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SUSTAINABLE DESIGN AND INTEGRAL LIFE-CYCLE ANALYSIS OF BRIDGES

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To the memory of my father

Vasco Manuel Vieira Pereira Gervásio

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ABSTRACT

Sustainable development is a concept that is gaining increasing relevance in all areas of society. Life cycle thinking is an essential element to consider in the fulfilment of the goal of sustainability. The application of life cycle thinking to the construction sector implies to consider every stage over the life cycle – from structure's conception to the end of its service life, and from raw material extraction to the management of building's demolition waste. The use of such an approach at the beginning of a design process is very important in the pursuit of sustainable construction, as the potential for influencing the full life cycle performance of a construction system is very high in the early stage of design and decreases as the process develops.

However, the implementation of a life cycle approach to construction systems raises important questions such as the long period of time considered for the analysis, usually about 100 years or more, and the uncertainties and variabilities unavoidable in such analysis.

Moreover, the multi-dimensional concept of sustainability implies the simultaneous consideration of environmental, economical and social criteria. Whilst the framework for the evaluation of the environmental criterion is currently well established in standards and other scientific documents, the economical and social criteria are at a much earlier stage of development.

Therefore, two main goals were pursuit in this research work: (i) the development of a comprehensive life cycle methodology, integrating environmental, economic and social criteria, for the assessment of bridge design at the early stage of its development; and (ii) the development of a decision making approach to aid in the selection amongst alternative designs of the most advantageous design in a sustainable perspective. Furthermore, in both cases, uncertainties and variabilities inherent to such analysis are addressed by means of a probabilistic approach.

The general framework of the proposed integral approach is based on the standardized framework for Life Cycle Environmental Analysis provided by the series of ISO standards 14040. This approach allows to identify the stages and relative processes leading to higher environmental, economical and social impacts over the bridge life cycle. Furthermore, the identification of the most critical processes allows to act upon these processes in order to minimize the corresponding impacts.

The developed decision making methodology is based on the framework described in the previous paragraph, although a multi-criteria approach is added in order to enable the comparison between alternative bridge designs. This approach may be used to assess different alternative designs and to select the best solution, offering the best score in a balance between environmental, economic and social criteria. Therefore, the multi-criteria decision approach

fulfils a dual purpose: (i) to aid the bridge designer in deciding whether the options he/she is taking are the ones that will lead the solution towards an efficiency design in the context of a sustainable construction system; and (ii) in the context of green public procurement, to provide an approach that enables the comparison of alternative bridge designs and the selection of the best alternative in relation to the most economically advantageous tender award criterion.

The proposed integral methodology is applied to three case studies: a composite steel-concrete bridge, a precast concrete bridge and a cast “in situ” concrete bridge. Then, the three case studies are compared based on the proposed multi-criteria approach. Finally, based on the results and comparison of the case studies, design recommendations are prescribed to help design teams to produce efficient bridges in the context of a sustainable construction system.

RESUMO

O desenvolvimento sustentável é uma questão que tem vindo a ganhar uma importância crescente em todas as áreas da sociedade. Com vista a alcançarem-se os objectivos da sustentabilidade é essencial ter-se em consideração o conceito de ciclo-de-vida. A aplicação deste novo conceito ao sector da construção implica uma abordagem que inglobe todas as fases ao longo do ciclo de vida de uma estrutura, desde a sua concepção até ao seu fim-de-vida e desde a extracção das matérias primas até à gestão dos resíduos resultantes da sua demolição. A utilização de uma abordagem deste tipo na fase inicial de desenvolvimento de um projecto é muito importante para a construção sustentável, na medida em que nesta fase o potencial para influenciar o comportamento de uma estrutura ao longo do seu ciclo de vida é muito grande, diminuindo rapidamente ao longo do desenvolvimento do processo.

Contudo, a implementação de abordagens de ciclo-de-vida a sistemas de construção conduz a questões importantes tais como a consideração de um longo período de tempo, geralmente cerca de 100 ou mais anos, e a inevitável existência de incertezas e variabilidades neste tipo de análises.

Além disso, o conceito multi-dimensional da sustentabilidade implica a consideração simultânea de critérios ambientais, económicos e sociais. Enquanto que a metodologia de avaliação de critérios ambientais está actualmente bem estabelecida, com base em normas e outros documentos científicos, os critérios económico e social encontram-se num patamar de desenvolvimento bastante inferior.

Assim, os dois objectivos principais deste trabalho de investigação foram: (i) o desenvolvimento de uma metodologia global de ciclo de vida, integrando critérios ambientais, económicos e sociais, para a avaliação do projecto de obras-de-arte na fase inicial do seu desenvolvimento; e (ii) o desenvolvimento de uma metodologia de tomada de decisão para auxiliar na selecção, entre projectos alternativos, da solução mais vantajosa numa perspectiva sustentável. Além disso, em ambos os casos, as incertezas e variabilidades inerentes a este tipo de análises foram tomadas em consideração por meio de uma abordagem probabilistica.

A metodologia integrada de ciclo de vida, desenvolvida neste trabalho, baseia-se no enquadramento geral da Análise Ambiental de Ciclo de Vida descrito na série de normas ISO 14040. Esta metodologia permite identificar as etapas ao longo do ciclo de vida da obra e correspondentes processos que conduzem a maiores impactos ambiental, económico e social. Além disso, a identificação dos processos mais críticos permite actuar sobre esses processos, a fim de minimizar os impactos correspondentes.

A metodologia de tomada de decisão proposta, embora baseada na metodologia referida no parágrafo anterior, integra uma análise multi-critérios de forma a permitir a comparação entre

soluções alternativas. Esta abordagem pode ser utilizada para avaliar obras-de-arte alternativas e seleccionar a melhor solução com base num compromisso entre os critérios ambientais, económicos e sociais. Desta forma, a metodologia de análise de multi-critérios cumpre uma dupla finalidade: (i) permite guiar o projectista nas suas opções relativas a projectos de obra-de-arte, no contexto de uma construção mais sustentável, e (ii) no âmbito de contratos públicos ecológicos, permite a comparação entre projectos alternativos e a selecção da melhor solução com base na proposta economicamente mais vantajosa.

A metodologia integral de ciclo de vida é posteriormente aplicada a três casos de estudo: um viaduto misto aço-betão, um viaduto de betão pré-fabricado e um viaduto betonado "in situ". Em seguida, os três casos de estudo são comparados com base na abordagem multi-critérios proposta. Finalmente, com base nos resultados obtidos e na comparação dos casos de estudos, são tecidas alguma recomendações relativas à concepção de obras-de-arte de forma a conduzir a estruturas mais eficientes no contexto da construção sustentável.

CHAPTER 1. GENERAL INTRODUCTION AND FRAMEWORK

1.1. INTRODUCTION

Sustainability or sustainable development became a wide spread concept at the end of the last century, leading to a global political acceptance.

There are several ways of defining sustainable development. However, the most well known definition, or at least the one that became widely publicized, is the one developed by the World Commission on Environment, in the Brundtland Report [1.1], which states that "sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs". Sustainability is a multi-dimensional concept that has environmental, social, political, economic, cultural and spiritual dimensions. Sustainable development is an approach that aims to balance at least the social, economical and environmental impacts of all our actions, now and in the future.

Although this might be seen as a modern issue that only came up in the last years, the problem was raised long before the end of last century. Unfortunately, it did not have too much impact in society as the effects of mankind´s activity were not seen then and they were considered as speculations. However, the deterioration of the global environment became clear over the last years, and unsustainable consumption and production, particularly in the industrial countries, is the main reason for this to happen.

In fact, the depletion of natural resources has been a problem that world population had to face since the beginning of civilization. The increasing growth of the population led to increased problems concerning the consumption of resources and deterioration of the natural environment. However, little action was taken to invert the situation due, mainly, to the lack of scientific and technological development. Fortunately, today, society has been provided with the scientific knowledge and development to deal with these problems, and most important, with the will to do it.

With the rapid growth of countries in the less developed world, promoting a sustainable development is now a fundamental issue in every sector of our lives.

1.2. SUSTAINABLE DEVELOPMENT

In the developed countries, since the second half of the 20th century, the major goal in all economic actions became short-term gains. This pushed societies to unlimited consumption of goods and materials and fossil-fuel energy with all the adverse consequences such as high production of waste and emissions to air, land and water.

The first call for attention on general environmental problems came with the publication of "The Limits to Growth" [1.2], in 1972. In this report, a world model was proposed to evaluate five major trends of global concern – accelerating industrialization, rapid population growth,

widespread malnutrition, depletion of non-renewable resources and a deteriorating environment. The major conclusions of this study were:

1. If present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.

2. It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential.

This report was considered too pessimistic and it gave rise to numerous public discussions; unfortunately, little actions were taken. Despite some inaccuracies in forecasting, this report was premonitory of the need for global environmental actions.

In 1987, the United Nations Commission on Environment and Development (the Bruntland Commission) drew attention to the fact that economic development often leads to deterioration, not an improvement, in the quality of people's lives. The Brundtland Report [1.1], “Our Common Future”, set up by the Commission, considered the environmental and development issues as a common challenge to be solved by collective multilateral action. This report, although criticized by some on the grounds of too much pessimism, is probably one of the most important documents of the 20th century and it is well representative of the growing global awareness in the second half of the century of the enormous environmental problems facing the planet, and of a growing shift towards global environmental action.

A few years later, in 1992, the United Nations held a Conference on Environment and Development (The Earth Summit), in Rio de Janeiro, where the nations of the world agreed with the principles and an action plan for a global sustainable development. The “principles of Rio” were compiled in a short document known as “The Rio Declaration on Environment and Development” (often shortened to “Rio Declaration”), consisting of 27 principles intended to guide future sustainable development around the world. The plan of action, known as Agenda 21 [1.3], is a comprehensive agenda aimed to be taken globally, nationally and locally by United Nations organizations, associated governments and major groups in which humans have an impact on the environment.

The principles and plan of action of the first Earth Summit were reaffirmed in the Second World Summit on Sustainable Development, which took place in Johannesburg in 2002. This Summit reaffirmed sustainable development as a central element of the international agenda and gave new impetus to global action to fight poverty and protect the environment.

In 2005, the United Nations adopted the UN Millennium goals [1.4], which cover issues ranging from halting extreme poverty to halting the spread of HIV/AIDS. 191 UN member states committed themselves to accomplish these goals by 2015.

At the European level, the European Union has been promoting and implementing several initiatives and actions in order to progress towards sustainable development. In this regard, a “European Strategy for Sustainable Development” [1.5] was proposed by the European Commission in 2001. This strategy proposed measures to address threats to the quality of life of

European citizens, and focused on issues such as climate change, poverty and emerging health threats. With the aim to promote sustainable development at a global level, a 2nd document [1.6] was adopted in 2002, which covered the external policies of the European Union.

In order to assess the results obtained until that moment and to promote further actions towards long-term Sustainable Development, the strategy of 2001 was revised during the period of 2004-2005. From this review, a new proposal for an European Sustainable Development Strategy [1.7] was prepared by the Commission, which was adopted by the European Council in June 2006. This new strategy reaffirms the need for global solidarity and recognizes the importance of working with partners outside the European Union, including developing countries which have a significant impact on global Sustainable Development. The overall aim of this renewed strategy is to support and promote actions enabling the European Union to achieve continuous improvement of the quality of life for both current and future generations through the creation of sustainable communities able to manage and use resources efficiently and to tap the ecological and social innovation potential of the economy, ensuring prosperity, environmental protection and social cohesion.

Sustainability is a fundamental issue in our lives and it is currently mentioned in every political speech around the world. Every sector of society has its own responsibility towards the achievement of the goals of Sustainable Development. The construction sector has major impacts in society, in economy and in environment, and therefore has a huge responsibility towards those goals. An overview of sustainable construction issues is presented in the next sub-chapter.

1.3. SUSTAINABLE CONSTRUCTION

1.3.1. Introduction

Sustainable construction was first defined by Charles Kibert during the First International Conference on Sustainable Construction in Tampa (1994), as "the creation and the responsible management of a healthy built environment based on resource efficient and ecological principles". Sustainable Construction results from the application of the principles of Sustainable Development to the global cycle of construction, from raw material acquisition, through planning, design, construction and operation, to final demolition and waste management [1.8].

The construction industry, being one of the most important contributors in resource consumption and waste production, and being a major contributor to the global economy, plays a fundamental role in the global sustainable development. Thus the sustainability of its products faces an environmental challenge that is greater than that of any other industrial sector.

The world population has more than doubled since 1950. Most of this growth has taken place in the developing world. In the next two decades, around 98% of world population growth will occur in developing countries. This demographic trend translates into an increased demand for buildings and infrastructures, which is higher for developing countries (Table 1). According to current patterns, expansion of the built environment will destroy over 70% of the Earth's land surface by 2032 [1.9].

Table 1.1. Infrastructure availability and needs (adapted from [1.9])

Type of country by income level	% of world population	Unpaved roads (%)	Population without sanitation (% of urban population)
High non-OECD	0.5	15.6	1.1
High OECD	14.9	18.7	2.4
Upper middle	8.2	44.8	7.5
Lower middle	35.5	52.8	9.5
Low	40.9	71.0	25.4

The overall economic contributions of the construction sector are equally important. Construction is the largest industrial sector in Europe. The share of the Gross Domestic Product (GDP) of the construction sector is approximately 10%-11% in the European Union (EU), and about 12% in the United States. In the developing world, it represents 2-3% of GDP. In most countries, the building and construction sector is the largest single employer. It provides 7% of world employment (28% of industrial employment) [1.10].

The most significant environmental consequence of construction is consumption of resources and energy. Construction consumes half of all resources taken from nature. Within the EU, half of all materials that are taken from earth's surface are used in the construction sector [1.11]. Mining and quarrying of materials used in construction generate large amounts of pollution and waste and account for considerable land use. In OECD countries, the construction sector consumes 25-40% of all energy used (including production and transport of building materials). The built environment is also the largest source of Green House Gases (GHGs) in Europe and it accounts for about 40% of world GHG emissions [1.9]. Concerning construction and demolition waste, the construction sector accounts for 30-50% of total waste generated in higher-income countries.

Sustainable Construction should be measured at least in 3-dimensions: environmental, economic and socio-cultural. Ecological sustainability is focused on three protection goals: (i) protection of resources (resource efficiency of materials, energy and soil, recycling); (ii) the ecosystem (waste management, emissions, pollutants, land use); and (iii) human health (human toxicity of building materials, pollutants). The goal of economic sustainability is the minimization of costs over the entire life span of a construction system taking into consideration the requirements of safety and quality of the proprietor. Socio-cultural aspects, such as welfare, health, safety and comfort, are of a much fuzzier nature and consequently they are much more difficult to take into account. However, socio-cultural aspects are crucial and often impose choices that contradict the better environmental and economical solutions [1.12].

