be considered all the energy associated to all the processes involved. This energy consumption is one of the main aspects that will influence the environmental impact, and therefore, it has a fundamental importance in the LCA.

The total amount of energy consumed in the life cycle must include the energy needed for the raw material extraction, the manufacture of the materials, the transportation, the energy used in the use and maintenance and finally the energy used in the end of life of the product, whether if it is recycled, incinerated or disposed. This is why is very complex to measure with accuracy the total amount of energy, but the precise the energy study, the better and reliable the LCA results would be. In order to measure the energy consumption in the LCIA, the amount of energy required directly or indirectly to produce one unit of finished product or subproduct, is used as a functional unit.

- Waste Generation:

This impact category considers the amount of wastes that are generated in the different processes and life stages of the product. It is important to divide the waste products in liquid or solid waste, because the effect on the environment is completely different for each case. It is not usually included in a LCA as an impact, but as the last stage of the life cycle. Normally it is taken into account the main subproducts used in the study and the impact of their disposal, as energy consumption in recycling, emissions caused by the incinerating or the land use for the disposal if it is not recycle, or the toxicity that they may cause.

- Heavy Metal Emissions:

Analogously to the waste generation impact category, the heavy metal emissions can be studied separately to the toxicity. This way the calculation can be more exhaustive and detailed if they are the main reason for the study. Some of the substances toxic for human and nature ecosystems that are usually included in this category are the chromium, arsenic, cadmium, mercury, thallium and plumb.

Aside from the impacts mentioned before, there are also several environmental aspects derived from the LCI that are not usually included in the impact categories but that represent also important factors in when studying the environmental impacts and should be taken into consideration, as recyclability or use of resources. Some particular examples of these issues are the use of renewable and non-renewable energy and material resources, the use or recycled resources or even the use of freshwater. These aspects are complicated to include in a LCA, but are fundamental to analyze the real impact of the studied product or process. The lists below summarize the main potential impact categories with the reference substance and unit, and the geographic scale in which the impact category has to be assessed.

IMPACT CATEGORY	UNITS
Global Warming Potential	Kg CO_2 eq./Kg
Ozone Depletion Potential	Kg CFC_{11} eq./Kg
Acidification Potential	Kg SO_2/Kg
Fresh Water Eutrophication Potential	Kg P eq./Kg to freshwater
Marine Eutrophication Potential	Kg N eq./Kg to seawater
Human Toxicity Potential	Kg 1,4 DCB eq./Kg to urban air
Photochemical Oxidant Formation Potential	Kg NMVOC eq./Kg
Particulate Matter Formation Potential	Kg PM_{10} eq./Kg
Terrestrial Ecotoxicity Potential	Kg 1,4 DCB eq./Kg to industrial soil
Freshwater Ecotoxicity Potential	Kg 1,4 DCB eq./Kg to freshwater
Marine Ecotoxicity Potential	Kg 1,4 DCB eq./Kg to seawater
Ionizing Radiation Potential	KBq U235 eq./Kg to air
Land Occupation Potentials	
Fossil Energy Resource Depletion Potential	Kg oil eq./Kg (nat. gas: MJ/Kg oil eq./m^3

Figure 27: Impact categories usually included in an LCA and reference substance

IMPACT CATEGORIES	Geographic Scale			
	Global	Regional	Local	Working Env.
Global Warming	✓			
Stratospheric Ozone Depletion	✓			
Photochemical Oxidant Formation		✓	✓	
Acidification		✓	✓	
Eutrophication		✓	✓	
Effects of waste heat water			✓	
Ecotoxicity		✓	✓	
Human Toxicity		✓	✓	
Working Environment				✓
Odor			✓	
Noise			✓	
Radiation				
Resource Consumption	✓	✓	✓	
Land Use			✓	
Waste			✓	

Figure 28: Geographic scale of the main impact categories

Optional Elements for the LCIA

Normalization:

The magnitude of the category indicator is calculated in relation to reference information (SAIC, 2006). This allows having a good overview of the impact studied taking into account previous information of a determinate area with specific characteristics and its average emissions, for example the emissions per capita on the EU. The normalization turns the indicators in unitless indexes, so the value that they represent is related to the data of a given area or studied group in a determined period of time (Guinée et al., 2001). More recent studies can be found in Hischier et al. (2009) for a world reference comparison. The normalization step has a large influence in the life cycle assessment, therefore, it is important to describe the more common methodologies and standards that can be use for normalization, and chose the best approach in each case.

Norris (2001) identifies two ways of defining normalization: On one hand there is the internal or case-specific normalization, supported by Hwang and Yoon (1981), Consoli et al. (1993) and Lippiatt, (1998, 2000), that stand that the normalization is only an operational step in order to get a commensurable value. Its main purpose is to allow and improve the comparison between the different impact categories, providing a common basis for the valuation step (SETAC, 1993). Or as said in BEES software manual, the purpose of normalization is to ”place all impact categories on the same scale”. On the other hand, there is the external normalization, so called due to the need of an external database as a reference. The table below represents the main characteristics of each approach.

Normalization goal	Type of Method	Description
Ponderate the values before weighting	Internal or case-specific approach	Divide the characterizated impact by a common basis from the same study (maximum value, sum...)
Evaluate the relative contribution and contextualize	External approach	Divide the characterizated impact by an estimated value for one region and time in particular

Figure 29: Internal and external approaches for normalization methods (Norris, 2001)

Authors as Finnveden and Lindfors, or Barnthouse et al. (1997) have described the normalization step as a way of contextualize and give a meaning to the characterization process. We can find some examples of this approach in several literatures summarized by Norris:

“The aim of the normalization of impacts is to better understand the relative proportion or magnitude for each impact category of a product system under study.” ISO 14042.33.

“The main aim of normalization is ... to relate the environmental burden of a product (or service) to the burden in its surroundings. In a sense normalization relates the micro world of an LCA to the macro world in which the product/service is embedded.” Lindeijer, 1996.

“The characterization results denote the contributions to well-known environmental problems. The meaning of the resulting numbers, however, is far from obvious. The effect scores become more meaningful by converting them to a relative contribution to the different problem types by means of normalization.”Guinée, 1995

A widely used method for normalization is to divide all values by the maximum value on each impact category. Another method used in this approach is the baseline method (Finnveden et al., 2002) where the values are divided by the values obtained from another alternative LCIA that is used as a basis for the normalization, and the results are shown in relation with the alternative. The other family of methods, on the contrary, gives more importance to interpreting the results in the right context, more than comparing it with the alternatives. This is performed by dividing each value of one impact category by the total impact result of that category, which is estimated from the total emissions of a reference system in a period of time as shown in the equation below.

$$N_i = \frac{S_i}{R_i}$$

Where N_i is the normalized value, S_i is the obtained value before normalization and R_i is the reference value and i is the impact category studied.

In 2008, Huijbregts et al. performed a study over 858 environmental interventions, and showed that all non-toxicity related impact categories were fully dominated by ten substances or substance groups: CO_2, CH_4, SO_2, NO_X, NH_3, CO, PM_{10}, NMVOC, and H-CFCs emissions to air, and emissions of compounds of N and P to freshwater.

Literature Ref.	Ref. Areas	Ref. Years	Intervention Types	Number of impact categories
Wenzel et al., 1997	Denmark	1990	Emissions	11
Breedveld et al., 1999	The Netherlands	1993/94	General	13
	EU_{15+3}	1990/94	General	12
Huijbregts et al., 2003	The Netherlands	1997/98	General	13
	EU_{15+3}	1995	General	13
	World	1990/95	General	13
Strauss et al., 2006	South Africa	2001	Abiotic resource extraction	2
Stranddorf et al., 2005	Denmark	1994	Emissions	11
	EU_{15}	1994	Emissions	11
	World	1994	Emissions	11
Bare et al., 2006	United States	1999	General	10
Lundie et al., 2007	Australia	2002/03	Toxic Emissions	5
Huijbregts, 2008	EU_{25+3}	2000	General	15
	World	2000	General	15

Figure 30: Main LCA normalization methods (Huijbregts, 2008)

Grouping:

In this step the different impact categories with similar aspects are classified together in order to make clearer the interpretation phase and the results (SAIC, 2006; Pennington et al., 2004). Grouping can be done in relation to the priority of the impact, for instance, or by the similarity of the impacts to the environment, or by any other characteristics of the impacts. In the ISO 14042 there are described two separate procedures. One consists on grouping "on a nominal basis", for example grouping by a similar characteristic of the impacts. While the other one consists on grouping "on an ordinal scale", that would be by ordering the impacts considering a value grade, for example by priority of the damage cause to the environment (Guinée et al. 2001).

Weighting and Valuating:

In order to get a weighted and unique value that summarize the whole LCA results, the different impact categories have to be summed considering their relative importance, this is achieve by using weighting factors for each impact category (SAIC, 2006; Pennington et al., 2004; Guinée et al., 2001; Brattebø et al., 2009). Analogously to what has been studied for the characterization factors, the following equations shows the procedure for obtaining the weighted potential impact indicator *EI* using the weighting factors W_i for each impact category i, and the normalized potential impact N_i.

$$EI = \sum W_i * N_i$$

Is in this step where the subjectivity of the weighting factors becomes controversial. Ethical or even cultural aspects involved in the choice of the factors that will prioritize the importance of some impact over others, differ across different points of view. This makes that the results obtained in the assessment phase are sometimes tied to subjective interpretation and therefore lacking the precision necessary to base a global LCA study (Finnveden, 1997; Bengtsson and Steen, 2000; Pennington et al., 2004).

It is important to remark that the normalization and the weighting methodologies should be congruent (Norris, 2001). If both steps of the LCIA are not based in correlated basis, this will lead to inaccurate and unrealistic results. To deal with this Norris propose two processes: The first solution is to perform both steps in a case-by-case basis, taking into account the alternatives. This requires different calculations of the values for each alternative and step. The second solution that he proposes is to perform an external normalization and then weight in separate steps using weight factors congruent with the normalization database. This solution requires consistency in the spatial and temporal frame used the life cycle inventory for all the impact categories and in the external database used for the normalization and weighting.

In this line, the table below shows the normalization and weighting factors for EDIP 97, EU-15, a global and a Danish reference for the main impact categories. For global impacts such as global warming or stratospheric ozone depletion, it is recommended to use a worldwide normalization reference. EU15 and the Danish references can be used when the goal is to compare with highly developed countries with a large contribution per capita. Regional and local impacts such as acidification, eutrophication, photochemical ozone formation, or toxicity related impacts, it is recomended to use the EU15 reference (Huijbregts, 2008).

		Normalization Factors					Weighting Factors				
IMPACT CATEGORIES (values per capita and year)		**EDIP97**	**Global**	**EU-15**	**Denmark**	**West-Europe**	**EDIP 97**	**Global**	**EU-15**	**Denmark**	**West-Europe**
Global Warming	Ton CO_2 eq.	8.7	8.7	8.7	8.7	4.73 e12	1.3	1.12	1.05	1.11	2.4
Stratospheric Ozone Depletion	Kg CFC_{11} eq.	0.2	0.103	0.103	0.103	-	23	14,22	2.46	Inf.	-
Photochemical Ozone Formation	Kg C_2H_4 eq.	20	22	25	20	8.24 e9	1.2	1	1.33	1.26	0.8
Acidification	Kg SO_2 eq.	124	59	74	101	2.74 e10	1.3	-	1.27	1.34	1.3
Eutrophication	Kg NO_3 eq.	298	95	119	260	1.25 e10	1.2	-	1.22	1.31	1
Abiotic Depletion	Kg Sb eq.	-	-	-	-	1.06 e10	-	-	-	-	0.01
Human Toxicity (air)	m^3 air	9.18 e9	4.87 e10	6.09 e10	5.53 e10	7.57 e12	1.1	-	1.40	1.42	1.1
Human Toxicity (soil)	m^3 soil	5.9 e4	4.18 e4	5.22 e4	1.79 e5	-	2.9	-	1.3	1.02	-
Human Tox. (water)	m^3 water	3.10 e2	1.02 e2	1.27 e2	1.57 e2	-	2.7	-	1.23	100	-
Ecotoxicity (water, acute)	m^3 water	4.8 e4	2.33 e4	2.91 e4	7.91 e5	5.05 e11	2.6	-	1.11	1.73	0.2
Ecotoxicity (water, chronic)	m^3 water	4.7 e5	2.82 e5	3.52 e5	7.4 e4	1.14 e14	2.6	-	1.18	1.67	0.2
Ecotoxicity (soil)	m^3 soil	3 e4	7.71 e5	9.64 e5	6.56 e5	4.73 e10	2.9	-	1	1.56	0.4

Figure 31: Normalization and weighting factors according four different references (Huijbregts, 2008)

There exist basically two different approaches for weighting, either qualitative or quantitative. Some of the most used quantitative methods that can be used are the Expert Panel methods, the Monetization method or Distance-to-Target methods. These three groups of weighting methods are described below.

- Panel Methods:

The Panel methods have been developed for a particular case (Finnveden et al.,2002). These cases can be used as a basic reference. Some of the authors that have develop this methods are: Kortman et al., 1994; Wilson and Jones, 1994; Nagata et al., 1995; Poulamaa et al., 1996; Huppes et al., 1997; Lindeijer, 1997; Sangle et al., 1999; Seppälä 1999; Harada et al., 2000; Mettier and Baumgartner, 2000. Although some generic weighting factors have been developed within this methodology, there are still many problems and issues that have to be solved for each particular case (Finnveden et al. 2002). We can find for example, the Eco-indicator 99 (Goedkoop and Spriensma, 1999), or a database with weight factors by country (Seppälä, 1999).

- Monetization Methods:

  The main purpose of the Monetization methods is to estimate the costs of the environmental impact. Some of the methods that can be found in the literature are the Environmental Priority Strategies (Steen 1999), the ExternE project (Dobson, 1998a, 1998b; van Beukering et al., 1998; Spandaro and Rabl 1999; Trukenmüller et al., 2001) and the Explicit LCA method (Newell, 1998), Ecotax ´98 (Johansson, 1999) or the Virtual Pollution Prevention Costs (Vogtlander and Bijma 2000). Many authors have written about different approaches of the monetization methods like Krozer (1992) or Huppes et al. (1997), or Craighill and Powell, (1995), Carlsson, (1997) and Sonesson et al. (2000).

- Distance To Target Methods:

  Distance to Target weighting methods (DtT) determinate the weighting factor regarding to the proximity of the actual environmental performance to the goals that are wanted to be achieve (Powell et al., 1997). This distance is defined as the actual emissions of a determined area and the critical level of emissions (Bengtsson and Steen, 2000). Some of the most used LCIA methods include DtT weighting methods, such as the Eco-scarcity, EDIP, Eco-indicator or the EPS 2000d. The Eco-Scarcity is a Swiss method that appears on 1990 (Ahbe et al.). The critical levels of emissions are based on the Swiss standards. The EDIP method (Wenzel et al., 1997; Hauschild and Wenzel, 1998) is based on Danish environmental policy. The Eco-indicator is based on the European average emissions. EPS 2000d (Steen and Ryding, 1992) is based on worldwide average emissions.

Several weighting methodologies that have been published and compared by many authors such as Lindeijer, 1996; Hertwich et al., 1997; Powell et al., 1997; Finnveden, 1999a and Bengtsson, 2000. The Dogma Project based on the Chalmers report CPM, 1998:1 collected and summarize seven of some of these authors and publications by chronological date:

- *Evaluation und Weiterentwicklung von Bewertungsmethoden für Ökobilanzen* (Braunschweig, Förster, Hofstetter, Müller-Wenk, 1994): Description and evaluation of eight different methods.

- *Comparison of four valuation methods* (Eriksson, Johannisson, Rydberg, 1995): Description of four methods and application to several countries by Chalmers University, Sweden.
- *Developments in LCA Valuation,* (Braunschweig, Förster, Hofstetter, Müller-Wenk, 1996: Compilation of previous research and discussion of development of weighting methods by Universität St. Gallen, Schweiz.
- *Valuation Methods within the Framework of Life Cycle Assessment. (*Finnveden, 1996): Compilation of existing methods and discussion of ethical principles by the Institutet för Vatten- och Luftvårdsforsk-ning in Stockholm, Sweden.
- *Normalization and Valuation,* (Lindeijer, 1996): Discussion of requirements for a good weighing method.
- *Evaluating the environmental impact of products and production processes: a comparison of six methods, (*Hertwich, Pease, Koshland, 1997): Comparison between different weighting methods and production conditions.
- *Approaches to Valuation in LCA Impact Assessment,* (Powell, Pearce, Craighill, 1997): Description of weighting methods and discussion about which one is acceptable trough a society perspective.

LCIA Methods

There are several methods used in the LCIA phase to get the indicators for the different impact categories, normalize, and weight them. As mention before, this is where reside the subjective aspects of the different assessment models, and the main reason for being criticize. A quick description of each method is included in this chapter.

- CML:

  One of the most common methods is CML. This method was developed by Leiden University and it is based in models from different previous studies from other countries such as Germany, Switzerland or Denmark. It uses a midpoint approach and provides good midpoint indicators. It is included in SimaPro software. The most important characteristics of this method are:

  - It has few characterization models for some impacts
  - It does not have any weighting method
  - It has different factors for ecotoxicity
  - It uses an infinite time period horizon, thus, some values are very high (metals)
  - It does not have impact categories for land use or particles
  - Transparency and good quality methods for calculation

- Eco-Indicator 99:

Swiss scientists developed this method, and it is focused on improving and making the weighting easier. This is achieved by analyzing just three endpoints, the most easily to understand and evaluate. This way the weighting and interpretation gets much clear and understandable. This method has developed three different versions regarding the management of subjectivity using the concept of cultural perspectives, hierarchical, egalitarian and individualistic. Each of which have different sets of choices and values. The main characteristics are:

- Different emissions to include to the other methods
- Different time frame
- Includes decomposition, land use, particles and ending of resources
- It weights by panel methods

The tree in the picture below represents schematically the methodology of the Eco-indicator.

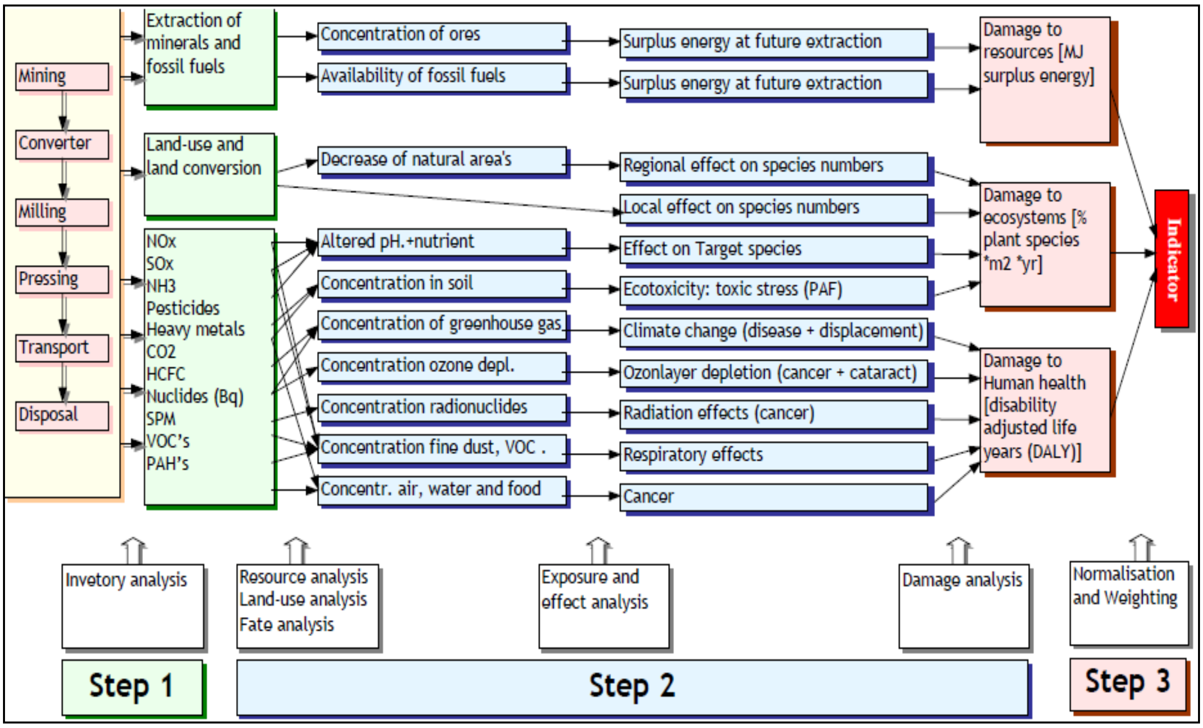


Figure 32: Ecoindicator '99 from SimaPro Manual

- EDIP:

This is a Danish method developed by environmental researchers; it is based in the CML method and improves it. EDIP is a very complete method that is based in a midpoint approach. The EDIP97 version included most of the emission impact categories, and also the resource uses and working environmental impacts (Wenzel et al., 1997, Hauschild and Wenzel, 1998).

For normalization, it uses an external database "by person" and the weighting models are based on political policies for reduction of emissions, use of resources and environmental impact. The updated version EDIP2003 (Hauschild and Potting, 2003, Potting and Hauschild, 2003) included spatially differentiated characterization models and it is mainly based in endpoint approach.

- EPS 2000d:

EPS 2000d is a method developed for supporting the product design phase. It helps assessing the choice between two different alternatives. It is based in endpoint approach, and category impacts such as human health, ecosystem resources, biodiversity, abiotic depletion or cultural values are chosen.

The characterization factors are defined by the location, size and frame time of the emissions, and it is considered the average change of a category indicator in relation with the change of an emission parameter, and estimated by the standard deviation due to the variability in the measured data.

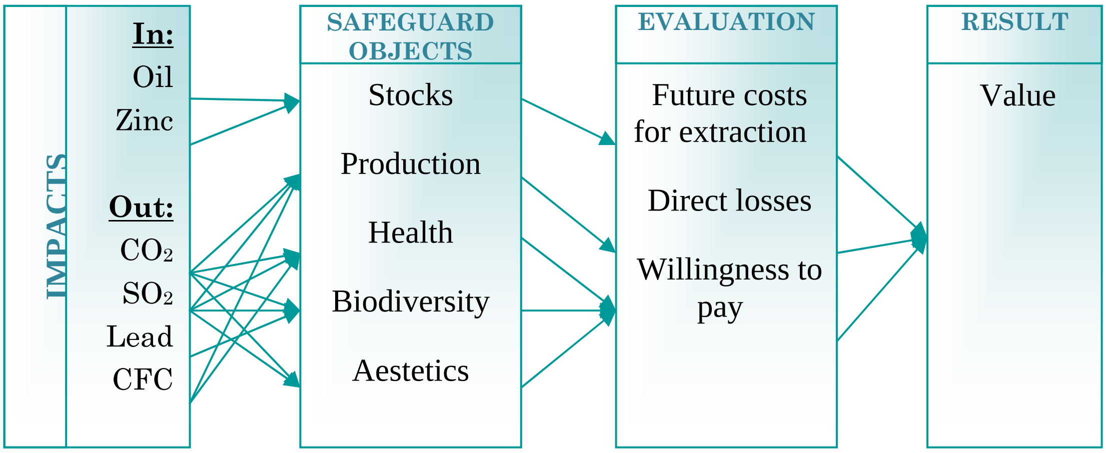


Figure 33: EPS methodology

- Ecopoints or Ecoscarcity:

This Swiss DtT method is also known as Knapsack, UBP or Ecoscarcity. Its first version is from 1990, but it has been improved and updated several times since then. It is a base on the Eco-indicator95, and its weighting methods are based on Swiss environmental policies. It is a widely used and complete method, and its strength relies on the well-established reference used for the model. The Ecoscarcity method is used mainly for standard environmental assessments of products, and it is also frequently used in companies for environmental system management.

Some of impact categories considered more important are the human health or ecosystem quality. The Ecoscarcity allows making comparative studies using the eco-factors. Originally, the eco-factors were weighting factors that are based on the annual statistical values obtained and the values considered critical by Swiss environmental policies for a determinate region. Lately there have being developed eco-factors for some other countries.

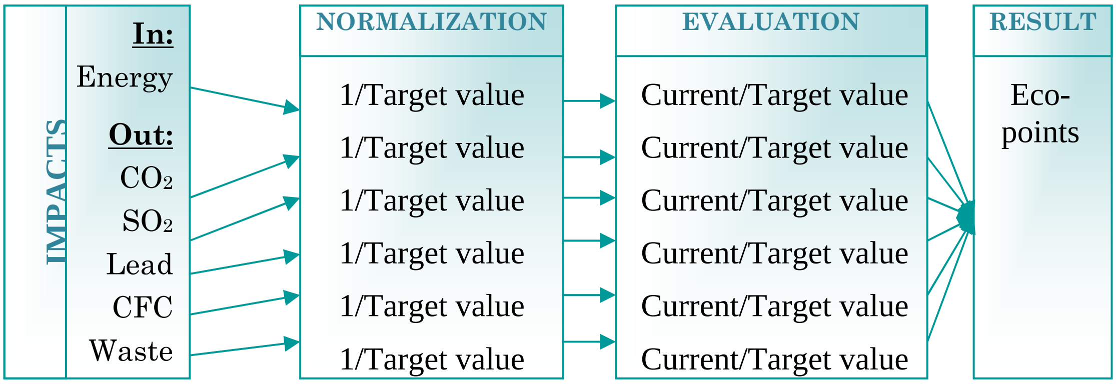


Figure 34: Ecopoints methodology

- IMPACT 2002+:

This method was developed in Switcherland by the EPFL University, and it improves characterization models from methods such us Eco-indicator or CML, and improves the calculation of human toxicity and ecotoxicity, which are now based on statistical responses and not in conservative hypothesis. For the calculation of the human toxicity, it considers carcinogen consideration, intake quantities, dose-response slope factors or the severity of the studied parameter. The method allows evaluating air emissions for indoor atmospheres and comparing them with the outdoor ones. It also includes the possibility of reusing resources. IMPACT 2002+ is based in a combination of midpoint and endpoint approaches, and includes fourteen midpoint impact categories and four endpoint damage categories (human health, ecosystem quality, climate change, and resources). All midpoint categories indicators are reference to a baseline, and related to the endpoint damage categories.

- WEST:

The IVF Work Environment Screening Tool, or WEST, is a screening method developed in Sweden to assess environmental risk and forecast the potential health damage in a working environment. It is also implemented in a computer program. This method evaluates nine environmental factors and assigns them positive or negative points, and it is possible to get a quantitative value of the results.

- JEPIX:

The JEPIX or the Japan Environmental Policy Priorities Index is a DdT method that was developed as a voluntary initiative of several private and public organizations of the environmental area in Japan, and it was first published in 2003 with the government support. It is based on the Ecoscarcity method, but it achieves to be more clear and understandable. However, it is based on political policies rather than on scientific models, and it supports decisions or choices derived from economical issues and economical costs due to the environmental impact costs. This way, it is considered a good complement to the other methods because it improves the studies with the economical point of view. It is remarkable to say that, in order to have a stable basis for the study, the weighting factors are scaled to some Japanish determinate geographical areas instead of scaling it to environmental policy factors, so the large variability in these policies do not affect the obtained results.

- TRACI:

  TRACI or the Tool for Reduction and Assessment of Chemical and Other Environmental Impacts, is a method developed by the US EPA (Environmental Protection Agency) and it emphasizes in the human and eco toxicity emissions. Although its main purpose is for being used in LCA studies, several research is being carried on in the areas of pollution prevention and sustainability measurements. TRACI is a very complete tool that is still in development in the United States.

- LIME:

  LIME or the Life cycle Impact assessment Method based on Endpoint modeling, is a LCIA method developed in Japan. It is based on an endpoint approach, and includes damage categories such as human health and ecological risk. Some of the midpoint impact categories that are considered in the study are global warming, human toxicity and resource consumption. The LIME method can be divided in three parts, characterization, damage assessment and weighting. These three parts are applied in the different steps of the assessment phase. It allows evaluating the potential socioeconomic impact due to the midpoint impact categories based on the user-cost concept. It also supports ecosystem evaluations and species extinction scenarios. The picture below explains the methodology LIME. It is taken from the Advanced Industry Science and Technology (AIST) website.

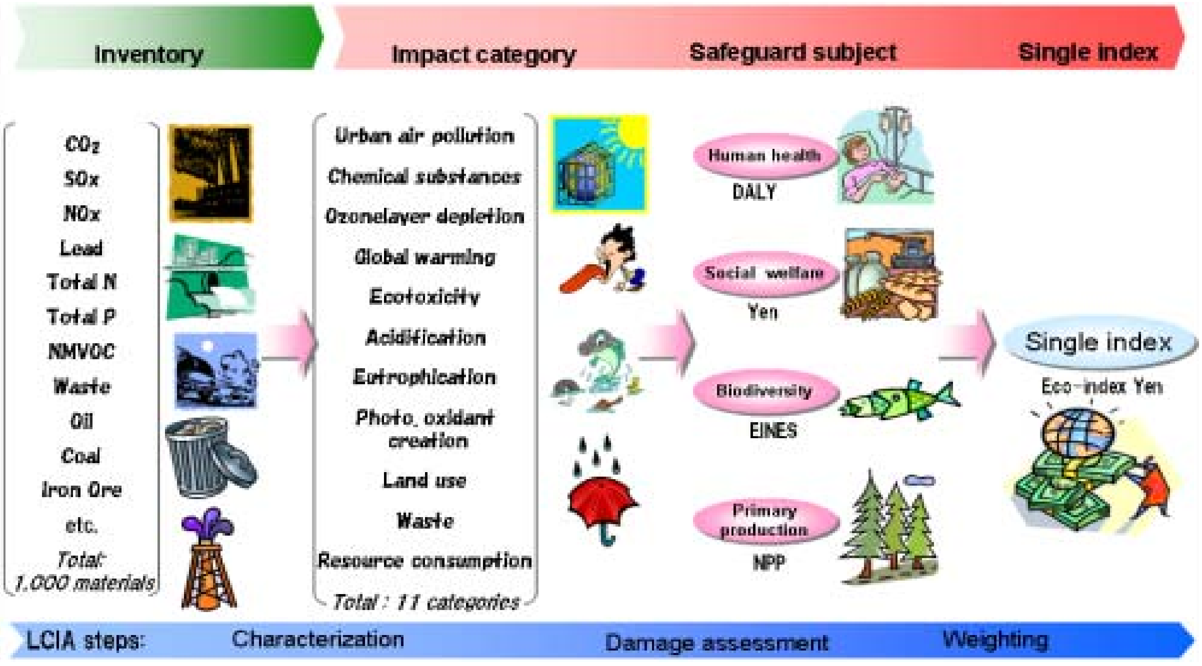


Figure 35: LIME methodology (AIST, 2011)

Main Conclusions for the LCIA Methods:

In order to clarify if it makes a big difference in the final results the choice of a particular LCIA method, L. C. Dreyer et al. (2003) performed a study to analyze the three most common used methods in LCIA: CML 2001, EDIP97 and Eco-indicator 99. The study shows that it is sometimes important to consider which method is going to be used regarding the goals of the study and the precision needed in the results.

In the study, the first two methods, CML 2001 and EDIP97, are very similar, and their main differences reside mostly in the normalization and weighting steps. These two methods are based in the midpoint approach, while the Eco-indicator is an endpoint method. The main differences between the first two methods founded in the study where on the chemical related impacts, such as human toxicity and eco-toxicity impact categories, where the values of the indicators obtained with both methods differed in two orders of magnitude. There were not important differences in the other impact categories. The causes of this variation rely on the fact that the main contributors to the human toxicity are different for each method. For example regarding the human toxicity, on CML2001 the most important contributor to the category are the metals, while in EDIP97 are solvent and nitrogen oxides. It is remarkable to say that these differences were reduced after normalization. When comparing to Eco-indicator99, however, the differences where important in several impact categories. In this case it was complicated to know the origin of this, because of the different framework and models that this method used.

In order to decide which method is better for a particular case, SETAC Europe second workshop gave some general criteria to consider when deciding the best choice (Dreyer et al., 2003):

- Method accepted by the international scientific community
- Environmental relevance of the impact category indicators studied
- Transparency and well-defined procedure for calculating characterization factors and indicators
- Quantification of the uncertainty of the values
- Feasibility in finding and calculating factors for all important substances in the inventory

2.2.5 Interpretation

In the interpretation phase, all results obtained in the inventory and assessment phase of the LCA are compiled and evaluated in order to get a final conclusion. The ISO14043 estipulate that the purpose of this phase must be not only to provide an analysis of the obtained results and obtain a conclusion, but also to provide an understandable presentation of those results (SAIC, 2006). In this step of the study, another tools can be useful to help in the decision making process, and many other aspects aside from the environmental issues can be included in the interpretation. This way not only the environmental damages can be relevant in the decision, but also cultural or economical aspects could be important too and may be considered here. Is in this phase where the significant aspects of the life cycle can be identified and the alternatives are evaluated or some activities can be adjusted if required. It is all part of an iterative procedure that leads to achieve the goal of the study and make improvements in the LCA study.

The interpretation must be consistent with the goals and the scope defined at the beginning of the study, and reflects the main purpose for the study. Also the accuracy and quality required to the data and sources must be verified so that the accuracy of the results and reliability of the study can be assured, with a clear knowledge of the boundaries, uncertainties and limitations that the study includes. The final conclusions must be according with all of the above and consider the subjectivity implied in the elections made in the middle steps of the LCA. The interpretation phase may also include recommendation for future analysis or research. An appropriate interpretation may include some of the following elements (Elcock, 2007):

- Sensitivity analysis:

  Analyzes the sensitivity of the study to the small change or errors in the studied data, and identifies the critical values that must be accurate, so that the study can be reliable. This is performed by statistical methods that changes the input parameters and analyzes the effect on the final results.

- Uncertainty analysis:

  Identify the uncertainties and the range and distribution of those estimated values and study their weight in the final results.

- Variation analysis:

  Evaluate the important aspects of the life cycle that most affects the final results, and would change significantly if the study is conducted in an alternative scenario, e.g. in a different country or with alternative resources.

- A contribution analysis:

  This analysis is performed to identify the main contributors to the different impact categories, in order to compare the elements and emissions within each category.

- A dominance analysis:

  In this case the analysis is performed to study the different activities or phases of the life cycle, and identify which ones have an important impact to the environment. This analysis can be carried out in order to study the main stages of the life cycle or, more in detail, to study the several activities included in each stage.

- A breakeven analysis:

  This kind of analysis is included when the goal is to compare two different alternatives, i.e. different products, material or processes, with different life cycles. This is a useful tool when comparing different life cycles of one product, for instance to compare the recycling of a bottle to the reuse of the same bottle. Another example is to compare two different materials used in the life cycle of one product and the impact that each one causes to the environment.

- A comparative analysis:

  A more wide analysis can be done in order to compare different systems regarding to one characteristic. This for example can be a comparison between two different countries consuming one unit of electricity (Heijungs et al., 2005).

2.3 Different types of LCA

The carrying out of an LCA may be sometimes complex and expensive; this is the reason why different ways of performing an LCA regarding its level of complexity appear. The need to support decision making processes in relation to the environment, even when there is no time, money or resources to do so, leads to the development of these different LCA methodologies. Many organizations as the Society of Environmental Toxicology and Chemistry (SETAC) and the US Environmental Protection Agency (USEPA) have worked on improving these streamlined methods. Also authors such as Weitz et al. in 1996, Todd and Curran in 1999 or Curran and Young, 1996 have made important research on this topic.

The decision of which LCA approach is better in each case must be done in congruency with the goals and limitations involving the studied system. The table below can be helpful in the election of the method. The main categories in which the different approaches can be divided in, in growing grade of complexity are: the conceptual LCA, the simplified LCA or the full LCA.

Goal and Scope considerations	More streamlined		Less streamlined
How will results be used?	Scoping, screening, identify hot spots	Estimate relative differences	Marketing, labeling, public policy
Is there a dominant life cycle stage?	Very dominant	Somewhat dominant	No dominant stage
Who is the study audience?	Internal	Internal and External	External
What is the threshold for uncertainty?	High uncertainty	Moderate	Low uncertainty
To what extent are reused/recycled materials used?	Recycled/reused materials	Virgin and reused materials	Virgin and recycled materials
How narrowly is the product defined?	Generic product	Product type	Specific product
How much is already known about the product?	High knowledge of all life cycle phases	High knowledge of some life cycle phases	Low knowledge of all life cycle phases

Figure 36: Guidance for identify the best LCA approach (Todd and Curran., 1999)

Study feature	More streamlined	Less streamlined
Completeness of life cycle stages	One stage only	All stages
Breadth of impacts/pollutants	Single impacts/ pollutants	All impacts/ pollutants
Quantification of data	Qualitative data	Quantitative data
Specificity of data	Generic/ averages	Product specific/ actual
Data quality	Estimates/ high uncertainty	Measured/low uncertainty
Transparency	Final totals only	Fully transparent
Temporal specificity	No specificity	Some specificity
Spatial specificity	No specificity	Some specificity
Scale	Local	Global
Availability of disaggregated data	Only aggregate data available	All available unaggregated data

Figure 37: Summarized profile to identify the grade of streamlining (Todd and Curran., 1999)

- **The Conceptual or Screening LCA:**

  This is the least complex of all of them, but also the least expensive in terms of time and money required to perform it. The quality data requirements are not very high, thus, the accuracy of the results is not very high, and the interpretation has to be done in congruence with the model uncertainties and limitations. It is mainly a qualitative study performed in order to identify the most significant impact categories or the life cycle stages that cause more damage to the environment. In this kind of study, it is not necessary to have very concrete data, and it gives a general estimation of the environmental damages. It must be simple and understandable and must go through the whole life cycle of the studied product in a non detailed way (Johansson et al., 2001). Te conceptual LCA can be performed as a first step to identify a critical area or stage of the life cycle which needs to be studied with a complete and exhaustive analysis (Weitz et al., 1996).