Therefore, a methodology for the assessment of the sustainability of a construction system should focus on the whole life span of the system, embracing the three main dimensions of sustainability (Figure 1.1).

The construction sector is very broad and its organization is often fragmented. Considering a wide definition of the construction sector, it comprises all the professionals (architects, engineers, urban planners, contractors, suppliers, manufactures, etc), decision makers (local governments, national and local regulatory agencies, project developers, etc) and researchers contributing to the development, maintenance, management and demolition of constructions making up the built environment. A close cooperation between these stakeholders is required

for the pursuit of the goals of sustainable construction. For example, in a carefully designed house, the façades may be oriented in such a manner so that the light inside the house is optimized in terms of energy requirements. If, however, next to this house a taller building is built, restraining the sun light and providing unnecessary shadow to this house, then the sustainable principles in which the house was conceived are compromised. This is just a small example of the decision-making chain, showing the link between the designers and the urban planners and/or city authorities. The way the construction sector is managed may be represented in Figure 1.2. The building by itself, or any other construction, is at the micro level.

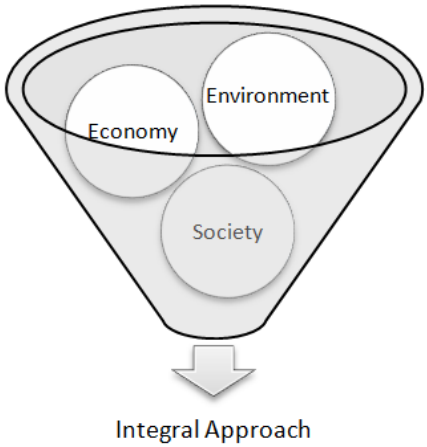

Figure 1.1. Global methodology for the assessment of sustainability

Any decisions taken at this level are not enough to guaranty the sustainability of the construction sector at the global level. It should be noted, however, that initiatives at this level are necessary to enable similar measures to be taken in the upper levels of the hierarchic chain of decision making.

At each level, in Figure 1.2, different stakeholders are involved, and in order to be successful in taking sustainable measures, a wide cooperation is required.

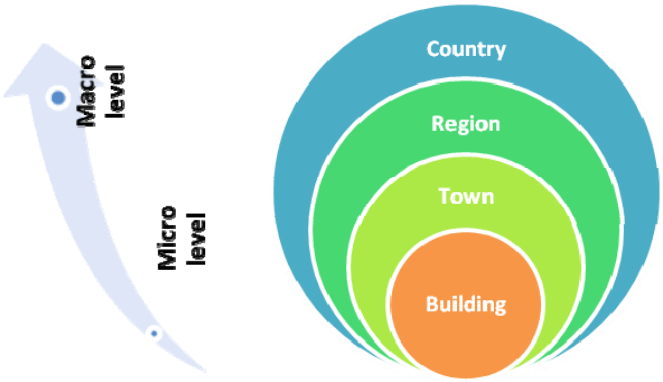

Figure 1.2. Decision-making chain in the construction sector

1.3.2. Agenda 21 on Sustainable Construction

Agenda 21 on Sustainable Construction [1.13] was developed due to the need for an internationally agreed Agenda to guide the work in implementing the principles of sustainability in the construction sector. This agenda, developed by CIB in 1999, defined the links between the

global concept of Sustainable Development and the construction sector (Figure 1.3). The implementation of the general concept of sustainability implies the consideration of environmental, economical and socio-cultural aspects together with the traditional factors addressed by the construction sector, leading to a new engineering concept [1.13].

Furthermore, it provides a global framework and terminology, addressing all stakeholders of the sector and leading to a common strategy towards the sustainability of the construction sector.

In Agenda 21 the main challenges faced by the construction sector in the pursuit of a sustainable sector are identified as: (i) the management and organization of the sector, (ii) an efficient construction process, and (iii) the reduction of resource consumption.

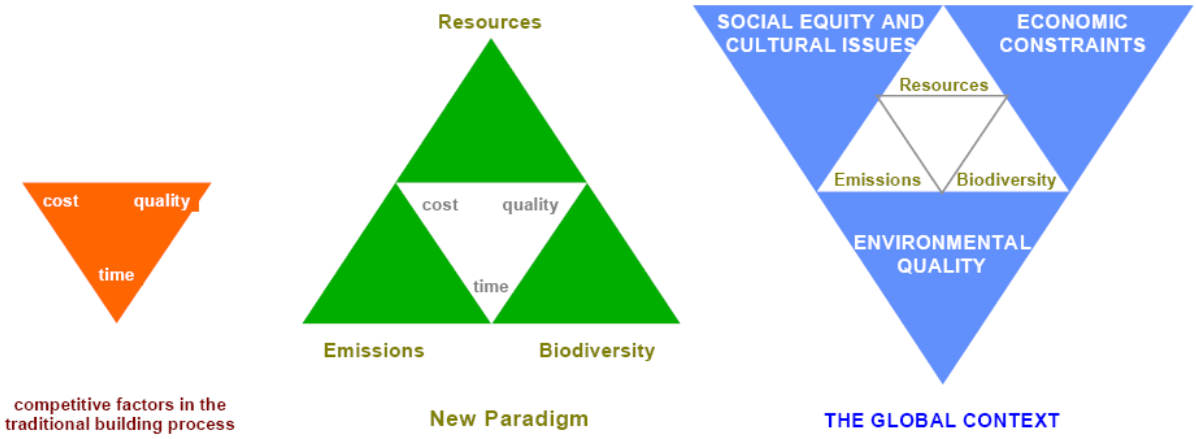

Figure 1.3. The new approach in a global context [1.13]

Naturally, these challenges should be addressed by the various stakeholders of the construction sector. Table 1.2 summarizes the main challenges attributed to each stakeholder.

Table 1.2. Construction challenges towards different stakeholders in the sector (adapted from [1.12])

Authorities	Financial incentives; Regulation, normalization; Labelling; Research.
Clients, owners, developers and investors	To set environmental, economic and social demands.
Users	Develop their own activities during the use of the building in an environmental friendly manner; Be demanding with respect to the selection of the building and consider environmental criteria in their choices.
Designers	Adopt an integrated approach to design; Consider the environmental qualities of construction materials; Design should focus on the exploration stage, durability of components, adaptability and (de)construction ability.
Industry	Promote the environmental features of their products; Cooperate with designers towards new construction and retrofitting technologies; Promote recycling.
Contractors	Reduce the environmental impacts of their processes; Take environmental consciousness as a factor for competitiveness; Select partners based on their expertise on environmental issues.
Maintenance organizations	Take environmental consciousness as a factor for competitiveness; Develop their own services to be environmentally sound; Cooperate with partners regarding environmental issues.

1.4. MOTIVATION, AIMS AND OUTLINE OF THE THESIS

1.4.1. Motivations

The role of the construction sector in Sustainable Development has been emphasized in the previous paragraphs. Buildings and bridges are among the most important engineering structures. Measures to make these kinds of constructions more sustainable rely mostly in life cycle approaches, covering the three main aspects of sustainability: environmental, economic and social/cultural. Life cycle thinking in the construction sector takes account of every stage – from structure's conception to the end of its service life, and from raw material extraction to the management of building's demolition waste. The use of such an approach at the beginning of a design process is very important in the pursuit of a sustainable construction, as illustrated in Figure 1.4. The potential for influencing the full life cycle performance is very high in the early stages of design and decreases as time goes by [1.10].

However, the application of life cycle approaches to buildings and/or bridges is far from being a straightforward process. One of the main reasons for this complexity is that the majority of life-cycle approaches have been developed for the assessment of relatively simple systems, such as, e.g., a detergent bottle or a coffee machine. However, a building or a bridge are much more complex systems, with particular characteristics (such as longer service life) that makes the application of LCA a much more difficult problem. Therefore, appropriate life-cycle methodologies and practical application operational tools are necessary to provide designers the means for performing such analysis in the initial stages of design.

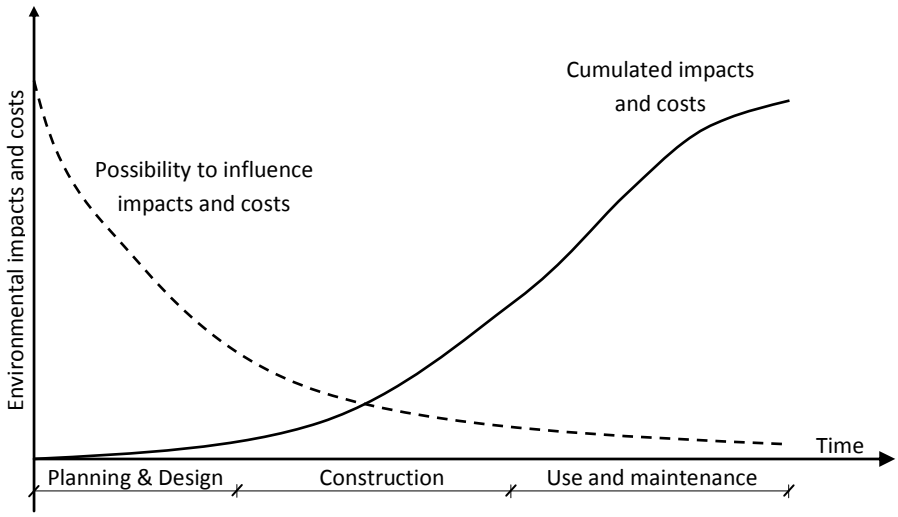

Figure 1.4. Influence of design decisions on life cycle impacts and costs [1.10]

Concerning environmental requirements, large differences can be found between life cycle sustainability factors for buildings and bridges.

In buildings, energy consumption dictates most of the environmental properties of a building's life cycle, although in structures with longer target service lives, flexibility and durability are also important issues to take into account.

On the other hand, bridges are often massive structures with longer service lives. Maintenance and repair under use are very difficult. Their life cycle quality depends on high durability and

easy maintainability during use, saving of materials and the selection of environmentally-friendly materials, minimizing and recycling of construction and demolition wastes.

Regarding buildings a lot of investigation work has been done over the last years and currently several methodologies and tools are available to deal with environmental and economic impacts of buildings or building's components (examples are provided in Chapter 3). Also some practical manuals on sustainability have been prepared for the building industry (references are also provided in Chapter 3), providing public and private professionals with suggested practices across the full cycle of a building project, from site planning to building design, construction, and operation.

In the field of bridge engineering there is little or no guidance on the application of the principles of sustainability to bridge construction and management. Regarding the economic assessment, life cycle cost methodologies are available and some are included in bridge management programs, although this may not be, always, a straightforward procedure, particularly in the case of the maintenance work, which requires estimation of future activities and relative costs. In the case of environmental assessment, although the international standards (ISO) set out the principal general requirements, its application to bridges is currently a major time consuming process, which is not normally justified in most design processes. This is mainly due to the lack of information concerning the environmental impacts of construction technologies and maintenance techniques.

In the context of a sustainable construction sector both types of constructions are relevant. However, the scope of this work is bridge construction, as there is an urgent need for clear and practical guidance on the application of sustainable principles for bridge engineers.

Before describing the aims and scope of the research work, it is important to clarify the meaning of the term bridge. In Portuguese the term bridge is usually used to refer to a structure that cross a water line, whilst viaduct is used to refer to structures that crosses a road or motorway. In English, however, both terms have slightly different meanings. Bridge is a structure that is built over a river, road or railway, while viaduct is a long high bridge, usually held up by many arches, which carries a railway or a road over a valley [1.14]. Therefore, in order to avoid the misunderstanding of terms between languages, throughout this text the term bridge is used to refer both to bridges and viaducts.

1.4.2. Goals and scope of the research work

This thesis has two main goals: (i) the development of an integral life cycle methodology for the assessment of bridge design in a sustainable perspective, at the early stage of its development; and (ii) the development of a decision making approach to aid in the selection amongst alternative designs of the most advantageous bridge design in the same perspective.

The integral methodology follows a life cycle approach, in which all stages over the bridge life cycle, from material production to dismantling and deposition of construction waste materials, are taken into account. By a sustainable perspective is implicit the balance between environmental, economical and social criteria, over the life cycle of the bridge. This approach allows to identify the stages and relative processes leading to higher environmental, economical and social impacts over the bridge life cycle. Moreover, the identification of the most critical

processes allows to act upon these processes in order to minimize the corresponding impacts. This approach will be applied to three case studies. Based on the results of the case studies, design recommendations are prescribed to help design teams to produce efficient bridges in the context of a sustainable construction system. The need for such a methodology at the early stage of the development of a project was enhanced in the last section (see Figure 1.4.).

The methodology is developed taking into consideration bridge design; however, the general approach may be applied to any other construction system, mainly infrastructures, with small adaptations in order to address the specific problems of each system. Furthermore, the approach is applied to the design of new bridges. However, it can also be used in the case of existing bridges, in the evaluation of rehabilitation strategies or in decisions regarding the rehabilitation or the demolition of an existing bridge.

The integral methodology is thereafter used to assess different alternative designs and to select the best solution, offering the best score in a balance between environmental, economic and social criteria. It is assumed that all the alternatives fulfil the safety requirements at the same level. Thus, a multi-criteria decision approach is developed, based in the criteria defined in the first approach, enabling the comparison between alternative bridge designs

The multi-criteria decision approach fulfils a dual purpose: (i) to aid the bridge designer in deciding whether the options he/she is taking are the ones that will lead the solution towards an efficiency design in the context of a sustainable construction system; and (ii) in the context of green public procurement, to provide an approach that enables the comparison of alternative bridge designs and the selection of the best alternative in relation to the most economically advantageous tender award criterion.

Moreover, through the development of the integral life cycle approach and the multi-criteria decision approach, the research aims to contribute to further developments in the current state of both approaches, as described in the following paragraphs.

Although the potential of life cycle analysis to aid in a decision making process is recognized, in practice, it is seldom used. As already referred, several factors contribute to this situation. Additional factors are the time needed to collect data and perform the analysis, the lack of data and/or the quality of the available data, and the availability of adequate methodologies. This research is meant to be a contribution towards the more practical use of life cycle approaches. The methodology is aimed to be used by professionals with little expertise in the field of life cycle analysis. Thus, recommendations and simplification rules are provided, based on contribution analysis of the processes included in the analysis over the life cycle.

Life cycle analysis implies a long time period of analysis, many assumptions are thus needed to deal with different strategies over the maintenance and demolition stages. In this approach different scenarios are used to address these issues and sensibility analysis are made in order to evaluate the importance of each parameter.

Moreover, many types of uncertainties are found in all steps of a life cycle analysis, in the methodology itself and in the simplifications that are needed to perform them. In this approach several types of uncertainties are taken into consideration by the use of probabilistic analysis and simulation methods, such as Monte Carlo simulation and Latin Hypercube.

1.4.3. Outline of the thesis

This thesis comprehends four main parts. The first part corresponds to the first four chapters and introduces the sustainable construction concept and provides an overview of the current knowledge in life cycle approaches. The second part consists of chapters 5 to 8 and presents the development of the integral approach. The third part corresponds to the application of the life-cycle methodology to three case studies. Finally, recommendations for practical design methodology for the assessment of the sustainability of bridges are given, together with the conclusions of the research. Each chapter is detailed in the following paragraphs.

Chapter 1 presents a brief overview of sustainable development and the applications of its aims to the construction sector, leading to sustainable construction. The reasons to conduct this research, its scope and aims, together with the organization of the work, are described in the end of this introductory chapter.

Chapter 2 describes the political and legislative framework with respect to the implementation of sustainable development. Special emphasis is naturally given to those guidelines and directives that are specific for the construction sector.

Chapter 3 gives an overview of the current development of life cycle analysis. Environmental, economical and social life cycle analysis are reviewed, and the aspects that need further development in each case are identified. Particular attention is given to those aspects that could lead to the development of a common integral approach.

Chapter 4 introduces the main framework for the development of the indicators used for the evaluation of global sustainable development. Furthermore, this chapter describes the main indicators used for the evaluation of sustainable construction. The differences between indicators for building evaluation and infrastructures evaluation are identified and examples are provided. In the end of the chapter, criteria used for the selection of indicators are provided.

Chapter 5 describes the development of the framework for the integral life cycle analysis. The main steps over the analysis are described in general. The emphasis of this chapter is on the first part of the integral analysis, the definition of the scope and functional unit, the collection of data and the assumptions and options that are needed for the analysis.

In Chapters 6, 7 and 8, the environmental, economical and social life cycle analyses are presented, respectively. In each chapter the developments and adaptations made in each analysis, according to the aims of this research, are described. Each chapter lists the indicators used for the evaluation of the corresponding category and presents its calculation methods. The sources of uncertainty are identified and taken into account in each case. The weighting method and normalization procedure used in each case are also described.

In chapters 9, 10 e 11, the integral methodology developed in the previous chapters is applied to three case studies. The examples analysed correspond to three bridges that were built in Portugal by the Portuguese Motorway Operator BRISA. In order to validate the methodology three different construction systems were selected: a composite steel-concrete bridge (Chapter 9), a precast concrete bridge (Chapter 10), and a cast “in situ” concrete bridge (Chapter 11).

Chapter 12 refers to the decision making procedure adopted in this research for the comparison between alternatives, according to the criteria selected in Chapters 6, 7 and 8. The multi-criteria

decision analysis incorporates the uncertainties indentified in previous steps of the analysis. It provides recommendations for a sustainable design of bridges. These recommendations are based on the results of the case studies performed in the previous chapters. Moreover, simplification rules for the integral methodology are provided in order to make the integral analysis a more practical methodology.

Finally, in Chapter 13 the main conclusions of the research are drawn and some recommendations for further research are indicated.

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CHAPTER 2. POLITICAL AND NORMATIVE FRAMEWORKS

2.1. INTRODUCTION

Sustainable Development is a fundamental goal of the European Union (EU). Consequently, the European Commission (EC) is making a strong effort to provide guidelines and recommendations and to implement directives in order to fulfil the aims of Sustainable Development. This chapter focuses on the main guidelines and directives which are closely related to the Construction Sector.

Sustainable Development became a fundamental objective of the EU when it was included in the Treaty of Amsterdam, in 1997, as an overarching goal of EU policies. The first EU Sustainable Development Strategy (SDS) [2.1] was launched at the Gothenburg European Council in 2001. The main aim of this strategy was to promote economic growth and social cohesion while paying due regard to environmental protection.

Although this strategy forms the core of European policies towards Sustainable Development, these also enclose other commitments, such as the commitments made at the 2002 World Summit on Sustainable Development and the Millennium Development Goals, which were agreed in 2000.

Despite important achievements with the implementation of this strategy, the remainder of unsolved problems, further globalization and the enlargement of the EU, led to the revision of this first strategy in 2006. Thus, following an extensive review process that started in 2004, the European Council adopted a renewed SDS [2.2] for an enlarged EU.

The renewed SDS represents an integrative strategy on how the EU will more effectively live up to its long-standing commitment to meet the challenges of sustainable development. The overall aim of this strategy, which complements the "Lisbon Strategy", is to identify and develop actions to enable the EU to achieve a continuous long-term improvement of quality of life through the creation of sustainable communities able to manage and use resources efficiently, able to tap the ecological and social innovation potential of the economy and in the end able to ensure prosperity, environmental protection and social cohesion. The strategy set overall objectives and concrete actions for seven key priority challenges to be achieved until 2010:

- Climate change and clean production;
- Sustainable transport;
- Sustainable consumption and production;
- Conservation and management of natural resources;
- Public health;
- Social inclusion, demography and migration;
- Global poverty and sustainable development challenges.

In order to assess the full implementation of this renewed strategy, every two years (started in 2007) the Commission produces a progress report on its implementation. According to the

conclusions of the first progress report [2.3], there have been significant policy developments in some of the seven key priorities listed above, namely climate change and energy, but progress on policy has not yet translated into substantial concrete action. The conclusions of the first report were reaffirmed on the second progress report [2.4]. Moreover, it underlines that the EU has taken the lead in the fight against climate change and the promotion of a low-carbon economy. However, unsustainable trends persist in many areas and the efforts need to be intensified. This report reviews EU policy measures in the areas covered by the SDS and launches a reflection on the future of the SDS and its relation to other cross-cutting priority strategies at EU level, namely the Lisbon strategy.

At the Portuguese level, the National Strategy for Sustainable Development and the respective plan of implementation were endorsed by Resolution no. 109/2007 [2.5]. This strategy was elaborated in order to meet the guiding principles of the European strategy. Its main purpose is the development of a model for sustainable development to make Portugal, by 2015, one of the most competitive and attractive countries of the European Union, in the frame of high economical, environmental and social standards.

The Construction sector is one of the European Union's key industries both in terms of output and employment (see key figures in Chapter 1). Over the last years the Commission has been assessing the industry's performance and competitiveness with the aim of developing actions contributing to further improvements. The actions carried out over the last years were primarily based on the Communication on the Competitiveness of the European Construction Industry [2.6], as described in the following paragraphs.

The Communication on the Competitiveness of the European Construction Industry identified four strategic objectives aimed at enhancing the competitiveness of the sector: (i) the development of a coherent quality policy, for which the Commission recommended the widespread adoption of quality schemes; (ii) the improvement of the regulatory environment in order to remove barriers to trade such as the ones caused by different types of national legislation, for which the Commission aimed to consolidate and simplify legislation related to the Single European Market applicable to construction products and public procurement; (iii) the creation of conditions necessary for sustained growth in provision of education and training at all levels; and (iv) a reorientation of the resources for research and development towards the continually changing needs of the sector, and the better dissemination of research findings. The Communication proposed more than 60 specific actions aimed at fulfilling these strategic objectives.

In the context of this Communication, an action plan [2.7] was agreed in 1999, between representatives of the European Commission, Member States and the Construction Industry. The aim of this action was "To develop a strategy for the use and promotion of environmentally friendly construction materials; energy efficiency in buildings and construction and demolition waste management, in order to contribute to sustainability". Three working groups were thus created to give answers to the three main topics of environmentally friendly materials, energy efficiency and waste management.

With regard to construction materials and products, the main recommendations to the construction materials industry made by the task group were: (i) a life-cycle approach to improve the environmental performance of construction products should be adopted; (ii) life-

cycle inventory based environmental data schemes should become general practice; (iii) national environmental data schemes should be harmonized on an EU basis (preferably through CEN); (iv) construction materials associations should promote the adoption of environmental audit schemes and environmental management systems. The action plan on "energy efficiency in buildings" led to several recommendations related to: (i) monitoring and benchmarking (like the development of new indicators which would demonstrate energy performance improvements, etc); (ii) stimulation mechanisms (e.g., encouraging owners of buildings to publish consumption figures, oblige owners to upgrade the energy efficiency of an existing building when more than 25% of the building is being refurbished, etc); (iii) fiscal measures (for example, to offer specific financial inducements to consumers, to develop energy rating certificates, etc); and (iv) regulatory and policy measures, such as the introduction of energy performance certification for buildings and to ensure that buildings should become exemplar on energy efficiency by means of public procurement policy. Finally, the "waste management" working group provided recommendations focusing on measures for waste minimization and measures to minimize the amount of waste going to landfills and to illegal dumping sites.

These recommendations and subsequently actions to implement them led to the development of guidelines and directives, which will be dealt with in more detail over the next sections.

More recently, the Lead Market Initiative [2.8], a coordinated and concerted action plan introduced by the EC to facilitate the emergence of innovative products and services, has chosen Sustainable Construction as one of the six market areas of interest. This initiative was endorsed by the European Council in May 2008. In a preparatory document to the Lead Market Initiative, the main barriers to the sustainable development of the construction sector were identified [2.9] and the roadmap [2.10] for sustainable construction proposed several actions in order to overcome these barriers. The barriers and the proposed actions are summarized in Table 1.1. These actions are for the time period of 2008-2011.

The sustainable consumption and production is a very challenging aspect of the European SDS, as it requires changes to the way products and services are designed, produced, used and disposed of, taking into account producer and consumer behaviours. To reinforce the European effort for further sustainable consumption and production and promote its sustainable industrial policy, an Action Plan [2.11] was introduced, in July 2008, which seeks to substantially change consumers and producers behaviours towards better products, a leaner and cleaner production and a smarter consumption.

This Action Plan identifies priority issues falling into three broad categories: (i) smarter consumption and better products; (ii) leaner production; and (iii) global action. In regard of smarter consumption, current EU legislation dealing with ecodesign and labelling will be revised. The leaner production category in the Action Plan focuses on developing tools to monitor, benchmark and promote resource efficiency through life-cycle thinking. Therefore, the Community Eco-Management and Audit System (EMAS) will be revised to increase the participation of companies and reduce the administrative burden and costs to SMEs. The review of current regulations will be dealt in more detail over the next sections. Finally, further actions towards global market for sustainable products are foreseen, apart from current European initiatives designed to promote good practice internationally (e.g., the "thematic strategy for the

sustainable use of natural resources" [2.12] and the "global energy efficiency and renewable energy fund" [2.13]).

Table 1.1. Roadmap for Sustainable construction (adapted from [2.10] and [2.9])

Policy instruments	Barriers	Actions
Legislation	The construction sector is already a highly regulated sector and new legislation should stimulate the sustainable development of the construction market rather that impose unnecessary additional burdens on top of current legislative requirements	- Promote a regulatory framework focussed on targeted performance outputs; - Screening of national building regulations to identify domains in which to integrate a performance based approach; - Assess the innovation potential of EU and national legislation on innovative approaches in construction.
Public procurement	Lack of incentives to offer tender solutions integrating quality, safety, environmental and life-cycle costs or integrating technological variants	- Provide guidance to allow the contracting authorities to motivate the choice of the award mechanism ("Most Economically Advantageous Tender" (MEAT) or "Lowest Cost") in a more sustainable way; - Promote Life Cycle Assessment and Life Cycle Costing approaches in both award mechanisms.
Standardisation, Labelling and certification	The standardization process is very much fragmented and adapting very slowly to technological progress and market development	- Expand the scope of Eurocodes in order to integrate other sustainability aspects in construction design (e.g. energy and environmental aspects) - Define the framework for technical assessment adapted to a rapid certification of innovative products to sustainable criteria.
Other actions	The construction sector is characterized by a complex and highly fragmented supply chain with various actors having competing interests among others. Lack of expertise and qualifications for innovation uptake.	- Show the business case for an effective supply chain and identify relevant contractual, management, financial and insurance arrangements. - Propose scenarios for future qualifications needs and develop an EU-wide strategy to facilitate the up-grading skills and competencies in the construction sector.

In the following sub-chapters a description of the main guidelines and directives with general application are introduced, followed by the guidelines and directives which are closely related to the construction sector.

2.2. GENERAL GUIDELINES AND DIRECTIVES

2.2.1. Green Public Procurement

Public authorities in Europe spend about 16% of the EU Gross Domestic Product on the purchase of goods, services and works [2.14]. Public procurement has a major influence in the trends of production and consumption. A higher demand from public authorities for "greener" products,

leads to higher opportunities for the development of “greener” markets and environmental technologies.

The strategic importance of public procurement for both the environment and competitiveness has been receiving growing attention at the European and international levels over the last years.

The EC Communication on Integrated Product Policy [2.15] proposed a strategy for reducing the environmental impact caused by products. In this Communication, the Commission decided on several actions to stimulate continuous improvement in the environmental performance of products throughout their complete life-cycle. In the relevant chapter on Green Public Procurement (GPP), the Commission encouraged Member States to draw up publicly available National Action Plans for greening their public procurement by the end of 2006. The need for promoting and adopting national action plans on GPP was again underlined in the Communication “Report on the implementation of the Environmental Technologies Action Plan” [2.16]. The possibility for integrating environmental considerations into public procurement was consolidated and complemented by the adoption, in March 2004, of the public procurement directives [2.17][2.18]. These directives introduced the “Most Economically Advantageous Tender” (MEAT) award criteria as an alternative to the “lowest price” in public purchases. The Most Economically Advantageous Tender is one that has the lowest evaluated cost and not necessarily the lowest submitted price. The criteria which the authority may use to determine that an offer is the most economically advantageous include, for example, quality, price, technical merit, aesthetic and functional characteristics, environmental characteristics, running costs, cost effectiveness, after sales service and technical assistance, delivery date and delivery period or period of completion. Therefore, the directives specifically refer the possibility of adopting environmental considerations in technical specifications selection and award criteria, and contract performance clauses.

The Commission [2.14], which is part of the Action Plan mentioned above [2.11], provides guidance on how to reduce the environmental impact caused by public sector consumption and how to use GPP to stimulate innovation in environmental technologies, products and services. This Communication highlights the importance of having a common set of GPP criteria to be used by Member States in order to avoid market distortions and a reduction of the EU competition. In this regard, it should be noted that a preliminary set of common GPP criteria has already been established for products and service groups in 10 “priority” sectors. Construction was identified as one of the priority sectors by the Commission. The set of GPP criteria distinguishes between core and comprehensive criteria (this issue will be developed in more detail in Chapter 4). Furthermore, the Communication includes the setting of indicative targets for GPP. As already referred, the revised SDS [2.2] set the target for 2010 of bringing the average level of EU GPP up to the standard achieved by the best performing Member States in 2006. Based on a study on GPP performance across EU Member States, the Commission proposes that by the year 2010, 50% of all tender procedures should fulfill environmental requirements as given by the core set of GPP criteria referred above.

In 2010, the Commission will monitor the GPP situation in all Member States. The result of the monitoring exercise in the best performing Member States will form the baseline for setting future targets.