- **The simplified or streamlined LCA:**

  This study balances the complexity of the results with the cost of getting accurate data and the time needed to carry out the LCA. This method consists first in perform the LCA methodology using a reduced selected data and limit the boundaries of the system to perform a generic analysis, not as simple as the conceptual LCA, but more superficial than a complete LCA. Another way of reduce the complexity of the study can be to focus on a few important aspects of the study and perform the simplified LCA to them. However, some authors as Johansson et al. (2001), think is better to perform a screening LCA first and then a complete one applied to the parts of the process that need to be studied. After the main study, it is usually made a simplification of the results to highlight the important outputs and a posterior analysis of the reliability of the results.

  There are several ways to make an LCA simpler. Weitz et al. (1996) and Todd and Curran (1999) divided this ways into categories, and studied them, in order to have a helpful tool to decide the best way of simplifying the study without losing too much accuracy and consistence. The result of their studies is summarized in the tables below.

  In 1998 Hunt et al. performed a study in the same idea, comparing this type of simplified methods with the complete ones. They studied this for several kinds of product industries and found out that, although it depended on the product industry in question, there were similar conclusions in some aspects. They realized that the wider the knowledge of the product cycle, the better the results obtained with a streamlining method. Another remarkable finding was that one of the best ways of simplifying is to use less accurate data in those parts of the life cycle less contributive to the impact categories or reducing or even eliminate the assessment phase of the LCA (Weitz et al., 1996; Curran and Young, 1996). The tables below summarizes and describes the streamlining approaches studied by the Research Triangle Institute, and shows the main advantage and disadvantages attached to some of the studied procedures.

Streamlining Approach	Application procedure
Removing upstream components	All processes prior to final material manufacture are excluded. Includes fabrication into finished product, consumer use and post-consumer waste management.
Partially removing upstream components	All processes prior to final material manufacture are excluded, with the exception of the step just preceding final material manufacture. Includes raw materials extraction and precombustion processes for fuels used to extract raw materials.
Removing downstream components	All processes after final materials manufacture are excluded.
Removing up and downstream components	Only primary material manufacture is included, as well as any precombustion processes for fuels used in manufacturing. Sometimes referred to as a “gate-to-gate” analysis.
Using specific entries to represent impacts	Selected entries are used to approximate results in each of 24 impact categories, based on mass and subjective decisions. Other entries within each category are excluded.
Using specific entries to represent LCI	Specific entries from the individual processes comprising the LCI that correlate highly with full LCI results are searched for. Other entries are excluded.
Using “showstoppers” or “knockout criteria”	Criteria are established that, if encountered during the study, can result in an immediate decision.
Using qualitative or less accurate data	Only dominant values within each of six process groups (raw materials extraction, intermediate material manufacture, primary material and product manufacture, consumer use, waste management, and ancillary materials) are used. Other values are excluded, as are areas where data can be qualitative or otherwise of high uncertainty.
Using surrogate process data	Selected processes are replaced with apparently similar processes based on physical, chemical, or functional similarity to the datasets being replaced.
Limiting raw materials	Raw materials comprising less than 10 % by mass of the LCI totals are excluded. This approach was repeated using a 30 % limit.

Figure 38: Streamlining approaches by the RTI (Todd and Curran., 1999)

Streamlining approach	Advantages	Disadvantages
Limiting or eliminating all or some upstream stages	Clear boundaries are set; all the products and processes directly involved in producing the studied item are included	Important environmental burden from raw material extraction or production may be eliminated from the analysis
Limiting or eliminating downstream stages (cradle-to-gate)	Includes some of the significant environmental concerns within the life cycle that can be used in product improvement	Ignores important stages in the life cycle, critical for long lifetime systems, like building
Limiting or eliminating upstream and downstream stages (gate-to-gate)	Data easily gathered by the company, processes studied are likely to be directly affected by the user	Benefits of looking at the life cycle of the material are lost
Focusing on specific environmental impacts or issues	Focuses on the issues important for the user, feasible and good data quality	Important environmental considerations may be excluded
Using qualitative and quantitative data	All potential environmental issues are detected over the whole life-cycle stages	Difficulty to assess the importance of each environmental concerns
Using surrogate process data	Assessments can be made for data that would otherwise be unavailable	Surrogates must be chosen very carefully, to ensure that they actually represent the studied process
Limiting the constituents studied to those meeting a threshold volume	Limit the number of items that must be studied	By disregarding hazard and toxicity, important environmental concerns may be left behind.

Figure 39: Advantages and disadvantages of streamlining approaches (Todd and Curran, 1999)

- **The complete LCA:**

  In a full LCA, all phases are performed in detail, with the largest and accurate data set that can be possible. The analysis can be conducted both qualitatively and quantitatively. This kind of study is performed when the results that are to be obtained must be very precise and the resources needed are available, such as time and money and above all access to many of the needed data. In a detailed qualitative LCA, the goal is to study the whole system in general, and it is usually performed in cases when there is not quantitative information such as in the assessment of alternatives in the design phase of a product (Johansson et al., 2001).

  Another different way of dividing the different LCA approaches regarding the goals of the study (Ekvall, 2003, Finnveden 2009) is in Attributional or Consequential LCA. The main characteristics of this approaches is described below.

- **Attributional LCA:**

In an Attributional LCA the study is focused on analyzing each phase of the life cycle and its subsystems. In this type of studies, the whole life cycle or its sub-phases are evaluated and described as a system. It uses average data for the environmental impacts. This is the most common type of LCA that is usually performed.

- **Consequential LCA:**

  A consequential LCA is performed to describe the effects that changes have on the different life cycle phases and processes. In this case, the data used is marginal, and represents the changes in the output flows due to a small change in the input flows. Only the changing variables have to be included in the study, which simplify and reduces the complexity of the study. This kind of LCA is used for describing only the consequences of those changes, and it does not remark the midpoint impacts and effects, this leads to uncertainties that have to be considered in the interpretation phase. Usually a consequential study is complemented with an attributional one, and it is rarely performed alone (Finnveden, 2009).

Although the LCA is a widely used tool for the environmental impact assessment, there are several other simpler methods that can be used, each of one can be better for each particular case. Analogously to the LCA methods, and from a more wide perspective, the environmental assessment methods can be divided in three categories (Milá et al., 2001), the concept introduction methods, the methods with an intermediate evaluation, and the advanced methods. The first group the methods are basically qualitative, and focus on identifying and describing the environmental situation. In this group, there are methods like the checklists. The second group of methods is semi qualitative, and may be focus on one particular aspect of the environmental management. In this group there are methods based on matrix, as the MET or the MECO. Finally, the last and more advanced group of methods includes the LCA and its simplified versions. In the picture these methods are shown in relation with time and cost of the study.

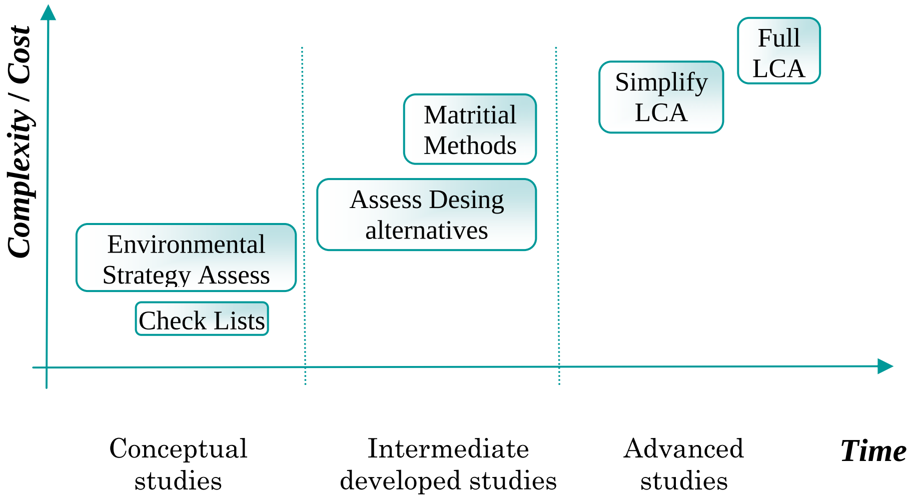
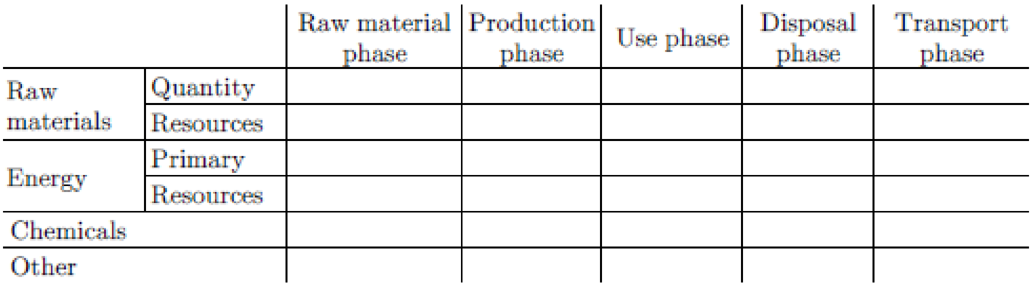


Figure 40: Environmental assessing tools regarding complexity and required time (Milá et al., 2001)

These methods from the first two groups, can be used first steps towards a full environmental study, and can be complementary to a LCV or a simplified LCV as shown in the graphic.

Some of these qualitative or semi-qualitative methods, as the matrix based methods like MECO (Material, Energy, Chemicals and Others) developed in Denmark, or MET, are widely used as an screening method, to help creating a clear and understandable structure for the LCA, allowing to easily identify the important areas for the study (Johansson et al., 2001; Pommer et al., 2003). In the MECO analysis, LCI is performed, and obtained the inputs and outputs of material, energy, other resources and emissions and wastes, for all parts of the product both in a qualitative and quantitative way (for the emissions and energy). In a MECO system, the input data is structured in a matrix where the rows represent the resources (material use, energy consumption, chemicals use and other aspects) and the columns are the different phases of the life cycle i.e. raw materials and manufacturing, product use, end-of-life management and material transport (Pommer et al., 2003). The best advantages of the MECO method is that can contemplate different impacts and concerns than the LCA, and that it can deal with either qualitative or quantitative data.



		Raw material phase	Production phase	Use phase	Disposal phase	Transport phase
Raw materials	Quantity					
	Resources					
Energy	Primary					
	Resources					
Chemicals						
Other						

Figure 41: Example of a matrix used in the MECO methodology (Pommer et al., 2003)

In the MET matrix the data included in the columns are the consumption and waste materials, energy consumption and emissions of toxic substances confronting the phases of the life cycle. The main disadvantage of the ERPA method is its lack of some life-cycle phases, and the subjectivity that involves the election of the coefficients.

Other alternative matritial method used as a previous step to complement the LCA is described by Johansson et al. (2001). The ERPA matrix (environmentally responsible product assessment) was developed by the AT&T Company (Graedel et al., 1995). This method represents the life cycle stages confronting the environmental concerns, as shown in the table below, and for each phase of the product life it is assigned a number that evaluates the magnitude of the contribution to each impact category (from 0: highest impact to 4: lowest impact), based on the experience or on previous studies. The sum of all values is scaled, evaluated, and weighted, in order to identify the most important environmental impacts and rank the parts of the life cycle regarding its contribution to the impact (Graedel ,1996).

Life-cycle stage	Environmental concerns				
	Material choice	Energy use	Solid residues	Liquid residues	Gaseous residues
Pre-manufacture					
Product manufacture					
Product packaging and transport					
Product use					
Refurbishment - recycling - disposal					

Figure 42: Product assessment matrix (Graedel et al., 1995)

There have been performed several studies to compare these methods in order to find the most appropriate one. Hur et al. (2005) carry out a comparative between a simplified LCA (quantitative approach) together with an ERPA matrix method and a complete LCA study. He concluded that the first two methods combined improved the final results by complementing each other. Although this changes for each particular case and circumstances, the general thought is that the best way is to combine a qualitative or screening method (e.g. simplified LCA or matritial method) with a quantitative one.

2.4 LCA Limitations and Uncertainties

Although the LCA methodology is widely used and it is in constant grow and development, it still presents some limitations that are mostly due to the uncertainty during the process. There exist different sources of uncertainty in the methodology. The different data used in the inventory is one of these sources. The methodologies used for analysis and evaluation can lead to different results and inaccuracy. The same happen with the references taken for normalization or even the boundaries chosen. When it comes to weighting there is also important to consider the subjectivity of the weighting factors, where ideological or cultural issues, or even lack of appropriate knowledge, cannot be obviated. It is important to know the model uncertainties in order to assess the reliability of the LCA, and thus make the right decisions or even work on reducing those uncertainties for further research. On 1992 a SETAC workshop was held, focus on LCA uncertainty (Fava et al., 1993) and more studies where carried on the topic on the following years. These studies were mainly focused on the LCI data quality. There were some studies about the uncertainty in the final results (Heijungs, 1992,1994), but they were not conclusive because they did not consider the input uncertainties and because of their lack of good statistical and analysis software to develop them. Since them, much research has been made and the methods and databases have being improved considerably, however, there is always going to be some uncertainty in the results, and it has to be considered in the decisions based on the LCA.

AUTHORS & Uncertainties Considerated	
Bevington & Robinson, 1992	Funtowicz & Ravetz, 1990
Systematic errors Random errors	Data uncertainty Model uncertainty Completeness uncertainty
Morgan & Henrion, 1990 Hofstetter,1998	Bedford & Cooke, 2001
Statistical variation Subjective judgment Linguistic imprecission Variability Inherent randomness Disagreement Approximation	Aleatory uncertainty Epistemic uncertainty Parameter uncertainty Data uncertainty Model uncertainty Ambiguity Volitional uncertainty
Huijbregts, 2001	US-EPA, 1989
Parameter uncertainty Model uncertainty Uncertainty due to choices Spatial variability Variability between sources and objects	Scenario uncertainty Parameter uncertainty Model uncertainty

Figure 43: Uncertainties classification according to several authors (Heijungs, 2004)

The differences on the data of the several existing databases reveal that there is not accuracy on the values shown on them. These differences can be caused by random errors on measurement, by the different methods used or even by the technological differences on the elements used (Finnveden et al.). It is important to remark the distinction between uncertainty on the values and the variability of the data during a period of time. However, both are sources of uncertainty and can be treated with similar approaches. There are three kinds of uncertainties due to the data that can be found on an LCA. Inexistent values, inappropriate values or data with more than one available value. This can also be applied for relationships or equations, or choices taken during the study (Heijungs et al.). It is remarkable to say that with the latest technology and software this methods have been improved and what some years ago may have been complex and a possible source of errors is now easier to perform.

There exist several approaches used in order to minimize the effects of the uncertainties on a Life Cycle Analysis. Some of the more common ones which are described by Heijungs et al. would be the scientific approach, which consists on emphasizing research to get better values; the constructivist approach which would discuss and vote the best values with the stakeholders; the legal approach, based on international standards, or the statistical approach, which, on the other hand, focus on narrowing confidence intervals for the values and parameters.

The fuzzy logic approach for the impact assessment in LCA has become an effective tool to deal with uncertainty, in order to create a helpful methodology for small companies that do not have enough resources to develop a complete and accurate LCA. Geldermann et al. developed a methodology for multi-criteria decision support based on fuzzy logic applicable to LCA. It is used to generate weight factors for the impact categories based on the introduced LCA preferences. Weckenmann and Schwan (2001) research on variability and uncertainties of the existing databases, and apply the fuzzy logic to make the best choices for the values taken for the inventory analysis based on statistical calculations. González et al. (2002) developed a methodology to make the LCA even if the company does not have the needed data to carry on the study. Ardente et al. on 2004 developed the FALCADE software (Fuzzy Approach to Life Cycle Analysis and Decision Environment). This program, also based on fuzzy logic, calculates potential impacts and allows dealing with uncertainties due to age of data, technology used, statistical issues and geographic representation. These and many other researchers have investigated on how to treat uncertainties using fuzzy logic in different stages of an LCA since then, and the research on this topic is increasing nowadays.

One important source of uncertainties in a LCA is involves the characterization models used in the assessment phase. These models are usually based on global approaches that may lead to significant variations in the obtained values when considering local or regional space scales (Brattebø et al. and Finnveden et al., (2009)). These characterization models are designed for a short time frame, and do not consider time variability. This is a handicap for making long-term assessments, and there is actual research in this field so that the impact on the emissions over time can be estimated.

2.5 Other Life Cycle Approaches

Besides the Life Cycle Assessment methodology, several other environmental assessment approaches and methods exist that are based on the study a product or system through its life cycle to assess, design or even evaluate alternatives regarding environmental issues. Some of these methods are described below, and sometimes performed complementarily (Elcock, 2007).

- **Life-Cycle Costing (LCC):**

  This life cycle approach is focus on studying the costs of a product, process or activity thorough its entire life. It is usually used in the design or development stage, to compare different alternatives. The costs included in the study are basically internal to the company. This includes not only normal costs such as the initial investment, capital, operating, abandonment, performance evaluation costs, but also indirect costs such as environmental permitting and licensing, reporting or waste handling.

- **Life-Cycle Value Assessment (LCVA):**

  In this kind of study, not only the environmental impact, but economic and social issues are taken into account. A Life-Cycle Value Assessment evaluates the several phases of the product's life cycle, i.e. the planning, production, consumption, recycling, decommissioning or disposal (Row et al., 2002). The main goals of these studies may vary, and can be financial or technical risk assessment, improvement goals or any other important matter for the company performing the analysis.

- **Life-Cycle Management (LCM):**

  The Life-Cycle Management is performed by a company as a way to coordinate all the departments and stages of the company regarding the environmental issues and policy. The whole life cycle of the product or process is studied but considering all parts of the company as a whole, instead of studying the impact for each operation or department. According to the SETAC, it provides a base for improving the company's development and assess their products from a life-cycle perspective. According to UNEP (2005), the LCM incorporates "the concepts of sustainable development, dematerialization, cleaner production, industrial ecology, eco-efficiency, etc. Policy and corporate programs used with LCM include supply chain management, extended producer responsibility, sustainable procurement, stakeholder engagement, corporate social responsibility, communication, etc. Procedural tools include design for environment, integrated and environmental management systems, product development processes, audits, environmental performance evaluation, labeling, environmental impact assessment, etc. Analytical tools include LCA, material flow analysis, environmental risk assessment, etc. Models include fate, dose-response, etc., and techniques include weighting, uncertainty, sensitivity analyses."

2.6 Existing Tools and Databases

There exist several tools and software programs to perform an LCA. These packages include several databases from different sources, and incorporate different methodologies to characterize, normalize or weight the results, and evaluate several impact categories depending on the selected method. This type of software allows comparing different results from different methodologies and databases and chose the one that best fit the requirements. In 1995, it was estimated that over 30 LCA programs had been developed already (Siegentholer, 1995). In 2000, Jönbrink et al. made a survey of all the available LCA software, and studied 24 of these packages. Some years later, Durabuild (2004) and SAIC

(2006) also made a compilation of available tools (See list below). Most of this software is commercial and some is still being developed (Thiebault, 2010).

SOFTWARE	PROVIDED BY	TYPE OF LCA	LCI DATABASES	LCIA METHODS
BEES 4.0	NIST, Building and Fire Research Department, US http://www.bfrl.nist.gov/oae/software/bees	n/a	Building products	n/a
Boustead model 5.0	Boustead consulting, UK http://www.boustead-consulting.co.uk/products.htm	Accounting & Function-based LCA	fuel production and materials processing operations	n/a
CMLCA	Leiden University, Netherlands	no process data	User defined	
JEMAI-LCA	Japan Environmental Management Association for Industry, Japan http://www.jemai.or.jp/english/lca/project.cfm	Function-based LCA	n/a	n/a
EDIP PC Tool	Danish Environmental Protection Agency, Denmark	Accounting & Function-based LCA	n/a	
EIO LCA	Carnegie Mellon University, US http://www.eiolca.net	Economic Input-Output LCA	491 sectors of the U.S economy, US NREL	n/a
ATHENA® Impact Estimator for buildings 4.0.66	The Athena Institute, Canada & US http://www.athenasmi.org	n/a	Building sector oriented	TRACI
EPS 2000 Design System	Assess Ecostrategy Scandinavia AB http://eps.esa.chalmers.se/introduction.htm	Screening & Accounting LCA	Materials, Process, Transport and products	EPS
GaBi 4	PE International, IKP University of Stuttgart, Germany http://www.gabi-software.com/	Function-based LCA	Ecoinvent data, among other	Eco'95,'99, Ecological Scarcity Method, CML 1996, 2001
GEMIS 4.5	Öko-Institut, Germany http://www.oeko.de/service/gemis/en/index.htm	Screening & accounting LCA	fossil fuels, renewables, processes for electricity and heat, raw materials, transports	CED, Cumulated material Requirement
GREET 1.8c.0 & GREET 2.7	Transportation Technology R&D Center (TTRDC), US http://www.transportation.anl.gov/modeling_simulation/GREET/index.html	n/a	Car fleet transport	n/a
IDEMAT	TU Delft, Netherlands http://www.idemat.nl	n/a	materials, processes or components	Eco'95,'99, EPS, CExD
LCAPIX 1.1	KM limited, US http://www.kmlmtd.com/pas/index.html	n/a	Boustead model, TELLUS, TME	EPS
MIET (Missing Inventory Estimation Tool)	Leiden University, Netherlands	n/a	U.S. input-output table and environmental data	n/a
EQUER	École des Mines de Paris, France http://www-cep.ensmp.fr/francais/logiciel/indexequer.html	n/a	Construction materials and processes (Ökoinventare, ETH Zürich)	Eco profiles
Envest 2	Envest, UK http://envest2.bre.co.uk/	n/a	construction materials, components and buildings	Ecopoints

Figure 44: Main existing software packages and databases. PART I. (Thiebault, 2010).

SOFTWARE	PROVIDED BY	TYPE OF LCA	LCI DATABASES	LCIA METHODS
SimaPro 7.2	Pré Consultants, Netherlands http://www.pre.nl/simapro.html	Screening, accounting & Function-based LCA	Ecoinvent v2, ETH-ESU 96 database, BUWAL 250, and IDEMAT 2001	Eco'95,'99, CMl 1992, CML 2000, EDIP, EPS 2000, Ecopoints'97, EPD, TRACI, Impact2002+, CED, IPCC
ECO-it	Pré Consultants, Netherlands http://www.pre.nl/eco-it/eco-it.htm	Screening LCA	commonly used materials, production, transport, energy and waste treatment processes	Eco 95', Eco'99
TEAM™ 4.0	Ecobilan, France https://www.ecobilan.com/uk_lcatool.php	Screening, accounting & Function-based LCA	Compatible with Ecoinvent data	Eco'99, CML 2000, IPCC
Umberto	Ifu Hamburg, Germany http://www.ifu.com/en/products/umberto	Accounting & Function-based LCA	Ecoinvent	n/a
LCAiT 4	Chalmers Industriteknik, Ekologik, Sweden	Screening, Accounting & Function-based LCA	production and combustion of fuels, production of electricity, and different transport modes	EPS, Eco-indicators, EDIP

Figure 45: Main existing software packages and databases. PART II. (Thiebault, 2010).

Chapter 3

Previous Research on LCA

3.1 LCA in the Construction Sector

Since the Industrial Revolution, the construction techniques have suffered a huge change, and it is just lately that the society is starting to understand the needs to control the environmental impacts. The constantly increase of the use of resources, or the emissions of contaminants in construction processes together with the increase on the distance from the raw materials extraction, to the manufacturing plant, and finally to the construction area, are some of the main changes that had contribute more to this. The construction sector is nowadays responsible for nearly 10 % of the world's economy, but also for much of the environmental damage caused by today's society. This has lead to a great pressure on the sector companies, which have been pushed to develop strategies to control the impact of their activities on the environment. An example of this contribution to the environmental damage can be seen when looking at the energy consumption involved in construction activities. The annual energy consumption of this sector is almost the 40 % of the total amount of energy consumed in the whole planet. Moreover, the use of resources can be considered the 50 % of the total amount of resources used, and generates about 50 % of the waste materials (Anink, D., Boonstra, C., and Mak, J., 1996) This environmental impact is present in all stages of the life cycle of products and operations, i.e. production, use and disposal.

In the decade of the 90's, this conscience of society and the need of an eco-friendly image lead the LCA methodology to become a necessary environmental tool for construction companies. Several studies have been performed since then, to evaluate the environmental impacts of the processes and more used construction materials, and nowadays there exists various reference databases and inventories that can be use to develop new LCA studies. However, the lack of consistency and the large differences that sometimes exists between the distinct sources and databases makes it difficult to obtain reliable results for comparative studies.

Although the energy consumption and waste management are two important factors in the equation, the studies are mainly focused on the environmental impact of the materials used in construction. The concrete industry, for instance, is known to generate nearly the 8 % of the CO_2 emissions (Jacobo, 2004) with a production of over 10 million tons per year. However, the end of life management is fundamental when dealing with construction activities like demolition. In the EU, over 450 millions of tons of waste is generated annually, and this volume is constantly increasing. The variety of the waste materials is also increasing, making it harder to reuse or recycle them properly, thus, just the 28 % of the waste is reuse or recycle (Symonds, Argus, Cowi and Prc Bouwcentrum, 1999).

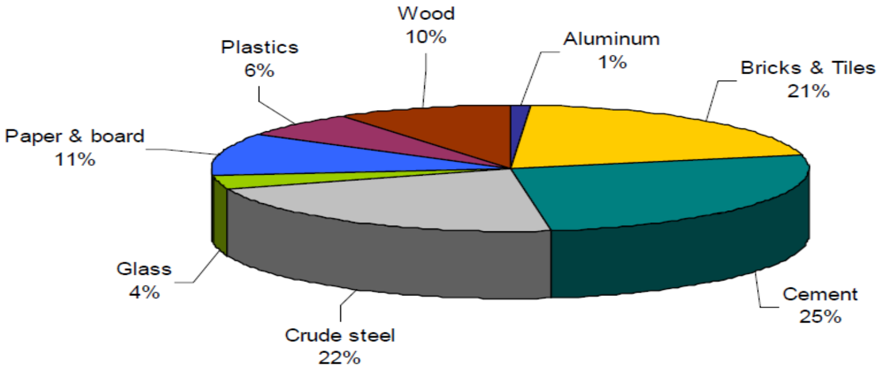


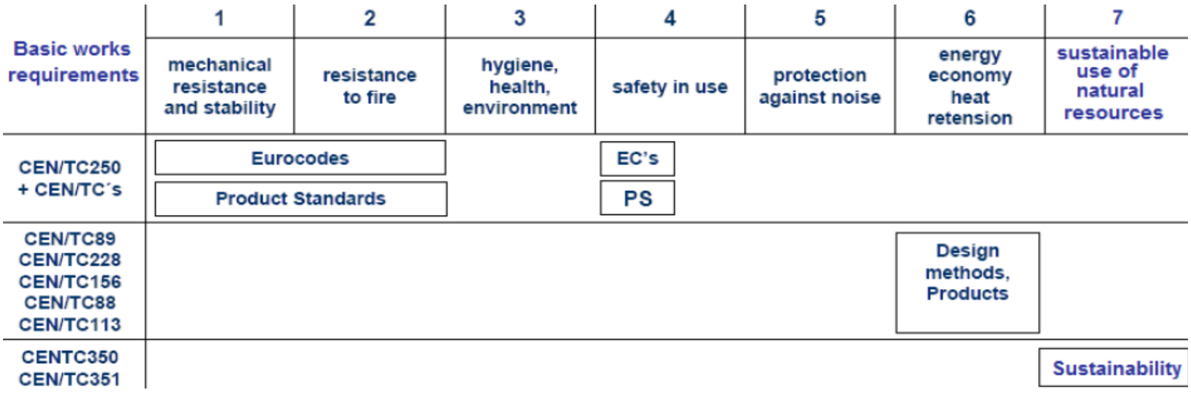
Figure 46: EU-27 production of bulk materials in 2004, (Patel, 2010)

3.1.1 EU policies on sustainable construction

In European Union, there is no existing an obligatory normative about the use of friendly materials in construction. However, the use of this kind of materials is recommended and incentivized. In this line there have been some workshops to develop the LCA as a useful tool for the environmental management. In order to perform this LCA studies, it is fundamental to have a wide knowledge of the impacts and emission data that the processes or products cause. This is not only a very complex task, but also quite expensive. The fact that many of the existing inventories and software tools are private is a handicap for the spread of these methods based on quantitative LCA studies, and makes it complicated to extend the use of these environmental tools and make them a common practice in the EU.

On the line of sustainable development, the EU contemplates in the Sixth Environment Action Programme four priority areas for action: climate change; biodiversity; environment and health; and sustainable management of resources and wastes, and provides a recommended structure for developing studies on this ambit. The European Commission proposes to carry on an Action Program regarding the sustainable construction (already existent in countries such as Sweden, UK or Finland) and to adopt the necessary means for support and promote the use of eco-labels on building materials using standardize normative or the Eurocode, not only for private companies, but also for the public administrations and governments. In relation to the continuous increase in the use of resources in the building sector, the EU has elaborated a systematic strategy and framework (2003).

In this line, the European Commission for Standardization (CEN) is preparing standards for assessment of the sustainability of construction products and works with a focus on environmental performance (CEN/TC350). The table below shows the requirements and existing or planned technical reports (TC) related to construction activities.



Basic works requirements	1 mechanical resistance and stability	2 resistance to fire	3 hygiene, health, environment	4 safety in use	5 protection against noise	6 energy economy heat retension	7 sustainable use of natural resources
CEN/TC250 + CEN/TC´s	Eurocodes Product Standards			EC's PS			
CEN/TC89 CEN/TC228 CEN/TC156 CEN/TC88 CEN/TC113						Design methods, Products	
CENTC350 CEN/TC351							Sustainability

Figure 47: Construction and Standardization (CEN, 2011)

The goal of the CEN/TC350 is to provide a common system for all European coutries for the sustainability assessment of construction activities. According to the workshop about this standards carried out in 2010, this assessment should be based in terms of environmental, social and economic performance, in accordance with a life cycle approach with quantifiable indicators. It is indicate that the assessment should consider the existing several EU policies on Construction products (CPR, Eco-design, Green Public Procurement, Energy-label, Eco-label, LMI). The table below describes some parts of these standards and shows the current status and estimated date of availability.

Ref.	TITLE	Current status	Availa ble
prEN 15643-3	Sustainability of Construction Works - Assessment of Buildings - Part 3: Framework for the assessment of social performance	Under Approval	2012-01
prEN 15643-4	Sustainability of Construction Works - Assessment of Buildings - Part 4: Framework for the assessment of economic performance	Under Approval	2012-01
FprEN 15978	Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method	Under Approval	2011-10
FprEN 15942	Sustainability of construction works - Environmental product declarations - Communication format business-to-business	Under Approval	2011-02
	Sustainability of construction works - Assessment of social performance of buildings – Methods	Under Drafting	2013-04

Figure 48: Status of the CEN/TC 350 Standards for Sustainability in construction (CEN 2011)

Different Approaches by Country

Besides the European Union's policy, each country has developed its own environmental policy. It is remarkable that northern countries as Sweden or Finland are heading the research on environmental practices, including the LCA studies, and had them already implemented in their society long time ago. A quick overview of the main aspects of some countries policies regarding LCA studies and environmental practices on the construction sector are described below.

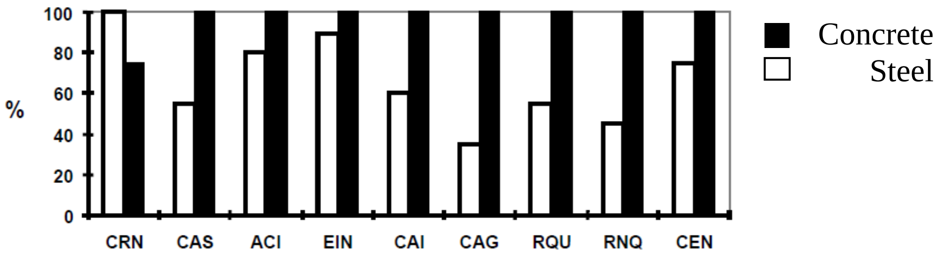
In the United Kingdom, the BRE organization has developed the Environmental Profile of Construction Products. This is a structured system to perform an environmental assessment for each company that wants to have the environmental profile. Two options can be chosen, to perform an inventory study, or an impact assessment through the life cycle. In Germany, the Stuttgart University and a group of companies and organization have conduct a study to create a methodology that helps performing an LCA for construction materials in order to have a company environmental statement or eco-labels for their products. This methodology is mainly based in complete and reliable inventory databases and checklists with a common base of boundaries and characteristics that can be applicable in all cases, and allows comparing different systems easily. In this line, some research is being made to create software for the LCA focus on construction materials and processes. In the Netherlands, in 1999, a group of Dutch companies of building products (NVTB) have created the MRPI (Environmental Relevant Product Information) method. This method is based in on the knowledge that quality data for the inventory is fundamental for getting good results. In this line, they try to standardize the LCA calculation method for building materials. In France, the French Association of Construction Products (AIMCC) performed studies to evaluate the environmental behavior of the building products. They create a common frame for inventories and qualitative reference data for LCA studies.

Council of European Producers of Materials for Construction

The Council of European Producers of Materials for Construction (CEPMC) is and European organization with members from all the main construction product associations of all European countries. This organization's mission statement is to "ensure the ongoing prosperity and sustainability of the national and European building materials industry." The European Construction Forum is a platform created by the CEPMC where all the members can work together to solve construction sector issues, as the environmental impact of the building products. The CEPMC has published several studies and position papers in the environmental area, which are meant to be a help and support for the companies on the sector to assess and manage their products. Position papers as the "Proposal for a Directive on Waste (Waste Framework)" (2006) or "Construction Standards for Sustainability" (2007) or "Eco-Labeling" (2006), establish criteria and methodology to allow performing a good environmental practice, and can be very helpful guidance for performing an LCA on construction systems.

3.2 Previous Research on Building Materials

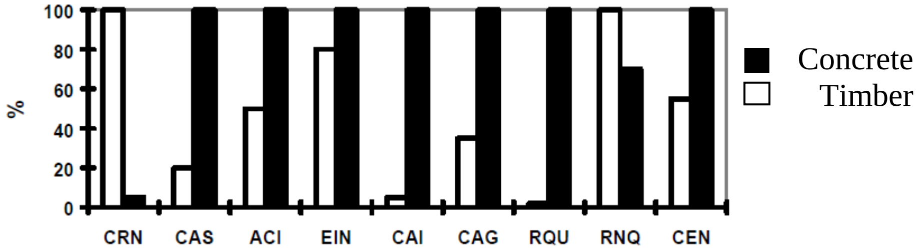
Some of the first life cycle assessment studies within the construction sector was performed in the Netherlands in 1992. This study was made as a comparative between two constructive alternatives, concrete or steel, for a highway bridge. In the study, the whole life cycle of all involved materials was evaluated, not only the steel or concrete. In this case, the concrete turned out to be better than steel in all main environmental impacts but the resource consumption, in which the steel had a better performance.



CRN: Abiotic depletion; CAS: Groundwater consumption; ACI: Acidification; EIN: Global Warming; CAI: Air pollution; CAG: Water pollution; RQU: Chemical waste; RNQ: Non-chemical waste; CEN: Energy consumption

Figure 49: Results for Zaltbommel bridge (Kortman and Lim, 1992)

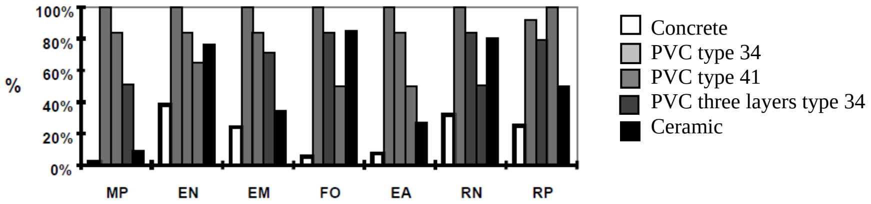
In 1993, other study compared two different track systems for the railways, wood and concrete tracks. The main findings were that the concrete tracks were environmentally better than the wood ones, in all aspects but again, the resource consumption and waste generation.



CRN: Abiotic depletion; CAS: Groundwater consumption; ACI: Acidification; EIN: Global Warming; CAI: Air pollution; CAG: Water pollution; RQU: Chemical waste; RNQ: Non-chemical waste; CEN: Energy consumption

Figure 50: Results for railway tracks (Hoefnagels et al., 1993)

In 1995 another LCA was performed to evaluate different waste-water treatment systems, with PVC, concrete or ceramic pipes. The high energy consumption rates for the PVC and the ceramic pipes made the concrete the best choice this time too.