Following the guidance from the European Commission, the Portuguese government approved in 2007 the National Strategy for Green Public Procurement, for the period 2008-2010, by a resolution of the council of ministers [2.19]. This strategy identifies the construction of public works as a priority area for which public entities should start their policy of green purchases. As a global aim it is expected that by 2010, 50% of all public procurement will include environmental criteria in their tender proceedings. The national strategy defined general and specific criteria to support the implementation of green purchases and foreseen the introduction of new requirements regarding green purchases in the new code of public contracting [2.20]. General criteria includes energy efficiency, reduction of greenhouse gases, prevention of pollutants' emissions, waste reduction, recycled content of products, minimization of environmental impacts and preservation of nature and biodiversity. However, no guidelines or procedures are currently provided for the quantification of those criteria.

2.2.2. Labeling systems

Following the European context of Integrated Product Policy [2.15], eco-labelling is encouraged as a market tool in order to promote the trade of products with low environmental impacts and to stimulate consumer demand for greener products.

The Ecodesign (EuP) Directive [2.21] established a framework for setting ecodesign requirements for energy-using products. Energy-using products are products which use, generate, transfer or measure energy (such as electricity, gas, fossil fuel). This includes consumer goods such as boilers, water heaters, computers, televisions, but also industrial products such as transformers, industrial fans and industrial furnaces.

Similar schemes, such as the Energy Labelling Directive [2.22], Energy Star Regulation [2.23] and Ecolabel Regulation [2.24] and other schemes developed by Member States (examples of European and international eco-labels are provided in [2.25]), provide consumers with information on the energy and environmental performance of products.

Most of product legislation addresses only specific aspects of a product's life-cycle. Although, the Ecodesign Directive takes a life-cycle perspective, the environmental impact of energy-using products covered by the Directive only accounts for 31-36% of the environmental impact of products [2.11]. This reason, together with the need to integrate different policy instruments to drive the performance of products upwards, led to an enlargement of the scope of the Ecodesign Directive. Hence, a recast of the Ecodesign directive [2.26] was proposed by the Commission in 2008, to extend it to a wider range of products, in order to cover all energy-related products. An energy-related product is defined as "any good having an impact on energy consumption during use", which include all energy-using products, plus energy-saving products such as windows and some water-using domestic devices, which can reduce water consumption and therefore the amount of energy needed to heat water.

It is also foreseen, that after the review of the Ecodesign Directive in 2012 [2.11], the Labelling Directive and Ecolabel Regulation will be further developed in order to comply with the Ecodesign Directive and to provide consumers information about the energy and environmental performance of products.

Labelling schemes may be used in tendering of construction works for the setting of criteria and for the verification of compliance with criteria, provided that [2.27]: (i) the requirements of the labels are based on scientific information, (ii) the labels are adopted with the participation of all stakeholders (such as governmental bodies, consumers, manufacturers, distributors and environmental organisations), (iii) the labels are accessible to all interested parties; and (iv) the specifications set by the labels are appropriate for the intended contract.

Type I and type II labels developed by ISO comply with these requirements, as described in the following paragraphs, although three types of labels are proposed:

i) Type I labels [2.28], which are based on life-cycle environmental impact, the criteria are set by an independent body and monitored through a certification or auditing process. Transparency and credibility is ensured by the third-party certification. Most of the existing official national and multinational eco-label schemes in Europe belong to this category. This group of labels is perhaps the most useful for contracting authorities in relation to the procurement of products and services;

ii) Type II labels [2.29], which are environmental claims made about goods by their manufacturers, importers or distributors (self-declaration claims). They are not independently verified, do not use pre-determined and accepted criteria for reference, and are arguably the least informative of the three types of environmental labels;

iii) Type III labels [2.30], which are not intended to make any judgement on the environmental quality of the product, but simply inform the consumer of its environmental impacts. The quantification of environmental impacts are based on LCA methods. The environmental score is compiled by a third party certification agency based on a number of performance indicators (EPI), e.g., energy use, air emissions, water emissions, etc. These labels may also be used by contracting authorities in order to compare the scores of different products, enabling to purchase those with the best environmental score.

The previous ISO labels have a general application. Regarding construction products, the European Committee for Standardisation (CEN) under Mandate 350 [2.31] “Sustainability of construction works” is preparing a suite of standards that are intended to provide the means for the type III label of building products. These future standards, which should become available in 2010, will simplify the process of green procurement in the construction sector.

2.2.3. Environmental management systems

Environmental Management Systems (EMS) are tools for any organisation – enterprise or public authority – to optimise their production processes, reducing environmental impacts and making more effective use of resources. An EMS integrates environmental management into an organisation’s daily operations, long-term planning and other quality control mechanisms. The implementation of EMS is promoted by the EC to further the competitiveness of the industry [2.11].

Recognition of EMS can be achieved through accredited certification to one (or more) of the main standards /schemes available. The two most recognised standards are the international standard ISO 14001 [2.32] and the EU Eco Management and Audit Scheme (EMAS) [2.33].

ISO 14001 [2.32] specifies requirements for an environmental management system to enable an organization to develop and implement a policy and objectives which take into account legal requirements and other requirements to which the organization subscribes, and information about significant environmental aspects. It applies to those environmental aspects that the organization identifies as those which it can control and those which it can influence. It does not itself state specific environmental performance criteria. It is applicable to any organization that wishes to establish, implement, maintain and improve an environmental management system, to assure itself of conformity with its stated environmental policy, and to demonstrate conformity with the standard.

The EMAS is a voluntary initiative designed to improve companies' environmental performance. It was initially established by European Regulation 1836/93 [2.34], although this has been replaced by Council Regulation 761/01 [2.33] and amended by regulation (EC) no. 196/2006 [2.35], to take into account the revision of standard ISO 14001 in 2004.

Its aim is to recognise and reward those organisations that go beyond minimum legal compliance and continuously improve their environmental performance. In addition, it is a requirement of the scheme that participating organisations regularly produce a public environmental statement that reports on their environmental performance. It is this voluntary publication of environmental information, whose accuracy and reliability has been independently checked by an environmental verifier, that gives EMAS and those organisations that participate enhanced credibility and recognition.

To strengthen and enhance the effectiveness of the Community eco-management and audit scheme a proposal for the revision of EMAS was launched in 2008 [2.36]. The objective of this proposal in thus to increase the number of organisations applying the scheme, to have EMAS recognised as a benchmark for environmental management schemes and to allow organisations applying other environmental management systems to upgrade their systems to EMAS. This Proposal also aims at encouraging EMAS registered organisations to take environmental considerations into account when selecting their suppliers and service providers.

These standards are complementary and well established. Its application is on voluntary basis, although, certification can offer significant benefits for both public and private sector organisations, namely, to ensure that legal responsibilities are met; a more effective management of resources and waste leading to smaller costs, etc.

Furthermore, an EMS has also advantages regarding green procurement by allowing organisations to clearly structure and monitor their environmental policy objectives, public authorities wishing to apply green public procurement may benefit from the instalment of a proper environmental management system. On the other hand, an EMS may be used as a way of demonstrating compliance with an environmental selection criterion related to the capacity of bidders to take environmental management measures during the performance of the contract.

2.3. GUIDELINES AND REGULATIONS FOR THE CONSTRUCTION SECTOR

As described in sub-chapter 2.1, the main areas of impact in relation to the construction sector are energy consumption, material consumption and waste production. In the following sections

the most relevant EU regulations in relation to these impact categories are briefly introduced. The implementation of European Directives into the Portuguese law will also be referred where applicable.

2.3.1. Energy regulation

2.3.1.1. Directive 2002/91/EC

In Europe the energy performance of buildings is based on the requirements laid down by Directive 2002/91/EC [2.37]. This directive covers all new buildings and existing buildings with a total net area of over 1000 m^2 that undergo major renovation.

The Directive gives no guidelines regarding the calculation procedures of energy performance, and European Member states are required to develop appropriate calculation procedures for determining the energy performance of buildings in accordance to the requirements laid down by the Directive. For this reason, a mandate (N° 343) was given to CEN committee to develop appropriate calculation procedures to support Member States in the national application of this directive. This result in the publication of a package of standards, which are listed in a CEN "umbrella document" CEN/TR 15615 [2.38]. Most Member countries partly or fully use their package of standards.

The transposition of the European Directive on the energy performance of buildings and the associated CEN standards into the Portuguese law led to the adoption of the following Decrees: (i) Decree 78/2006 [2.39] - Building Certification National System on Energy and Interior Air Quality (SCE); (ii) Decree 79/2006 [2.40] - Air Conditioning Energy Systems Code (RSECE); and (iii) Decree 80/2006 [2.41] - Thermal Performance Building Code (RCCTE). These new/reformulated regulations specify requirements for new buildings and major renovations, which are mandatory since 3 July 2006.

The main objectives of the SCE are:

- To ensure that the buildings fulfil the requirements included in RCCTE and RSECE, related to energy efficiency, use of renewable energy systems, and the indoor environment conditions;
- To certify the energy performance and the indoor air quality in buildings;
- To identify the appropriate measures or necessary improvements to archive higher energy performance.

The RSECE defines hygienic and thermal comfort conditions. It enforces rules for the efficiency of HVAC systems, for its maintenance, and for the indoor air quality. The main objectives of RSECE are:

- To assure the thermal comfort and indoor air quality conditions in buildings;
- To limit the energy consumption in buildings (by determining the maximum limits);
- To assure the quality of HVAC equipment in buildings (design, installation and maintenance);

- To ensure the renovation of the energy certificate (the certificate has a validity of 10 years or 6 years in case of services buildings with a total net floor area over 1000 m^2).

The RSECE is applied in two different phases of the building life-cycle: design and operation. During the design phase, this law is used for the appropriate sizing of the HVAC equipment and to estimate the energy consumption. In the operation phase it is used to verify the estimated energy consumption. This regulation mainly concerns large buildings (net floor over 1000 m^2) or buildings with centralized HVAC systems, with an installed power over 25kW. Residential and service buildings with a net floor area lower than 1000 m^2 and/or with a centralized air-conditioned system, with an installed power below 25 kW, are covered by RCCTE.

RCCTE is applied both to new buildings and large refurbishing works (cost of the works 25% higher than a new building with the same characteristics). Compared to the previous requirements, this new regulation of the thermal behaviour of buildings almost duplicated the thermal performance requirements in both new and renovated buildings and imposed the use of solar collectors for hot water heating, whenever it is suitable their application. The main objectives of RCCTE are:

- To set the limits in the primary energy consumption per net square area of the buildings;
- To set the requirements for thermal comfort, during the heating and the cooling seasons as well as the minimum ventilation requirements in order to assure acceptable indoor air quality levels;
- To set the maximum U-value for all construction elements of the envelope;
- To impose the use of minimum shadow devices in all windows;
- To set the maximum energy consumption for sanitary hot water production, including the mandatory use of solar collectors for all buildings;
- To set the minimum quality and efficiency requirements to all cooling and heating systems (for non residential uses).

The energy certificate is aimed to inform the building's users, owners or potential buyers about the energy performance of the whole building or part of it. Energy certification is compulsory to obtain the operation permit of new buildings, in case of major refurbishing operations, when a residential or service building is sold or rented (the maximum validity of the certificate is 10 years) and it should be renewed each 6 years in case of service buildings with a net floor area over 1000 m^2.

2.3.1.2. Directive 2006/32/EC

The Directive 2006/32/EC [2.42] aims at increasing the energy end-use efficiency in Member countries by reducing the energy consumption by 9% by 2016. Although the target is indicative and thus not mandatory, Member States have a clear legal obligation to adopt and aim to achieve the target, using appropriate cost-effective energy services and other energy efficiency improvement measures.

Further, this Directive aims at removing the barriers that prevent the efficient use of energy and creating a market for energy services. In this respect, it promotes energy efficiency mechanisms such as financing and informative instruments, public procurement requirements and voluntary agreements.

2.3.2. Construction materials regulation

The use of construction products in European Union is subjected to the requirements of the Construction Products Directive (CPD) [2.42].

The aim of the CPD is to secure free movement of construction products by implementing the CE-marking of construction products and to break down technical barriers to trade in construction products between Member States in the European Economic Area (EEA). According to this Directive, a construction product is a product which is produced for incorporation in a permanent manner in construction works, including both buildings and civil engineering works.

The Directive does not aim to harmonise regulations. Member States and public and private sector procurers are free to set their own requirements on the performance of works and products. The purpose of the CPD is to harmonise national laws with respect to the essential requirements applicable to construction products in terms of health and safety.

Construction products may only be placed on the market if they are fit for their intended use. In this regard, they must be such that works in which they are incorporated satisfy, for an economically reasonable working life, the essential requirements with regard to mechanical strength and stability, safety in the event of fire, hygiene, health and the environment, safety in use, protection against noise and energy economy and heat retention, as set out in Annex 1 to the Directive.

The essential requirements are defined in the first instance in interpretative documents drawn up by technical committees and are then elaborated further in the form of technical specifications. The latter may consist of harmonised European standards adopted by the European standardisation bodies (CEN and/or CENELEC) or a system of European technical approvals, in case there is no harmonised standard, no recognised national standard and no mandate for a European standard. Where neither a European standard nor guidelines for European technical approval yet exist, construction products may continue to be assessed and marketed in accordance with existing national provisions conforming to the essential requirements.

As consequence of the CPD a construction product must have a CE mark. By affixing the CE mark to products which are subject to the Construction Products Directive and to additional EC directives, the manufacturer declares the product's conformance to the provisions of all relevant directives. Products bearing the CE mark may be circulated and traded freely in the EU and the EEA. As such, the CE mark is an 'EU passport' for construction products, as it were. It is thus a requirement prior to placing a product on the market in the European Economic Area.

The application of the CPD has confirmed the need of a harmonised legislative framework to consolidate the Internal Market in this field. However, some of the concepts used would have required clarifications and the whole structure of the CPD could be simplified. All this would obviously increase the credibility of the whole system, comprising standards, organisational

structures and market surveillance. For these objectives, the Commission has recently adopted a proposal for a Construction Products Regulation (the CPR) [2.44].

The proposed Regulation will replace the Construction Products Directive. The aim of the revision is to address some perceived problems with the text of the current Directive and the ways in which it has been implemented, rather than to completely revise the practical processes for CE marking of products, which are already established in all Member States.

2.3.3. Waste regulation

To reverse the trend of increasing waste production with increasing development and welfare of population the European Community identified waste prevention and management as one of the most important priorities, as expressed in the 6th Community Environment Action Programme [2.45] launched in 2002. This programme highlighted the importance of clarifying the difference between waste and non-waste, and the need to develop measures regarding waste prevention and management.

Within this framework, European Directive 2006/12/EC [2.46] aimed at setting requirements for the permit and operation of waste disposal facilities, and addressed disposal options for specific types of waste to control the movement of waste within, into and out of the EU. It focussed on encouraging the prevention and reduction of waste and reducing its potential for harm through cleaner technologies, new disposal techniques and new, more environmentally friendly products. Other objectives had a clear influence on the efforts undertaken to foster sustainable construction in Europe: (i) promoting waste recovery such as recycling, reuse, reclamation and energy recovery; (ii) ensuring this without endangering human health or harming any other part of the environment.

In order to move forward with the process of building up a waste policy, a new waste framework directive (2008/98/EC) [2.47] was published in 22 November 2008. This directive came into force on 12 December 2008 and Member States are required to implement it into national law by 12 December 2010. This new directive repealed the previous waste framework directive (2006/12/EC). The aim of this Directive is to make the EU closer to a “recycling society”, seeking to avoid waste generation and to use waste as a resource. It sets the basic concepts and definitions related to waste management and lays down waste management principles such as the “waste hierarchy” and the “polluter pays principle”.

According to this Directive, the following waste hierarchy should be applied as a priority order in waste prevention and management legislation and policy: 1) prevention, 2) preparing for re-use, 3) recycling, 4) other recovery, and 5) disposal. To reduce the amount of waste generated the first priority is given to waste prevention or reduction at source. In case, it cannot be prevented, than priority is given to the recovery of materials by reusing or recycling. Where waste cannot be reused nor recycled than it should be safely incinerated, with landfill only used as a last resort.

By the polluter-pays principle it is expected that the waste producer and the waste holder should manage the waste in a way that guarantees a high level of protection of the environment and human health. This Directive enhances the producer responsibility in order to support the design and production of goods taking into account the efficient use of resources during their whole life-cycle including their repair, re-use, disassembly and recycling.

Moreover, within this Directive it is expected that Member States will take the appropriate measures in order to establish an integrated and adequate network of installations for waste disposal and recovery.

In order to comply with the objectives and move towards a European recycling society with a high level of resource efficiency, the Directive laid down important targets for the recycling of waste for the year 2020: 50% for household waste recycling and 70% for construction and demolition waste.

In the Portuguese context, the transposition of the European Directive 2006/12/EC [2.46] to the Portuguese law resulted in the revision of previous legislation and in the creation of a new legislative framework, decree no. 178/2006 [2.48], for the general management of waste. The management of waste from construction and demolition was been done according to the general requirements in this law.

However, the complex management of construction and demolition waste, very often, creates problems in the application of current legislation. Therefore, in March 2008, decree no. 46/2008 [2.49] was published introducing a legislative framework for the specific management of construction and demolition waste. This new law strengthens the legal basis for the creation of a market for construction and demolition waste, which was already planned in the previous law. A new mandatory requirement in this law specifies a previous selection of the construction and demolition waste before its deposition in landfills, thus increasing its potential for recycling or any other form of valorisation. Furthermore, reflecting the new European directive [2.47], this new law lays down the waste hierarchy and the principle of responsibility in the management of construction and demolition waste for all intervenient over its complete life cycle.

2.4. OTHER REGULATIONS

2.4.1. Noise regulation

The European Noise Directive [2.50], adopted in 2002, provides a common basis for tackling noise across the EU. According to this directive, each Member State has to draw up " noise maps" for places near major roads (more than six million vehicle passages a year), railways (with more than 60 000 train passages per year), airports and agglomerations with more than 250 000 inhabitants; and action plans have to be made to reduce noise where necessary and maintain environmental noise quality where it is good. Furthermore this Directive aims at developing a long-term EU strategy, which includes objectives to reduce the number of people affected by noise in the longer term, and provides a framework for developing existing Community policy on noise reduction from source.

The regulation of noise in Portugal is based in i) Decree-law no. 9/2007 [2.51], which approves the National Regulation of Noise (this Decree was corrected by Decree-law no. 278/2007); and ii) Decree-law no. 146/2006 [2.52], which transposes to the Portuguese law the European Noise Directive. The scope of the Portuguese Regulation is wider than that of the EU Directive, as it applies, except for transport infrastructures, to all activities producing noise, in a temporary or permanent basis or other sources of noise with potential nuisance effects.

2.4.2. Economic regulation

The public procurement directives [2.17][2.18] introduced the "Most Economically Advantageous Tender" (MEAT) award criteria as an option to the "lowest price" in public purchases. A recent study [2.53], financed by the European Community, proposed the use of Life-cycle Cost (LCC) analysis in the public procurement of construction works and products, by means of MEAT. According to this report, LCC is highly relevant to public works procurement. A proper application of the methodology is expected to enable procurers and those concerned with delivering public works projects to ensure that all costs associated with the design, construction, operation and disposal of the works they are procuring are taken into consideration at an appropriate stage in the procurement process.

However, there is no specific legislation in Europe requiring LCC to be taken into account in procurement procedures. Currently, guidance for LCC analysis of building and constructed assets is provided by the International Standard ISO 15686-5 [2.54]. This standard provides the procedures for performing LCC analyses of building and constructed assets and their parts, including cost or cash flows, arising from acquisition through operation to disposal. Its main content covers principles of life cycle costing, instructions for LCC appraisal of options/alternatives, appraisal of life cycle costs in investment options, decision variables, uncertainty and risk, and worked examples.

Also, the European Committee for Standardisation (CEN) under Mandate 350 [2.31] "Sustainability of construction works" is preparing a suite of standards that are intended to provide the means for the sustainability assessment of buildings at the building level using a life cycle approach and quantitative indicators for the environmental performance, social performance and economic performance of buildings. In relation to the economic performance, draft standard prEN 15643 – Part 4 [2.55] describes the specific principles and requirements for the assessment of economic performance of a building, taking into account its technical characteristics and functionality. This standard is expected to be published in 2012.

2.4.3. Social regulation

The social dimension of sustainable development is the one with lesser regulations. This section focuses on the few standards under development covering the social criteria and on the concept of corporate social responsibility.

As already referred, in the suite of standards under development by the European Committee for Standardisation (CEN), the social performance is covered in the draft standard prEN 15643 – Part 3 [2.56]. Its purpose is to provide a social framework with principles and requirements to support the sustainability assessment of construction works. The purpose of the suite of standards within this framework is to enable comparability of the results of assessments.

The assessment of social aspects of organizations (social responsibility) and management processes are not included within this framework. However their results, which will impact the social performance of the object of assessment, will be taken into account in this standard. This standard is expected to be published in 2012.

Corporate Social Responsibility (CSR) is a concept whereby companies integrate social and environmental concerns in their business operations and in their interaction with their stakeholders on a voluntary basis [2.57]. It is about enterprises deciding to go beyond minimum legal requirements and obligations stemming from collective agreements in order to address societal needs. Through CSR, enterprises of all sizes, in cooperation with their stakeholders, can help to reconcile economic, social and environmental ambitions. As such, CSR has become an increasingly important concept both globally and within the EU, and is part of the debate about globalisation, competitiveness and sustainability. In Europe, the promotion of CSR reflects the need to defend common values and increase the sense of solidarity and cohesion.

The European Commission is co-financing initiatives to support CSR in three industrial sectors: chemicals, textile and construction. Regarding construction, a Building Responsible project in the construction sector (BRE Project) is currently under developed [2.58]. The aims of this project are:

- To verify and demonstrate that the adoption of socially responsible actions enhance the competitiveness of the business in the construction sector in comparison with the adoption of social dumping behaviours;
- To provide companies in the construction sector with proper cognitive tools for developing innovative CSR policies;
- To raise awareness among the actors of the construction sector, thereby contributing to the promotion of the culture of corporate social responsibility, in line with the objectives of the Lisbon Agenda and with the EU strategy of promotion of CSR.

The conclusions of this project, and similar initiatives in the other two sectors, are not yet know, however, it is expected that based on the experience of these projects, conclusions may be found about how CSR can be a driver for the competitiveness of different industrial sectors.

Although the latest developments in the field of public procurement are concentrated in the field of GPP [2.14], progress is also being made on “Socially Responsible Public Procurement” (SRPP). The European Commission is currently developing a guide [2.59], to be published later in 2009, to support public authorities in taking into account social considerations in their public procurement.

As the concept of CSR is increasingly being addressed by many different types of organizations, there is a growing need for tools to help them to define and address what CSR means and how to implement it throughout their organizations. Therefore, the International Organization for Standardization (ISO) decided that the time had come to consider the value of developing management standards on CSR, and a standard providing guidelines for social responsibility is currently under development. The guidance standard will be published in 2010 as ISO 26000 [2.60] and be voluntary to use. However, it will not include requirements and will thus not be a certification standard.

2.5. CONCLUDING REMARKS

The aim of this chapter was not to address all the existing regulations in Europe relative to Sustainable Development, that would have been almost an impossible mission. The purpose of

this Chapter was simply to present the most important regulations in relation to the aims of this dissertation. Nevertheless, this may have been an overambitious task and the risk of lacking some relevant regulation and the risk of getting outdated are high. These facts are a consequence of the strong efforts that are being made by the European Commission in order to promote the development and use of approaches leading to a more Sustainable Society. These efforts were underlined in this Chapter, where for each subject the most relevant activities were described, showing an almost continuous updating of directives and other regulations.

Nevertheless, some reflections may be taken from the previous text. At the EU level, Sustainable Development is primarily promoted and monitored in the context of individual EU policies. The success of Sustainable Development is however linked to the integration the individual policies. In this regard, the EU SDS plays a central role in promoting the overall objective of Sustainable Development, although consistent measures towards this aim are still missing.

Considering the three main dimensions of Sustainable Development, society, economic and environment, much of the emphasis has been given to the environmental component alone. Although not entirely ignored the other two aspects are by far at a different lower level of acknowledgement.

Public procurement will assume a fundamental role in the strategy for Sustainable Development in European Community. The inclusion of environmental and social criteria in public procurement is one means for establishing a new interconnection between the various community actions and policies, providing a broader approach to SD. Naturally, the stimulating and disseminator roles played by Member States governments will also be essential in the wide spread of best practices.

A major trend is observed in the EU strategies: the promotion of the life cycle thinking in business and public administration. The life cycle perspective helps decision makers in business and government to take into account all the impacts associated with the supply, use, and end-of-life of goods and services (products). This provides a fair basis for product comparisons, to effectively identify options for improvements, and to monitor progress in its performance. So far, life cycle approaches are mainly developed for the environmental aspect; however, it is expected that in the near future, the life cycle thinking will enlarge its scope in order to entail the two other objectives of Sustainable Development. However, integrative methodologies are needed in order to enable the effective implementation of the EU strategy towards SD.

The consideration of the complete life cycle of constructions systems implies major changes in the way that those systems are currently planned and designed. This will probably lead to the review of major codes and regulations or to the development of new codes for life cycle approaches.

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CHAPTER 3. SUSTAINABLE ASSESSMENT METHODOLOGIES

3.1. INTRODUCTION

In this chapter current methodologies for the assessment of the sustainability of a product or a product system are reviewed.

Regarding a construction system, a sustainable assessment means an evaluation that takes into consideration the objectives of Sustainable Construction. Thus, a sustainable assessment shall take into account, at least, the three main criteria environmental, economic and social (also known as the three pillars of sustainability).

In this context, an approach for a truly sustainable assessment meeting the consensus of the scientific community is yet to be developed, although many attempts are currently being made, as it will be indicated along this chapter.

There is, however, general consensus about the scope of a sustainable approach. It is widely accepted that a sustainable assessment should be based on a life cycle approach.

A life cycle approach aims at supporting decisions in public policy and in the private sectors by taking into consideration the effects along the supply-chain and during the use and end-of-life stage of products. Products may have totally different impacts during different stages of their cycle, for example, some materials may have an adverse environmental impact during its production stage, but have relatively low impacts on its use or end-of-life stage; or a construction system may be expensive during its construction, although leading to less maintenance needs and thus, less costs during its operation stage. In a life cycle approach the "shifting of burdens" from one stage to the other is taken into account.

Hence, the life cycle of a product, illustrated in Figure 3.1, includes all the production processes and services associated with the product through its life cycle, from the extraction of raw materials through production of the materials which are used in the manufacture of the product, over the use of the product, to its ultimate disposal and eventual recycling of some of its constituents. Transportation, storage, retail, and other activities between the life cycle stages shall be included where relevant.

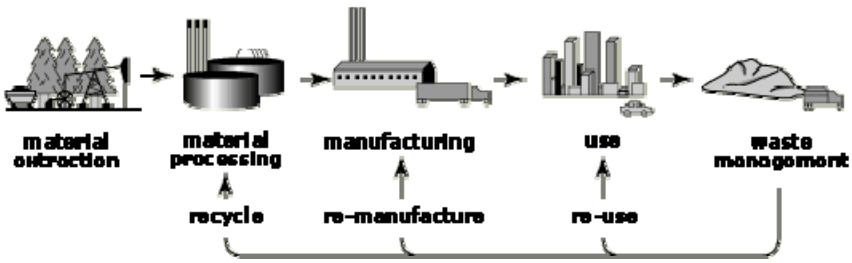

Figure 3.1. Life cycle of a product

3.2. LIFE CYCLE APPROACHES

A construction process encloses a wide variety of technologies and practices. Furthermore, the differences stages over the life cycle of a construction, from raw material acquisition until demolition, are handled by different professionals with little interaction between them. Traditionally a construction process is analysed according to its individual components or stages and optimized separately. The links between each stage and the broader collective effect of these components is often not considered, nor are their upstream and/or downstream impacts.

A life cycle approach recognizes and avoids trade-offs by including the complete life cycle. The shifting of problems into the future is thus avoided according to the principles of Sustainable Development [3.1]. Hence, the sustainability of a construction process implies a broader life cycle perspective, where functional, environmental, economic and social aspects are considered collectively and in the long-term.

Although it is worldwide acknowledged that the combination of the economic, environmental and social aspects in order to obtain “best values” solutions is a major step towards the achievement of Sustainable Development, they have been developed separately in response to economic, environmental and social problems.

The integration of the economic and environmental aspects is being supported by some authors over the last years. Norris [3.2] refers that the traditional separation between economic analysis and environmental analysis has limited the influence and relevance of life cycle environmental analysis for decision-making. Furthermore, this separation ignores the important relationships and trade-offs between the life cycle economic and environmental performances of alternative products.

Hunkeler and Rebitzer [3.3] argued that the analysis of the three main aspects of sustainability, should be kept independent in order to enable the balancing between environmental, economic and social dimensions, according to the principle of Sustainable Development.

More recently, Kloepffer [3.4] refers that there are two ways of taking into account environmental, economic and social aspects in the sustainability assessment of products. The first option consists in the analysis of three separate life cycle assessments, as given by expression (3.1),

$$LCSA = LCA + LCC + SLCA \tag{3.1}$$

where, LCSA is Life Cycle Sustainable Assessment, LCA is (environmental) Life Cycle Assessment, LCC is Life Cycle Costing and SLCA is Societal Life Cycle Assessment. A condition for the application of this expression is that the system boundaries of the three assessments should be consistent.