MP: Raw material consumption; EN: Energy consumption; EM: Emissions; FO: Photochemical formation; EA: Ecotoxicity (water); RN: Non hazardous waste generation; RP: Hazardous waste generation

Figure 51: Results for waste water pipes (Intron, 1995)

One year later, in Finland, a similar analysis was made between two pavement materials, concrete or asphaltic, but there were not entirely conclusive (Häkinen and Mäkelä, 1996). This study was continued later by Spanish researcher, finding that concrete pavements were better for the environment than asphalt pavements. Anyway, the amount of the compounds of each material was so significant in the final results that the interpretation may vary with the type and circumstances of each case.

There have been done a lot of studies and research about construction materials, other studies on this topic aside from the ones mentioned above and that were also made in the 90' were performed by SBI (1993), Ankele and Steinfeldt (1995), TNO e Intron, (1994), Vold and Rønning, (1995) or Intron, (1995). These studies are very import because they become the basis for further research on the topic. It is important to remark that in these studies the cement and its derivates were environmentally better than the other alternatives, because they can be reused and recycle. They are not toxic and the resources used to product them are abundant. This is why, generally the cement base products tend to have better results in the LCA, against metal or other materials. However, the energy consumption in the production is very high, and emissions like CO_2, NO_x or SO_2 are important too. It is therefore important to make a good and congruent interpretation and always have in mind the impact categories that need to be prioritize in the analysis.

A very clear and complete study about building materials was performed in the Spain in 2007. In this case, the products were studied to analyze the impact of each part of the life cycle and to identify which were the more contributive to the global impact, and which inventory flows were more significant. This study was also performed to check if the environmental impacts have been decreased since the last study.

For the cement, the extraction of raw materials was minimal, with a 1 % of the impact due to the electricity and diesel consumption. The main contributor to the impact is by far, the production phase. On this phase, a 74 % of the whole amount is caused by the materials used in the process, mainly the production of clinker, because of its consumption of petcoke (30 %) and emissions (16 % CO_2 and 26 % NO_x). The 17 % of the impact in the production phase is caused by electricity or diesel consumption and 1 % to the infrastructure or machinery. On the distribution phase, the 7 % is due to truck transportation.

They also made a comparison with the data obtained in a previous study, and they found that in the new production of cement all impact categories had been reduced. The values for acidification, ozone depletion and eutrophication were significantly lower in the new product.

For the asphalt they found that the 35 % of the environmental impact of the production phase, again the most contributive one, is due to the materials (Bitumen with 45 %), the 12 % to the emissions and 10 % to the energy consumption. The CO_2 emissions represent the 7 % and 3 % is the electric consumption and 1 % the diesel. In this case, 20 % of the global impact is caused by distribution.

3.3 Previous Research on Bridges

There are not so many LCA studies that have been performed to assess the environmental impact of bridges. In this line, road and highway bridges count with the most extended literature. There exists a few published LCA studies applied to railway bridges, and most of them are focus on the railway system more than in the whole bridge structure and its constructive processes.

An extensive literature exists however for Life Cycle Cost modeling of concrete bridges. LCC studies were developed earlier than the LCA. One example of this is the LCC published by M. A. Ehlen, which includes agency and user costs (driver delay, vehicle operating and vehicle accident costs) and external costs. Ehlen divided these external costs in the environmental costs associated with construction materials (pollution from mining, processing, and transportation) and the environmental costs due to the construction activities (Ehlen, 1997). Another approach on LCC of bridges was published by Richard Chandler in “Life-Cycle Cost Model for Evaluating the sustainability of Bridge Decks: A comparison of conventional concrete joints and engineered cemented composite link slabs” (Chandler 2004).

In this chapter, the main Life Cycle Assessment methods that can be found in the literature are summarized and described below in appearance order.

- **Steel-Concrete Composite Bridges (Widman, 1998):**

  In the study, Widman compared two different modalities of composite road bridges to evaluate the main impacts to the environment and identify which parts of the bridge needed to be improved in this way. A steel-concrete box girder in eight spans formed the first bridge, and two I steel girders in a single span formed the second one. The different sections of the bridges can be seen in the Figure.

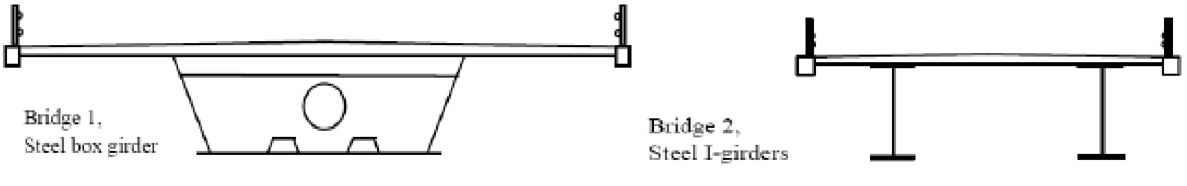


Figure 52: a) Steel box girder bridge and b) steel I-girders bridge (Widman, 1998)

The study was carried out through the whole life cycle of the bride, and all the parts that formed the bridge where included without counting terrain reinforcement or the piles nor bearings or joint. It was also evaluated the amount of emissions due to the bridge structure, road and traffic. For the study, the most accurate and latest data available was used and provided by several companies in Sweden, Norway and Finland, and three different methods where used for the LCIA. These three methods were the Environmental Priority Strategies in Product Design (EPS), the Environmental Theme Method and the Swiss Ecoscarcity Method. Each method got to different and complementary conclusions:

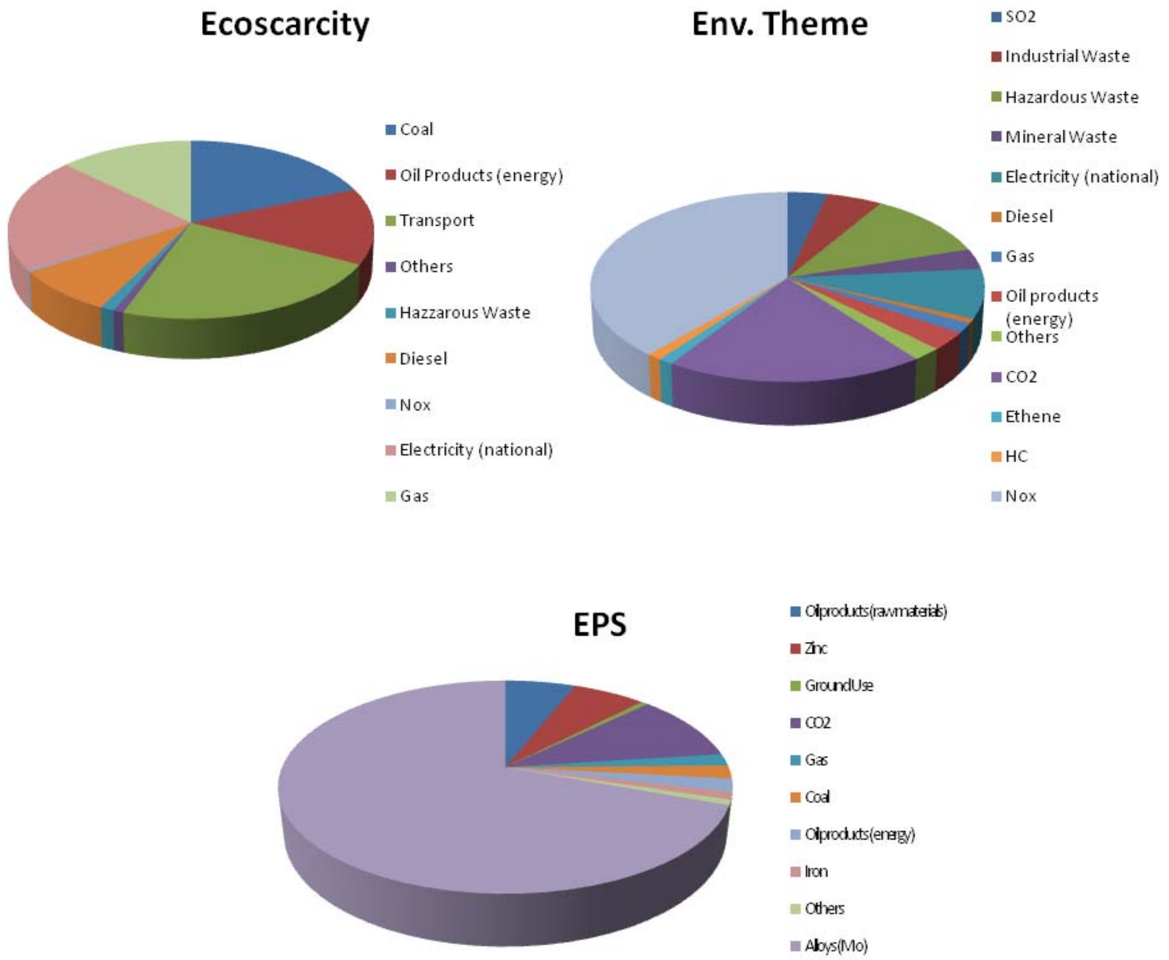


Figure 53: Results of the three methods for the box girder bridge (Widman, 1998)

- The Environmental Theme Method exposed that the most significant impacts where due to the CO_2 and NO_x emissions.
- The Ecoscarcity Method showed that the fossil fuel combustion was the main contributor to these impacts.
- The EPS Method contemplated the small amounts of Molybdenum and Zinc consumption on the steel alloy because of its rarity in the environment.

The main conclusions of this study were that the main CO_2 emissions where caused by the production of cement and steel, where the concrete contributed with nearly 50 % of the CO_2 emissions. In the comparison between the emissions due to the bridge, road and traffic in the use phase, and traffic was by far the main contributor to the air pollutant emissions. In the study, both bridges obtained similar results regardless the use phase. In this aspect, both bridges differed because of the differences in the traffic load that each bridge has (Widman 1998).

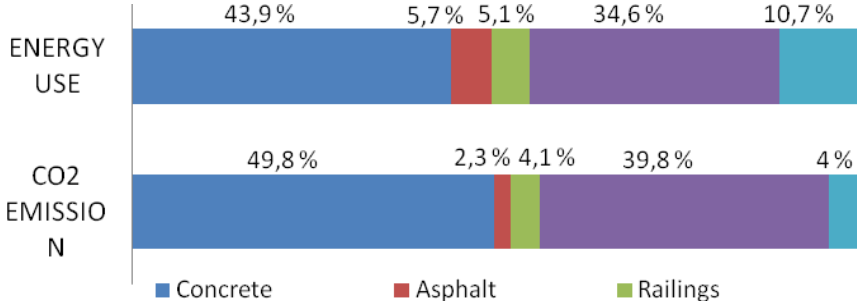


Figure 54: CO_2 emissions and energy distribution for the box girder bridge (Widman, 1998)

- **Steel and Steel-Reinforced Concrete Bridges (Horvath And Hendrickson (1998):**

In 1998, Horvath and Hendrickson developed a Life Cycle Assessment to evaluate two different alternatives for a highway in USA covering a distance of 428,2 meters, a steel girder bridge in 8 spans with several lengths and a steel-reinforced post-tensioned concrete girder bridge in 9 spans of 40,8 meters Thiebault (2010). They used an Economic Input-Output LCA for evaluating the raw material extraction, manufacture and processing phases and existing data for the other studied phases, and only electricity, fuels, ores and fertilizers consumption was assessed.

The category impacts included were the toxic emissions, ozone depletion, hazardous waste generation and management, and contaminant emissions. The results of the study were that the steel girder bridge has higher environmental impact due to the concrete production, but it has to be considered the reusability and recyclability of the steel. However, this may differ if more category impacts were included in the study (Brattebø et al. 2007).

- **Pre-stressed Concrete T-girder, Pre-stressed Concrete Box-girder and non composite steel box girder (Itoh & Kitagawa, 2000):**

Itoh and Kitagawa performed an LCA to compare three kinds of bridges, a simple pre-stressed concrete T-girder bridge, with 8 spans of 18,8 meters; a simple pre-stress concrete box girder bridge with 3 spans of 50 meters, and a simple non-composite box girder steel bridge with 3 spans of 50 meters. All of the bridges had 150 meters of total length (Thiebault, 2010). The main findings of this study can be summarized as:

  - The number of spans of the bridge conditioned the part of the bridge with more environmental impact, the superstructure or the substructure. In bridges with more spans the substructure was more important.

  - Another important result was that the steel box girder has higher environmental impact than the pre-stressed concrete box girder.

  - The production and manufacturing of materials was the phase with more contribution to the environmental impact.

- **Brick Arch bridge management (Steele** et al.**, 2002):**

  This study, performed in UK, was conducted by Steele et al., who developed a methodology for assess the environmental impact of an arch bridge during its 120 years of service life (Thiebault, 2010). The bridge was entirely made by bricks but a concrete slab footpath, and has 10.5 meters of span. In the study, the studied phases were the transportation of materials, the construction, and use and maintenance activities. The end of life proposed solution was strengthening and repairing, thus, demolition and waste disposal were not considered. SimaPro and three different inventory databases were used and from the Building Research Establishment. For the LCIA was chosen the Ecoindicator '99 methodology, and normalization was performed referring to European average values per capita and year. The main goals of the study were to compare:

  - Three different maintenance rates and identify which was the best practice regarding environmental issues.
  - Two structure strengthening technologies: concrete saddle construction or a new method of anchoring the arch barrel.

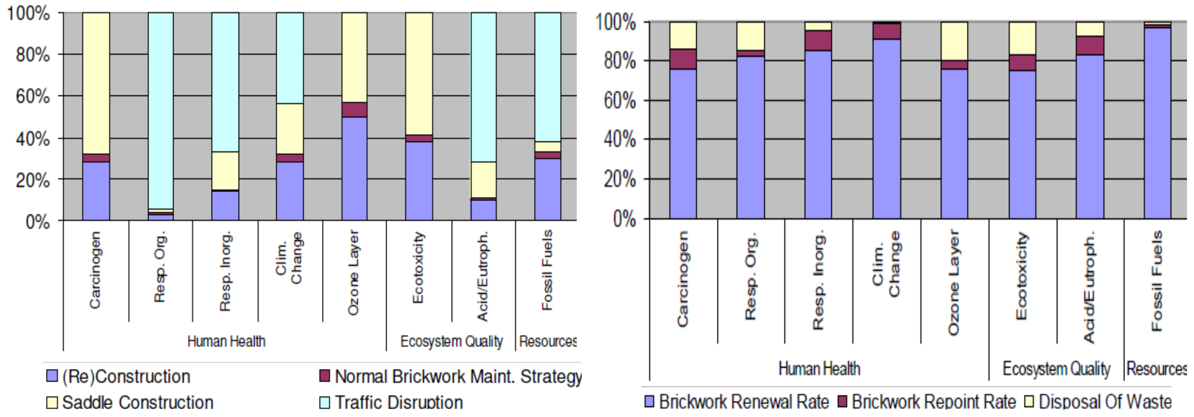


Figure 55: Results for a) Strengthening Operation and b) Repairing Operations (Cole, 2008)

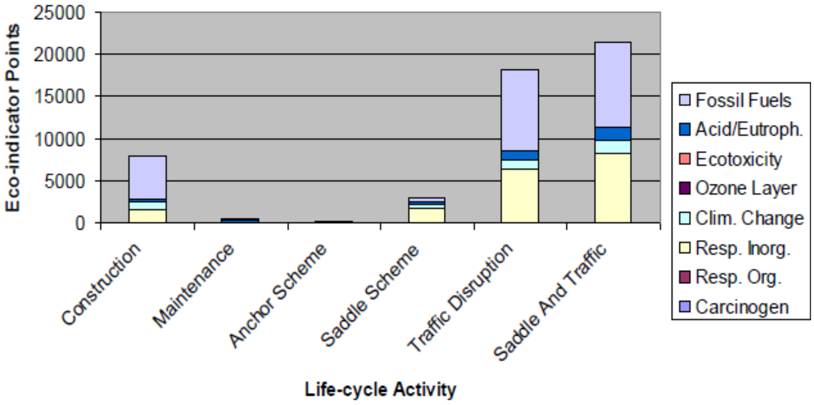


Figure 56: Global LCA results (Cole 2008)

The main conclusions obtained by Cole, are illustrated in the graphics and can be summarize as:

- The construction phase, which in this study included the material manufacture, is by far the main contributor to the environmental impact of the bridge's life cycle. Maintenance and Strengthening were not so important.
- The manufacture of the materials is the main cause of this contribution, being the clay brick production the most impacting.
- Good maintenance operations lead to long-term environmental saving.
- The new anchoring methodology has much better environmental performance. This is probably a consequence of the impact of disrupting the traffic in the other alternative.

- **Conventional vs. Minimized Girder Bridges (Itoh & Kitagawa, 2003):**

Another studied carried out by Itoh and Kitagawa in 2003 was to compare two different alternatives of I steel girder bridges. In the first bridge, the deck was built with reinforced concrete, and has an expected life of 60 years before girder replacement. In the second bridge instead, the deck was built with pre-stressed concrete, and therefore needed less I girders to support the loads. This last bridge is constructed to last a period of 100 years. In the pictures, both sections are shown.

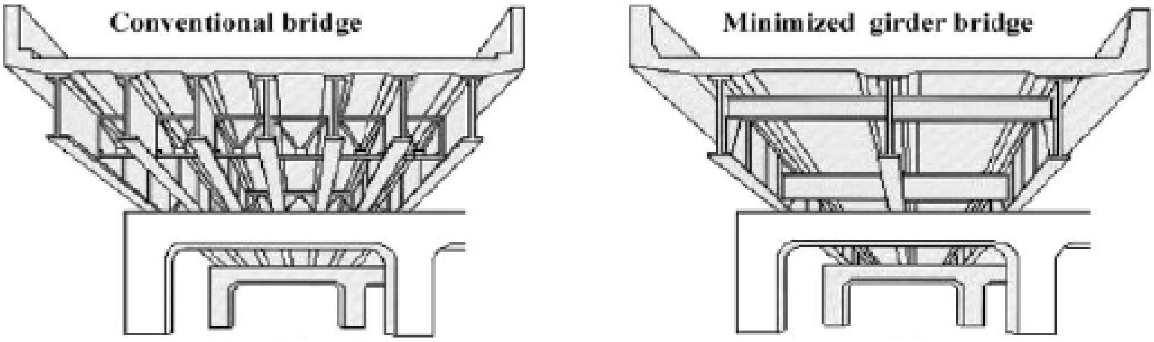


Figure 57: a) Conventional bridge and b) minimized girder bridge (Itoh et al., 2003)

In this case, the raw material extraction or the end-of-life management were not included as studied phases, and only the construction and maintenance activities were taken into account. As maintenance activities where considered the maintenance for the pavement and deck, the paintings of the girders, joints and bearings, and the demolition machinery for the replacement activities (Thiebault, 2010). The main conclusions were:

- The minimized girder bridge emitted less CO_2 than the conventional one.
- The main contributors in both bridges to the CO_2 emissions were the girders, deck and pavement.
- The pre-stressed concrete deck of the minimized girder bridge required more height, thus more concrete amount, and has higher CO_2 emissions than the conventional bridge.
- Considering the maintenance and replacement over a period of 120 years, the conventional bridge had higher CO_2 emissions.

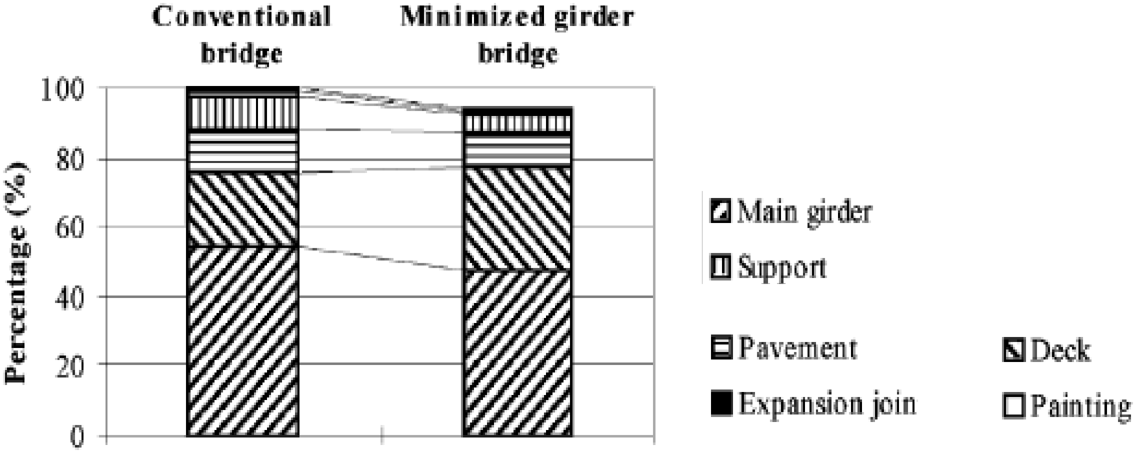


Figure 58: CO_2 emissions at construction phase (Itoh et al., 2003)

- **Steel-Concrete and Pre-stressed Concrete Decks (Martin, 2004):**

This study was performed in Australia to evaluate two different deck alternatives for a single 33 meters span bridge. The two alternatives were a steel-concrete composite deck and a pre-stressed concrete deck, and all the life cycle phases were studied. Two different scenarios were taken into consideration, the use of recycled and reused materials, and the use of new materials.

The obtained results were that the steel-concrete composite bridge had 39 % more energy consumption and 17 % more greenhouse emissions then the pre-stressed concrete deck. Regarding the different sources of material used, the pre-stressed bridge with recycled material's scenario demanded 8 % less energy, while the steel-composite bridge had 30 % less greenhouse emissions due to the better recyclability of steel against the concrete (Thiebault, 2010).

Natural Resources	Environment	Societal	Economic
Materials: New Virgin Reused Recycled Locally sourced **Energy:** Consumption Embodied **Waste:** Reuse Design for reuse Recyclinig Design for recycling **Land Utilization:** Protection Reclamation Rehabilitation **Water:** Sources	**Ecology and Culture:** Habitat Biodiversity Cultural heritage **Land Use:** Location Context of surroundings **Design and Operation:** State-of-the-art methods Environmental management Flexibility to extend life **Transport:** Mode of freight transport Degree of transportation required **Air Quality:** Emissions Dust	**Form and Space:** Aesthetics Pedestrian Scale Community severance Security well-being **Amenity:** Landscaping Noise Vibration Conflict with surroundings **Inclusion:** Consultation Accountability Env. reporting **Access:** Physically impaired **Health and Welfare:** Construction	**Viability:** Financial viability Societal and env. spend Societal and env. R&D **Social Benefits/Costs:** Infrastructure links Financial viability **Transport:** Travel dependency Modes **Employment and Skill base:** Jobs Investments in skills Training **Competitive Effects:** Effects on local economy

Figure 59: Aspects that must be considered in an environmental assessment of concrete bridges (Martin, 2004)

Another study in the same line, was carried out in The Netherlands, and compared three different types of concrete deck, lightweight concrete, normal density and high strength concrete. Besides the longer durability of the high-strength concrete, there were no significant differences in energy consumption between the alternatives.

- **Comparison of 2 bridge deck systems (Keoleian and Kendall, 2005):**

  In the study carried out by Keoleian and Kendall in 2005, two alternative concrete bridges with steel reinforced concrete deck were evaluated. The total length of both bridges was 160 meters and the first one was a traditional bridge with mechanical steel expansion joints, and the second one had engineered cemented composite link slabs. The bridges were studied over a period of 60 years of service life, but the traditional system of expansion joints was assumed to last 30.

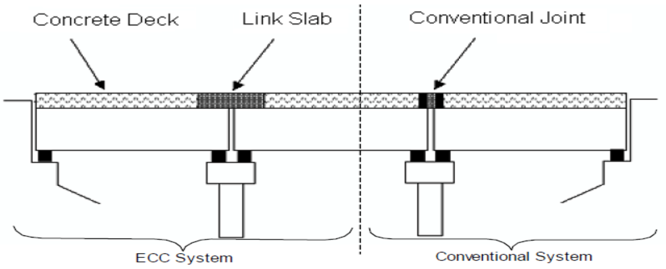
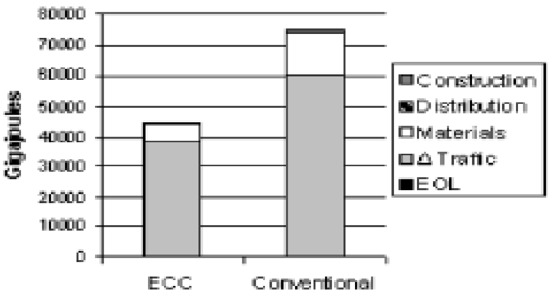


Figure 60: Bridge decks with a) ECC link slab and b) conventional mechanical steel expansion joint (Kendall et al., 2005)

  20 % of the steel was recycled. The studied impact categories were the energy consumption, material consumption, emissions to air and water, solid and waste generation. It also included socio-economic impacts as the costs due to construction and rehabilitation, to the delays and environmental pollutant damage costs. To get more reliable results, several traffic scenarios were studied, in order to identify better the impacts of each phase, which may be occulted by the high impact of the traffic (Thiebault, 2010).

  The main results obtained were that the second type of bridge had 40 % less energy consumption, emitted 39 % less CO_2, and has 37 % less cost than the first one (Keoleian et al., 2005). Keoleian et al. concluded that if the cement manufacture process were more efficient, the total amount of energy consumption will be reduced significantly. The analysis showed that the maintenance activities have an important influence in the final results. The energy consumption and the potential global warming impact are illustrated in the graphics below.



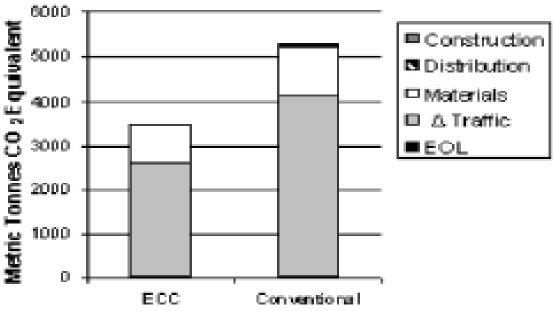


Figure 61: Total energy consumption and global warming potential by phase (Kendall et al., 2005)

- **Different forms and materials for a road bridge (Collings 2006):**

  In 2006, Collings carried out a study to find the best alternative for the environment between three different types of bridges and three different groups of materials to cross a river. As shown in the picture, the total length of the bridge was 152 meters in all the cases, and 120 meters had to be over the water. The first bridge was a cantilever bridge, the second was a cable stay bridge, and the third bridge was form by a steel arch.

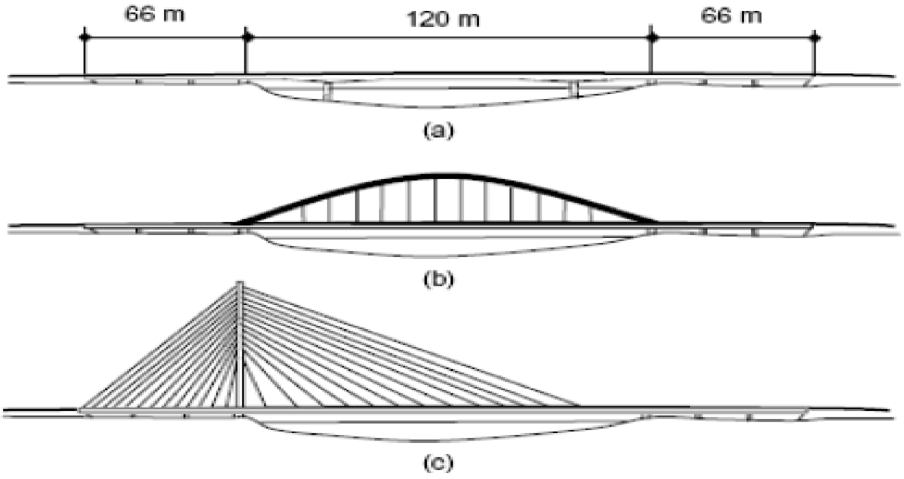


Figure 62: a) Cantilever bridge, b) arch bridge and c) cable stayed bridge (Collings, 2006)

  There were also studied the girder's systems and materials, and the alternatives were an orthotropic steel girder, a concrete girder and a steel-concrete composite girder. The maintenance operations that were included in the study were the replacement of the bearings, the repainting of the steel girders, the bridge resurfacing and waterproofing recoating. The main findings of the study are summarized below.

  - The concrete girder was the one with the less energy consumption and the lower CO_2 emissions in all cases, and the arch bridges doubled its rate.
  - The energy consumption increased with the span length, and depended on the material of the girder (see Figure).
  - Painting, waterproofing and resurfacing were the main contributive activities to the CO_2 emissions of the maintenance activities, which obtained similar values for all alternatives.
  - The construction phase in all cases had slightly more CO_2 emissions than the maintenance phase.

- **Construction, Maintenance and Repair of Bridges (Itoh** et al., **2005):**

The goal of this study performed in Japan by Itoh et al. in 2005, was to evaluate the impacts of the bridge construction and maintenance phases mainly applied to the more common bridges in the country. In the maintenance there was also included the recovery and reparations of the bridge after natural disasters as earthquakes, which are frequent in Japan. The environmental impact studied was mainly the global warming potential impact caused by the production of materials, painting, coating, welding, machinery and transportation involved in construction and maintenance operation over 100 year of service life. For this purpose, fifteen non-concrete-filled steel box piers were studied. For the emissions caused by the reconstruction and repairing seismic damage, statistical values were used and complex calculations on the damage caused.

Seismic damage condition description	Seismic recovery (duration)	CO_2 emissions (%)
The bridge is seriously damaged and reconstruction is required.	Replacement (3 months)	101
The structural damage is serious and the function is completely lost. It needs more than 2 months to recover.	Rehabilitation (2 months)	27
The structural damage is obvious, but the minimum function for emergent usage is achievable. The potential recovery duration is from 2 weeks to 2 months.	Rehabilitation (2 weeks)	18
The function is not damaged obviously and the damage can be repaired within a couple of days.	Repair (some days)	0,9
The structural damage is not obvious and specific repair is not recommended.	None	0

Figure 63: Seismic damage states and the corresponding CO_2 emissions (Itoh et al., 2005).

- **LCA and LCIA methodology (Gervasio** et al.**, 2007):**

This study presents an LCA methodology together with a Life Cycle Cost Assessment. This methodology is used to assess the construction phase of two deck alternatives for a bridge of 90 meters of length. The first alternative was a steel-concrete composite highway bridge in three spans, and the second one was a concrete deck with two pre-stressed U-girders. For the inventory they used data from steel US companies and databases from the International Iron and Steel Institute and cement producers. In the study, six environmental impact categories were included, global warming, acidification, eutrophication, air pollutants, smog formation and water intake (Thiebault, 2010).

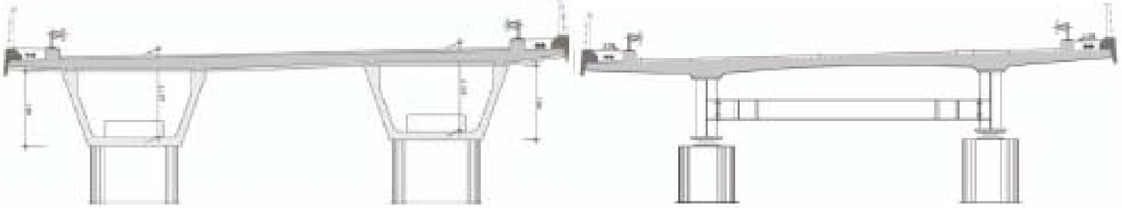


Figure 64: a) Pre-stressed concrete deck and b) steel-concrete composite deck (Gervasio et al., 2007)

Although in almost all the impact categories both alternatives obtained similar results, for the potential photochemical smog, the values for the concrete deck were much higher. Therefore, Gervasio et al. concluded that the steel-concrete deck was the best option regarding environmental issues (Gervasio et al., 2007).

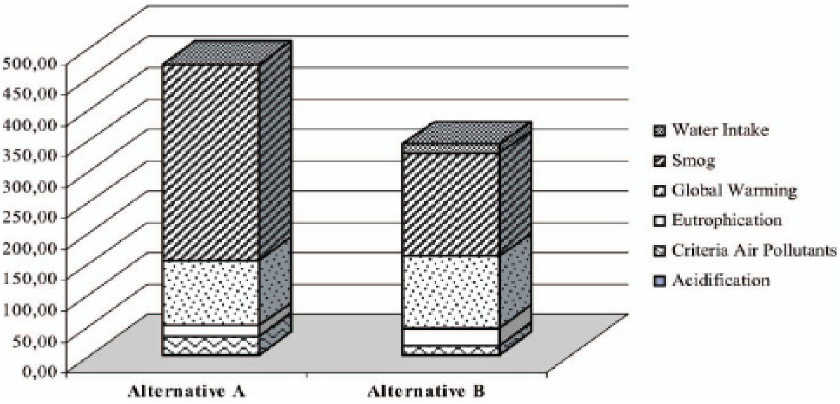


Figure 65: Normalized impacts of concrete-concrete (A) and steel-concrete composite (B) alternatives (Gervasio et al., 2007)

- **Concrete Highway Bridge Decks in Corrosive Environment (Lounis** et al.**, 2007):**

In the study, Lounis and Daigle presented a life cycle methodology for designing highway concrete bridges. This tool considered the physical, economic and environmental aspects of the bridge through its service life time, and includes all the life phases of the bridge. They applied this methodology to assess two concrete highway bridge decks of 35 meters of span, in corrosive environment, one with high-performance concrete and the other with normal concrete. High performance concrete was suppose to last over 45 years, and included supplementary cementing materials included in the inventory. The normal concrete had an expected service life of 15 years. The study was performed in a 30 frame time, so the maintenance and replace activities were included.

The results, which are illustrated in the graphics below, were that the use of the high performance concrete increased the service life of the deck, reducing the maintenance and replacing needed operations. As a consequence of this, it emitted 65 % less CO_2 in the construction and maintenance phase than the normal concrete one, and the waste generation was reduced in nearly 30 % for the high performance concrete deck (Lounis et al., 2007).

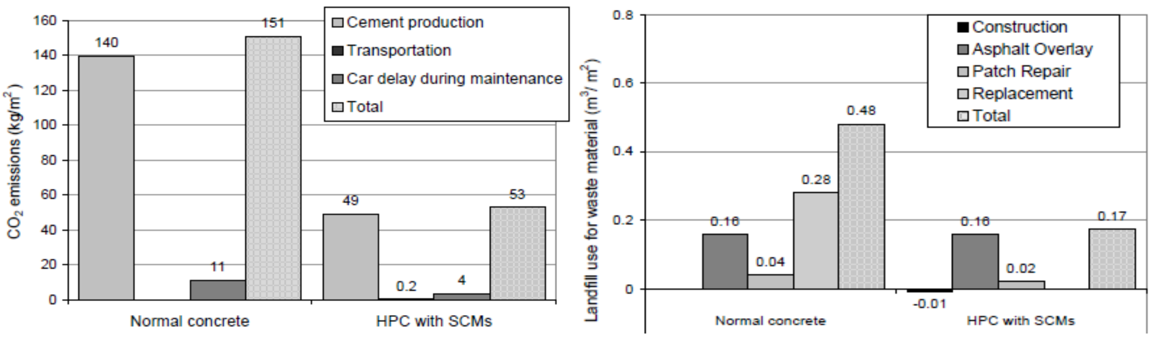


Figure 66: CO_2 emissions and volume of waste materials for normal and high performance concrete (Lounis et al., 2007)

- **Steel Box Girder, Concrete box Girder and Wooden Arch Bridge (Brattebø** et al.**, 2009):**

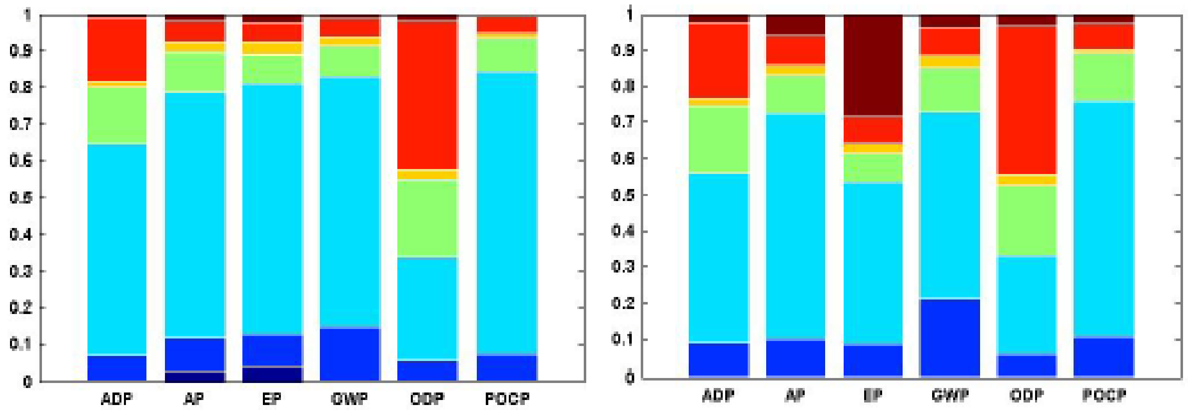
Brattebø et al. in Norway, performed an LCA on three different bridges with very different characteristics and span length during a period of 100 years of life time. The first bridge was a bridge of 42.8 meters with a steel box girder (Klenevågen). The second one was a concrete box girder bridge of 39.3 meters (Hillersvika). And the last one was an arch bridge made of wood with 37.9 meters of span (Fretheim). All the life cycle phases were considerate, and the processes included are summarized in the next table.

MATERIALS	CONSTRUCTION	USE, REPAIR AND MAINTENANCE	END OF LIFE
- Extraction - Manufacture	- Preparation of foundation - Concreting abutments - Wooden formwork - Erection of the girder, - Diesel consumption - Transport of materials, parts and workers	- Repaint the steel box girder (every 20 years) - Inspection of the steel cables of the wooden arch (every 25 years) - Repaint of wood surfaces (every 15 years). - Replace of 10 % of the parapets steel on 100 years	- Recycle all the steel - Reuse of all the concrete - Incineration of wooden components

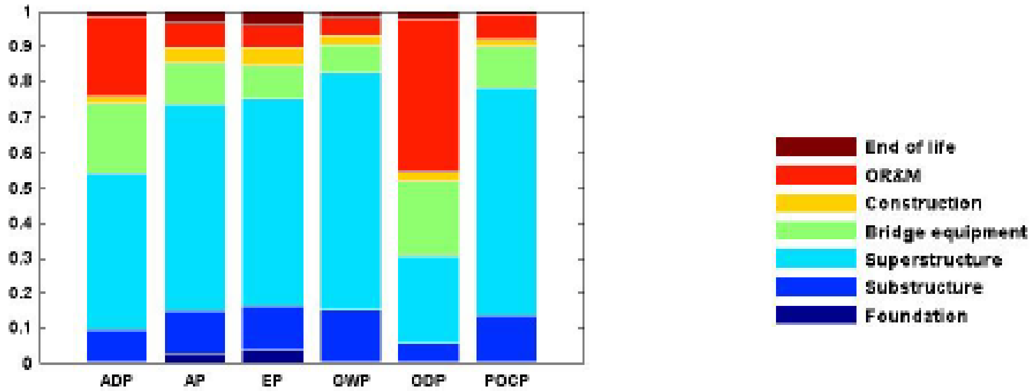
Figure 67: Life cycle phases and processes included in the ETSI study (Brattebø et al. 2009)

The study was made with data from the software SimaPro and normalized and weighted in regarding the total emission factor for Wester Europe (1995). Six impact categories were analyzed, and the results were presented showing the different contributions of both the different phases and the parts of the bridge to each impact category.

They found that the construction phase was not very relevant, and that the superstructure has a greater contribution to all environmental potential impacts, regardless the ozone layer depletion. The main results are shown in the graphics below (Thiebault, 2010).



(a) Klenevågen (b) Fretheim



(c) Hillersvika

Figure 68: Contributions of each bridge part to each impact categories (Brattebø et al., 2009)

- **Bearings and Abutment Design (Eriksen, 2009):**

In 2009, Eriksen performed an LCA on two bridges, to compare two different types of abutment systems over a period of time of 120 years. The first bridge was a concrete bridge with classical abutments of 18 meters of total length in two spans. The other was a concrete-steel composite bridge of 40 meters long in single span with integral abutments. The impact categories included in the study were those ones related with human health, ecosystem quality and consumption of resources, and the method used for the LCIA was the Eco-Indicator and the data was taken from the Ecoinvent and the International Iron and Steel Institute.

All the phases of the life cycle were studied, including the recycling of the steel (80 % with an efficiency of 95 %) and the reuse of the concrete in the end of life phase. The results were presented by phase and by impact category (see graphics below). The conclusions were that the new abutment system had better environmental performance in all impacts and that the construction phase was the one with higher contribution these impacts. It is important to remark that if the end of life management was different without considering recycling or reusing materials, the results would change considerably.

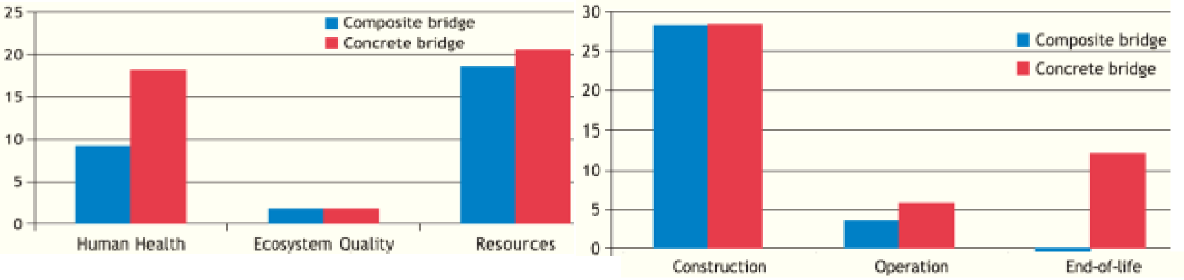


Figure 69: Total damage to the environment where the blue represents the composite bridge, and the red represents the concrete bridge, a) per impact category and b) life cycle stage (Eriksen, 2009).

- **Wood and Ultra High Performance Concrete Bridge (Bouhaya** et al.**, 2009):**

The goal of this study was to assess a new type of bridge structure, made of wood and ultra high performance concrete. This innovate structure was suppose to provide high strength with a minimum environmental impact (Bouhaya et al., 2009). Bouhaya et al. carried out a simplified LCA focus on the energy release and greenhouse gas emissions. The bridge had 25 meters of total length in single span. All the parts of the bridge were included but the foundation and the auxiliary equipment and it was considered in a period of 100 years of service life.

The study assessed all stages of the life cycle, with especial attention to the end of life. In this phase, for the wood waste management, three scenarios were considered: dumping and use as landfill; burning and use for heating; and recycling. For the concrete, the 40 % was supposed to be recycled. The machinery used for construction and demolition was included, as well as the maintenance activities and replacing for the wood. The concrete was assumed not to need maintenance. The main conclusions were:

- The production of the materials was the phase with higher energy consumption, with a 73,4 % of the total amount.
- Wood contributed positively to the greenhouse gas emissions impact due to its CO_2 biomass, and reduces the emissions in the fabrication and maintenance phases.
- Of the three studied end of life scenarios, regarding the CO_2 emissions, recycling was the best option for the wood disposal, while burning was the worst. In relation to the energy consumption, burning the wood seems to have lower rates, but not significantly.

They concluded that no scenario can be chosen as the best one, and that the election would depend on the goals of the designers. These results are summarized in the graphics below.

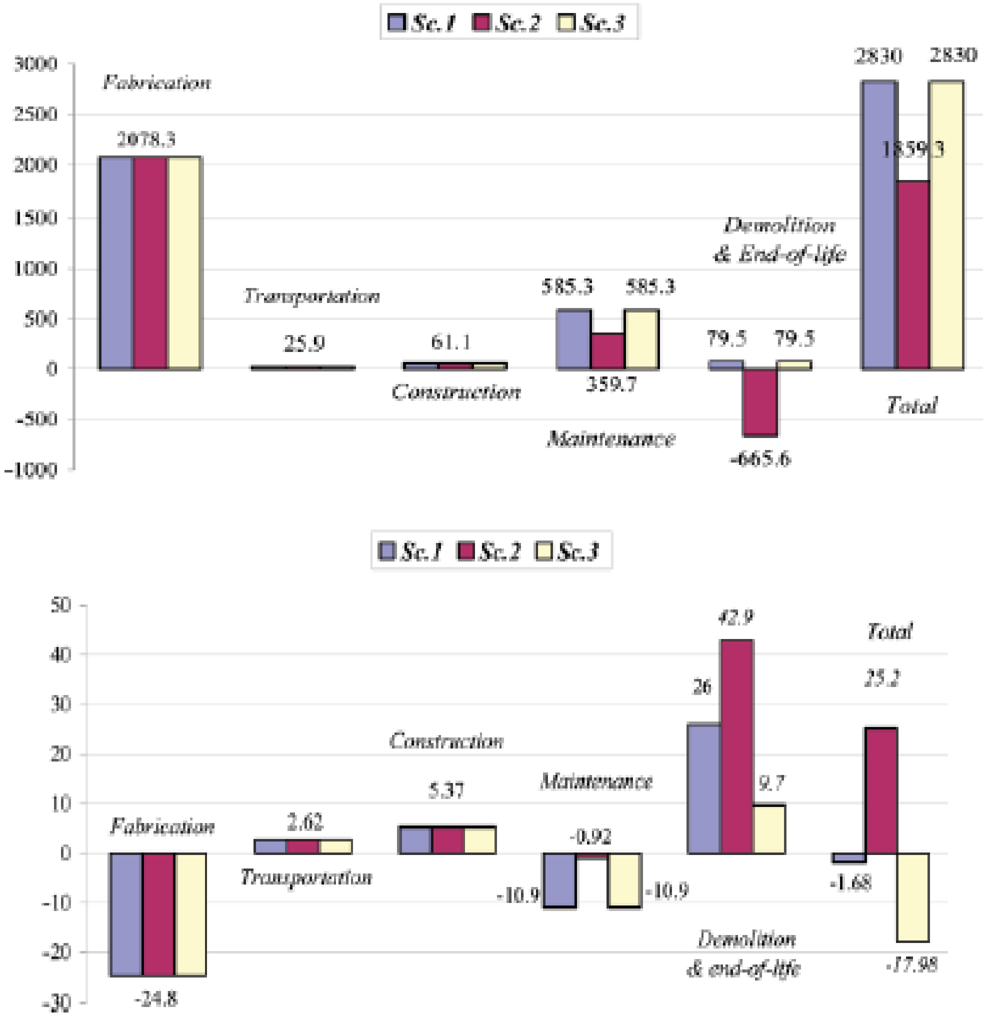
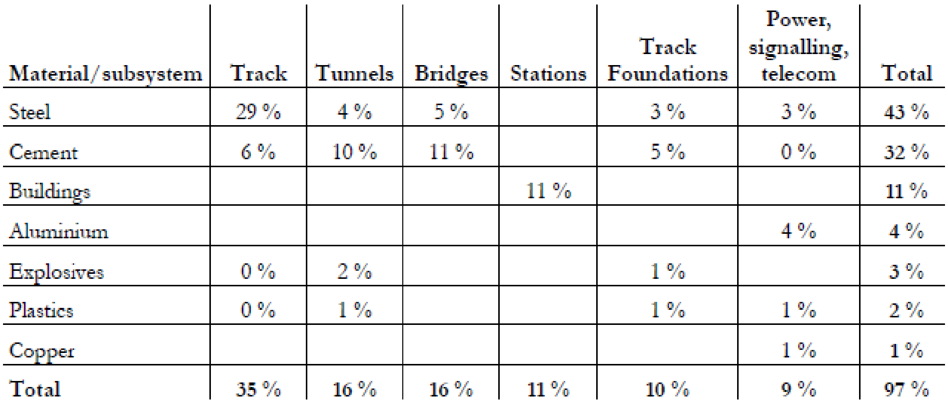


Figure 70: Distribution of a) energy and b) greenhouse gas emissions by phase (Bouhaya et al., 2008)

- **Life Cycle Assessment of Railways and Rail Transport (Stripple and Uppenberg, 2010):**

This was the first Environmental Product Declaration (EPD) for rail infrastructure and transport. The study included models to evaluate tracks and their foundations, the electric power system and the control, the tunnels, bridges and terminals, and finally the passenger and freight transportation over a service life of 60 years. The study revealed that the infrastructure was the main source of environmental impact of the whole rail system. The distribution of the impact contribution of each rail system part is shown in the table below.



Material/subsystem	Track	Tunnels	Bridges	Stations	Track Foundations	Power, signalling, telecom	Total
Steel	29 %	4 %	5 %		3 %	3 %	43 %
Cement	6 %	10 %	11 %		5 %	0 %	32 %
Buildings				11 %			11 %
Aluminium						4 %	4 %
Explosives	0 %	2 %			1 %		3 %
Plastics	0 %	1 %			1 %	1 %	2 %
Copper						1 %	1 %
Total	35 %	16 %	16 %	11 %	10 %	9 %	97 %

Figure 71: Contribution to global warming of each part of a rail system (Stripple et al., 2010)

The main conclusions regarding the bridge infrastructures were that the extraction and production of materials were the main contributors to the environmental impacts, while maintenance or transportation has significantly less importance. Infrastructure operation, obviously, had no effect. No contribution was made to ozone layer depletion.

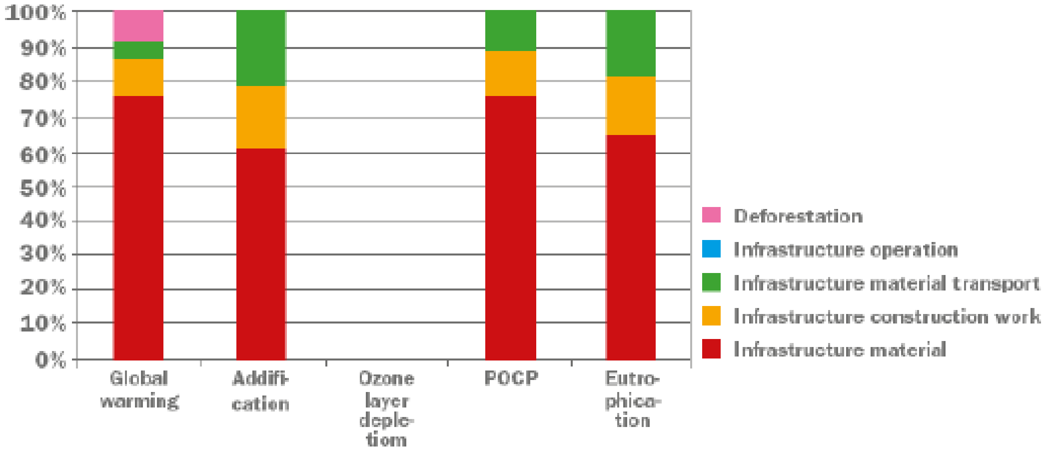


Figure 72: Distribution of the contribution to the impact categories of each bridge aspect (Stripple et al., 2010)

For railway bridges in particular, the conclusions were that the use of non-renewable materials was an important factor for the global impact contribution. The solid rock was the most used non-renewable material (68,8 %), followed by sand and gravel(15,9) and limestone (14,1 %).

3.4 Main conclusions

Some conclusions can be made after reviewing all the previous research about LCA of bridges and construction materials. It is a common result from all studies that the material production is the life cycle phase that has higher contribution to the environmental impacts. In this line, the production of concrete and steel has the worst environmental performance of all the used materials. This fact is increased too due to the large quantities of these two materials used in bridge construction. Of these two materials, the production of steel seems to be more harmful to the environment than production of concrete; however, it requires more concrete to achieve the strength behavior provided by a steel structure. It is also important to consider the end of life of these two materials, because it seems that the process of recycling the steel is worse than the reuse of concrete, although the process of separate the reinforcement from the concrete leads to the fact that recycling steel has less potential impact associated. Traditional brick bridges appear to be a good environmental choice, including that they can easily be reused in other constructions in the end of life of the bridge. However, the strength and durability requirements for the bridge structure should always be over the environmental performance of the materials involved, and here, steel and concrete have better results.

Regarding the material stage of the life cycle of bridges, future bridge designers should focus on using durable materials produced with more environmental friendly processes, or develop and extend the use of new sustainable materials without losing structural strength. A good management that promotes the reuse of existing materials can also reduce considerably the environmental burdens associated to the extraction and processing of the materials used, and decreases the use of natural resources together with the amount of waste generation. Trying to prolong the service life of the components included in the bridge will also result in lower environmental impacts. It will contribute to reduce the maintenance operations needed, like resurfacing or waterproofing, by using higher quality materials. However, it is preferable to increase the maintenance operations if it would imply to prolong the overall bridge life. Another important aspect to consider is to reduce the transportation from the providers to the construction site, by using local industries instead of buying the materials far away from the construction site, even if it may imply bigger marginal costs.

Another important fact that stands out from the literature is that the traffic disruption while construction or maintenance activities, can contribute significantly to the impact categories by incrementing for instance the diversion distance or the amount of traffic. In relation to this, the duration of the construction stage may be important, however it does not suppose a big burden when assessing the whole life cycle, because it contributes considerably less than the material extraction and production or the end of life stages. On the contrary, the frequency of the maintenance activities, and the traffic disruption attached to them, has be revealed to be an important issue to consider in the design phase, trying to identify the components which requires more reparations during lifetime and change them to better alternatives. For the end of life stage, not only the environmental burdens of recycling or disposal should matter, transportation from the bridge site to the disposal places has turned out to be a significant issue to take into consideration.

One important issue that is pointed out by Brattebø et al. in their report, is that the design of bridges should be able to be adapted and improved to future requirements, without needing to demolish or replace them, e.g. enlargement of the deck of abutments for increasing traffic rate (Brattebø et al., 2009).

Regarding the LCA methodology used in the studies from the literature review, some general conclusions can also be taken. Due to the interaction of the life cycle phases, it seems important to include all phases in the LCA, in order to be able to use the more complete and accurate results in the decision making process.

Chapter 4

Railway Bridges LCA

4.1 Railway Bridges LCA Tool

4.1.1 Performing a LCA of Railway Bridges

To develop a useful tool to perform a life cycle assessment of a railway bridge, it has to be considered and applied all the previous research and knowledge acquired while studying the LCA methodologies and literature. Although almost all the previous LCA performed in bridges has been for road and highway bridges, the conclusions taken from them can perfectly be applied to develop a LCA of a railway bridge. The main differences of both kinds of bridges are in the structural requirements for the materials, where the railway bridges need higher strength than road bridges, due to the loads and vibrations suffered by the bridge when the train crosses, but moreover in the case that the train has to brake over the bridge. For this reason, railway bridges are usually made on concrete or steel, disregarding the wood as structural material. These structural requirements lead to the need of using more quantities of concrete or steel, with higher quality, and therefore, make the environmental impacts of railway bridges larger than the ones caused by a road or highway bridge. Another basic difference is the rail structure. This part of the bridge has to consider mainly the ballast and rail tracks, but does not need to consider train traffic related components as the cables or communication components.

In this LCA tool, the author considers important to include all life cycle phases, highlighting the importance of concrete and steel by using good quality inventory databases at least for this materials. The paint and coating used for steel in the construction phase and in the later maintenance activities are also important and will be included in the program. It is important to separate the bridge in subparts, in order to locate which is the most contributive part to the environmental impacts. This will allow comparing, for instance, a steel deck bridge with a concrete or composite deck bridge, where the substructure can remain the same, and the impact of the superstructure can be assessed easily.

The program should be able to consider energy used in transportation of the materials from the providers to the construction site, and may consider the transportation of the workers too. In the case of study of this thesis, the railway bridge is located in the city center, and the work transportation will not affect the total burdens of the bridge construction; however, for a bridge construction far away from the closest city, it may imply great fuel consumption, and the tool should consider it. Diesel consumption from machinery in the construction phase should be included too. The environmental impacts attached to the traffic disruption should be considered, however, it is may be complicated to evaluate and implement in the program.

As the maintenance activities have been revealed to be important in previous research, the tool should have the choice to include a complete set of maintenance operations, as it is a railway bridge, above all, it should include the rail related maintenance and repair operations, but without forgetting the steel coating. It must allow choosing the frequency of these operations, in order to evaluate different alternatives with different maintenance requirements. For the end of life assessing, the tool should include several alternatives for the main contributors to the environmental impacts, concrete, steel and wood. It should consider the recycling, reuse, incineration and the waste disposal of these elements. A good idea would be to include the machinery and diesel consumption of the demolishing activities, and the fuel consumption of the transportation of waste materials from the bridge site to the final destination or recycling plant.

4.1.2 Model Description

The aim of this thesis is to develop a tool, considering all the previous objectives and requirements, to assess the environmental impact of the different phases of a railway bridge life cycle and the subparts of the bridge structure, and provide reliable results to evaluate and compare them in order to identify which system components have greater impact on environment. The LCA model for railway bridges developed is a tool where different kind of railway bridges can be assessed. The model is implemented in the Microsoft Office spreadsheet application, Excel, and can be used to assess any concrete, steel or composite bridges, or bridges which has a unique design, as the one studied in this report. The software allows performing the Life Cycle Assessment for two different bridges and obtains a comparison between them; although it can be used for assess one bridge only. The program has the option to study the bridges as an entire entity, or to obtain the results calculated by area. This option allows comparing bridges with different typologies and sizes.

For each bridge, the model inputs will be the different quantities of materials and energy used, in each phase of the life cycle for each part of the bridge. These phases are the material extraction and production, the construction, use and maintenance, and the end of life of the bridge. As mentioned, the inputs are divided not only by phase, but also in the different parts of the bridge: the auxiliary structure, substructure and superstructure. To these parts the rail system and transport have been added as additional parts of the bridge system in order to provide a more detailed analysis of the bridge. The model allows studying and assessing each phase separately for the whole bridge, but also makes it possible to study each part of the bridge through all the phases, or even study the environmental impact of each part of the bridge due to one of the included phases of the life cycle. One important characteristic of this program is that allows calculating the results according to several reference sources, showing the differences in the graphics. As normalizing and weighting steps are optional in the ISO14040, there is also the option to display the characterizated results without normalizing or weighting.

The model outputs for each bridge will be calculated for the whole bridge system or for the bridge parts; for the whole life cycle or for each phase separately. For the impact assessment stage, six environmental potential impact categories are evaluated: The abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and the photochemical oxidation. The results for each impact category are normalized and weighted according to the reference chosen by the user. The outputs for the comparison of the two bridges show the global environmental impact and the potential impact categories for each bridge system. If the user introduces the same values for each bridge, this tool can be used to visualize and compare the results for different references in the comparison output graphics. The graphic below represents the basic structure of the model for each bridge.

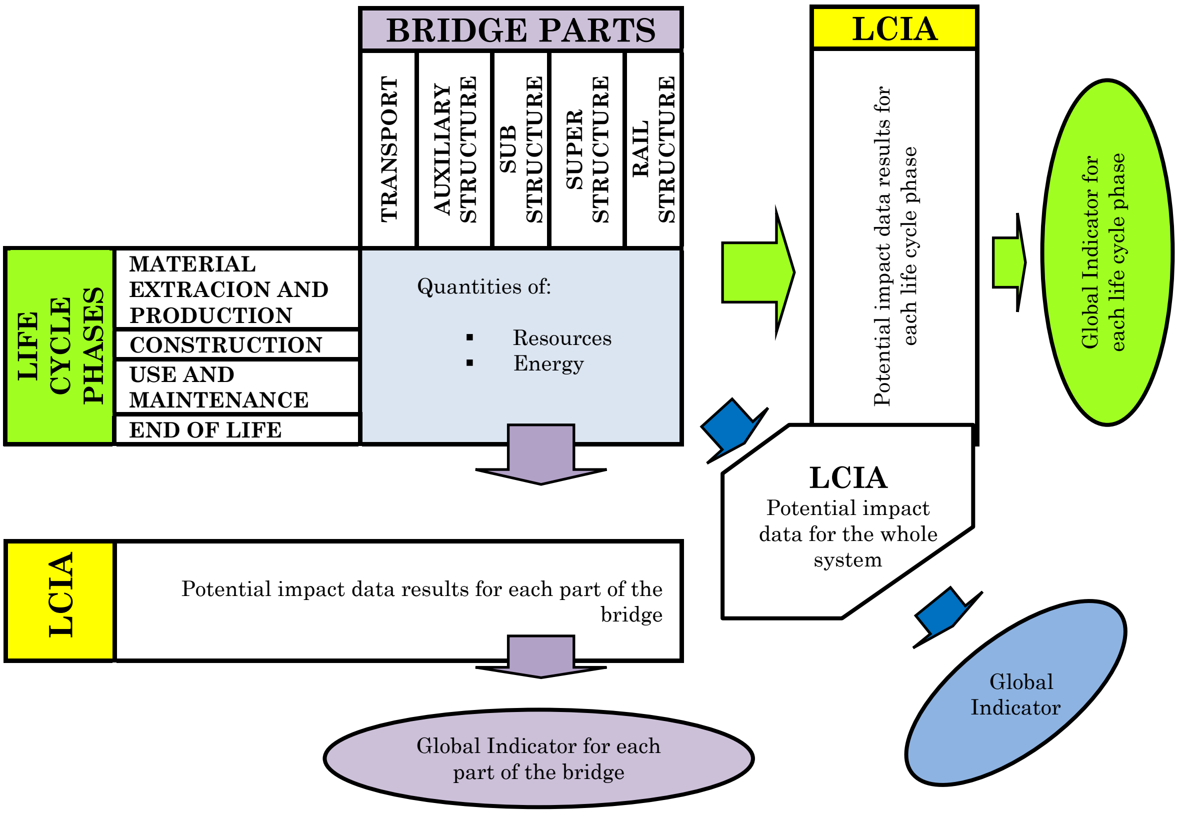


Figure 73: Graphic description of the LCA tool

The tool has the option to introduce very detailed data, but it is also possible to introduce the total amounts of resources when there is not available detailed data for each part of the bridge structure. This alternative is handy tool. It is also useful when the goal of the study is to provide a general idea of the environmental impact of the bridge as a whole. Another option is to leave empty the data which is not wanted to be considered, or is not applicable or unavailable. In this case, the results will have to be interpreted consequently.

Functional Unit, Boundaries, Assumption and Limitations

The functional unit of the model can be defined as 100 years of service life of a concrete, steel or composite railway bridge. Thus, the model is built on a time horizon of 100 years of service life. This assumption is made for the bridge structure since the construction phase is finished, and condition the frequency of maintenance operations or repairing activities that should be included, e.g. the change of materials with a shorter service life, and its consequent contribution to the use of resources, energy and their posterior disposal.

Regarding the boundaries of the model, as mentioned before, the parts of the bridge that are evaluated include the substructure and the superstructure of the bridge. The auxiliary structures are also taken into consideration, which includes temporal formwork, terrain retainer walls or anchorages. For the rail structure several scenarios can be studied: the traditional ballasted system, fixed tracks or the embebed rail technology. The transport, which includes the transportation of the material from the providers to the construction site, of workers and of the wasted materials to recycling plants or disposal place, is, on one hand included as a part of the bridge system, and on the other hand integrated in each life cycle phase. This allows obtaining results for, either the whole fuel transportation used in all the bridge life, or as a contributor to each life cycle phase. Transport does not include the machinery used in construction, and does not consider the transportation of the workers and materials for the maintenance activities.

The life cycle phases of the bridge are: The material phase, which includes the extraction and production activities. The construction phase includes the energy consumption of the machinery used, but it does not include the environmental impact of the machinery per se. As the goal of this model is to assess the railway bridge infrastructure, in the use and maintenance phase is not taken into account the railway traffic. The operation activities during the use phase as well, are not considered because they are usually due to rail traffic, i.e. communication systems and signaling, and they are beyond the scope of this study. The maintenance activities considered will consist on repairing and replacing certain components periodically in a 100 year timeframe. The end of life phase considers three scenarios for the waste materials, incineration, recycling and disposal, although not all materials have the choice of recycling or incineration. As some of this input data is usually not available, the program allows including just the available one. The results would be obtained for the given data values, which should be taken into consideration in the interpretation phase.

4.1.3 Impact Assessment Methodology

The potential impact categories included in the model are the abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and the photochemical oxidation. In the program, the classification and characterization of the emissions for each inventory inflow are precalculated using SimaPro 7.1.5. 2008. and Ecoinvent Database v2.01. 2008, values used in the study performed by the Norwegian university NTNU (Brattebø et al., 2009). The values in kg equivalents of the main relevant substance for each potential impact are already given for each material or activity. However, the tool includes the option to develop its own inventory, and contains several characterization factors and data for some of the resources. This option is not thoroughly developed because it is believed that the values from software packages are far more accurate and can lead to better results. Data for some of the resources included in the tool was not found in the literature, future developments should focus on including and extending the inventory database. In relation to the data chosen for the impact assessment of the concrete, values for the poor and high performance concrete for some impact categories (marked by green cells in the program) were calculated for the program and for the abiotic depletion and ozone layer depletion, the values for normal concrete where use because of the lack of data.

In order to compare all impact categories on a common basis, the results can be normalized, weighted and summed to get a single score for each bridge. For the normalization, the reference is the total emissions in Western Europe in 1995 (Brattebø et al., 2009). For the weighting factors, it is possible to choose which reference is wanted to be used: US-EPA, EDIP97, a global reference, EU-15, a Denmark reference, Harvard or BEES (Stranddorf et al., 2003 and Brattebø et al., 2009). Further improvements of the program would be to include more reference sources. The implemented factors for each method and categories included are shown in the appendix A. When the user wants to get just the characterizated results, with no normalization or weighting, the choice “none” must be selected. It has to be considered in the interpretation phase, that some references do not take into account some of the studied impact categories, e.g. EDIP does not consider abiotic depletion.

4.2 Program Structure

4.2.1 Model Architecture

The program is an application on Microsoft Excel 2007 and consists on several spreadsheets. It is built using Macro applications and Visual Basic for Applications (VBA), which makes it incompatible for earlier versions of Excel. It is basically formed by the home page, two sets of sheets for each bridge LCA, and a sheet for displaying the comparison between them. The organization tree summarizes and represents a graphic description of the computer model architecture.

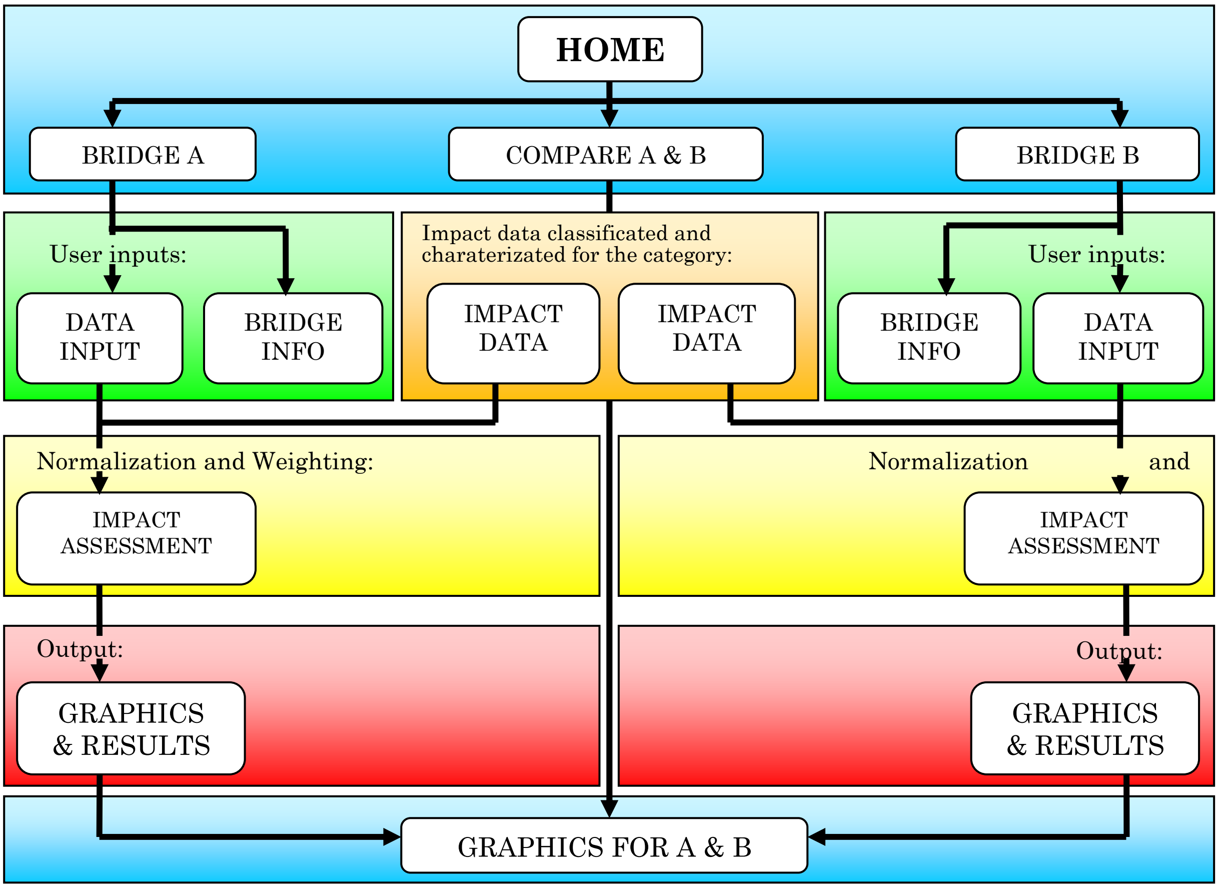
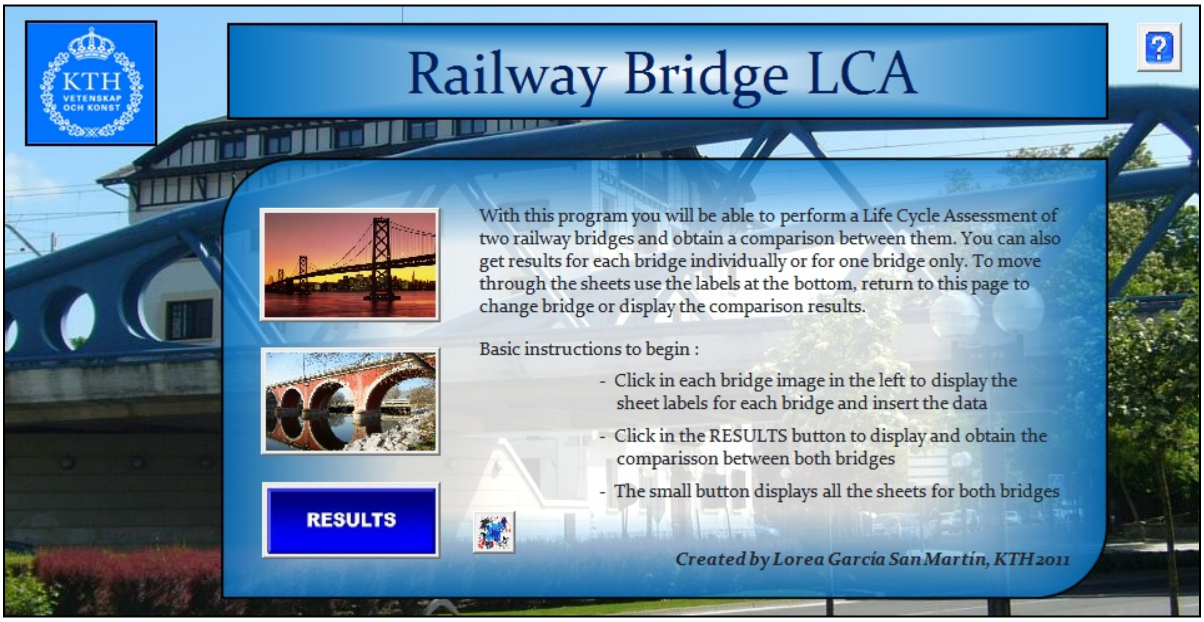


Figure 74: Program architecture tree

4.2.2 Graphical User Interface

From the main page “HOME”, the user can chose which set of sheets activate by doing click in the buttons. Each button with a bridge picture displays the sheets related to each bridge and hides the sheets from the other and brings the user to the “BRIDGE INFO” sheet. The RESULTS button hides all the bridge’s sheets and displays the results of the comparison between both bridges. Another small button allows displaying all sheets at once. The help button is in the right side of the top of each sheet, and provides information of the tools available on each sheet. In this page, there is a direct link to KTH website in the left side. Each sheet contains an arrow that drives the user back to the index. The picture shows a capture of the main page.



With this program you will be able to perform a Life Cycle Assessment of two railway bridges and obtain a comparison between them. You can also get results for each bridge individually or for one bridge only. To move through the sheets use the labels at the bottom, return to this page to change bridge or display the comparison results.

Basic instructions to begin :

- Click in each bridge image in the left to display the sheet labels for each bridge and insert the data
- Click in the RESULTS button to display and obtain the comparisson between both bridges
- The small button displays all the sheets for both bridges

Created by Lorea García San Martín, KTH 2011

Figure 75: Capture of the HOME sheet of the program

If the user chooses the first bridge, several sheet labels appear in the bottom of the page (see figure 78). The structure is analogous for both bridges.

Figure 76: Labels of each sheet related to the first bridge

The first sheet corresponds to the main information of the bridge. The data that the user must introduce includes: name, location, construction Company, designers, year of construction, typology, main characteristics and author and year of the study. The user must also specify which reference source wants to use to normalize and weight the obtained results. This option can be change afterwards in the output pages.

Next sheet is the “DATA INPUT”. This is where the user must enter the data values of the bridge, i.e. detailed quantities of material resources, energy consumption, etc. In the top of the sheet, the name of the bridge is display. By each bridge system part there is a column with the total amount of resources. If the user does not have detailed information, this column can be used to write the total quantities for each part of the bridge. If this information is as well unavailable, the user can use to TOTAL QUANTITIES column in the right for the whole bridge quantities. The cells with grey background are for variables not considered or not applicable, e.g. the transport for construction machinery. In the picture, just one of the maintenance activities is shown for space reasons.

The input data is organized in a table where the rows are the life cycle phases of the bridge: materials, construction, use and maintenance and end of life, with their sub phases. These phases are subdivided in subcategories, as can be seen in the capture. For the Material phase, the different resources are included. The

Construction phase is basically formed by energy consumption, and it is subdivided in hours of used machinery, which later will be converted to diesel consumption, the electricity consumption, number of workers and duration in days, which will be used for calculating the transportation fuel. The Use and Maintenance phase is divided in the reparation and maintenance activities, which are also subdivided in a third level of resources and energy consumed in each activity. For the End of Life phase, the three considered scenarios are contemplated, incineration, disposal and recycling, with a third level of detail, with the resources and energy consumption for each scenario. All of these inputs are described thoroughly later.