The other option, as given by expression (3.2), takes into account the economic and social aspects as additional impact categories in the impact assessment stage of LCA.

$$LCSA = LCA\ new \tag{3.2}$$

According to Kloepffer [3.4], the advantage of the 1st option is its transparency as the three dimensions are assessed independently and thus, advantages and disadvantages are clear between different dimensions. However, the author argues that there should be no compensation between the three aspects. In regard of option 2, the author refers that in that case only one model for data collection would be necessary for the assessment of the three dimensions.

Among the methodologies for the life cycle analysis of each of the main aspects of Sustainability, the Environmental aspect is the one with a higher level of development. On the other end, the Social aspect is the one that only recently started to gain increased attention from the scientific community. Although one of the aims of this work is the combined analysis of the three main aspects of sustainability, the followings sections provide a review of current life cycle approaches dealing with each of the main aspects of sustainability individually.

3.3. LIFE CYCLE ENVIRONMENTAL ANALYSIS (LCEA)

3.3.1. Brief historical review

The first steps on developing a method for assessing a product's environmental impacts were taken in the 60s by Rachel Carson in *Silent Spring* [3.5] where various environmental problems created by human activities were discussed. These methods were, however, restricted to calculate the energy requirements and solid waste, neglecting the evaluation of the potential environmental effects.

The energy crisis of the 1970s and the publication of *Limits to Growth* [3.6] had a major influence on general environmental awareness. One of the results was a detailed system for analyzing the energy required to manufacture individual products. Again, these first methods were mainly restricted to calculate the energy requirements and solid waste, neglecting the evaluation of the potential environmental effects.

The United Nations played a major rule in the global environmental concern. In a report published in 1987, the Bruntland Report (Our Common Future) [3.1], the critical and globally threatening environmental problems resulting from the poverty in the South and excessive consumption in the North were stressed out. The report called for strategies for an environmentally sound economic development – a Sustainable Development. Sustainable development is an approach that aims to balance the social, economic and environmental impacts of all our actions, now and in the future. This well known worldwide concept has increased interest in LCEA in two ways: first, methods have been developed for quantifying product impacts on different categories of environmental problems (such as global warming and resource depletion); secondly, LCEA studies have started to become more widely available for public use.

An association of industries created in 1992, the Society for the Promotion of Life Cycle Development (SPOLD), developed a database network to stimulate the development of LCEA as an accepted management tool for the necessary restructuring of company policies towards sustainable development. The widespread need within the LCEA community for reliable inventory data was addressed by SPOLD with the development of the SPOLD format [3.7]. This

common format for exchange of life cycle inventory results allowed data to be understood compared and exchanged, disregarding how it was stored in their original database. The SPOLD format for life cycle inventory data has found wide acceptance and can be found in many databases and software.

Standardization has also given LCEA a major push for wider acceptance. The need for standardization in environmental reporting became clear, in the end of the 1980s, when environmental reports on similar products often contained conflicting results because they were based on different methods, data and terminology. Starting in 1990, the Society of Environmental Toxicology and Chemistry (SETAC) took the lead in LCEA development. Their efforts resulted in the first international formulation of a Code of Practice for LCEA [3.8] and it represented a fundamental step for the following standardization carried out by the International Organization for Standardization (ISO) Technical Committee. Since then ISO took over the leadership in standardization and the first international standards on LCEA were developed: (i) ISO 14040 - Principles and framework [3.9], (ii) ISO 14041 – Goal and Scope [3.10], (iii) ISO 14042 – Life Cycle Impact Assessment [3.11] and (iv) ISO 14043 – Interpretation [3.12]. In 2006 these standards were reviewed and replaced by updated versions: ISO 14040 – Principles and framework [3.13], and ISO 14044 – Requirements and guidelines [3.14], the latter substituting the 14041, 14042 and 14043 standards.

Over the last years the European Commission has been promoting the use of life cycle environmental approaches in their strategies for a Sustainable Development. In the EC's communication on Integrated Product Policy [3.15] it was concluded that Life Cycle Assessments provide the best framework for assessing the potential environmental impacts of products currently available. This documented underlined the need for more consistent data and consensus on LCA methodologies. To address these problems the EC launched in 2005 the project "European Platform of Life Cycle Assessment" [3.16]. This project is a joint project between the European Commission's Environment Directorate-General Environment and the Commission's Directorate-General Joint Research Centre (JRC-IES).

Today, knowledge on how to carry out an LCEA is improving rapidly. The value of the technique is being increasingly recognized and it is being used for strategic decision making in the framework of sustainability by the industry and the public sector. LCEA is also used to improve the competitiveness of the industry and industries' products and in communication with governmental bodies. Information from LCEA can also support public policy making in eco-design criteria setting, in green public procurement and in environmental product declarations (EPDs).

3.3.2. General foundations of LCEA

Life Cycle Environmental Analysis (LCEA) is usually simply designated by Life Cycle Assessment or Life Cycle Analysis (LCA). However, in this dissertation the designation of LCEA is used to differentiate between the evaluation of the environmental criterion and the other criteria (economical and social).

LCEA is an objective process to evaluate the environmental burdens associated with a product process or activity by identifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to affect environmental

improvements. In this context, environmental impacts, including relevant safety, health, and social factors are quantified and summed up across the product or service life cycle [3.8].

A LCEA identifies and quantifies material usage, energy requirements, solid wastes, and atmospheric and waterborne emissions throughout the product life cycle (i.e. cradle-to-grave).

The International Standards ISO 14040 [3.13] and 14044 [3.14] specify the general framework, principles and requirements for conducting and reporting life cycle assessment studies. Regarding these standards, life cycle assessment shall include definition of goal and scope, inventory analysis, impact assessment, and interpretation of results. The various phases are interrelated.

3.3.2.1. Definition of goal and scope

The goal of an LCEA Study shall clearly state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated.

In the scope of an LCEA Study the main issues to be considered and clearly described are the functional unit and the system boundaries.

3.3.2.2. Function and functional unit

The scope of an LCEA Study shall clearly specify the functions of the system being studied. A functional unit is a measure of the performance of the functional outputs of the product system.

The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCEA results is particularly critical when different systems are being assessed to ensure that such comparisons are made on a common basis.

3.3.2.3. System boundaries

The system boundaries determine which unit process shall be included within the LCEA.

Several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience.

The selection of inputs and outputs, the level of aggregation within a data category, and the modelling of the system should be modelled in such a manner that inputs and outputs at its boundaries are elementary flows.

3.3.2.4. Life cycle inventory analysis

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. These inputs and outputs may include the use of resources and releases to air, water and land associated with the system.

The qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundaries.

Data collection can be a resource - intensive process. Practical constraints on data collection should be considered in the scope and documented in the study report.

3.3.2.5. Life cycle impact assessment

The impact assessment phase of LCEA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis. In general, this process involves associating inventory data with specific environmental impacts, and is made of two parts (i) mandatory elements, such as classification and characterization; and (ii) optional elements, such as normalization, ranking, grouping and weighting.

The classification implies a previous selection of appropriate impact categories, according to the goal of the study, and the assignment of LCI results to the chosen impact categories. Characterization factors are then used representing the relative contribution of a LCI result to the impact category indicator result.

Normalization is usually needed to show to what extend an impact category has a significant contribution to the overall environmental impact. In the weighting step the normalized indicator results for each impact category are assigned numerical factors according to their relative importance. Weighting is based on value-choices rather than natural sciences, thus the ISO standard 14044 distinguishes between internal and external applications, and if results are intended to be compared and presented to the public, then weighting should not be used.

Grouping is an optional step of life cycle assessment in which impact categories are aggregated into one or more sets. According to ISO standard 14044 [3.14], two possible procedures can be used: sorting of the category indicators on a nominal basis and ranking of the category indicators on an ordinal scale.

3.3.2.6. Life cycle interpretation

Interpretation is the phase of LCEA in which the findings from the inventory analysis and the impact assessment are combined together. The main aim of this stage is to formulate the conclusions that can be drawn from the results of the LCEA. In addition, the results of previous stages of LCEA and the choices made during the entire process should be analyzed, namely the assumptions, the models, the parameters and data used in the LCEA should be consistent with the Goal and Scope of the study.

3.3.3. LCIA methodologies

3.3.3.1. Introduction

Life Cycle Impact Assessment (LCIA) methods aim to connect life cycle inventory results to category indicators and to category endpoints. According to ISO 14044 [3.14], category indicators may be chosen anywhere along the environmental mechanism between intervention and endpoint. LCIA methods are usually grouped into two main types of approaches (i) problem-oriented methods, determining environmental impact category indicators (e.g. global warming potential) and (ii) damage-oriented methods aiming to determine environmental damage indicators or “endpoints” at the level of the ultimate societal concern (e.g. damage to human

health). The first approach is also called mid-point methods while the latter is called end-point methods.

The classical, problem-oriented methodology developed by SETAC [3.8] comprises for each category indicator, a characterization model and characterization factors derived from the model. In this method impact categories are linear functions, i.e. characterization factors are independent of the magnitude of the environmental intervention, as given by expression (3.3):

$$impact_{cat} = \sum_i m_i \times charact_factor_{cat,i} \tag{3.3}$$

where, m_i is the mass of the inventory flow *i* and $charact_factor_{cat,\,i}$ is the characterization factor of inventory flow *i* for the impact category.

In the problem-oriented approach a list of impact categories needs to be defined. A default list of impact categories may be given by [3.17]: (i) depletion of abiotic resources, (ii) impacts of land use, (iii) climate change, (iv) stratospheric ozone depletion, (v) human toxicity, (vi) ecotoxicity, (vii) photo-oxidant formation, (viii) acidification, (ix) eutrophication. Other categories can be included depending on the goal and scope of the LCA. A problem-oriented approach is mass oriented, emissions are taken into consideration independently of the site or the time of release. Therefore potential environmental impacts are evaluated instead of “real” impacts [3.18]. Another drawback of this method is the unclear environmental importance of the impacts, making the subsequent weighting step difficult. A review of the most representatives mid-point approaches is presented in sub-section 3.3.3.2.

In a damage-oriented approach, interventions are assessed according to their modeled potential damage to the environment. The damage categories may be defined according to several grouping criteria: (i) biotic (living organisms in nature), abiotic (non-living elements of nature), human population and also man-made environment [3.19]; or (ii) human health, natural environment, natural resources and man-made environment. In a final step these damage indicators may be aggregated into a single (eco) index. In either case the resulting number of damage indicators is less than the number of impact categories, which makes the weighting step easier. A review of this kind of approaches is given in sub-section 3.3.3.3.

Damage indicators may be defined by impact pathways. An impact pathway [3.20], see Figure 3.2, consists of linked environmental processes expressing the casual chain of relationships from the pollutant emission through transport and chemical conversion in the atmosphere to the impacts on various receptors, such as human beings, ecosystems, building materials, etc. According to Krewitt et al. [3.18] a detailed impact pathway approach allows to quantify the “actual” effect resulting from the exposure to a burden at a specific place and time, rather than estimating a “potential” impact.

The impact pathway approach may also be used for environmental monetary valuation, transforming the welfare losses resulting from impacts into monetary values. In an EU project on External Costs of Energy (ExternE) [3.20] an impact pathway analysis was developed to support the quantification and valuation of environmental impacts resulting from electricity generation technologies.

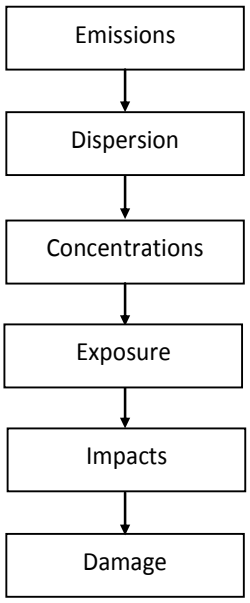

Figure 3.2. General Impact pathway

Because these methods were initially developed with the aim of reducing the number of categories to be weighted they are also referred to as top-down approaches. On the opposite problem-oriented approaches are also called bottom-up approaches. However, a drawback of a top-down approach is that the definition of impact categories is not a free choice. Both types of approaches are represented in Figure 3.3.

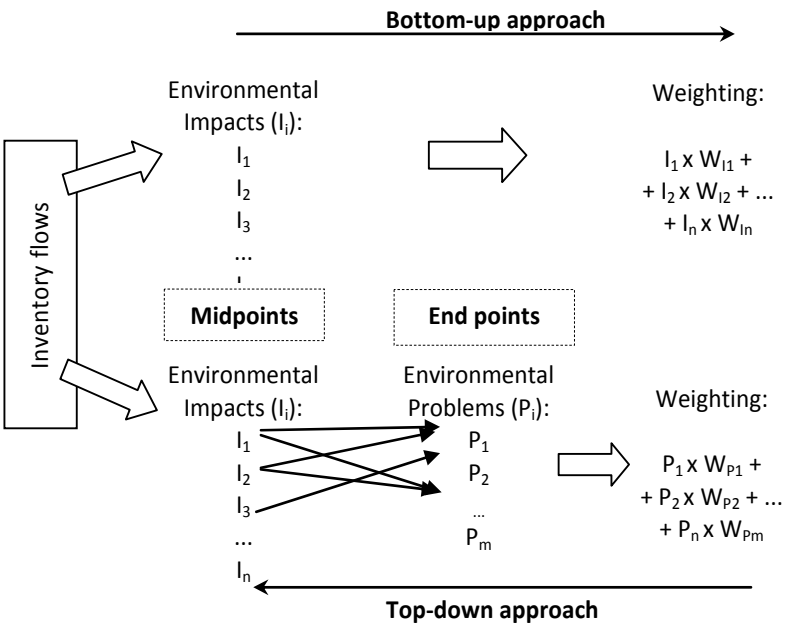

Figure 3.3. Life-cycle assessment approaches

In Figure 3.3, the arrows linking inventory flows to environmental impacts (mid-point) are subject to several kinds of uncertainties due to current limits of scientific knowledge. The level of uncertainties tends to rise towards the end-point categories as current available information regarding the impact pathways to the damage level is even more uncertain or with lack of agreement. Lenzen [3.21] made a quantitative analysis regarding the implications of uncertainty

using a mid-point or an end-point approach towards a decision making process. He concluded that if endpoint information is too uncertain to allow for a reasonable confidence decision, then it is preferred to make the assessment in midpoints terms taking into consideration stakeholders' subjective judgments.

As a result of a joint project between the United Nations Environment Programme (UNEP) and SETAC, a LCIA approach was proposed [3.22] combining the two types of methods described above. This LCIA midpoint-damage approach aims to become a widely acceptable LCA framework providing a common and consistent basis for further development of mutually consistent impact assessment methods. This approach offers the practitioner the choice to use either midpoint or damage indicators, depending on modeling uncertainty or an increase in results interpretability. Sub-section 3.3.3.4 reviews a current mid-end point approaches.