The "IMPACT DATA" spreadsheet gathers all the values for each impact category for all the resources and activities considerate. These values are provided in kg equivalents of the main contributive substance and are the results of classification and characterization of the emissions of the inventory. These values are taken from SimaPro 7.1.5. 2008. and Ecoinvent Database v2.01. 2008, (Brattebø et al., 2009). For further improvements, the program includes the option of calculate these values too, but in this version is not developed because of the loss of quality that it would attach. This sheet also includes the normalizing and weighting factors for the different reference sources available. The user does not have to change or insert any values in this sheet.

Next sheet is "IMPACT ASSESSMENT". It is where all the calculations are made for all the different parts and phases. Values for all impact categories are obtained, normalized and weighted and finally added to get a global indicator. Some auxiliary calculations needed for the later graphic results are carried out in the next sheet "Calculations". Again, these sheets are not for the user to fulfill.

When the data of the bridge is entered, the program calculates the environmental impacts for all the parts involved. These results are compiled in several graphics that can be seen in the OUTPUT sheets of each bridge.

This sheet displays and summarizes all the results for the studied bridge. In the top of the page the user can change the normalizing and weighting reference source and see the changes in the graphics. A global indicator for the total potential environmental impact of the bridge is shown too. The graphics that are shown are:

- For the whole bridge system:
  - Potential impacts of the bridge
  - Potential impacts by life cycle phase
  - Potential impacts by part of the bridge
  - Weighted single scores for each potential impact category by life cycle phase
  - Weighted single scores for each potential impact category by bridge part

- For each part of the bridge:
    - Potential impacts by life cycle phase
- For each life cycle phase:
    - Potential impacts by bridge part
- Distribution of the environmental impact of the materials used

The results page can be exported as an image file by clicking the button "Export to File". The file will be created in the same folder as the program, and named BRIDGE1 and BRIDGE2 respectively.

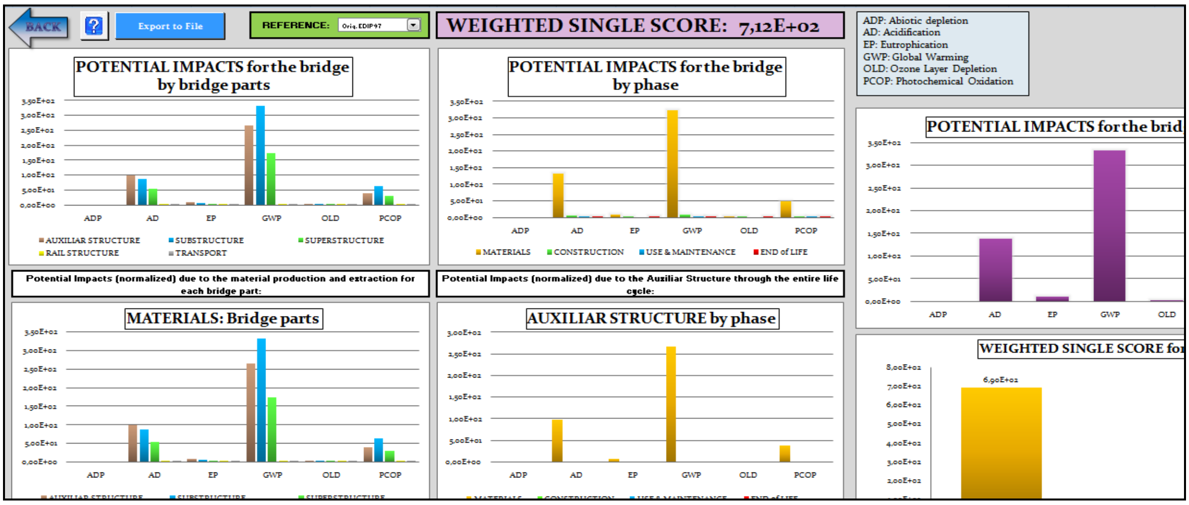


Figure 77: Capture of the "OUTPUT" spreadsheet

After having completed all the information for the both bridges, the user can go to the home page and select "RESULTS". The sheet for the comparison is now displayed.

Figure 78: Labels displayed after selecting RESULTS in the HOME page

In the sheet "COMPARISON A & B" the user can take a look to the graphics to compare both bridges. The graphics for the global indicators and for the potential impact categories of both bridges are included. From this sheet, the user can also change the chosen reference for normalization and weighting factors, and check the differences in the graphics. This tool also allows comparing the same bridge with different reference sources, if the user has introduced the same data in both bridge's input data sheet. This sheet also has the option to be exported as an image file by clicking the button "Export to File". The file will be created in the same folder as the program, and named COMPARISON.

4.3 Life Cycle Phases

4.3.1 Materials:

MATERIALS	CONCRETE	blinding concrete
		mass concrete
		pre-stressed concrete
	STEEL	passive reinforcement steel
		active reinforcement steel
		steel
	OTHER MATERIALS	polystyrene sheet
		asphalt sealing
		bitumen
		cement mortar
		limestone
		stone aggregate
		epoxy coating
		polyurethane coating
		chlorinated painting
		timber formwork
		wood
		rubber
		pvc
		corkelast
		neoprene
		glue laminated wood
		aluminium
		copper
		glass
		mastic
		epoxy paint
		powder coating (steel)
		creosote impregnation (wood)
		salt impregnation (wood)
		blasting

Figure 79: Materials included in the program

The materials included in the study can be seen in the figure 83. The emissions of each material include its extraction and production until it is ready for distribution (from cradle to gate). The emissions corresponding to one material are classified, characterizated and added to get a final indicator for each impact category in kg equivalents of the main contributive substance. As mentioned before, this process is performed outside the program with SimaPro and Ecoinvent databases. However, some emissions for some materials are included. Some materials, like concrete or steel, have more relevance than others because they are used in high quantities. Some of these materials, which are very common in bridge construction, are described thoroughly below.

Concrete:

Concrete is nowadays, one of the main used materials in railway bridges together with the steel. It is mainly formed by cement Portland, aggregates and water. All of these materials are widely available in nature; therefore, the use of concrete does not have importance impact in resources depletion. However, the process of producing and manufacturing the concrete, and the big amounts of concrete produced every year, makes it very contributive to the environmental damage. The table shows the composition of a normal concrete based on the standards for concrete of the Michigan Department of Transportation (MDOT, 2003).

COMPONENT	g /l of Concrete
AIR	0,05
CEMENT	474
GRAVEL	938
SAND	655
WATER	200

Figure 80: Mass concrete composition (MDOT, 2003)

Type of Concrete		Water kg/m^3	Water/ concrete	Density kg/m^3	Cement		Aggregate		
					Type	Kg/ m^3	Kg/m^3	Type	Size
Normal concrete	C 20/ 25	186	0.62	2377	CEM I 42.5	300	1891	round	0/32
Concrete for sole plate and foundation	C 20/ 25	178.8	0.55	2387	CEM III/B 32.5	325	1883	round	0/32

Figure 81: Composition of two types of normal concrete (Kellenberger et al., 2007)

In the model, three types of concrete are included regarding their use and strength, blinding concrete, mass concrete and pre-stressed concrete. The blinding concrete is used to prepare the ground and protect the structure below. It does not have any structural function and has a very poor quality. The mass concrete or normal concrete, is used when not a very high strength is required, it has a medium quality and can have passive reinforcement. The pre-stress concrete is concrete with high strength that is used with active reinforcement steel (pre-tensioned or pos-tensioned). The composition of the three of them varies, and so does the potential impacts of the concrete.

To obtain the concrete, cement, gravel aggregates and water is mixed. The main component of the concrete is the cement, and it is formed mainly by clinker. To obtain the clinker, as it is shown in the flow diagram, the first step is extracting the gravel, sand, limestone, clay and bauxite. Those materials are processed separately. The limestone is crushed, then, part is milled and the other part burned, crushed again and hydrated. The clay is mixed with the crushed limestone to produce calcareous marl. All of the obtained elements are mixed together with the bauxite and gravel and sand. Then the mix is burned in a rotary kiln. The cement is then obtained by grinding the clinker together with gypsum, other additional milling substances and blast furnace slag.

The process of kiln heating is one of the most energy consuming processes in concrete production. In this step, big amounts of CO_2 emissions from the limestone are liberate, aside from the fuel burning emissions due to the heating. There exists several alternatives of kiln heating, varying the wet and dry processes, adding preheating or pre-calciner processes; all of them with different grades of efficiency.

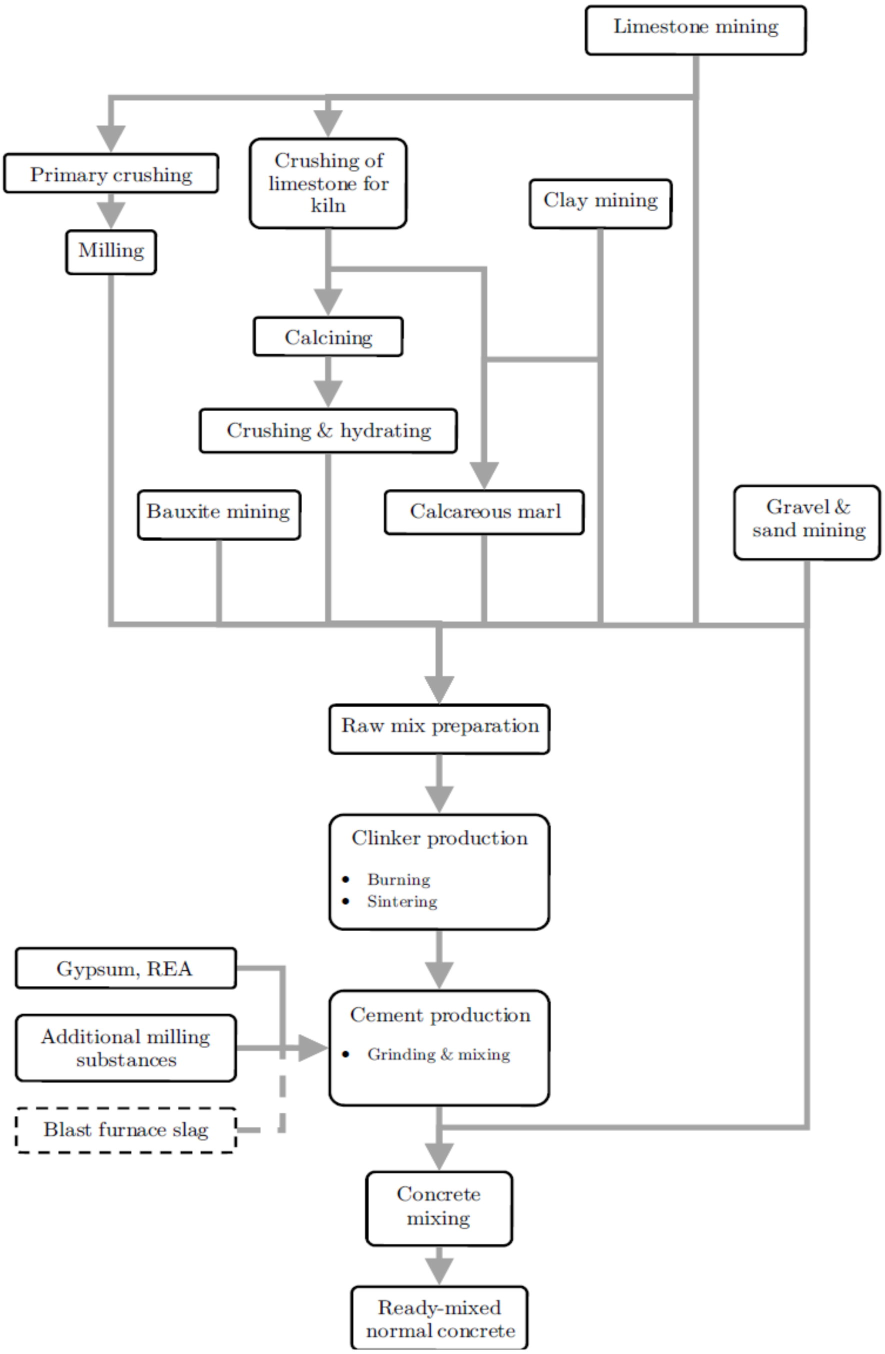
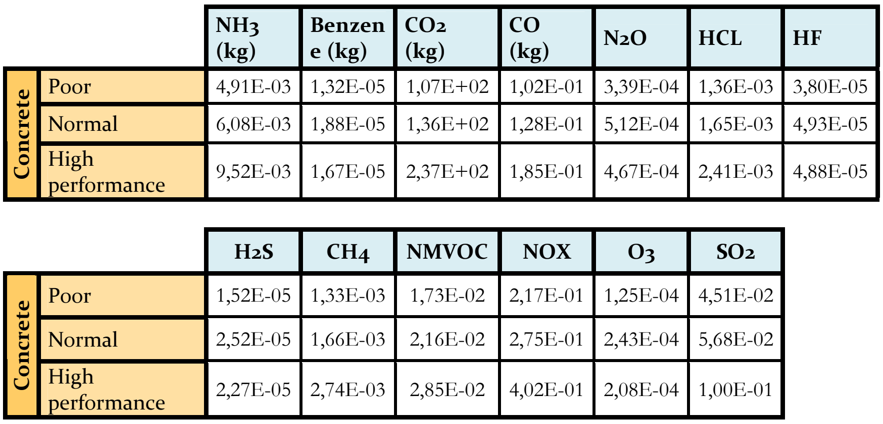


Figure 82: Concrete production process tree (Thiebault, 2010)

For the calculation of the environmental impacts of the concrete, it has not been considerate the plants infrastructure, the machines, the lubricating oil or the wear of the steel and synthetic rubber parts, or the wear of the rotary kiln for clinker production, neither the treatment of the wastewater and packaging of concrete (Thiebault, 2010).

In the program the values available from software packages as SimaPro have been prioritize, however, some values were not found, and have been calculated by the program. This is the case of poor and high performance concrete. Because of the lack of good inventory data, the values for abiotic depletion and ozone layer depletion for the three types of concrete were the same (SimaPro values for normal concrete). The values for the three types of concrete included are listed below; the characterized values were shown in figure 87.



		NH_3 (kg)	Benzene (kg)	CO_2 (kg)	CO (kg)	N_2O	HCL	HF
Concrete	Poor	4,91E-03	1,32E-05	1,07E+02	1,02E-01	3,39E-04	1,36E-03	3,80E-05
	Normal	6,08E-03	1,88E-05	1,36E+02	1,28E-01	5,12E-04	1,65E-03	4,93E-05
	High performance	9,52E-03	1,67E-05	2,37E+02	1,85E-01	4,67E-04	2,41E-03	4,88E-05

		H_2S	CH_4	NMVOC	NOX	O_3	SO_2
Concrete	Poor	1,52E-05	1,33E-03	1,73E-02	2,17E-01	1,25E-04	4,51E-02
	Normal	2,52E-05	1,66E-03	2,16E-02	2,75E-01	2,43E-04	5,68E-02
	High performance	2,27E-05	2,74E-03	2,85E-02	4,02E-01	2,08E-04	1,00E-01

Figure 83: Emissions considered for one m^3 of concrete

Steel:

Steel is another important source of environmental impact in infrastructures. It is formed approximately by 96 % of iron, 3 % of coal and 1 % other material, depending on the requiring characteristics in the service life of the steel. There are four different types of steel considered in the program: reinforcement steel, lower grade steel, construction and stainless steel. Each type has its own processes and different composition and components. For instance, to produce the stainless steel, or any alloyed steel, it is required nearly double energy consumption than to produce carbon steel.

There exists two ways of producing steel, in basic oxygen furnaces, which represents the 63 % of the produced steel, or in electric arc furnaces through graphite electrodes, which counts for the rest 37 % of the production (Classen et al., 2009). This last way is more expensive but requires considerably less energy consumption and emits less CO_2 to the atmosphere (Thiebault, 2010). The table below shows the inventory flows of conventional steel production against the electric production for an un-allowed and low alloyed steel.

Raw material/ Pollutant	Unit	un-alloyed converter steel	low-alloyed converter steel	un- and low-alloyed electric steel
Bentonite	kg/kg	1.44E-02	1.44E-02	0.00E+00
Chromium	kg/kg	0.00E+00	3.03E-02	0.00E+00
Coal	kg/kg	5.01E-01	5.67E-01	1.40E-02
Dolomite	kg/kg	2.75E-03	2.75E-03	0.00E+00
Iron	kg/kg	3.45E-01	3.45E-01	0.00E+00
Iron scrap	kg/kg	2.13E-01	1.25E-01	1.11E+00
Limestone	kg/kg	3.07E-01	7.51E-01	1.41E-01
Manganese	kg/kg	0.00E+00	2.19E-02	0.00E+00
Molybdenite (MoS2)	kg/kg	0.00E+00	3.96E-04	0.00E+00
Natural gas	m3/kg	1.07E-02	4.26E-02	2.69E-02
Nickel	kg/kg	6.00E-03	4.50E-02	0.00E+00
Niobium	kg/kg	0.00E+00	2.64E-03	0.00E+00
Oils products	kg/kg	1.06E-02	1.65E-02	7.75E-03
Tungsten	kg/kg	0.00E+00	1.24E-03	0.00E+00
Vanadium	kg/kg	0.00E+00	2.36E-03	0.00E+00
Water	m3/kg	9.84E-03	1.10E-02	0.00E+00
Production energy	MJ/kg	11.7	20.8	3.3
Transport energy	MJ/kg	0.467	0.488	0.339
CO	Kg/kg	3.08E-02	3.11E-02	2.67E-03
CO2	Kg/kg	1.19E+00	1.46E+00	8.00E-02
CH4	Kg/kg	4.00E-06	2.61E-05	2.39E-06
NOX	Kg/kg	1.15E-03	1.96E-03	5.62E-04
SO2	Kg/kg	1.89E-03	2.99E-03	9.93E-05
NMVOC	Kg/kg	1.68E-04	2.65E-04	2.44E-05
PM10	Kg/kg	2.20E-03	4.07E-03	3.65E-04
Oils	Kg/kg	4.27E-06	7.04E-06	0.00E+00
TSS	Kg/kg	0.00E+00	2.66E-04	0.00E+00
BOD	Kg/kg	6.41E-05	6.41E-05	0.00E+00
DOC	Kg/kg	2.32E-06	2.32E-06	0.00E+00
Solid waste	Kg/kg	1.35E-01	7.84E-01	1.07E-01

Figure 84: Steel Inventory: Resources and Emissions (Thiebault, 2010)

The first step in the process is to extract the coal and the iron ore. This raw iron is formed by 46 % of pure iron. This percentage is increased to 65 % in the mine by washing and grinding the ore, and later it is turned into pellets and sinterized. This sinter is carried to the blast furnace, where together with the coal and some iron ore is melted with great amounts of oxygen (air). The temperature in the furnace is over 1300 °C, which leads to a big energy consumption and CO_2 emissions. The obtained material, which has a very high percentage of carbon, is enriched with oxygen and some additional components to eliminate non desirable elements as carbon excess, silica or phosphorus and get the wanted composition. This material is poured into molds to, after passing quality tests, is carried to the rolling mill. The tree represents the process of manufacturing cast iron and steel.

In the program, values for the four types of steel have been taken from SimaPro and Ecoinvent databases, used in the study performed by the Norwegian University NTNU (Brattebø et al., 2009). In these values, analogously to the concrete, the mines or plants infrastructures, machines, lubricating oil or wear of the steel and synthetic rubber parts or the furnaces are not considered. However, for future developments of the program, there have been included the description and inventory flows for the processes of extracting and producing the steel, including the galvanization.

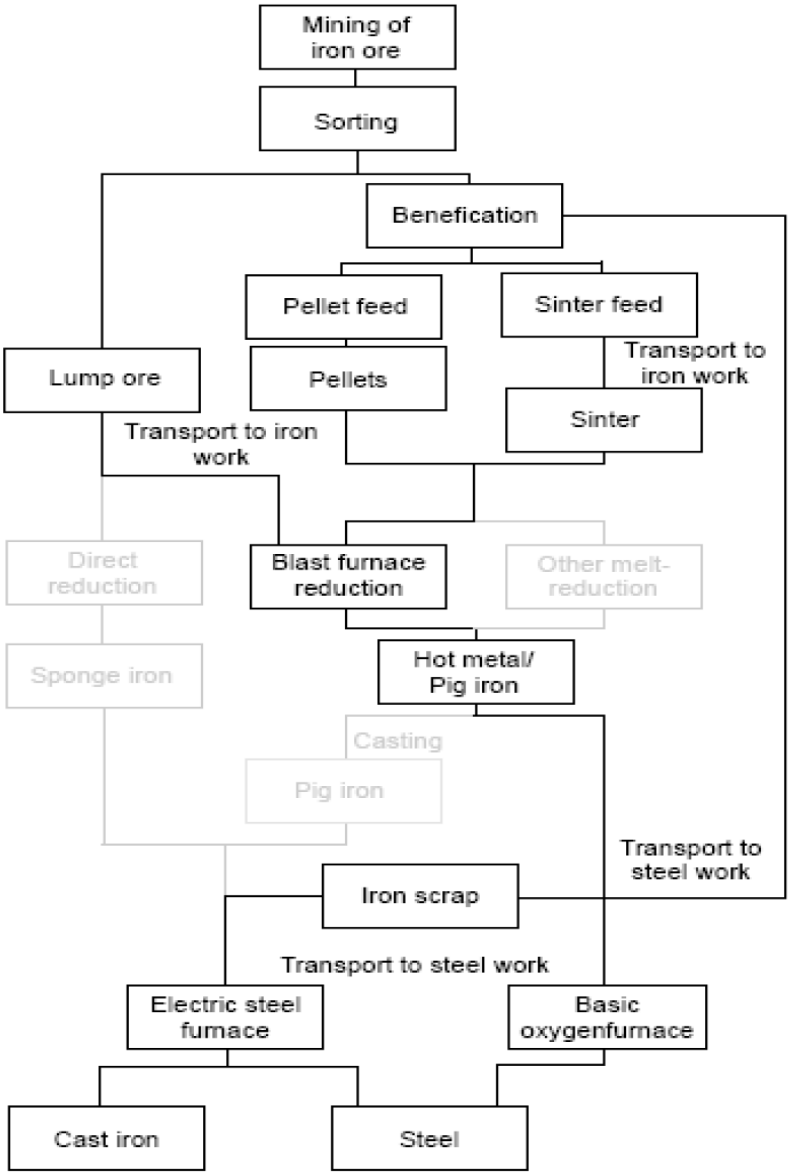


Figure 85: Steel production process tree (Thiebault, 2010)

After the process of obtaining the steel with the desired composition, to produce the steel beams, the steel is formed by hot-rolling and then is galvanized with zinc coating. When the process of manufacturing is done, the steel is welded to form the structures. The inventory flows for these processes are shown in the tables below. For more information about the processes and the inventory check "Design of railway bridges considering LCA" by Vincent Thiebault.

Raw material	Unit	hot-rolling steel
Natural gas	(m3/kg)	4.30E-02
Oils products	(kg/kg)	5.30E-04
Steel	(kg/kg)	5.00E-02
Water	(m3/kg)	5.50E-03
Production energy	(MJ/kg)	2.15
Transport energy	(MJ/kg)	0.182
CO	(kg/kg)	4.40E-05
CO2	(kg/kg)	1.44E-03
CH4	(kg/kg)	8.74E-02
NOX	(kg/kg)	6.04E-05
SO2	(kg/kg)	9.03E-07
NMVOC	(kg/kg)	2.83E-04
PM10	(kg/kg)	3.23E-06
Oils	(kg/kg)	0.00E+00
TSS	(kg/kg)	1.46E-04
BOD	(kg/kg)	3.80E-05
DOC	(kg/kg)	1.20E-05
Solid waste	(kg/kg)	1.85E-02

Figure 86: Hot-Rolling steel production (Thiebault, 2010)

Raw material	Unit	zinc coating
Natural gas	(m3/m2)	3.54E-01
Oils products	(kg/m2)	3.01E-01
Water	(m3/m2)	4.18E-03
Zinc	(kg/m2)	1.05E+00
Production energy	(MJ/m2)	26.9
Transport energy	(MJ/m2)	1.43
CO	(kg/m2)	1.01E-04
CO2	(kg/m2)	1.68E+00
CH4	(kg/m2)	3.96E-05
NOX	(kg/m2)	9.89E-04
SO2	(kg/m2)	6.08E-04
NMVOC	(kg/m2)	2.31E-06
PM10	(kg/m2)	2.71E-03
Oils	(kg/m2)	1.73E-06
TSS	(kg/m2)	3.74E-06
BOD	(kg/m2)	2.20E-04
DOC	(kg/m2)	4.95E-06
Solid waste	(kg/m2)	2.49E-01

Figure 87: Zinc coating for “semi finished” steel (Thiebault, 2010)

Raw material	Unit	arc welding, steel
Steel	(kg/m)	5.36E-02
Production energy	(MJ/m)	-
Transport energy	(MJ/m)	8.72E-02
CO	(kg/m)	1.31E-03
CO2	(kg/m)	8.89E-02
CH4	(kg/m)	9.63E-08
NOX	(kg/m)	9.20E-05
SO2	(kg/m)	1.09E-04
NMVOC	(kg/m)	2.54E-05
PM10	(kg/m)	2.90E-04
Oils	(kg/m)	2.38E-07
TSS	(kg/m)	1.68E-05
BOD	(kg/m)	4.20E-06
DOC	(kg/m)	7.21E-07
Solid waste	(kg/m)	2.96E-02

Figure 88: Arc welding inventory flows (Thiebault, 2010)

Another way to protect the steel surface is the powder coating. In this technique, the coating is applied in powders that are cured by heating to form a protective layer. In the table, there are values for a mixture of epoxy and polyester resin with titanium dioxide (Thiebault, 2010).

Raw material	Unit	powder coating, steel
Epoxy resin	(kg/m2)	2.83E-02
Natural gas	(m3/m2)	9.47E-01
Polyester resin	(kg/m2)	2.83E-02
Titanium dioxide	(kg/m2)	3.42E-02
Production energy	(MJ/m2)	39.7
Transport energy	(MJ/m2)	0.346
CO	(kg/m2)	5.34E-04
CO2	(kg/m2)	1.81E+00
CH4	(kg/m2)	7.01E-05
NOX	(kg/m2)	1.01E-03
SO2	(kg/m2)	2.04E-05
NMVOC	(kg/m2)	5.03E-04
PM10	(kg/m2)	3.48E-05
Oils	(kg/m2)	5.19E-06
TSS	(kg/m2)	4.16E-04
BOD	(kg/m2)	1.93E-05
DOC	(kg/m2)	6.75E-06
Solid waste	(kg/m2)	4.39E-02

Figure 89: Powder coating inventory flows (Thiebault, 2010)

PVC:

In railway bridges construction, PVC is not used in big quantities as steel or concrete. However, it is an important contributor to the environmental impact and it has been considered important to include the process of manufacturing and inventory flows in this thesis.

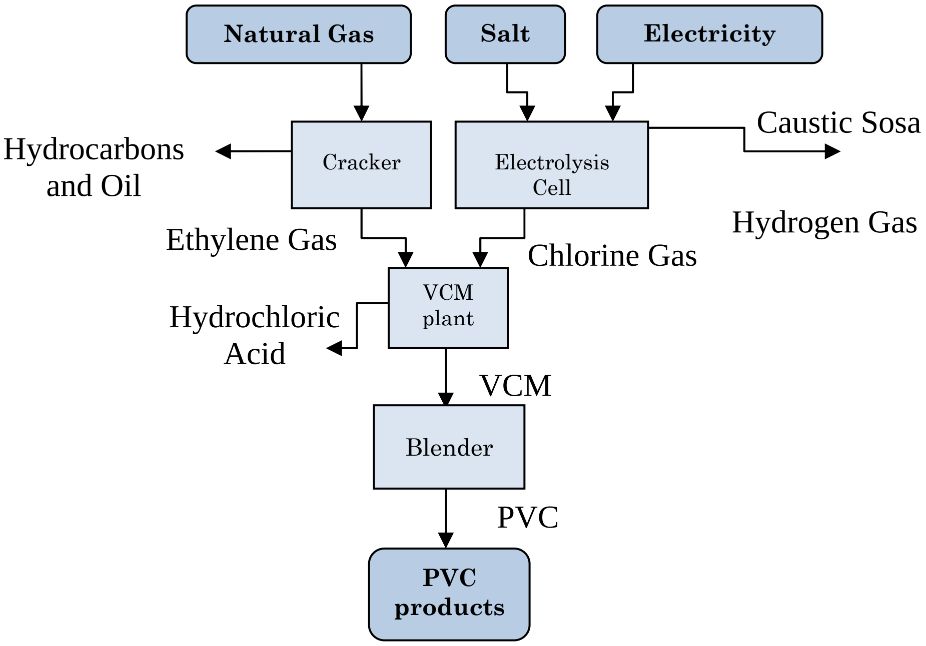


Figure 90: Process tree of PVC production

Next table shows the inventory data for PVC production and the considered critical volume by the Swiss Ministry.

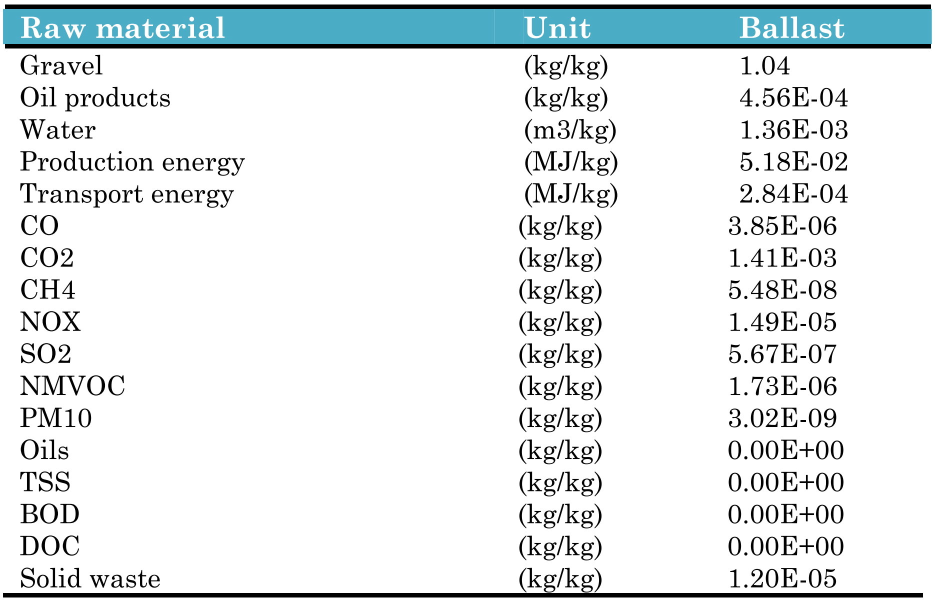
Pollutant	Process-related emissions (g/kg)	Emissions as critical volume (m^3)
Atmosphere:		
Particles	0,182	2600
CO	0,247	31
HC	1,372	91
N_2O	0	0
NO_X	0,792	26400
SO_2	0,782	26067
Aldehydes	0,001	33
Cl-organics	0,169	16900
Other organics	0,05	50000
NH_3	2	0
HCl	0	0
Cl_2	0,0003	15
Hg	0,00028	4014
Water:		
Dissolved solids	18,529	
AOX	0,015	0,15
Other organics	0,524	0,0524
Suspended particles	0,062	0,0031
COD	0	0
Oil	0,001	5,0e-5
Phenolics	0,005	0,1
Fluorides	0	0
Hg	2,0e-5	0,0017
Solid Waste	79,9	

Figure 91: PVC Production inventory flows (Tötsch and Gaensslen)

Ballast:

Another important material when assessing a railway bridge is the ballast. Although there are other choices, like ballast less tracks, this remains the more frequently used when the geometry and characteristics of the railway allows it.

Ballast is obtained by crushing gravel, and it is used to guaranty the stability of the railway. It distributes the pressure from the train to the ground, and avoids that the rainwater remains in the platform by allowing its drainage. It must fulfill quality requirements regarding the material and the grain. Next table collects the inventory data for ballast.



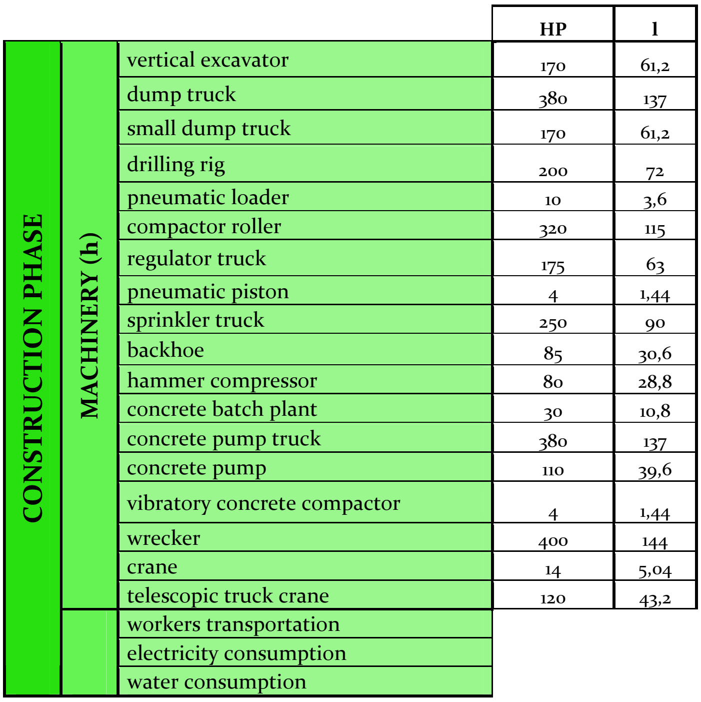
Raw material	Unit	Ballast
Gravel	(kg/kg)	1.04
Oil products	(kg/kg)	4.56E-04
Water	(m3/kg)	1.36E-03
Production energy	(MJ/kg)	5.18E-02
Transport energy	(MJ/kg)	2.84E-04
CO	(kg/kg)	3.85E-06
CO2	(kg/kg)	1.41E-03
CH4	(kg/kg)	5.48E-08
NOX	(kg/kg)	1.49E-05
SO2	(kg/kg)	5.67E-07
NMVOC	(kg/kg)	1.73E-06
PM10	(kg/kg)	3.02E-09
Oils	(kg/kg)	0.00E+00
TSS	(kg/kg)	0.00E+00
BOD	(kg/kg)	0.00E+00
DOC	(kg/kg)	0.00E+00
Solid waste	(kg/kg)	1.20E-05

Figure 92: Ballast production inventory flows (Thiebault, 2010**)**

4.3.2 Construction:

The construction phase considers the diesel consumption due to the machinery used. The more common used machines in railway bridges construction are included (check the list in the left). The user must provide the hours of use of each machine (which are usually included in the project) and the program calculates the diesel consumption for each machine. This phase also includes the electricity and water consumption.

The program can also evaluate the diesel consumption due to the transportation of the workers to the construction site. To do so, the user should include the total number of workers, the duration of the construction phase and the travels per day (columns). The electricity and water consumption are included but have not associated impact load, this is let for further developments of the program.



			HP	l
CONSTRUCTION PHASE	MACHINERY (h)	vertical excavator	170	61,2
		dump truck	380	137
		small dump truck	170	61,2
		drilling rig	200	72
		pneumatic loader	10	3,6
		compactor roller	320	115
		regulator truck	175	63
		pneumatic piston	4	1,44
		sprinkler truck	250	90
		backhoe	85	30,6
		hammer compressor	80	28,8
		concrete batch plant	30	10,8
		concrete pump truck	380	137
		concrete pump	110	39,6
		vibratory concrete compactor	4	1,44
		wrecker	400	144
		crane	14	5,04
		telescopic truck crane	120	43,2
		workers transportation		
		electricity consumption		
		water consumption		

Figure 93: Construction phase included in the tool

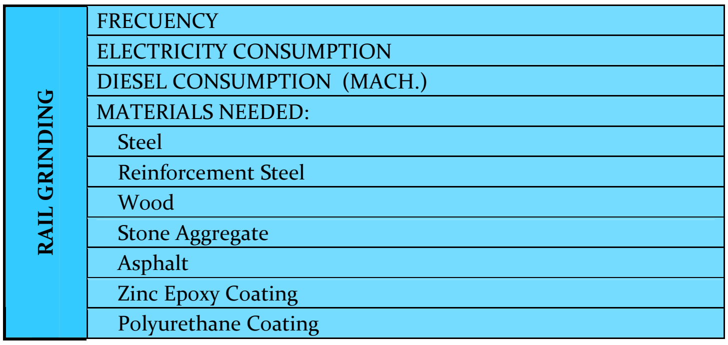
For the calculations of the diesel consumption of each machine, the equation below has been used. The formula takes in consideration the size of the machine in question, and gives coefficients from 0,1 for a small machine to 0,5 for a big one. The used values are listed in the table above. However, these are estimated values and it is recommended to the user to use their own.

$$D = C * \frac{1}{HP} + 20\,\% * C * \frac{1}{HP}$$

D = Diesel consumption in litres
C = Coefficient between 0,1 and 0,5 depending on size
HP = Power of the machine in Horsepower units

4.3.3 Use and Maintenance:

In order to ensure a long and adequate service life of the railway bridge, various maintenance activities must be performed over its lifetime. These activities can be divided into two main groups: routine activities and inspections, which are held several times a year, and periodic and repairing activities, which guaranty a good structural integrity and prevent and repair defects in the structures and surfaces, and are performed with frequencies of several years. This model considers the maintenance activities from this last group, because it is considered that these are the activities that require more resources and energy cost. It has been considered the maintenance for the steel structures and for the rail structure, and includes seven maintenance activities: Rail grinding, ballast tamping, rail replacement, sleeper renewal, fastener renewal, ballast renewal and repainting. The picture shows a capture of one example of these activities.