In the following the main currently available mid and end point approaches are briefly described. A more general description can be found in the webpage of the UNEP/SETAC Life Cycle Initiative [3.23].

3.3.3.2. Mid-point approaches

3.3.3.2.1. EDIP97

EDIP97 is a midpoint approach developed in 1997 by a joint effort from the Technical University of Denmark, the Danish Environmental Protection Agency and several Danish industrial companies. The method covers most of the emission-related impacts, resource use and working environment impacts [3.24][3.25]. It also includes normalization factors based on person equivalents and weighting factors based on political reduction targets for environmental impacts and working environment impacts, and supply horizon for resources.

3.3.3.2.2. CML 2001 - Dutch Handbook on LCA

The Dutch Handbook on LCA [3.26], published in 2001 by the Center of Environmental Science of Leiden University (The Netherlands), describes the procedure to be applied for conducting a LCA project according to the ISO standards. The method follows a mid-point approach and for most impact categories a baseline and a number of alternative characterization methods is recommended. In this guide a comprehensive list of characterization factor and normalization factors are supplied.

3.3.3.2.3. TRACI (The Tool for the Reduction and Assessment of Chemical and other environmental Impacts)

TRACI [3.27] is an impact assessment methodology developed by the U.S. Environmental Protection Agency that facilitates the characterization of environmental stressors that have potential effects, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria–related effects, human health cancer effects, human health noncancer effects, and fossil fuel depletion. The methodologies underlying TRACI reflect state-of-the-art developments and best-available practice for life-cycle impact assessment (LCIA) in the United States.

3.3.3.2.4. Comparison between mid-point approaches

The main mid-point environmental categories and other characteristics of the reviewed

Table 3.1. Main characteristics of mid-point approaches

LCIA METHODOLOGY		EDIP97		Dutch LCA Handbook		TRACI	
MID-POINT CATEGORIES	Global warming	CO_2 eq./kg emission		CO_2 eq./kg emission		CO_2 eq./kg emission	
	Stratospheric ozone depletion	CFC-11 eq./kg emission		CFC-11 eq./kg emission		CFC-11 eq./kg emission	
	Human health/ Human toxicity	Via air	m3 air/g emission	kg 1,4 DCB eq. /kg emission		Cancer	Benzene eq./kg emission
		Via water	m3 water/g em.			Noncancer	Toluene eq. /kg emission
		Via soil	m3 soil /g emis.			Criteria pollutants	DALYs/kg emission
	Ionising radiation	——		DALYs/kg emission		——	
	Photo oxidant formation	Ethylene eq./ kg emission		kg ethylene eq./kg emission; kg formed ozone/kg emission		NO_x eq./ kg emission	
	Acidification	SO_2 eq./ kg emission		SO_2 eq./ kg emission		H+ moles eq./ kg emission	
	Eutrophication	Combined potential	NO_3^- eq. /kg emi.	kg PO_4^{3-} eq./kg emisión kg NO_x eq. /kg emisión (average Europe)		N eq./kg emission	
		Separate N potential	N eq. /kg emi.				
		Separate P potential	P eq. /kg emi.				
	Ecotoxicity	Chronic in water	m^3 water/g emi.	kg 1,4 DCB eq. /kg emission (emitted to fresh water, sea water or industrial soil)		2,4-D eq. / kg emission	
		Acute, chronic, in water	m^3 soil/g emi.				
	Resource depletion	Non-renewable	kg	Land	m^2 a	Fossil fuel	Surplus MJ/kg
		Renewable	m^3	Abiotic resouces	Kg antimony eq.	Land	T&E count/m^2
						Water	liter
	Waste/land filling	kg waste		——		——	
	Malodours air	——		m^3 air		——	
	Work environment	h		——		——	
Normalization		Yes, at the European level		Yes, at the Netherlands level, Western Europe level or World level		Yes, at the U.S. level	
Weighting		Yes, based on scientific, political and normative considerations		No		No	

approaches are represented in Table 3.1.

3.3.3.3. End point approaches

3.3.3.3.1. EDIP2003

EDIP2003 is an updated version of EDIP 97 methodology [3.28] which follows an end-point approach for most impact categories. This new version of the methodology supports spatially differentiated characterization modelling which covers a larger part of the environmental mechanism than the previous methodology. This part of the general method development and consensus programme covers investigations of the possibilities for inclusion of exposure in the life cycle impact assessment of non-global impact categories (photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity, human toxicity, noise). This new approach was also developed with the aim of making easier and operational the introduction of working environment in LCA. For the assessment of the working environment the following impact categories were included: fatal accidents, total number of accidents, CNS function disorder, hearing damages, cancer, muscolo-sceletal disorders, airway diseases (allergic), airway diseases (non-allergic), skin diseases and psycho-social diseases. Normalization and weighting procedures are done in a similar way as previous version.

3.3.3.3.2. Eco-Indicator 99

Eco-indicator 99 [3.29] is an end-point approach developed in The Netherlands by Pré Consultants with the aim of simplifying the weighting step. Thus only three environmental damages categories (endpoints) were chosen: human health, ecosystem quality and resources. Damage models were developed to establish the links between inventory data and damage categories. Thus important concepts were developed and introduced in the methodology such as the DALY approach, the introduction of the PAF and PDF approach, as well as the surplus energy approach. Normalization is made using European normalization values. The management of subjective choices and weighting is made by the use of cultural perspectives leading to different versions, each with a different set of choices.

A limiting assumption is that all emissions and land uses are occurring in Europe and subsequent damages occur in Europe, apart from global impacts.

3.3.3.3.3. Environmental Priority Strategies (EPS) 2000

The Environmental Priority Strategies in Product Development System, the EPS System, was developed by the Swedish Environmental Research Institute, adopting an economic approach to assess environmental impacts [3.30][3.31]. In this approach category indicators are chosen to represent actual environmental impacts on any or several of five safeguard subjects: human health, ecosystem production capacity, biodiversity, abiotic resources and recreational and cultural values. The characterization factor is the sum of a number of pathway-specific characterization factors describing the average change in category indicator units per unit of an emission. Characterization factors are given for emissions defined by their location, size and temporal occurrence. Weighting factors for the category indicators are determined according to people's willingness to pay to avoid one category indicator unit of change in the safe guard subjects. The final result of the EPS system is a single number summarizing all environmental impacts.

3.3.3.3.4. Swiss Ecoscarcity Method (Eco-Points)

The method of environmental scarcity – sometimes called Swiss Eco-Points method – allows a comparative weighting and aggregation of various environmental interventions by use of so-called eco-factors [3.32]. The method was first published in 1990 by the Swiss Federal Office of Environment, Forests and Landscape, but the currently updated version is from 1997. The method supplies characterization factors (eco-factors) for different emissions into air, water and top-soil/groundwater as well as for the use of energy resources. These factors are based on the annual actual flows (current flows) and on the annual flow considered as critical (critical flows) in a defined area (country or region). Eco-Points are thus calculated for a product, using the Eco-Factor determined for each inventory flow. The Eco-Points for all inventory flows are added together to give one single, final measure of impact.

3.3.3.3.5. LIME

LIME is a damage assessment approach developed by LCA National Project of Japan. LIME can be used to evaluate the damage on endpoints such as human health and ecological risk caused by 11 impact categories, including global warming, human toxicity and resource consumption. In the framework of LIME [3.33][3.34], damage functions are defined as the quantitative relationships between an inventory of causative substances or activities and potential effects on each category endpoint. The approach includes characterization, damage assessment and weighting. A damage factor (DF) of certain impact categories is defined as the sum of damage function for individual safeguard subjects, i.e. human health, social assets, biodiversity, and primary productivity. The results of the weighing step can be expressed as monetary values.

3.3.3.3.6. Comparison between end-point approaches

The main end-point environmental damage categories and other characteristics of the reviewed approaches are represented in Table 3.2.

Table 3.2. Main characteristics of end-point approaches

LCIA METHODOLOGY	Eco-indicator 99	EPS 2000	LIME
Human health	DALYs	Person yr	DALYs
Natural environment	PDF/m2/yr	kg	EINES (Expected Increase in Number of Extinct Species)
Natural resources	MJ surplus	kg	NPP (Net Primary Productivity) (kg)
Man-made environment	—	—	Social assets: Loss of economic value (Japanese Yen)
Normalization	Yes, at the European level	—	—
Weighting	Yes, based in the concept of Cultural Theory	Yes, based in WTP to avoid damage	Yes

3.3.3.4. Mid-End Point approaches

3.3.3.4.1. IMPACT 2002+

The IMPACT 2002+ life cycle impact assessment methodology developed at the Swiss Federal Institute of Technology, in Lausanne (EPFL) proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via fourteen midpoint categories to four damage categories [3.35]. For IMPACT 2002+ new concepts and methods have been developed, especially for the comparative assessment of human toxicity and eco-toxicity. Human Damage Factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities. All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources. Normalization can be performed either at midpoint or at damage level.

3.3.4. Other approaches in LCEA

3.3.4.1. Economic Input/Output

One of the reasons for current LCA being criticized regards the difficulty of knowing where to draw the boundary around the analysis. Practical use of LCEA involves drawing a boundary that limits consideration to a few producers of interest in the chain from raw materials to consumers. Researchers at Carnegie Mellon have found that limiting the analysis in this way may lead to consideration of only a fraction of the total environmental discharges associated with the product or process. Therefore, they used models of industrial activity (input-output tables) to develop an economy-wide LCEA technique by linking the economic input-output tables with environmental databases (conventional pollutants, TRI, energy use, ore use, fertilizer use, global warming potential, and ozone depleting potential, etc.). The method is called Economic Input-Output Life Cycle Assessment, or EIO-LCA [3.36].

The input-output analysis technique that forms the basis of the model was developed by Leontief [3.37]. Leontief assumed that the complicated interactions within an economy can be approximated by proportionality relationships.

Input-output analysis has been used extensively for planning in the USA and throughout the world**.** Many countries collect and publish input-output tables for their economies. The tables are used to calculate the resources and supply chain requirements required to support an increase in the demand for output of specific sectors.

The main advantages of EIO-LCA tool over other LCEA techniques is that it can be used to examine the total direct and indirect economy-wide effects (effects of suppliers) on emissions and energy consumption resulting from changes in production; and it uses the entire country economy as the boundary for the analysis.

The approach has also limitations. The amount of desegregation in economic sectors may be insufficient for the desired level of analysis. EIO-LCA models include sectors of the economy rather than specific processes. Detailed analysis of the environmental impacts of the activities of the individual members of the supply chain will require more traditional LCA techniques. The use and disposal phases of certain products may be too difficult to analyze with EIO-LCA.

3.3.5. Uncertainties and variabilities in LCEA

There are major uncertainties about the extent to which outcomes of LCEAs reflect real-life environmental impacts. The implementation of the uncertainties (related to lack of knowledge) and variabilities (related to the quality of data) in LCEAs is needed in order to make the results of such analysis much more precise and reliable [3.38].

There are many ways of classifying uncertainty; according to Huijbregts [3.38], the following types of uncertainty and variability may be distinguished:

1) parameter uncertainty – imprecise measurements, incomplete or outdated measurements, and general lack of data in the inventory analysis and in the models;
2) model uncertainty – spatial and temporal characteristics are forgotten in the inventory analysis, simplified and linear (instead of non-linear) models;
3) uncertainty due to choices – choice of the functional unit, allocation procedure, characterisation methods, weighting, etc;
4) spatial variability – variability across locations, such as physico-chemical and ecological properties of the environment, background concentrations of chemicals and human population density, is generally not taken into account;
5) temporal variability – differences in emissions over the time
6) variability between objects/sources – variability caused by different inputs and emissions of comparable processes in a product system, for instance, due to the use of different technologies in factories producing the same material.

Many kinds of approaches aimed to reduce uncertainty in the analysis. The statistical approach (Monte Carlo analysis or fuzzy set theory) aims to explicitly incorporate uncertainties in the analysis. A review of approaches to deal with uncertainties in LCA can be found in Chapter 5.

3.3.6. LCEA in the construction sector

Construction is responsible for a major proportion of environmental impacts in the industrial sector. During the last years there has been an increasing interest in the environmental assessment of the built environment. LCEA methods described in the previous sections can be directly applied to the building sector. However, due to its characteristics there are additional problems in the application of standard LCEA methods to buildings and other constructions. The main causes may be listed as [3.39]: (i) the life expectancy of buildings is long and unknown and therefore subjected to a high level of uncertainties, (ii) buildings are site dependent and many of the impacts are local, (iii) building products are usually made of composite materials which implies more data to be collected and associated manufacturing processes, (iv) the energy consumption in the use phase of a building is very much dependent on the behaviour of the users and of the services, (v) a building is highly multi-functional, which makes it difficult to choose an appropriate functional unit, (vi) buildings are closely integrated with other elements in the building environment, particularly urban infrastructure like roads, pipes, green spaces and treatment facilities, and it can be highly misleading to conduct LCEA on a building in isolation. Nevertheless, several LCEA methodologies and tools have been developed over the last years focusing on the environmental assessment of the built environment and they are described in the following paragraphs.

Currently there are two major classes of assessment tools for the built environment [3.40]: (i) qualitative tools based on scores and criteria and (ii) tools using a quantitative analysis of inputs and outputs using a life cycle approach. Within the first group of tools there are systems such as LEED (in the US), BREAM (in the UK), GBTool (*International Initiative for a Sustainable Built Environment* (iiSBE)), etc. These methods, also known as rating systems, are usually based on auditing of buildings and on the assignment of scores to pre-defined parameters. Although mainly qualitative some parameters may also be quantitative and even use LCEA (mainly in the quantification of material credits). Usually these systems are used to obtain green building certifications and eco-labels. In relation to infrastructures, a similar rating system, CEEQUAL, was developed in the UK for the assessment and awarding scheme in civil engineering and public realm projects. However, this kind of tools is outside the scope of this work, thus in the following the focus will be on the second group of tools, which are based on LCA.

Regarding the second type of methods another distinction is made between LCA tools developed with aim of evaluating building materials and components (e.g. BEES [3.41]) and LCEA approaches for evaluating the building as a whole (e.g. Athena [3.42], Envest [3.43], EcoQuantum [3.44]). The latter are usually more complex as the overall building performance depends on the interactions between individual components and sub-systems as well as interactions with the occupants and the natural environment. The selection of an appropriate tool depends on the specific environmental objectives of the project.

The precision and the relevance of LCEA tools as a design aid was analyzed in a project developed in the frame of the European thematic network PRESCO (Practical Recommendations for Sustainable Construction) [3.45]. In this project, several LCA tools were compared, based on case studies, with the global aim of the harmonization of LCA based assessment tools for buildings. Other comparative analysis regarding tools for environmental assessment of the built environment may be found in Jönsson [3.46] and Forsberg & von Malmborg [3.47].