RAIL GRINDING	FRECUENCY
	ELECTRICITY CONSUMPTION
	DIESEL CONSUMPTION (MACH.)
	MATERIALS NEEDED:
	Steel
	Reinforcement Steel
	Wood
	Stone Aggregate
	Asphalt
	Zinc Epoxy Coating
	Polyurethane Coating

Figure 94: Example of a maintenance activity included in the tool

As mentioned before, the use is not considered, i.e. it is not taken into account the railway traffic, and the operation activities during the use phase because they are usually due to rail traffic: communication systems and signaling, and they are beyond the scope of this study. The maintenance activities are considered in a 100 year timeframe, and the user must include the frequency desired as number of times performed in 100 years. The table below summarizes and describes these activities and gives average values for their periodicity. It includes the recommendations given by CENIT (Centre for the Innovation in Transport, SPAIN) and the values incorporated to the model (Brattebø et al., 2009).

ACTIVITY	DESCRIPTION	CENIT	MODEL
Rail Grinding and Tamping	Grinding is the maintenance action done on the rail to control rolling contact fatigue defects. Tamping done to to correct the track's alignment.		1
Ballast Tamping and Cleaning	Ballast tamping is packing and pushing the ballast underneath the sleepers. It should be done every time geometry goes under the intervention limits. It is 40 to 50 % of the total railway maintenance budget during lifetime. Ballast cleaning is done to eliminate trapped water inside the ballast in order to restore the track quality and stiffness.		0,5
Rail Replacement and Renewal	Rail replacement is done when rail breaks occur on the track. Rail renewal is done when the rail deterioration reaches maintenance or safety limits.	40-60	25
Sleeper Renewal	Sleeper renewal is done when the sleeper deterioration reaches maintenance or safety limits.	Timber:10/12 Concr.: 30/40	50
Fastener Renewal	Fastener renewal is done when the fastener deterioration reaches maintenance or safety limits.		25
Ballast Renewal	Ballast renewal is done when ballast deterioration reaches maintenance or safety limits.	25-30	20
Repainting	Consists on applying new layers of paint to the steel components when the existing ones have defects or on a full removal and replacement.		30

Figure 95: Maintenance activities and recommended periodicity

The periodicity of the maintenance activities varies widely with the policy of the bridge management. These policies can consist of:

- Replacing the failed parts just at failure.
- Replacing the parts periodically. In this case, replacement interval is a decision variable.

Besides, for the sleepers:

- Replacing the parts when the k consecutive sleepers have failed first.
- Replacing all the failed sleepers when the k consecutive sleepers have failed or when a specific time t is elapsed from the last replacement, whatever occurs first.

The model considers that replacement and renewal are performed periodically before failure occurs. It does not take into account the failure scenario. It allows the user modifying the estimated periodicities for each activity.

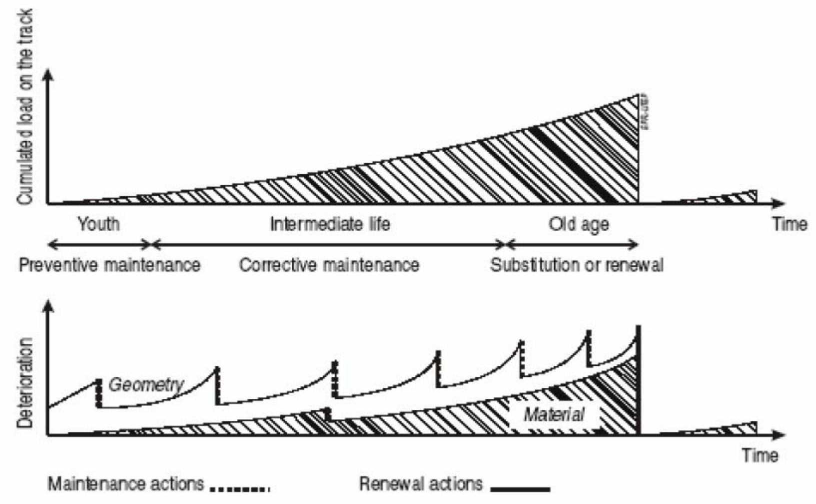


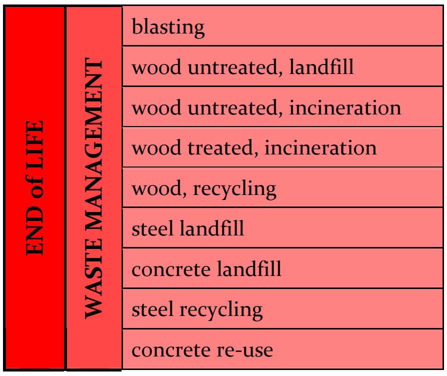
Figure 96: Life and maintenance of a generic railway component (AAVV, 2003)

The duration of the lifetime of each component depends on several factors, among which the most important one is the intensity of use of the railway line. That is the main reason why the type of line and rail transit has a considerable influence in determining the frequency of maintenance activities. The program includes estimates, but if you want greater accuracy the user should modify these values.

Component	Lifetime in millions of tons	Lifetime in Years
Conventional Rail UIC-60	300	30-35
Rail plate UIC-60 (ballast less)	400	35
Plates	965	60-65
Sleepers	500	30-40
Ballast	300	25-30

Figure 97: Estimated lifetime for the main components (Puebla et al., 2000)

4.3.4 End of Life:



END of LIFE

WASTE MANAGEMENT

blasting
wood untreated, landfill
wood untreated, incineration
wood treated, incineration
wood, recycling
steel landfill
concrete landfill
steel recycling
concrete re-use

Figure 98: End of Life phase included in the tool

The end of life phase considers the waste management of the main materials involved. Three scenarios are considered, incineration, recycling and disposal, although not all materials have the choice of all of them. For the steel, the end of life alternatives is recycling or disposed in landfills. The user must introduce the quantity of steel that is going to be recycling or dispose for each bridge component or for the whole system. For the wood, the program includes landfill, incineration and recycling. And for the concrete, landfill and reusing are the available choices.

The reuse and recycling of materials have no impact attached, as it happens with the landfill. For further improvements, it could be useful to incorporate reusing of materials as negative values, and consider the use of non reusable materials, and consider the burdens of the land filled materials. This phase also accounts the blasting materials. Transportation from the materials to their last destination is included in the impact data, and estimated to be 15 km from the construction site (Doka, 2009). For the reinforced concrete, the steel is recovered by specific processes. The diesel consumption for these processes is shown in the table below (Doka, 2009).

Unit		Reinforced concrete	Reinforcing steel	Plain concrete
Tearing with hydraulic devises	h/m3	0.173	-	0.118
Diesel consumption	kg/h	19	-	19
MJ/m3		1.41E+02	-	9.60E+01
Material density	kg/m3	2300	-	2200
Specific diesel consumption	MJ/kg	0.0613	0.63413	0.0436
PM10 emissions	kg/kg	8.00E-05	-	-

Figure 99: Diesel consumption for reinforced concrete dismantling (Doka, 2009)

4.4 Bridge System Overview

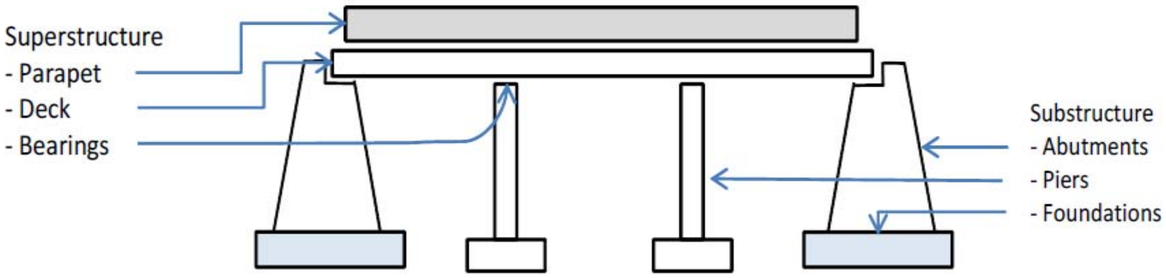


Figure 100: Superstructure and Substructure of a Railway Bridge

- Auxiliary Structure and Terrain:

  In this group of columns it is included everything related with the preparation of the terrain, before the construction and after the disposal of the bridge. It also includes the terrain reinforcement and retaining structure, and the temporary structure. The temporary structure can be the formwork or any kind of auxiliary structure needed for the construction.

- Superstructure:

  The superstructure of the bridge is divided in two main categories, the load bearing structure, and the special structures. In the first group, all the structural elements are included, i.e. box girders, cross beams, truss, cable system, arches and the bridge deck. The special structures include all the additional elements needed for the bridge that are over the substructure. To this category belongs the bearings, expansion joints, draining system, the parapet, electrical installation, and finally the coating, painting or other surface treatments.

- Substructure:

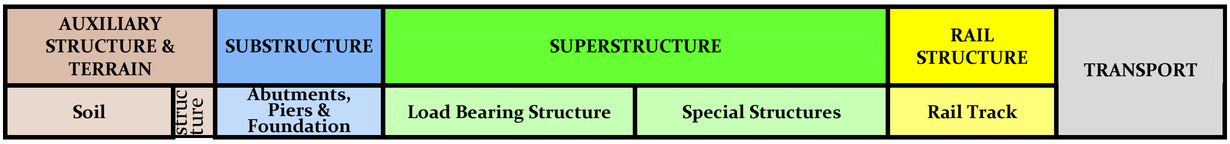
The substructure comprises the structures needed for transferring the loads from the superstructure to the terrain below, i.e. foundations, abutments and piers. The program subdivides this category in piles, walls, base slabs and bridge seats, and piers. In this group is also included the waterproofing needed for the elements that are in contact with the soil.

- Rail Structure:

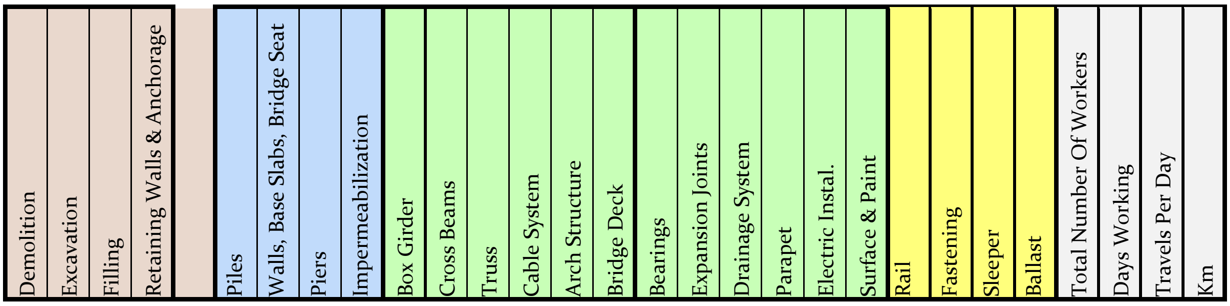
Under this category, there are all the elements related to the railway system: rail track, fastening, sleepers and ballast. The construction activities of the rail system are considered in the construction activities and included in the superstructure.

- Transportation:

The transport accounts the impact caused by the fuel consumption, it considers the production and related emissions of the fuel, but it does not consider the impact of the vehicles per se. It is included as a part of the bridge system in order to facilitate the assessment of the environmental impacts due to the transportation alone. It is also integrated in the material and construction phases. The first three columns have one sole function, which is calculate the km of the total workers in the construction phase (considered by car). This value is placed in the forth column, which also collects the distances covered by the materials from the gate of the factory to the construction sites. There exist as well, hidden columns which are used for the calculations that represent each mean of transport: car, truck, ship, plain or train. These columns collect the kilometers and multiply them per quantities of each material. For this version of the program, only the truck option is available, thus, it is considered that the kilometers entered by the user for the transportation of the materials are covered by truck, and it does not consider the kilometers done before the truck transportation, by ship, train or plain. The transport is not considered for the maintenance or end of life activities. Further development of the program may include the workers transportation in maintenance activities and the transportation of the material disposal, which now is included in the materials and considers the disposal 15 km away from the construction site. This way, the user can decide the distance and obtain more accurate results.



AUXILIARY STRUCTURE & TERRAIN		**SUBSTRUCTURE**	**SUPERSTRUCTURE**		**RAIL STRUCTURE**	**TRANSPORT**
Soil	structure	**Abutments, Piers & Foundation**	**Load Bearing Structure**	**Special Structures**	**Rail Track**	



Demolition	Excavation	Filling	Retaining Walls & Anchorage		Piles	Walls, Base Slabs, Bridge Seat	Piers	Impermeabilization	Box Girder	Cross Beams	Truss	Cable System	Arch Structure	Bridge Deck	Bearings	Expansion Joints	Drainage System	Parapet	Electric Instal.	Surface & Paint	Rail	Fastening	Sleeper	Ballast	Total Number Of Workers	Days Working	Travels Per Day	Km

Figure 101: Parts of the Bridge System included in the model

Chapter 5

Case of Study: “Puente de Castilla” Railway Bridge

5.1 Bridge Description

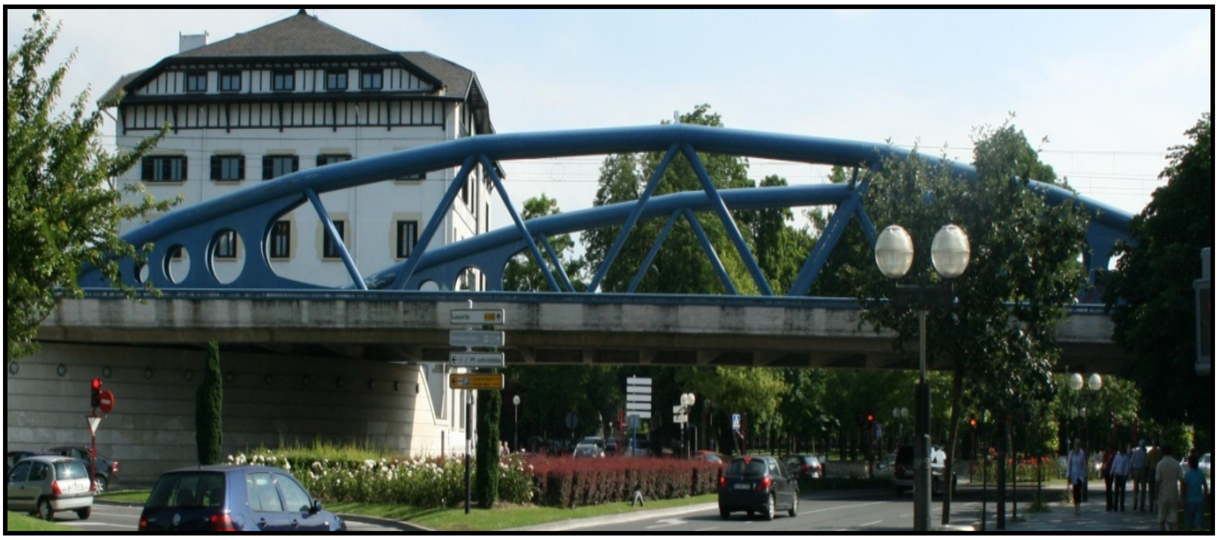


Figure 102: Puente de Castilla (Vitoria, Spain)

In this thesis, the LCA program is going to be applied to perform a Life Cycle Assessment of a Spanish railway bridge. The bridge chosen is located in the city centre of the city Vitoria-Gasteiz, and is called “Puente de Castilla” due to the street that crosses behind. This bridge was built in 1994 to replace an old steel bridge. This old bridge, built at the beginning of the 20th century, had 9 meters of span and, due to its short span, prevented the normal development of the city by restricting the access of traffic and divided the city into two separated parts. Moreover, this old steel bridge was not designed for supporting the out coming high speed train lines that communicate Spain and France.

To solve this situation, the city council decided to build a new bridge with larger span and higher requirements, and remove the existing barrier between both sides of the city. The new bridge, which was going to be property of RENFE, the railway company in Spain, had to respect the small height of the existing rails, increase the span length, capable to support double railway track of high speed trains and consider the obliquity of the roads that cross behind. The best solution was designed by Javier Manterola and Amando López, they adopted a tied arch bridge with one tubular steel arch set on each side of a pre-stressed concrete deck supporting double railway track with a 64 m span set very skew to the road (54,7º). Given the small height of the previous bridge and existing tracks, the track system chosen was a embedded rail track system, which needs less height than a common ballast track system, and none maintenance activities during the service lifetime.

The tied arch bridges with lower deck or bowstring, was an ideal solution for this bridge. This typology of bridge has two main characteristics. On one hand, it has strength behavior as it is an arch structure, which does not transfer horizontal loads to the foundations as the deck is tied to the arch. The union between the arch and the lower deck, increases the stiffness, and provides better response to unsymmetrical loads, which was an important factor in this case, due to the obliquity of the crossing roads under the bridge. This union provides considerable bending stiffness to the arch and takes advantage of the compression capacity of the pre-stressed concrete deck to resist the bending. For the arches of the new bridge, a double arch tubular structure was used in order to make the arches as slim as possible and control the buckling in the perpendicular plane, which is also solved by the bending stiffness of the uprights and diagonal hangers tying the arch to the deck. The bridge being a railway bridge makes it necessary to control the bending caused by railway loads, even more if they are not symmetrical. For this purpose, the connection between the arch and the deck was triangulated.

On the other hand, the appearance of the bowstring bridge was a valuable point for this bridge that was going to be placed in the middle of the city. This kind of bridges allows having a minimum depth of the beam section below the platform, and this makes it a good alternative for bridges with relatively large span and little space below the bridge. The tubular steel arches painted in blue gives the bridge a modern look to integrate in the city atmosphere.

Due to the major importance of the rail line Madrid-Paris, which the bridge belongs to, in order not to interrupt the rail or road traffic during the bridge construction, the bridge was totally built parallel to its final location. Once the bridge was totally erected, the old bridge was moved to a different location in the city, and nowadays is shown as a monument to the old steel rail bridge builders. The new one was shifted to its final position and then the rail infrastructures and communications adequated and prepared for the opening. The whole process took just fourteen hours of traffic interruption.

The data used in the study was provided by the Urbanism Department of the city Council of Vitoria. The source is the project report handled by the designers and director of the construction processes, Jesús Marcos Egido. However, data regarding the maintenance and end of life foresights were impossible to find, and have been estimated by the author from other bridges. Most of the figures are taken directly from the project report.

5.1.1 Superstructure

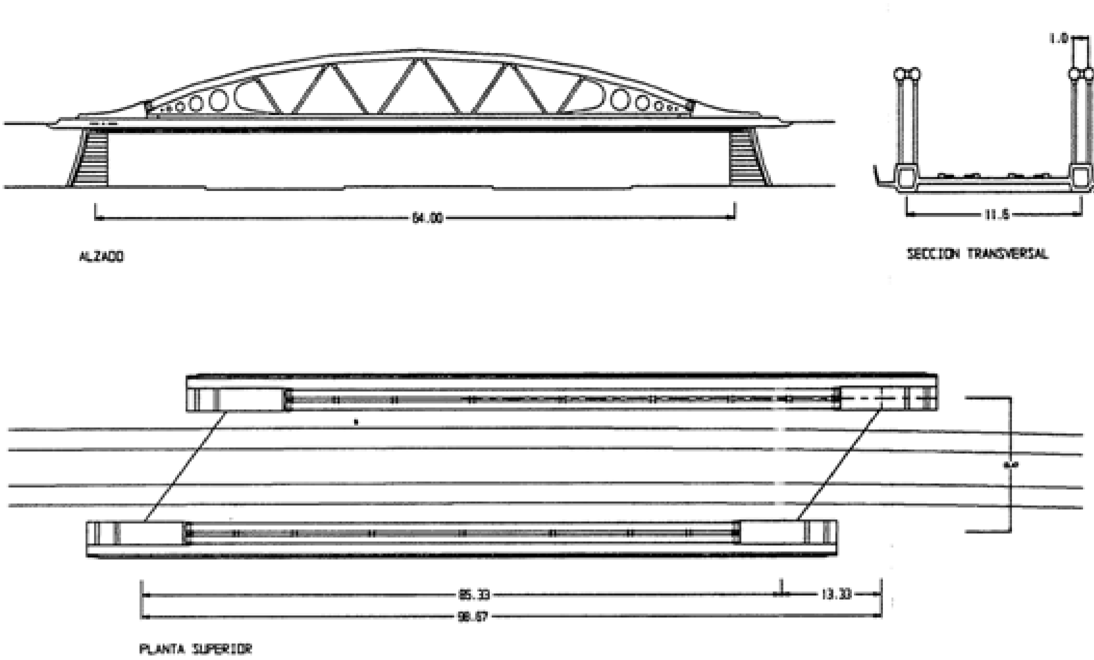


Figure 103: Main views of the bridge

As mention before, the deck is built with pre-stressed concrete, and constitutes the base for the rail platform and also the bottom chord of the trussed steel arches. It is formed basically by two longitudinal beams with a distance of 11,60 meters between each other that are tied together by two transversal end-beams with 54,7° of obliquity with the longitudinal ones, and several cross beams perpendicular to the longitudinal beams. Figure 108 shows the model that the designers used to calculate the structure.

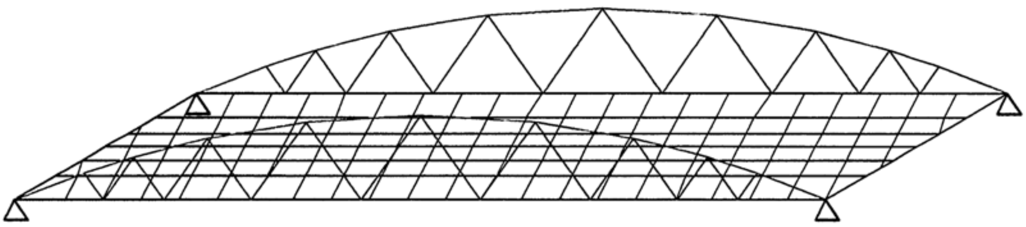


Figure 104: Structure model

The longitudinal beams have a polygonal section, an irregular hexagon with two parallel sides with 0,275 meters of thickness, the upper and lower sides: with

1,40 meters for the upper side, and 1,20 meters for the lower side. Both beams have 1,60 meters of height. The web thickness is 0,265. The hollow is filled with concrete in the intersection with the transversal beams and in the unions with the arch triangulation tubes. As shown in figure 109, each beam is pre-stressed with 8 cables formed by 19 strands of 0,6” of diameter.

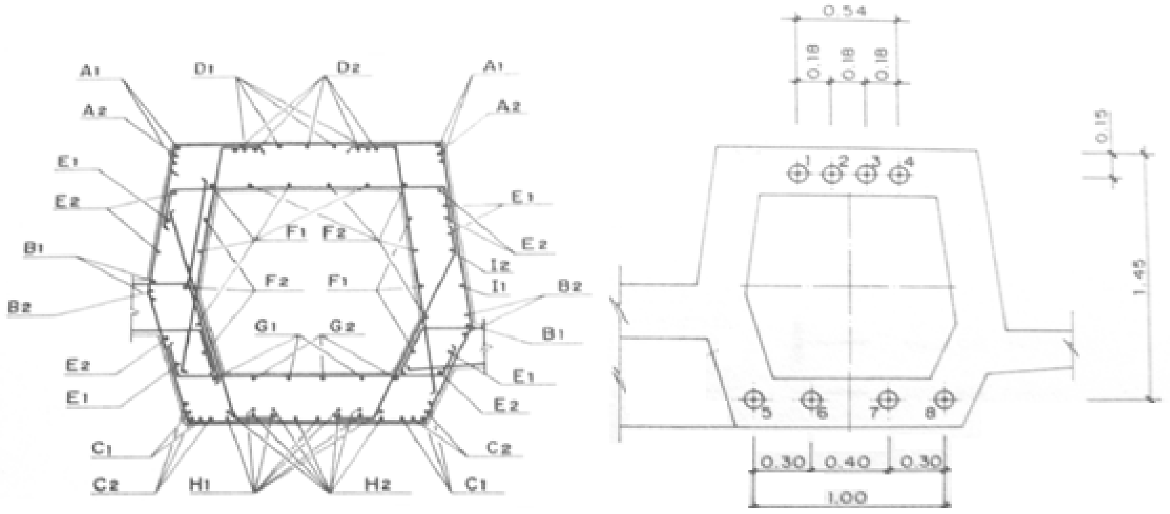


Figure 105: Longitudinal beams cross-section: a) passive reinforcement and b) pre-stressed reinforcement

The deck also has a group of cross beams of 0,5 meters of with, located perpendicularly to the longitudinal beams, and separated 3 meters from each other. Over all the beams, it is placed a concrete slab with 0,3 meters of with that makes the ensemble work as a whole. The slab has three holes to place the supports and concrete blocks coming from the substructure that allow anchoring the bridge from wind and the train braking effects. These loads are transmitted and supported along the slab by two groups of three pre-stressed cables of 0,6” of diameter in each side of each hole. The rest of the slab reinforcement is passive steel reinforcement.

The arch structure is formed by two groups of two steel tubular trussed arches, one pair in each side of the bridge, which supports the deck. Each pair of arch structures is placed over the longitudinal beams coincident with their vertical plane.

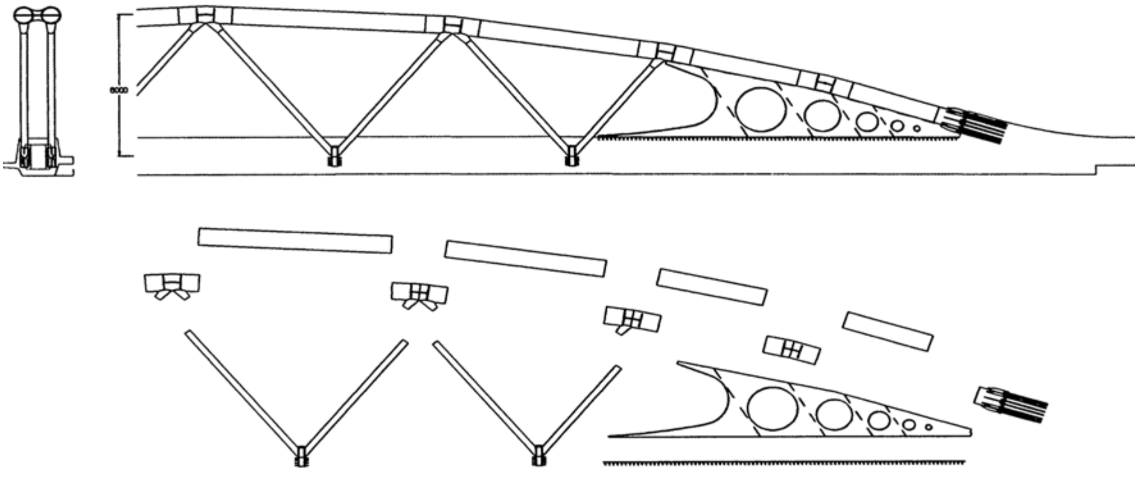


Figure 106: Arch structure: Main steel tubes, truss and distribution plate

Both arches have a maximum height of 6 meters and consist of an eight-sided polygon inscribed in a circle of 174 meters of diameter. Each pair of arches has a main group of tubes of 711 millimeters of external diameter and 25 millimeters of thickness of steel AE-355D (old Spanish terminology for steel).

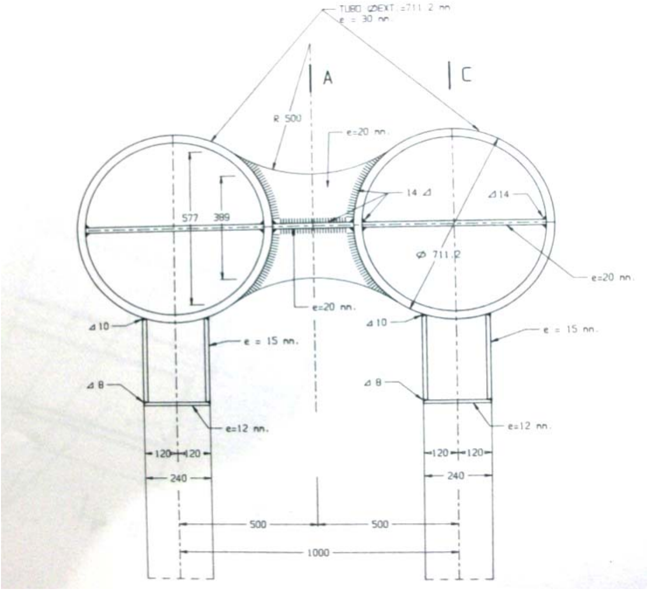


Figure 107: Cross-section of one pair of the steel arch tubes

Both arch tubes are separated by 1 meter and braced together by plates of 20 millimeters of thickness in the unions between the arches and the truss triangulation tubes. In these unions, the thickness of the steel tubes increases to 30 millimeters within a distance of 1 meter in each side, but remaining constant the external diameter of the tubular structure.

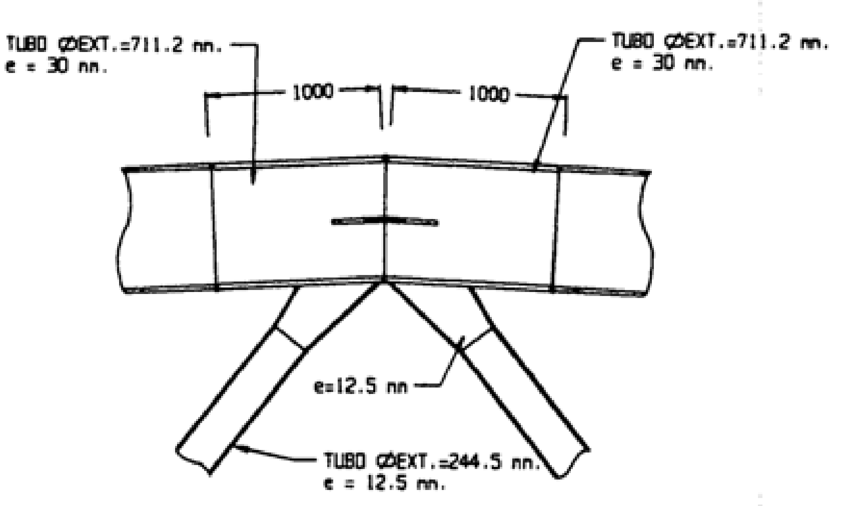


Figure 108: Design draft of the union between the arch and triangulation tubes

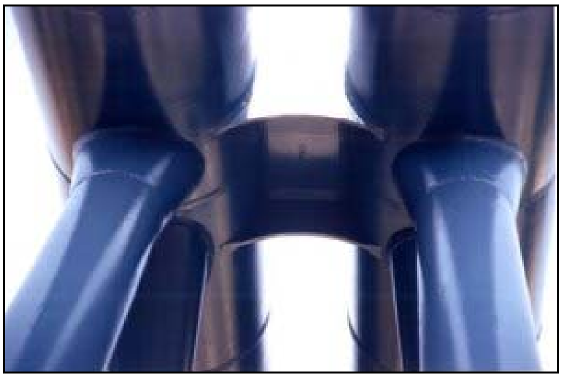


Figure 109: Picture of the union between the arch and triangulation tubes

The connection between each pair arch tubes with the deck is done by a distribution steel plate of 1960x960x60 millimeters and by two groups of 16 bolts of 40 millimeters of diameter and 1500 millimeters of length, distributed in two respective circles of 420 millimeters of radius. The last part of the arch tubes increases their thickness to 30 mm, and is directly welded radially to 8 plates inside and 8 outside of the tubes, of 700x290x15 millimeters to the tubes and to the anchorage plate with the bolts (figure 114).

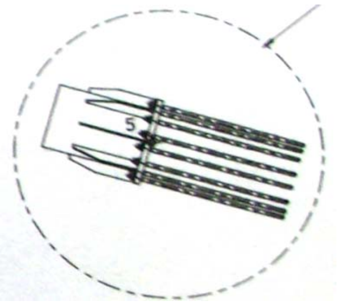


Figure 110: Connection between the arch tubes and the concrete slab by 16 bolts

Each arch tube is also joined to the deck by plates of 200 millimeters of thickness that cover the last part of the triangulation and fill the space between the arch tubes and the longitudinal beams of the deck. These plates are alighted by five circle holes and each pair of plates are connected in the inner side by plates of 15 mm of thickness with similar inclinations to the triangulation tubes.

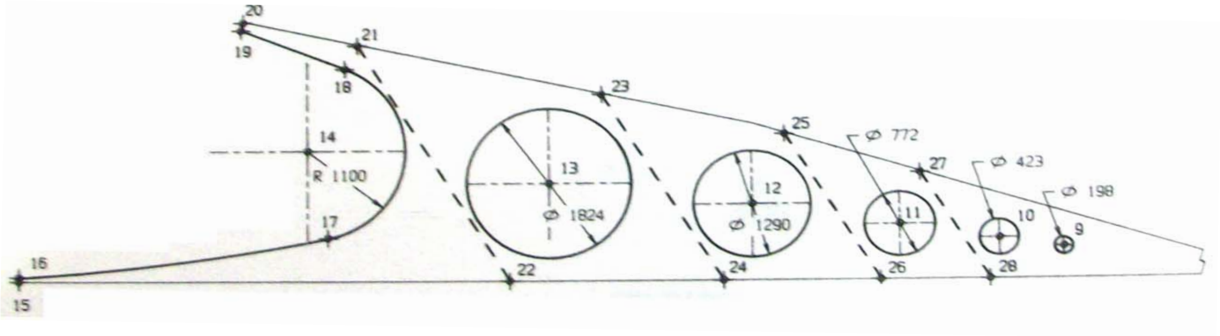


Figure 111: Connection plate between the arch tubes and the concrete slab

The plates are directly welded to the steel tubes and connected to the concrete by another horizontal plate of 13176x300x15 millimeters anchored to the concrete by bolts of 22 millimeters of diameter and 100 millimeters of length.

The truss joins each arch tube to the deck, and consists of a triangulation of smaller steel tubes of 244,5 millimeters of external diameter and 12,5 millimeters of thickness. The connection to the arch tubes is done by tubes of 400 millimeters that increase their radius with 8º of inclination welded to the arch tubes and to the truss tubes. In these joints, the designers avoided using union plates due to the fatigue caused by the train traffic.

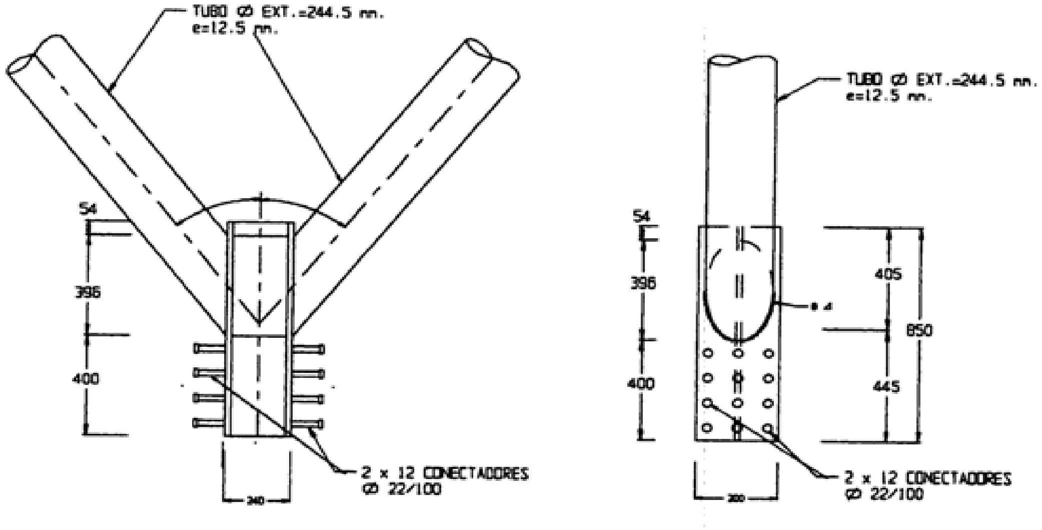


Figure 112: Connection between the truss tubes and the concrete deck

The unions between each tube and the concrete in the lower part is achieved by welded plates with H shape of 850x300x20 millimeters for the flanges and

850x200x20 millimeters for the web, which is vertically placed into the concrete. The plates have a set of 12 bolts in each side of 22 millimeters of diameter and 100 millimeters of length, which will be inside the concrete and will transmit the loads to the deck (see figure 116). This particular component of the bridge structure has the mission of transmitting the horizontal components resulting from the axial loads in the triangulation tubes to the deck.

All the concrete parts of the bridge that are in sight have its surfaces painted in white and all steel parts where painted with metallic blue coating.

The bearings are made of neoprene, and there are three different types of pairs. The first pair of bearings is for vertical loads are placed in the intersections between the longitudinal beams and the transversal beams, over the abutments. These bearings have 450 millimeters of diameter and 209 millimeters of height compressed and 239 millimeters of height of the neoprene. The second pair is for absorbing the braking effects and consists of two pair of bearings of 400x200x85 millimeters and 400x200x61 millimeters of neoprene. Last pair of bearings is for the wind loads, and have 250x200x85 millimeters and 250x200x61.

The drainage system consists of PVC tubes of several diameters and variable cross-section.

5.1.2 Substructure

The superstructure of the bridge is supported by the substructure. The abutments are formed by reinforced concrete of 5,30 meters of height for each side. They are formed by two rectangular blocks, one in the lower part of 3,44 meters of height and 2,40 meters of width and the higher one of 1,86 meters of height and 1,2 meters of width. The abutments are anchored to the soil by pre-stressed cables of 7 straps of 0,5” of diameter in order to make them able to support train braking effects.

Each abutment has its own foundations. These foundations consist of three pairs of piles. The pairs of piles in the external sides have 1,5 meters of diameter and 10 meters of total length, and the ones in the center have 1,8 meters of diameter and 12 meters of length. The dimensions of the slabs for the head of the pairs of piles are respectively 7,95x2,00x2,20 meters for the external piles and 8,25x2,30x2,80 meters for the ones in the center. Both piles and slabs are reinforced with passive steel.

In each side of the abutments there are retaining walls of reinforced concrete for containing the terrain. These walls decrease the height from 5,5 meters in the highest point, and have 0,5 meters of thickness. They are supported by base slab foundations of reinforced concrete. The walls also have rubber joints between each module to allow expansion and prevent the water flow. The surface of the walls and abutments is covered by limestone plates of 0,50x0,50x0,03 meters.

The impermeabilization of the parts that are in contact with the terrain is achieved with bitumen layers. The impermeabilization between the longitudinal beams and the deck slab is achieved by asphaltic fabric and mortair.

5.1.3 Rail structure

Due to the requirements of a specific height for the rail track, imposed by the existing tracks and the height of the old bridge, there was not enough between the new structure and the rails to use ballasted tracks. To solve this, the designers chose a different alternative of fixed tracks: an embebed rail system. In this kind of system, the rail is embebed in the concrete by polymer compound foam that supports the rail tracks and absorbs the vibrations and noises very efficiently. In figure 117 it is shown the height gain in the embebed system versus the traditional ballasted track.

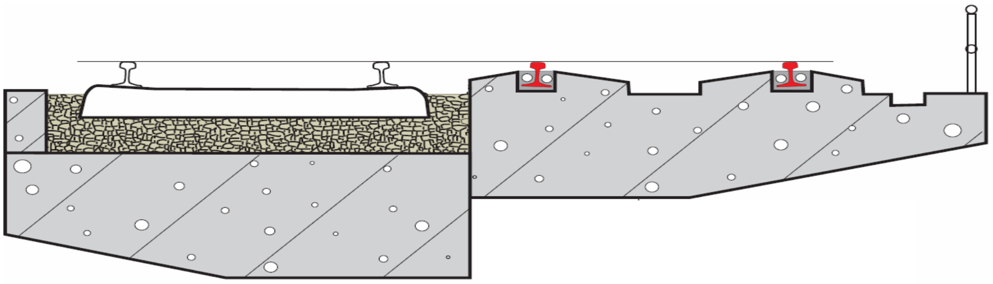


Figure 113: Ballasted track system vs. embebed rail system ("study of the railroad in Sant Feliu de Llobregat")

This system does not need any maintenance, is waterproof and provides good adherence to both the concrete and the rail. In this system, the track does not need to be aligned and tamped.

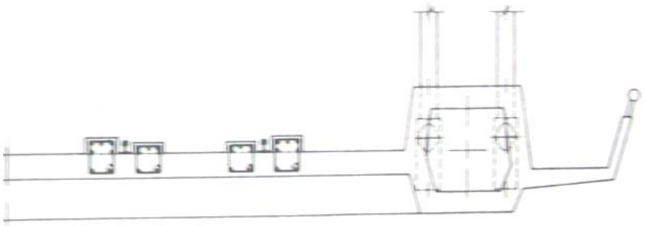


Figure 114: Cross-section of one side of the deck and rail system

In this case, the embebed rail is surrounded by reinforced longitudinal beams inside the deck structure that support and transmit the loads to the structure. Figure 119 shows a cross-section of the rail system and the longitudinal beams.

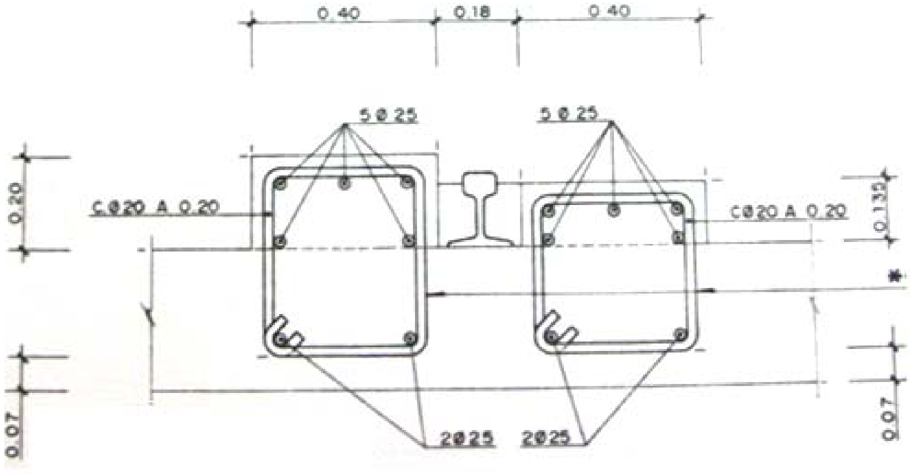


Figure 115: Cross-section of the embebed rail system

5.2 Life Cycle of the Bridge

5.2.1 Material Phase

The available data for the quantities of each material used in the bridge was the one included in the final report of the construction project of the bridge. Therefore, there was only available data for the whole bridge project, and the values for each components of the bridge were estimated by the dimensions of each one included in the report. Appendix B shows the detailed quantities of each material used.

In this material inventory is included the material used for the auxiliary elements used to move the bridge, because it was included in the bridge project report even though it was an external company hired by the construction company who was in charge of moving the bridge. However, there was no data available for the process of moving per se in the bridge report. In this case, there was a big amount of materials used in the temporary structure, as the operation of moving involves great loads and it was required to even build foundations for the auxiliary structure. Although this materials do not belong to the bridge structure, in this study, it is considered that it is important issues regarding the environmental impact of the construction process, and the not inclusion of it would mean an important limitation in the performance of the LCA.

Figure 121 shows from above, the auxiliary structure built to move the bridge once finished. In the lower part of the picture there can be seen the couple of pairs of piles built just for the auxiliary structure. The x lines represent the formwork which is right below the longitudinal beams. The four pairs of piles for the bridge foundation can also be seen.

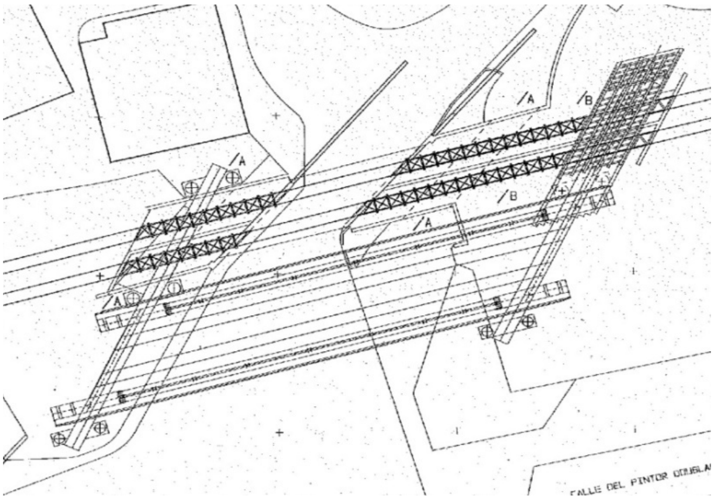


Figure 116: Auxiliary structure to move the bridge

For the distribution of materials, there was no available information of the distances to the supplier industries. Therefore, as the bridge was located in the city center, and the city has an important number of industries, including steel and concrete plants in the surroundings, it was considered that the distances were approximated by 5 kilometers. In case of the corkelast for the embebed system, the closest provider was 45 kilometers away.

5.2.2 Construction Phase

The bridge project report was very exhaustive in the hours of use of each construction machine. The values for the diesel consumption were estimated as mention in previous chapters, and the results for the diesel consumption correspondent to the use of each construction machine are displayed in the table in Appendix B. For the electricity or water consumption there were no indicated data, therefore those values were not included in the LCA.

As mentioned in the material phase description, in the construction phase there was no information available about the process of moving the bridges. Therefore, the life cycle assessment is going to be without taking that into account. However, if there were not lack of data, it would be recommended including it in the study.

Figure 122 shows schematically the basic steps followed in the bridge construction. In the first stage the formwork is placed, and the connectors truss-deck, the triangulation tubes and the arch anchorage are joined to the concrete when it is poured. In the second stage, the connectors arch-deck are placed and the elements are tied to the concrete deck. In the third stage, the unions between the triangulation tubes and the arch are set. Finally, the arch is put in place and the formwork is removed.

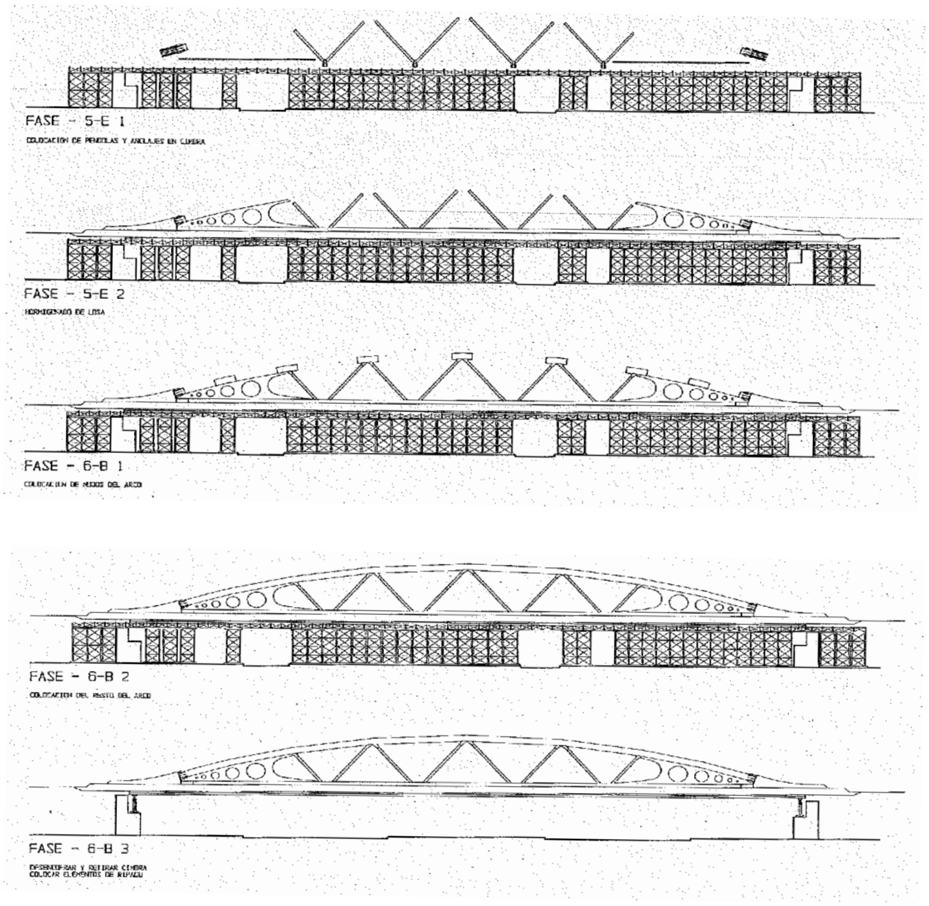


Figure 117: Scheme of the Construction stages

5.2.3 Use and Maintenance Phase

In this phase, the use was disregarded, as the model does not consider it (see model description). For the maintenance activities, there was no available data provided by the city Council, therefore, some assumptions have been made based on other bridges included in other studies. The considered maintenance activities were as follow:

- The steel parts were assumed to be repainted with polyurethane paint every 30 years. With the same amount used for the painting in the construction phase.
- The embebed rail system does not require any maintenance activities, neither tamping the rail track.
- Rail grinding was assumed to be done every year.
- Rail replacement or renewal every 25 years

5.2.4 End of Life Phase

There were no references of foresight scenarios for the end of life of the bridge or a proposed waste management line. For the LCA of this bridge, all the formwork wood used was assumed to be disposed as landfill.

The end of life phase considers the waste management of the main materials involved. Three scenarios are considered, incineration, recycling and disposal, although not all materials have the choice of all of them. For the steel, the end of life alternatives is recycling or disposed in landfills. The user must introduce the quantity of steel that is going to be recycling or dispose for each bridge component or for the whole system. For the wood, the program includes landfill, incineration and recycling. And for the concrete, landfill and reusing are the available choices. 90 % of the steel was assumed to be recycled and 10 % use as landfill. For the concrete, 70 % of the concrete was assumed to be reuse and 30 % used as landfill. These assumptions are based on similar actuations in other constructions in the proximity of the bridge. The detailed information is displayed in a table in Appendix B.

5.3 Results and Interpretation

Once all the data of the bridge is introduced into the program, the potential impacts are calculated and results are shown in tables and in graphical format. The obtained results are discussed and interpreted below.

5.3.1 Characterizated results

As normalization and weighting are not mandatory step in a Life Cycle Assessment, first are going to be described the obtained results for the characterizated values.

	POTENTIAL IMPACT DATA					
	ADP	**AD**	**EP**	**GWP**	**OLD**	**PCOP**
	kg Sb eq	**kg SO2 eq**	**kg PO4 eq**	**kg CO2 eq**	**kg CFC11 eq**	**kg C2H4**
PRODUCT STAGE	12327,65	7160,00	1408,51	2107472,7	0,13	534,44
CONSTRUCTION	15,77	18,909	4,07	2396,76	0,00030	0,45
USE & MAINTENANCE	536,89	370,58	43,00	71909,68	0,0030	23,60
END of LIFE	202,18	218,07	14195,71	321190,37	0,0036	81,77
Total:	13082,50	7767,57	15651,29	2502969,55	0,1386	640,28

Figure 118: Characterizated numeric results for whole bridge

The total contribution of the bridge to each category impact is shown in the table above. It is remarkable that the potential contribution to the ozone layer depletion is minimal, while the contribution to the global warming is extremely high. This last fact is due to the important quantities of CO_2 emissions in the products manufacture and raw materials extraction.

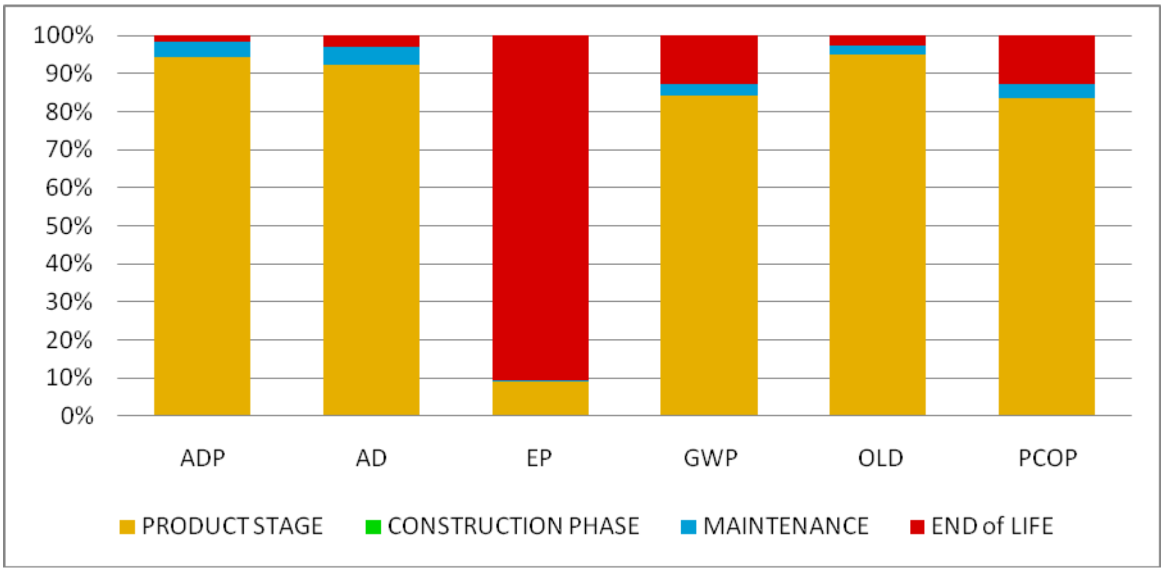


Figure 119: Relative contributions from life cycle phases to each impacts category for the whole bridge

The results for each life phase of the whole bridge to the potential impact categories shows that the main contributor is the material stage for abiotic depletion, acidification, global warming and photochemical oxidation. On the contrary, for the eutrophication, the main contributor is the end of life phase, which is what was expected as it was a large quantity of wood disposed as landfill, and this causes an increase of nutrients in the soil (eutrophication). the study shows that the maintenance activities have very little potential effect in the environment, with nearly no contribution of the construction processes.

All the results obtained with the program should be interpreted considering that, in general, the main contributor to the environmental impact is the material stage. Due to this relevance of the material stage in the environmental impacts, it is also important to analyze the contribution of each material used in the construction of the bridge. This distribution is displayed in the graphic below, considering all the impact categories together.

The graphic stands out the fact that the production of steel and concrete is the cause of the 76 % of the total amount of environmental impact in the material phase. The concrete production represents the 41 % of this contribution, while the steel contributes with 35 % of the total amount of potential impact. Taking into consideration the fact that the global warming had the highest value as seen in the previous results, and in congruence with the analysis of the production processes for the concrete and steel in chapter 4, it is clear that this contribution is due to, in the case steel production, the high CO_2 emissions in the process of heating the furnaces to temperatures over 1300ºC. In this line, it should be considered the use of steel produced with electric arch furnaces. In the case of the concrete production, the main reason for this is the CO_2 emissions during the clinker production. The wood formwork has an important contribution too, with the 23 % of the total potential impacts. The rest of the material production is barely irrelevant for the study. Having this in mind, for further studies, lack of data of materials other than steel, concrete, timber and bitumen may not imply greater differences in the results, and the study can be simplify considerably.

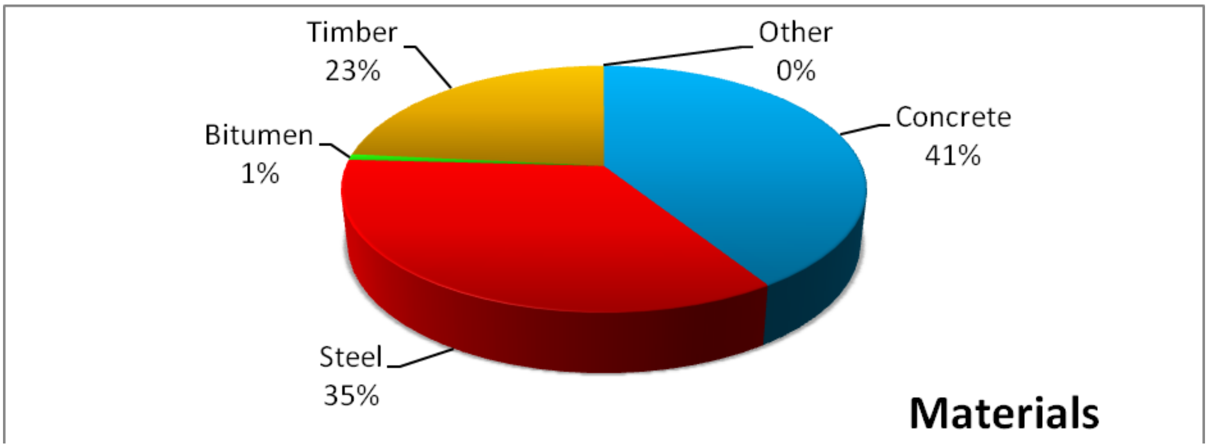


Figure 120: Distribution of the environmental impact of the material stage in materials used (Characterizated results)

The graphics below shows the potential impacts related to each input parameter in the whole lifetime of the bridge. In the graphics, the parameters with no associated input data are not displayed. As the global warming potential has such higher values, two graphics have been generated, one with all potential impact categories and another one without the global warming potential. The results show that from the three types of concrete used to build the bridge, the normal concrete used with non pre-stress reinforced steel is the one with worst environmental performance, this is a consequence of the quantities of each type of concrete more than of differences in the process of production, because the total amount of normal concrete was 2812,77 m^3 while for the pre-stress concrete it was 603,31 m^3 and for the blinding concrete it was 443,85 m^3.

Regarding the behavior of the steel, although the structural steel is in lower quantities (216,08 tons), than the reinforcement steel (356,30), it contributes more to all the potential impacts categories. The reason for this should be found in the differences in the process of manufacturing the reinforcement rebars, which are mostly cold forming, and the structural steel, formed by hot-lamination, which has greater heating requirements and thus, produce more CO_2 emissions. The steel used for the rail tracks in the replacement operations, although it is present in small quantities, as it is carried out every 25 years, in 100 years of life time is also revealed to contribute in an important way to the impact categories. As mentioned before, the production of timber formwork also has an important impact, but is also responsible of the impacts caused for its disposal as landfill. This parameter is one of the important issues that have to be taken into consideration if it is wanted to improve the environmental behavior of the bridge. It is remarkable that the diesel consumption of the construction machinery has no special contribution to the environmental impacts. In the graphic, the fuel consumption in materials distribution is included in each material contribution.

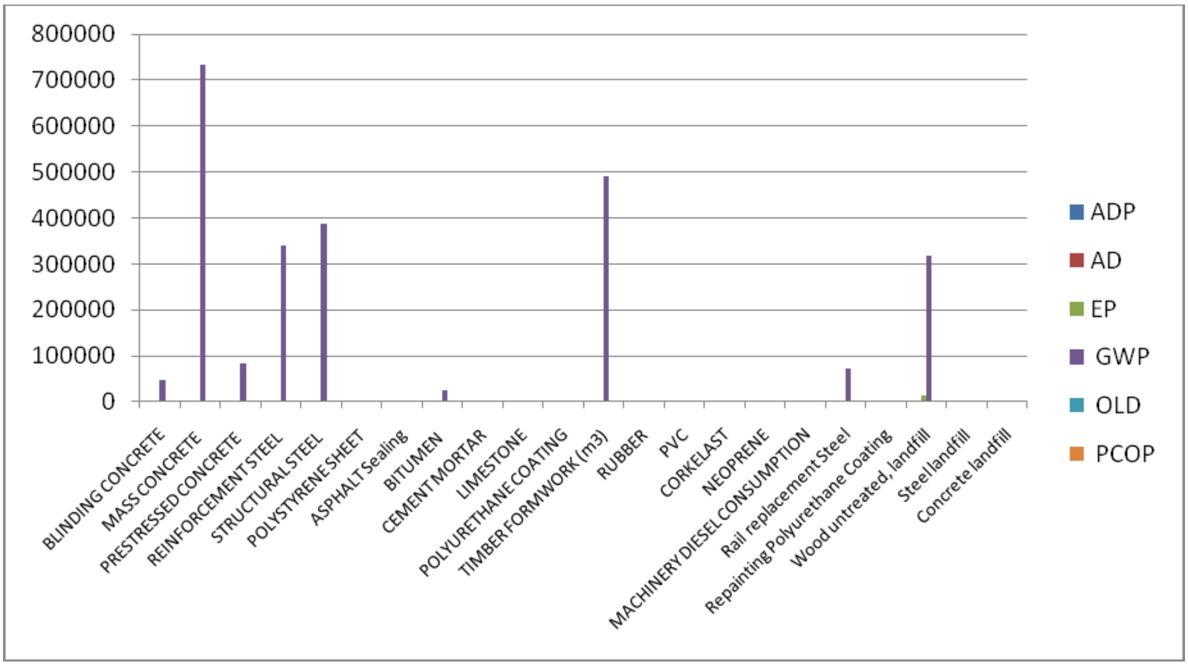


Figure 121: Contribution to each impact category of each input parameter thorough lifetime

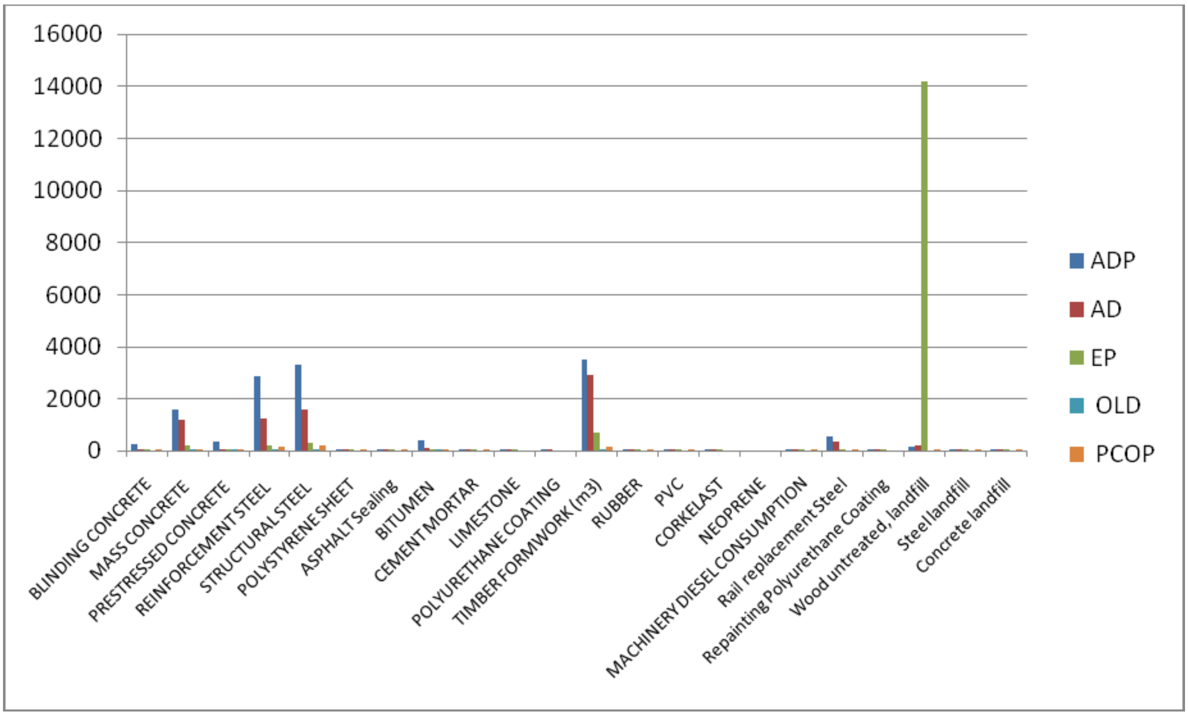


Figure 122: Contribution to each impact category of each input parameter thorough lifetime without including the GWP

When assessing the whole life time of the bridge, the program reveals that there is not a predominant part of the bridge that contributes most to each impact category. Analogously to the previous interpretations, in this case, the auxiliary structure is the main contributor to the eutrophication, because of all the wood formwork used and disposed as landfill in the temporary structure. However, the auxiliary structure does not contribute to the photochemical oxidation, again because the wood is the predominant material of this bridge part.

Another remarkable result is that the auxiliary structure has the highest contribution in all category impacts. One explanation for this is that the timber has a high contribution to the global warming, and it is all concentrated in the auxiliary structure, contrary to the concrete or steel, which are distributed in substructure and superstructure. In this particular bridge, the auxiliary structure had important quantities of concrete and steel, because the loads that this auxiliary structure supported while moving the bridge were very high. As mentioned in the description of the bridge, there was also need to build its own foundations for the auxiliary structure.

As it was expected, the rail structure has very little contribution to the potential impacts, and no contribution at all to the eutrophication. Other interesting fact is that the transport has nearly no contribution to each impact category, with the exception of a small contribution to the ozone layer depletion. It has to be remembered that the diesel consumption due to the machinery in the construction phase is not considered in the transport. Another reason for this is that the bridge was located in the city centre, and almost all the provider companies where within a radius of 5 km (with the exception of the corkelast, which was 45 km away from the construction site).

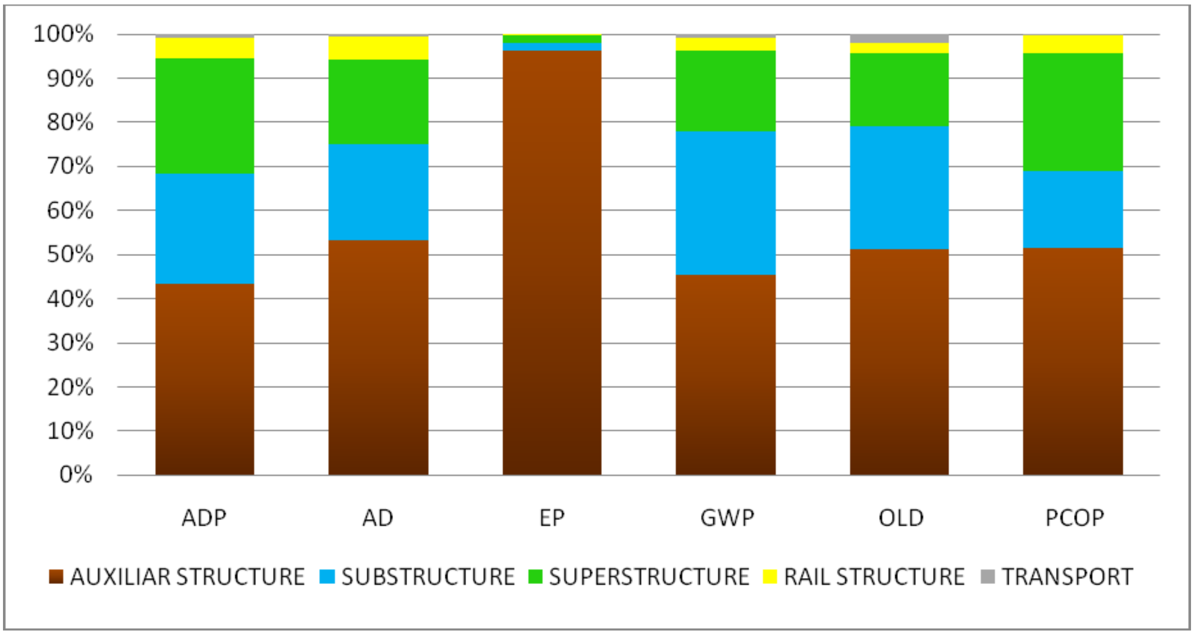
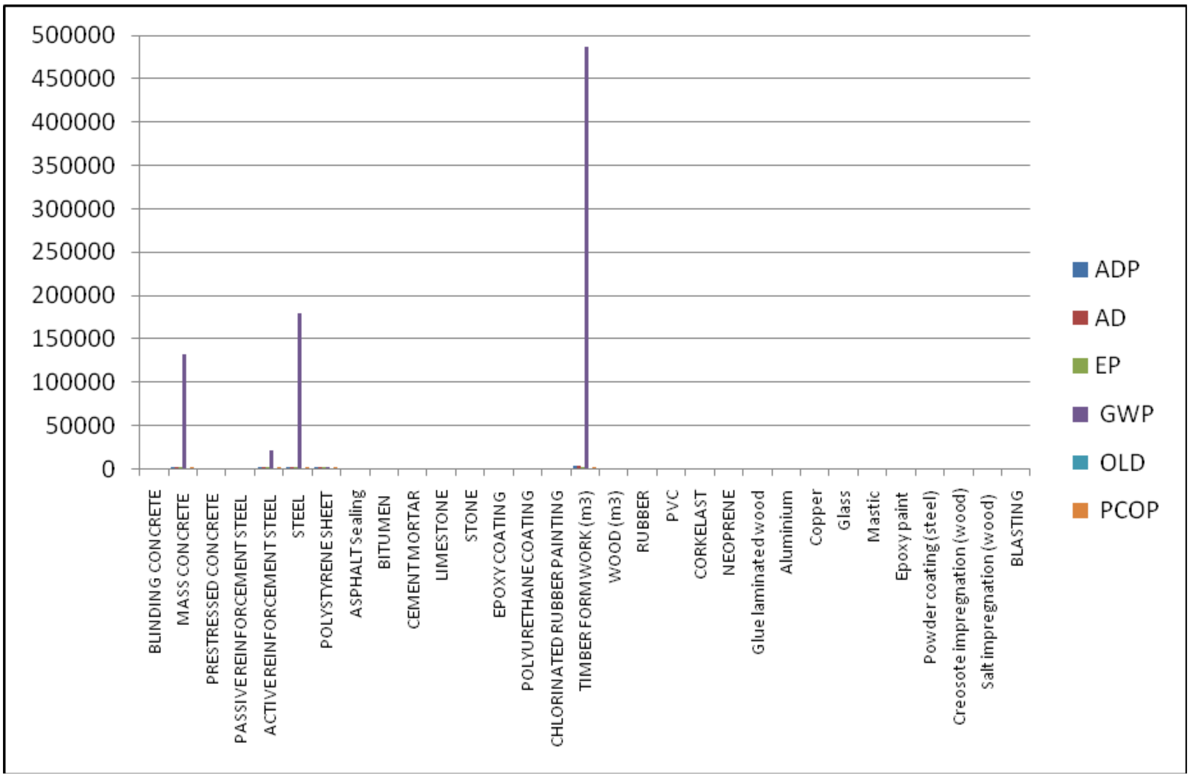


Figure 123: Relative contributions from the bridge components to each impacts category thorough all lifetime

As the results reveal such importance of the auxiliary structure in the environmental impact, this phase is going to be assess individually too. The following graphics show the different materials that form the auxiliary structure. As the global warming potential had values so high that does not allow assessing the other impact categories, a second graphic is generated without the GWP.

In both graphics, the main contributor to the impacts is the timber formwork, which surprisely does not only contribute to the eutrophication, but also to the abiotic depletion and to the acidification with higher values than for the EP. After the timber formwork, the steel is responsible of an important part of the environmental impacts of the auxiliary structure, followed by the concrete. It is important to remember that the input values for these materials for the auxiliary structure were 100,4 tons of structural steel for the structure that will support the bridge during construction and then help to move it to the right position, 507,21 m^3 of concrete for the foundations of the steel structure and 5456,25 m^3 of formwork.



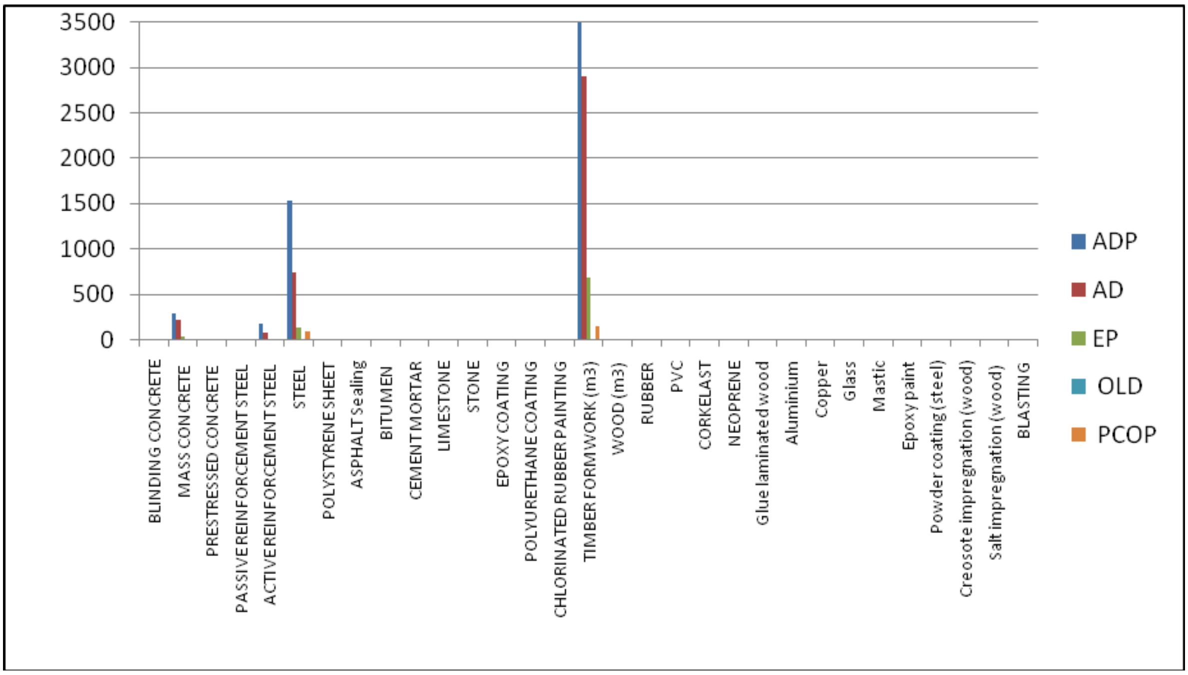


Figure 124: Contribution to each impact category of each component of the auxiliary structure a) with the GWP and b) without the GWP

Aside from the auxiliary structure, to evaluate which structure contributes more to each impact category, the transportation and auxiliary structure are eliminated from the graphic. There are no special differences between the substructure and the superstructure. The substructure is slightly more contributive to the global warming and ozone layer depletion because it has more concrete than the superstructure.

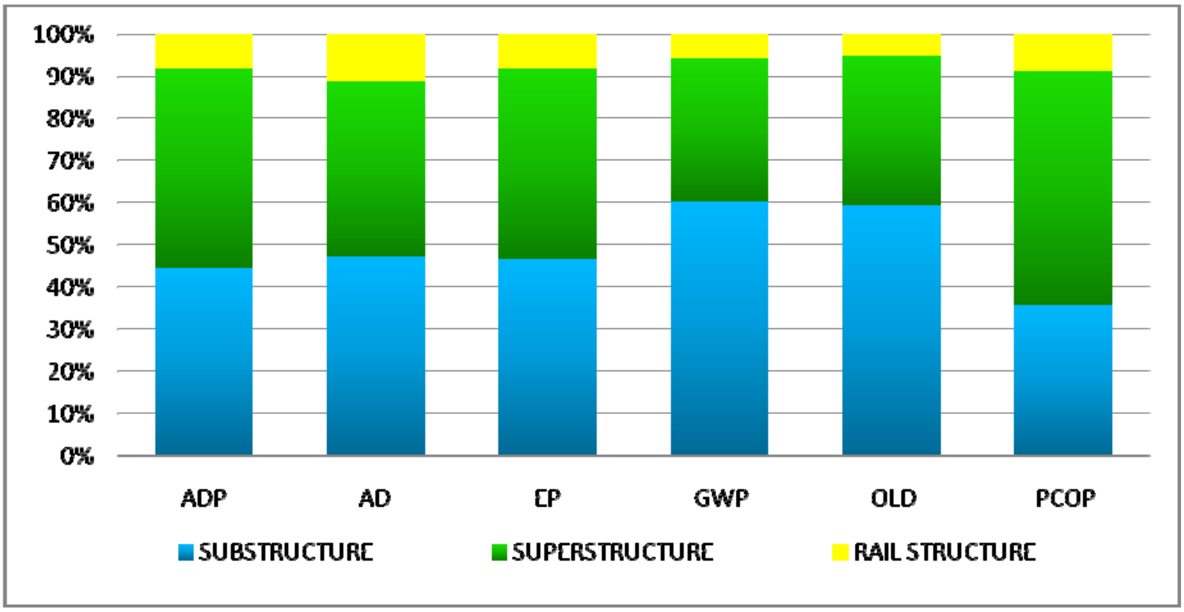


Figure 125: Relative contributions from the substructure, superstructure and rail structure.

5.3.2 Different Weighting Methodologies:

The program provides different results according to seven different weighting methods. These methods are the US-EPA, Harvard, BEES, EDIP, EU-15, Denmark and Global. Each method use different weighting factors. As seen in the description of the model, some of these references do not consider all the included impact categories. Only three methods, US-EPA, BEES and Harvard consider all of them. The other four does not take into consideration abiotic depletion. Using a global reference is only useful when studying the global warming, ozone layer depletion or the photochemical oxidation. BEES weighting factors are similar for the six categories, while Harvard prioritizes global warming and ozone layer depletion against abiotic depletion. US-EPA gives to the global warming a weight factor three times higher than to the other categories; while the global reference or the EDIP prioritize the ozone layer depletion.

These differences are shown in the graphic below, where all the relative results for each categories are displayed for all the weighting methods. It is remarkable that Harvard and BEES give generally higher values for all impact categories than the other methods. EDIP, EU-15, Denmark and the Global references are similar between each other, and generally give the lowest values for all impact categories but the ozone layer depletion. In this particular category, The global reference and EDIP show very high values. US-EPA obtains average values for all categories, but the global warming, which has the highest value of all the impact categories and methods. The choice of which method is better, will depend on each particular case. For instance, if a bridge has materials or processes with high impact to the ozone depletion, and the study must emphasize this aspect of the environmental performance, a global reference or EDIP method should be used. If the study should include the abiotic depletion, then Harvard methodology would provide a better result.

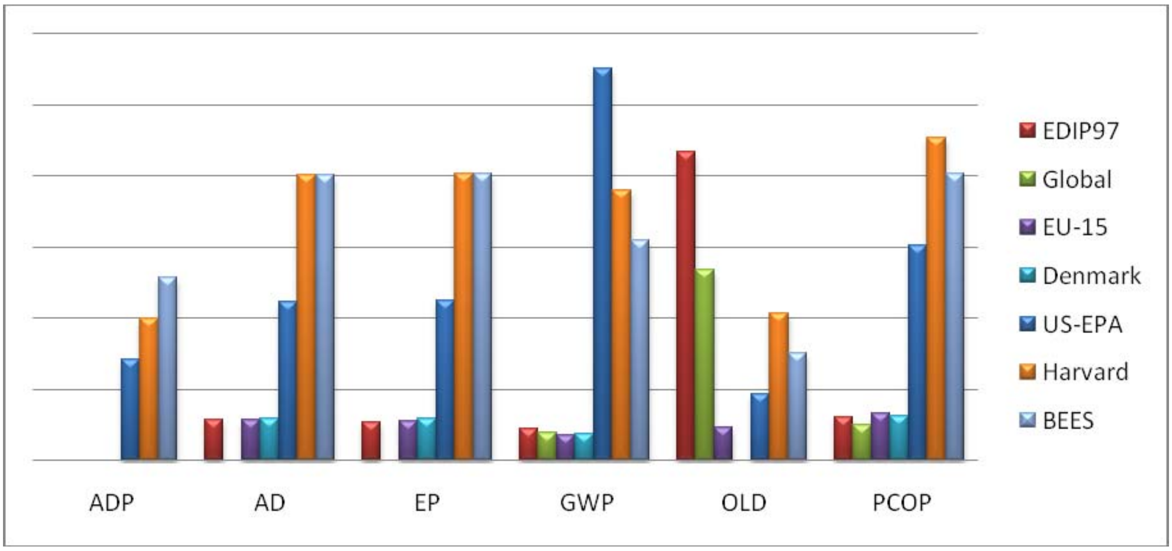


Figure 126: Relative results for each impact category in accordance with the different weighting methods

The author of this thesis considers US-EPA a good reference to assess the life cycle of this case of study because of the importance given to the global warming potential. The table below summarizes these weighting factors.

	ADP	AD	EP	GWP	OLD	PCOP
US-EPA	5	5	5	16	5	6

Figure 127: Weighting factors chosen for each potential impact categories (US-EPA)

5.3.3 Weighted Results:

	POTENTIAL IMPACT DATA (weighted values)					
	ADP	AD	EP	GWP	OLD	PCOP
	kg Sb eq	kg SO2 eq	kg PO4 eq	kg CO2 eq	kg CFC11 eq	kg C2H4
PRODUCT STAGE	4,154E-06	1,310E-06	5,648E-07	7,013E-06	7,899E-09	3,880E-07
CONSTRUCTION	5,314E-09	3,460E-09	1,632E-09	7,976E-09	1,827E-11	3,318E-10
USE & MAINTENANCE	1,809E-07	6,781E-08	1,724E-08	2,393E-07	1,835E-10	1,713E-08
END of LIFE	6,813E-08	3,990E-08	5,692E-06	1,068E-06	2,195E-10	5,937E-08
Total:	4,408E-06	1,421E-06	6,276E-06	8,329E-06	8,321E-09	4,648E-07

Figure 128: Weighted numeric results for whole bridge

The table displays the total weighted results of the Life Cycle Assessment. For the normalization, the program used the total emissions of Western Europe in 1995. For the interpretation, the weighting factors were taken from the reference source US EPA. This reference was chosen for the interpretation step because, aside from including all the impact categories of the study, it gives more importance to the global warming. All the different weighting methods are compared and described later.

As expected, the results reveals that the most relevant impact categories in total weighted results is the global warming potential GWP, followed by the eutrophication EP, and the abiotic depletion ADP. The acidification AD, has lower results followed by the Photochemical Oxidation (PCOP). The less relevant impact category was the Ozone Depletion Potential (ODP), which can be neglected in the results.

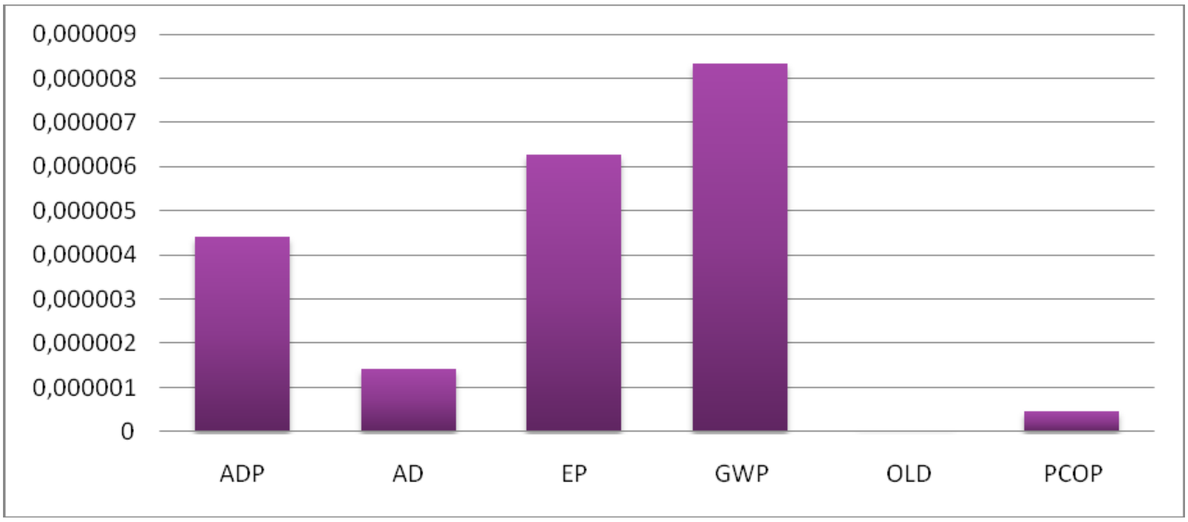


Figure 129: Weighted results for all impact categories

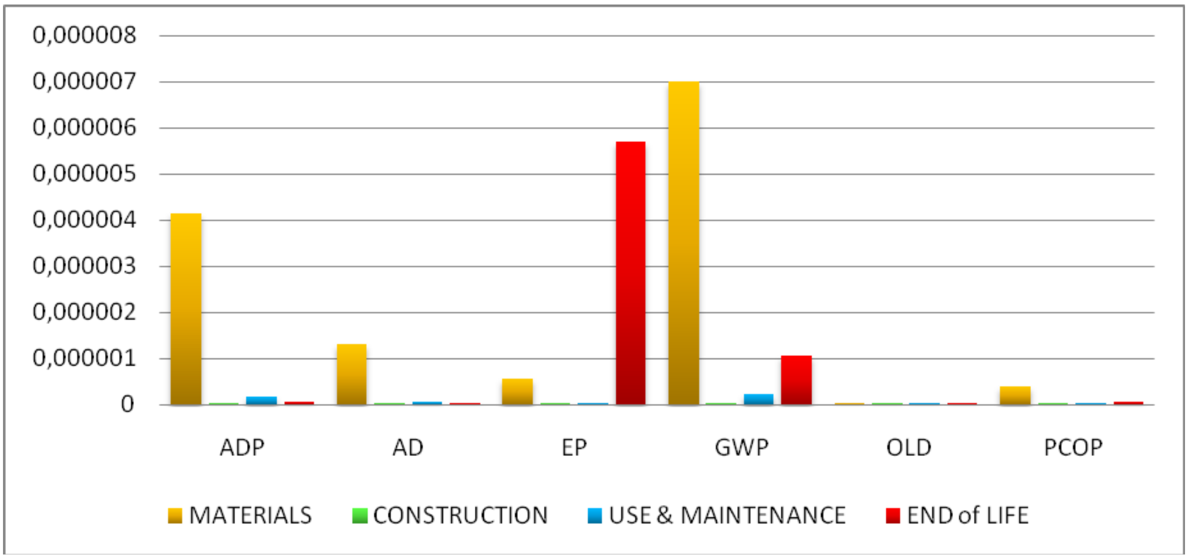


Figure 130: Weighted results for all impact categories by life cycle

The detailed graphic, with the distribution in life cycle phases the conclusions it is revealed that, as analyzed before, the principal contributor to the potential eutrophication is the end of life phase and the disposal of the wood as landfill. Also in congruence with previous interpretations, the potential global warming is mainly caused by the materials extraction and production and the high levels of CO_2 emissions required in the processes of concrete and steel manufacturing. However, there exists a smaller contribution to the potential global warming from the end of life phase, associated with the recycling of the steel. It is also considerable the contribution to the abiotic depletion from the materials production.

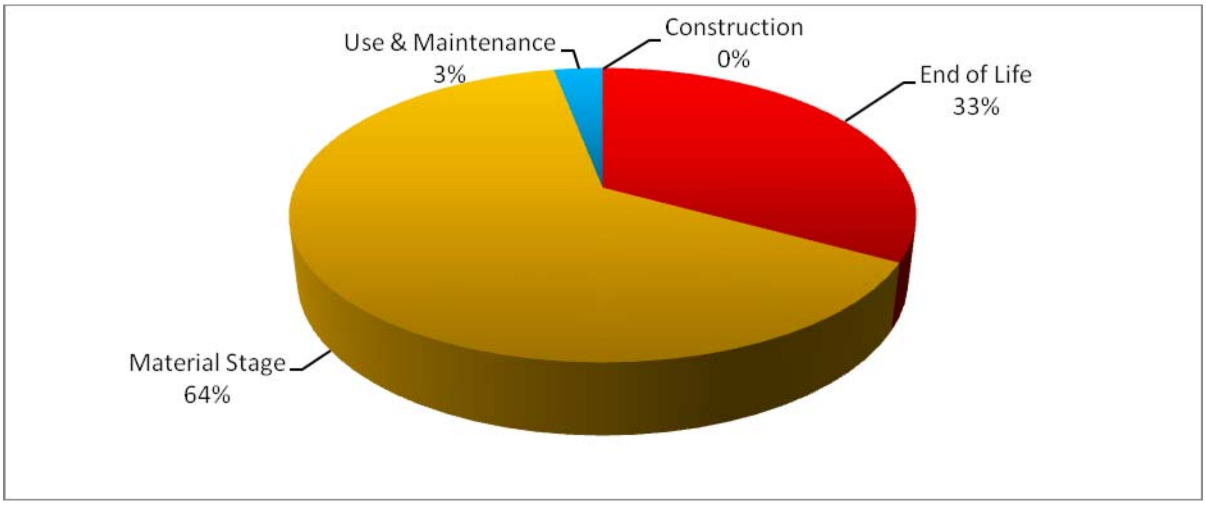


Figure 131: Distribution of the environmental damage by life cycle phases

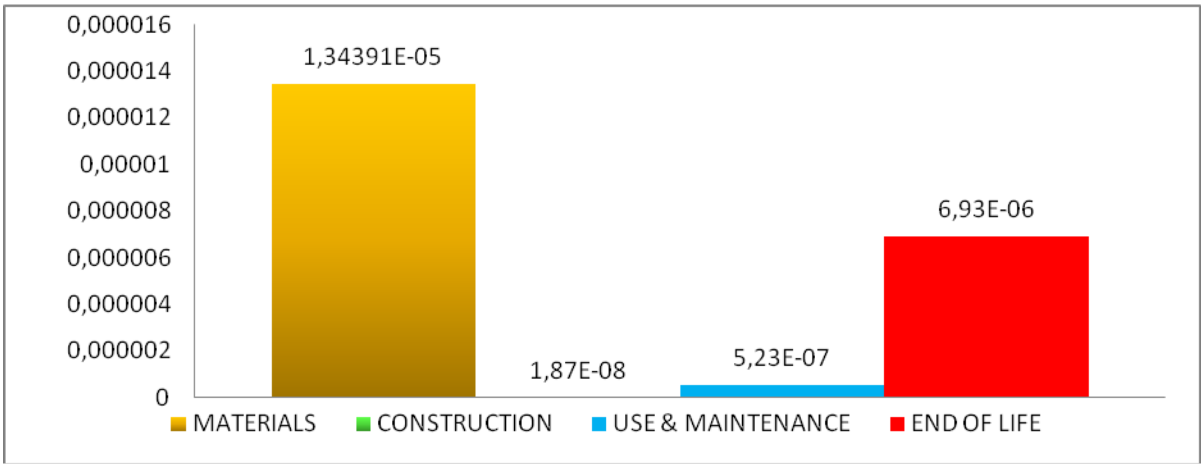


Figure 132: Total weighted scores for each life cycle phase

If the analysis is performed considering the different parts of the bridge, see figure 140, the weighted results remark the importance of the auxiliary structure in the eutrophication and in the global warming. Another fact that can be analyze in this graphic more clearly, is the difference between the superstructure and the substructure in the contribution to the potential global warming. This difference is stressed with the weighting factors in the US-EPA method, as mentioned before.

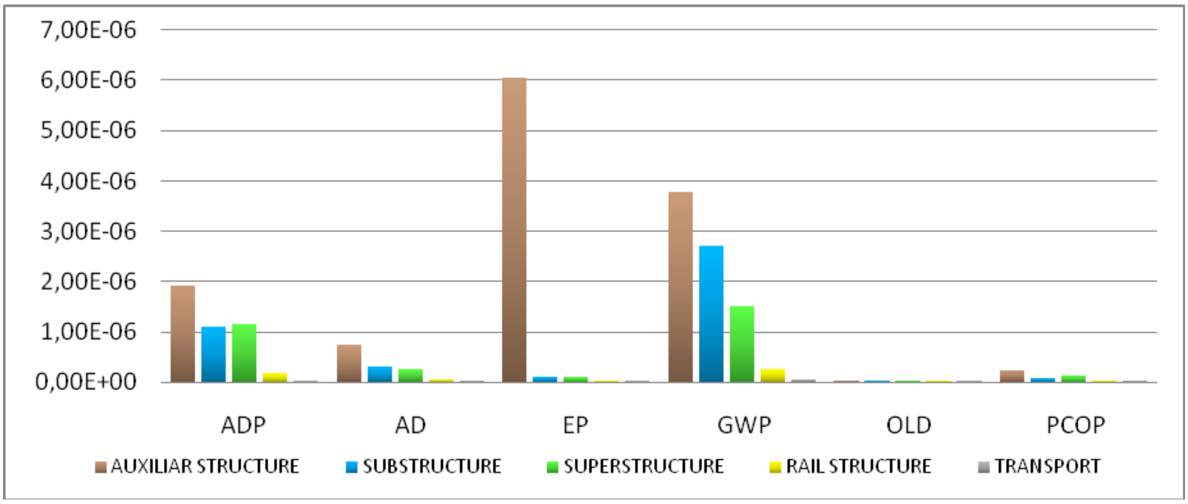


Figure 133: Weighted results for all impact categories by part of the bridge

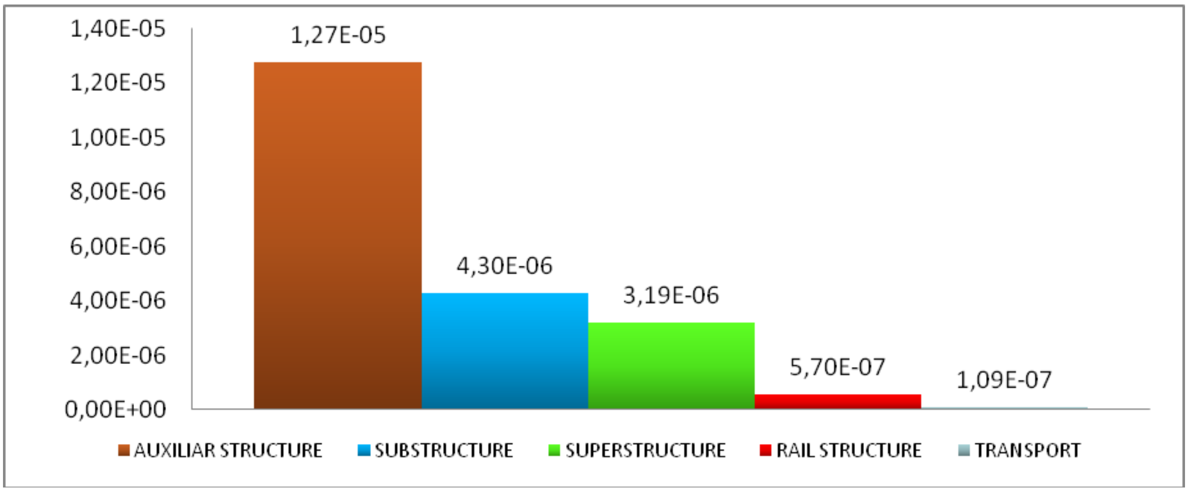


Figure 134: Total weighted scores for each bridge part

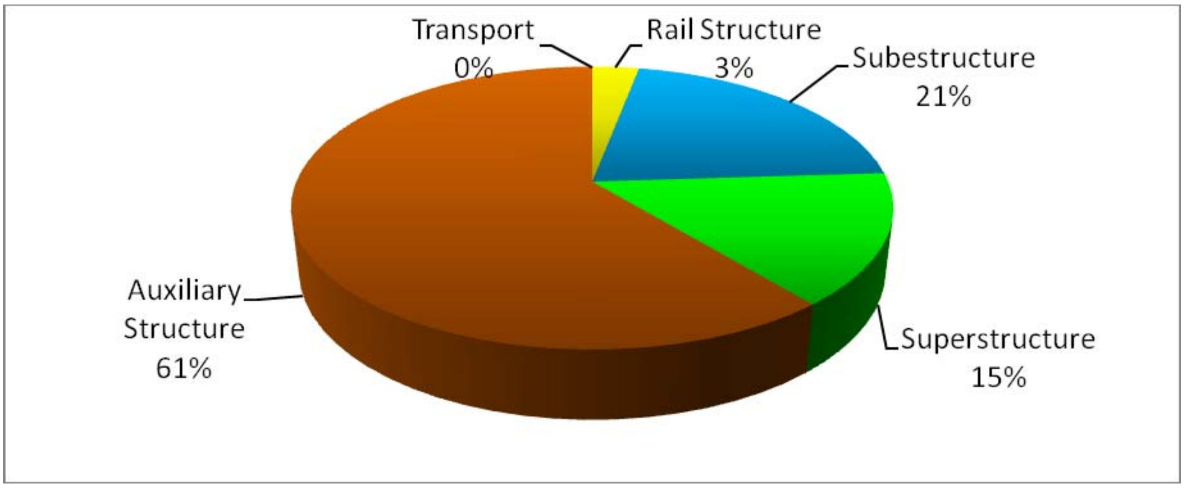


Figure 135: Distribution of the environmental damage by bridge parts

As the substructure and superstructure have similar behaviors in mostly all environmental potential impacts, the author does not consider relevant to show the graphics for each one. However, for more detailed information see with all the graphics provided by the program.

The weighted results for the distribution of the environmental impact of the material stage show that the steel is responsible for the 41 % of the impact while concrete is responsible for the 41 %, while in the characterizated results, the concrete had more relevance with the 41 % of than the steel, which had associated the 35 % of the potential impacts of the material stage. Having in mind that the reference used for the weighting factors, US-EPA, gives more importance to the global warming potential, this fact leads to the conclusion that the process of producing steel has higher potential impact regarding the GWP. Timber also has increase the contribution to the impacts to 28 % from the 23 % in the characterizated results.

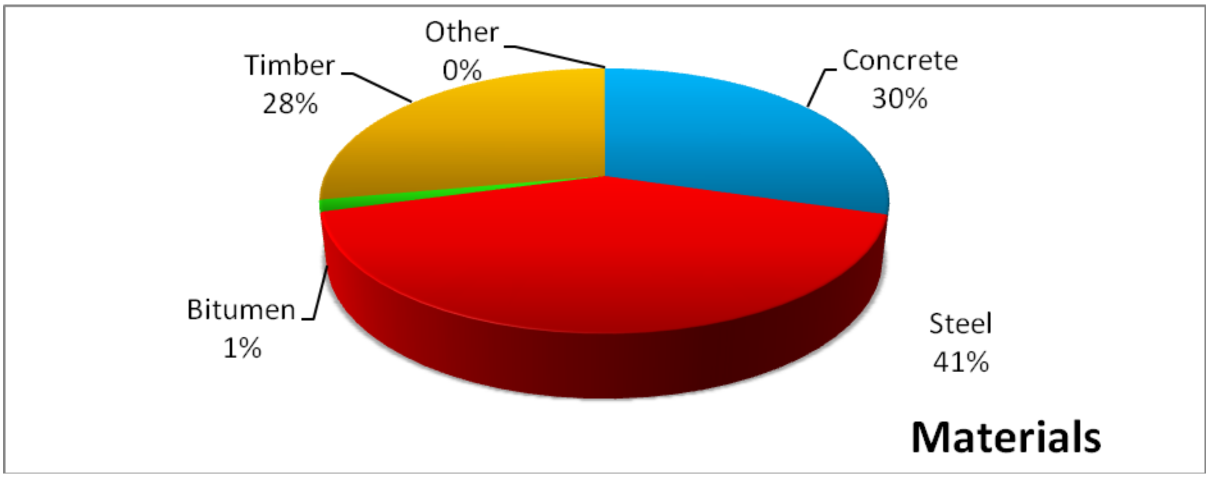


Figure 136: Distribution of the environmental impact of the principal materials included in the material stage (weighted results)

Chapter 6

Conclusions and Further Research

6.1 Conclusions for the case of study

Some important conclusions can be taken from the results obtained in the life cycle assessment of the railway bridge “Puente de Castilla”. First of all, it has to be remarked the importance of the material stage, i.e. the raw material extraction and production processes. Which main contributors are the concrete and steel, but wood for the formwork should not be obviated because it entails a significant burden too. As it was revealed in previous studies performed to bridges and construction materials, concrete production seems to be less contributive than steel to the global potential impacts, but the contribution to the global warming seems to be higher than the steel production, while the energy consumption in this last procedure is considerably higher. However, electric arc furnaces should be considered for producing steel and the environmental impacts of steel manufacture will decrease drastically, (which however, will not happen to the economical cost). Reinforcement steel has less contribution to the environmental impacts than structural steel, due to the different processes of producing each type. Different types of concrete also have different contributions to the potential impacts, with non pre-stressed reinforced concrete as the main contributor. However, although the unitary loads attached to each type differ, the differences in the study are mainly due to the quantities used in the construction.

The construction phase has no significant contribution to the global potential impacts, and use and maintenance phase has very little attached impact. In the case of the maintenance phase, the main cause for this is the replacement of the steel rail tracks, which is estimated to be done every 25 years.

On the other hand, the end of life phase has greater importance. Not as much as the material production, but it definitely has to be taken into consideration. In this particular case of study, the steel and concrete were mostly assumed to be reused and recycled, while the timber formwork was assumed to be disposed as landfill. The recycling of the steel has contribute to the potential impacts of the end of life phase, but the main cause of this high values is the eutrophication associated to the disposal to the soil of the timber formwork. It should be considered to be reused in other constructions to reduce this burden.

When studying the different sub components of the bridge, in this particular case of study, the auxiliary structure gains a mayor importance. But it has to be considered that it needed large quantities of steel and concrete to build a structure to support the bridge while construction and then support the loads of moving the bridge to its last location (19 meters away). The substructure and superstructure does not have significantly differences in the environmental potential impacts, although the substructure contributes a little more than the substructure to the global warming potential. Transportation of materials and workers has a minor contribution to the global impacts of the bridge.

Regarding the different studied potential impact categories, the global warming appears to be the one with higher damage, followed by the eutrophication and the abiotic depletion. The high values for the global warming impact are mainly due to the emissions during the production of steel, concrete and timber, in decreasing order. The eutrophication, as mentioned before, was due to the disposal of the timber formwork, and the abiotic depletion is assumed to be related too to the production of materials. The ozone layer depletion can be totally obviated because there is barely any contribution to it, and the photochemical oxidation also has very low values for the whole bridge.

In relation to the normalization and weighting methods, the normalization reference used in the tool uses emissions for Western Europe in 1995, and for the weighting factors, the author had considered the best choice to use the reference from the US Environmental Agency Protection for this case of study, which highlights the importance of the global warming. The study shows the differences found in selecting the different methodologies, and should serve as a guideline for selecting the most appropriate one. This choice must be performed with the goal of the study in mind, knowing which method highlights which impact category and that some of these methods does not consider all the six impact categories included in the tool. For instance, if it wants to be highlighted the ozone layer depletion, EDIP methodology should be used, however, it does not evaluate the abiotic depletion, which has been revealed to be important in this case of study.

6.2 Further research and recommendations

The aim of this thesis was to create a guide and an application program to help infrastructure designers and engineers to perform Life Cycle Assessment of railway bridges, in order to build new bridge structures and improve the existing ones in accordance with a better environmental performance. The first chapters provide a complete overview and analysis of the existing literature and research, and show the state-of-the-art in Life Cycle Assessment methodologies. It means to be guidance for future developments and research. In this line, the developed model is easy to use and turn out to be a flexible tool that allows including only the available information with a wide range of possibilities for the obtained results. This way, the designer can decide the grade of detail wanted according to the goals of the study. The results and conclusions taken from the case of study can serve as valuable information and data for comparing other railway bridges and alternatives, and can be used as a reference to compare orders of magnitude of the values obtained for the environmental impacts and other outflow parameters.

Regarding the Excel application tool, although the principal objectives of the LCA tool have been achieved, lack of time leaves some aspects that can be improved with further development. For instance, it would be important to increment the existing database, by adding more materials and including the Life Cycle Inventory stage, instead of using external software for getting the characterizated values for each impact category. Nevertheless, it may attach uncertainties if it is not performed with an extensive and accurate database, this is why it has been preferred to use an external software package for the LCI in this first version. It will be appropriate too, to incorporate more potential impact categories, and calculate also endpoints such as human health and consider land use and water use. More weighting and normalization methodologies can also be added, although for this version, the most representative ones have been selected. In relation to the input data, further improvements can consider the traffic disruption in maintenance operations. Although the most significant materials and end of life scenarios are already considered, it can be extended to all materials used in the bridge construction; as well as considering that the reuse of materials and use of renewable energy sources have a negative contribution to the overall environmental impact.

As a good environmental practice, engineers should tend to use existing infrastructures and adapting them to the new requirements. In this case, the quantities or materials and energy are quite narrowed and known. However, in the design phase, the engineers may not know exactly the required amounts of resources. It may be a of the greatest interest for the application tool to include the most common used structures and allow calculating the required material quantities by entering the desired geometry for the bridge structure or for some of the bridge parts.

Finally, further improvements can add to the program several complementary analyses to measure the quality of the data and results, such as a sensitivity analysis, and uncertainty and variation analysis.

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Appendix A

LCIA characterization factors

A.1 Characterization factors

Table A.1: Characterization factors for abiotic depletion (Guinée et al., 2001):

Natural resources	kg Sb eq./kg
Chromium	8.58E-04
Iron	8.48E-08
Manganese	1.38E-05
Molybdenum	3.17E-02
Nickel	1.08E-04
Niobium	2.31E-05
Tungsten	1.17E-02
Vanadium	1.16E-06
Zinc	9.92E-04
Fossil energy (kg Sb eq./MJ)	4.81E-04

Table A.2: Characterization factors for acidification (Huijbregts., 2001; TEAM, 1999):

Substances	kg SO_2 eq./kg
NH_3	1,6
HCl	0,0274
HF	0,05
H_2S	0,059
SO_2	1,2
H_2SO_4	0,02
NO_2	0,5

Table A.3: Characterization factors for eutrophication (Huijbregts., 2001; TEAM, 1999):

Substances	kg PO_4 eq./kg
NH_3	0,35
N_2O	0,27
NH_4^+	0,42
NO_2	0,13
P compounds	3,06
P	3,06
NO_3-	0,095
NO_2-	0,13
N_2	0,42
P_2O_5	1,336

Table A.4: Characterization factors for global warming in 100 years of frametime (Huijbregts., 2001; TEAM, 1999):

Substances	kg CO_2 eq./kg
CO_2	1
N_2O	360
CH_4	24
CF_3Br	6900
CF_4	5700

Table A.5: Characterization factors for ozone layer depletion (Huijbregts., 2001; TEAM, 1999):

Substances	kg CFC_{11} eq./kg
CF_3Br	12
CH_3Br	0,37
CFC_{11}	1
CF_2Br	1,4
CCl_4	1,2

Table A.6: Characterization factors for human toxicity (Guinée et al., 2001):

Substance	kg 1,4-DCB eq./kg
NOX (as NO2)	1.20E+00
SO2	9.60E-02
PM10	8.20E-01
NMVOC17	-

Table A.7: Characterization factors for photochemical oxidation (Huijbregts., 2001; TEAM, 1999):

Substances	kg C_2H_4 eq./kg
Benzene	0,189
CH_4	0,007
CH_3CHO	0,527
C_2H_2	0,168
CH_3COCH_3	0,178
C_4H_{10}	0,41
C_4H_8	0,959
C_2H_6	0,082
C_2H_5OH	0,268
C_2H_4	1
CH_2O	0,421
C_7H_{16}	0,529
C_6H_{14}	0,421
H_xC_x	0,4
CH_3OH	0,123
C_3H_6	1,03
CH_3CH_2CHO	0,603
$C_6H_5CH_3$	0,563

A.2 Normalization and Weighting factors

Table A.8: Normalization and weighting factors included in the tool (Huijbregts, 2008)

	Source	ABIOTIC DEPLETION ADP	ACIDIFICATION AP	EUTROPHICATION EP	GLOBAL WARMING GWP	OZONE LAYER DEPLETION ODP	PHOTOCHEMICAL OXIDATION POCP
NORMALIZATION FACTORS							
West Europe '95	Brattebø et al., 2009	1,48E+10	2,73E+10	1,25E+10	4,81E+12	8,33E+07	8,26E+09
WEIGHTING FACTORS							
US-EPA	Brattebø et al., 2009	5	5	5	16	5	6
Orig. EDIP97	Brattebø et al., 2009	0	1,3	1,2	1,3	23	1,2
Global	Stranddorf et al., 2003	0	0	0	1,12	14,22	1
EU-15	Stranddorf et al., 2003	0	1,27	1,22	1,05	2,46	1,33
Denmark	Stranddorf et al., 2003	0	1,34	1,31	1,11	1E+16	1,26
Harvard	Brattebø et al., 2009	7	9	9	11	11	9
BEES default	Brattebø et al., 2009	9	9	9	9	8	8

Appendix B

Case of Study: Detailed Data

B.1 Material quantities

Table B.1: Material quantities used in each part of the bridge structure.

RESOURCES			Uds	TRUCK (km)	AUXILIARY STRUCTURE	SUB STRUCTURE	SUPER STRUCTURE	RAIL STRUCTURE
MATERIAL PHASE	Concrete	blinding concrete	m³	5	0,00	443,85	0,00	0
		mass concrete		5	507,21	2255,73	49,83	0
		pre-stressed concrete		5	0,00	0,00	603,31	0
	Steel	passive reinforcement	ton	5	22,06	167,19	132,72	0
		active reinforcement steel		5	0,00	0,00	34,34	0
		structural steel		5	100,04	0,00	112,58	3,456
	Other Materials	polystyrene sheet	kg	5	59,14	0,00	0,00	0
		asphalt sealing	kg	5	0,00	1334,00	0,00	0
		bitumen	kg	5	0,00	16030,00	0,00	0
		cement mortar	m³	5	0,00	80,00	4,34	0
		Limestone	m³	5	0,00	0,00	28,31	0
		polyurethane painting	m³	5	0,00	0,00	0,46	0,0055
		timber formwork	m³	5	5456,25	0,00	0,00	0
		Rubber	m	5	0,00	0,00	19,00	0
		Pvc	m³	5	0,00	0,00	376,00	0
		Corkelast	kg	45,00	0,00	0,00	0,00	6,17
		neoprene	m³	5	0,00	0,00	0,93	0

Table B.2: Diesel consumption in litres of the construction phase

		RESOURCES	AUXILIARY STRUCTURE	SUB STRUCTURE	SUPER STRUCTURE
CONSTRUCTION PHASE	MACHINERY	vertical excavator	5,2	122	0
		dump truck	6,8	62	0
		small dump truck	133	0	0
		drilling rig	83	0	0
		pneumatic loader	0,4	0	0
		compactor roller	4,6	0	0
		regulator truck	0,5	0	0
		pneumatic piston	0,2	0	0
		sprinkler truck	0,5	0	0
		backhoe	46	0	0
		hammer compressor	8,6	0	0
		concrete batch plant	0,4	6,3	0,5
		concrete pump truck	27	139	44
		concrete pump	5,7	31	12
		vibratory concrete compactor	0,9	3,9	2,7
		wrecker	1	0	1,1
		crane	0	0	0
		telescopic truck crane	0	0	13

Table B.3: End of Life data input

			AUXILIARY STRUCTURE	SUB STRUCTURE	SUPER STRUCTURE	RAIL STRUCTURE
END of LIFE	WASTE MANAGEMENT	Blasting (kg)	0	0	0	0
		wood untreated, landfill (m^3)	5456,25	0	0	0
		wood untreated, incineration(m^3)	0	0	0	0
		wood treated, incineration (m^3)	0	0	0	0
		wood, recycling (m^3)	0	0	0	0
		steel landfill (ton)	36,63	50,15	83,89	1,04
		concrete landfill (m^3)	152,16	809,87	195,94	0
		steel recycling (ton)	109,89	150,46	251,67	3,11
		concrete re-used (m^3)	304,32	1619,74	391,88	0

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