Most approaches and implementation tools referred in the previous paragraphs have been mainly developed for the evaluation of buildings. For infrastructures, as referred in Chapter 1, the use of LCEA is far from being a common practice. However some attempts to consider LCEA in relation to infrastructures have been made over the last years. An environmental input-output life cycle assessment (EIO-LCA) was proposed by Horvath and Hendrickson [3.51] for the comparison of a steel bridge and a steel-reinforced concrete bridge. Keoleian et al. [3.49] introduced a life cycle environmental analysis for the comparative analysis of engineered cementitious composite link slabs and conventional steel expansion joints. These comparative analysis were based only on the inventory stage (collection of data) of a life cycle environmental analysis. Other simplified life cycle environmental approaches, restricted to one or two indicators, were also proposed by Itoh and Kitagawa [3.48], based only on CO_2 emissions, by Lounis and Daigle [3.50], based on CO_2 emissions and waste production, and Bouhaya et al. [3.52], based on CO_2 emissions and energy release.

3.3.7. Further developments in LCEA

3.3.7.1. Improving the environmental impact assessment

One of the main limitations in current LCEA methodologies is due to the lack of spatial and temporal details in the analysis. Regarding spatial differentiation in LCEA, although a lot of work

has been done [3.53][3.54] further research is needed in order to make it feasible for practical applications in LCA.

Other improvements are foreseen in the development of more accurate non-linear models for impact characterization and in the consideration of new impacts in LCEA (e.g. noise).

3.3.7.2. Extending the scope of life cycle analysis

In the pursuit of the aims of the sustainable development other aspects, apart from the environment, should be considered. To fulfil the needs of this holistic concept the social and the economic aspects need also to be considered in a life cycle approach. The importance of both subjects has been acknowledged by SETAC and a working group had been created which is dedicated to Life Cycle Costing and its integration and compatibilization with LCEA. Information on the activities of the working group can be found in Rebitzer and Seuring [3.55].

3.3.7.3. Integration with other tools

Another strategy to improve and to overcome some limitations in current LCEA methodology proposed by Udo de Haes et al. [3.56] is to use other types of approaches in combination with LCEA – use of a toolbox. Among other advantages, the use of a toolbox allows the possibility to consider spatial and temporal aspects and the integration of other types of impacts into the combined analysis. For instance, when information regarding local impacts is important the use of LCEA together with environmental risk assessment can be more practical than downscaling LCEA to the local level [3.57]. Several methods to integrate risk assessment in LCEA can be found in Mathews et al. [3.58].

The use of a LCC together with LCEA to integrate the economical perspective in a life cycle assessment was already discussed in the previous sub-section. These two tools share a similar framework providing many synergies and thus enhancing the application of life cycle approaches for decision making. Another proposal to integrate economic and social perspectives into LCEA is discussed by Weidema [3.59] regarding the combined analysis of LCEA with a cost-benefit analysis.

3.4. LIFE CYCLE COST ANALYSIS (LCCA)

3.4.1. Introduction

LCCA is an economic method of project evaluation in which all costs arising from owning, operating, maintaining and ultimately disposing of a project are considered to be potentially important to that decision [3.60]. The LCCA enables comparative assessments to be made over a specified period of time, taking into account all relevant economic factors both on terms of initial capital costs and future operational costs [3.61].

Life cycle cost analysis is not a new methodology, in fact it has been used as a stand-alone approach for a long time and standards for LCCA will be available soon [3.62]. An introduction to LCC analysis and application can be found in Fuller and Peterson [3.60]. LCC methodology as a stand-alone tool can be found in several programs, for example BridgeLCC 2.0 [3.63], a software for the preliminary design of bridges or BLCC 5.0 [3.64], a software for the evaluation of long-

term costs and savings of energy and water conservation and renewable energy projects. Currently there are also available LCA tools integrating LCC: BEES [3.41], Envest [3.43], Legep [3.65], EcoEffect [3.66], etc.

LCCA is suitable for the evaluation of construction assets design alternatives that satisfy a required level of performance but may have different initial costs; different operation, maintenance and repair (OM&R) costs; and possible different life spans. Another suitable application for LCCA are energy conservation projects in which the increase in the initial capital cost of a new building, for instance, is justified from the energy reduction costs over the project life. LCCA provides a significantly better assessment of the long-term cost effectiveness of a project than alternative economic methods that focus on first costs or on operating related cost in the short term.

Although there is an extensive research activity in the field of LCCA, in practice, it is not commonly applied in the Europe.

The early development of LCCA took place in the US. In 1990, the Federal Energy Management Program of the US Department of Energy published [3.67] life-cycle costing rules and procedures to be followed by all federal agencies in evaluating the cost effectiveness of potential energy and water conservation projects and renewable energy projects in federal facilities.

LCCA have long being receiving attention as a tool to assist US transportation agencies in decision making processes and in managing assets, since US laws required that consideration should be given to life-cycle costs in the design of bridges, tunnels and pavements. Recommendations for the use of LCCA are given by several publications of the Federal Highway Administration [3.68][3.69]. However, LCCA is not universally used in US transportation agencies mainly due to a lack of a common accepted methodology for LCCA. To overcome this problem a methodology for life-cycle cost analysis of bridges, to be used by US transportation agencies, was proposed [3.70]. The major innovation in this approach is the explicit introduction of vulnerability and uncertainty in the analysis.

An intensive literature review of LCCA and its application can be found in [3.71].

3.4.2. Scope of LCCA

Life Cycle Cost Analysis (LCCA) or simply Life Cycle Costing (LCC) is often confused with Whole Life Costing (WLC). However, ISO 15686-5 [3.72] eliminates this confusion and the terminology followed in this dissertation is in accordance to this standard. Thus, LCCA includes all the costs due to construction, operation, maintenance and end-of-life of an asset; while WLC includes wider costs and incomes (it may include external costs, e.g., environmental costs). The differences between LCCA and WLC are illustrated in Figure 3.4.

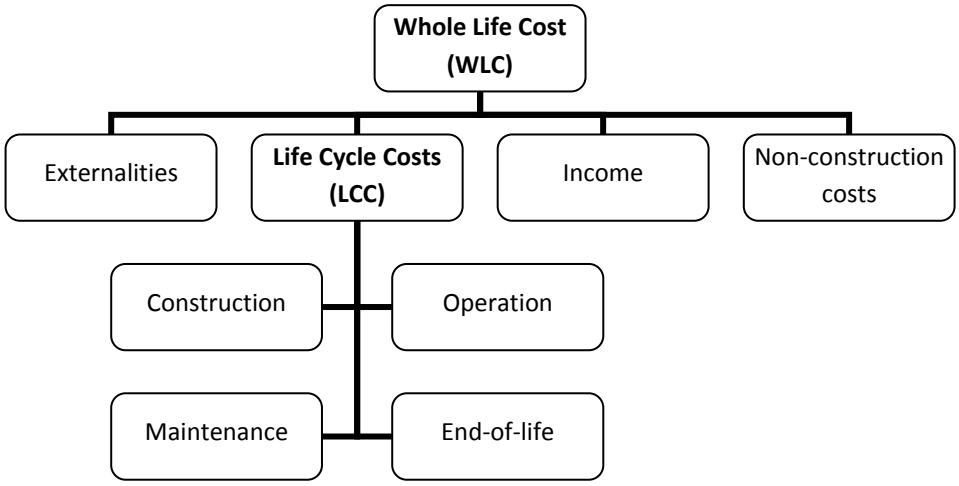

Figure 3.4. Distinction between LCC and WLC according to [3.72]

Furthermore, the standard provides a list of items that may be included in each category, as represented in Table 3.3.

Table 3.3. Costs categories according to ISO 15686-5 [3.72]

Externalities	Life Cycle Costs	Income	Non-construction costs
(may include costs due to environmental burdens)	All costs arising from construction to end-of-life	Income from sales Taxes on income 3rd party income during operation Taxes Disruption, other	Land, Finance User support costs Taxes, other

3.4.3. Mathematical modelling

Different costs occur at different points in the life cycle of a construction asset. These costs cannot be compared or simply summed up due to the varying time value of money. The present value represents the amount of money that would be needed to be invested today, at an interest rate equal to discount rate, in order to have the money available to meet the future cost at the time it is predicted to occur. The basic discount formula is given by [3.60]:

$$PV = \frac{FV}{(1+d)^n} \tag{3.4}$$

where, PV is the present value, FV is the value in the future, *d* is the interest rate and *n* is the number of years in the future.

PV can be calculated using a nominal discount rate or a real discount rate. Nominal costs are quantified based in a nominal discount rate. A real discount rate reflects the time value of money without accounting for the effects of inflation and deflation, while a nominal discount rate takes into account those effects. A real discount rate is used when all cost data are denominated in terms of “constant” currency, that is, currency with constant purchasing power. A nominal, or also known as market, discount rate is used when all cost data are denominated in “current” currency, that is, currency that change in value from year to year. The relation

between a real discount rate (d_{real}) and a nominal discount rate (d_{nom}), assuming a general inflation (or deflation) rate of a, is given by [3.60]:

$$d_{real} = \frac{1 + d_{nom}}{1 + a} \tag{3.5}$$

The Life Cycle Cost is calculated as a Present Value (PVLCC) of the accumulated costs (C_t) incurred at time t, over a period of time (T), and at a real discount rate (d), as given by the following formula:

$$PVLCC = \sum_{t=0}^{T} \frac{C_t}{(1+d)^n} \tag{3.6}$$

When choosing between alternative solutions the solution with a lower PVLCC is the best option. It is possible to use alternative or supplementary methods of economic evaluation for the comparison between alternative solutions. Table 3.4 summarizes some of these methods.

Table 3.4. Alternative methods of economic evaluation (adapted from [3.60])

Method	Application	Comment
Net Savings (NS) (NS is a variation of the Net Benefits (NB) method)	NS is applied when benefits occur primarily in the form of future operational cost reductions. It calculates the net amount, in present-value currency, that a project alternative is expected to save over the study period.	If NS > 0 the project is considered to be cost effective. LCC and NS are consistent in the evaluation of alternative project solutions.
Savings-to-Investment Ratio (SIR) (SIR is a variation of the Benefit-to-Cost Ratio(BCR))	SIR expresses the ratio between the savings of an alternative and its increased investment cost (in present value terms).	If SIR > 1 the project is considered economically viable. The project with the lowest LCC is not generally the alternative with the highest SIR.
Adjusted Internal Rate of Return (AIRR)	AIRR is a measure of the annual percentage yield from a project investment over the study period. AIRR can be used to decide whether to accept or reject a project alternative or to allocate a given investment budget, it should not be used to select among project alternatives.	If AIRR > MARR, the project is economic; if AIRR < MARR, the project is uneconomic; and if AIRR = MARR, the project is economically neutral. (the Minimum Acceptable Rate of Return (MARR) is generally equal to the discount rate used in the LCCA) The alternative with the highest AIRR will not generally be the alternative with the lowest LCC.
Payback (DB)	PB measures the time required to recover initial investment costs. Simple Payback (SPB) ignores time value of money and Discounted Payback (DPB) does not. PB is not valid for selecting among alternative projects; it is best used as a screening method.	PB ignores all costs and savings, as well as any residual value, occurring after the payback date.

Most models found in the literature employ the present value method [3.73], as given by expression (3.4). This is also the approach chosen in this dissertation.

Different nomenclature and/or cost breakdown structure are however used to describe the components of the life cycle analysis. Many examples of different cost breakdown schemes, according to different authors and applications, are provided in [3.73]. Ehlen and Marshall [3.74] proposed a cost breakdown scheme for bridges based in three levels (see Figure 3.5). The first level refers to the time when costs occur. Thus, in this level, costs are divided according to the life cycle categories: construction; operation, maintenance and repair (OM&R); and disposal. The second level sub-divides the costs in relation to the component that generates the cost: (i) by functional element of the structure, (ii) by activities not assignable to functional elements (e.g., overhead), and (3) by any activities associated with the introduction of a new-technology material. Finally, in the third level, costs are grouped according to the entity that bears the cost in (i) agency costs, (ii) user costs and (iii) 3rd party costs.

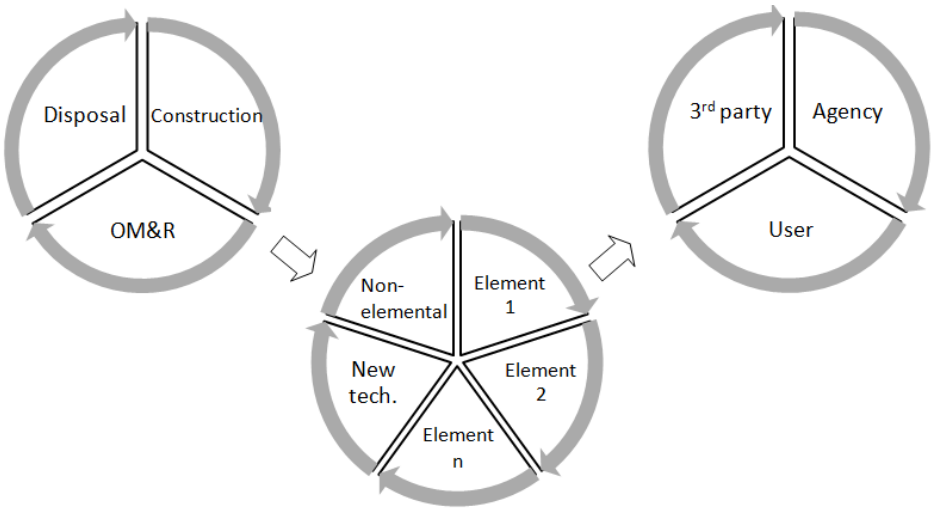

Figure 3.5. Cost breakdown scheme for bridge (adapted from [3.74])

Agency costs are all costs incurred by the project's owner or agency over the study period. These include but are not limited to design costs, capital costs, insurance, utilities, and servicing and repair of the facility. User costs are the costs assigned to the direct users of the bridge. For example, construction or maintenance activities often cause traffic congestion which may impact the drivers' personal time and even its safety. Finally, third-party refers to costs incurred by entities who are neither the agency nor direct users of the bridge. Examples of these costs are the lost sales for a business establishment whose customer access has been impeded by construction of the project, or whose business property has been lost through the exercise of eminent domain, etc.

3.4.4. Data requirements

The selection of data for a LCCA is a time-consuming and hard process. Not only because the time span of analysis is long but also because of the several categories of data involved. Data may be classified into three main categories (i) performance data, (ii) economic data and (iii) cost data.

All of the parameters used in LCCA can influence the outcome of the analysis and therefore any management decisions based on that analysis.

The various categories of data are discussed over the following sub-sections.

3.4.4.1. Performance data

One of the basic steps in a LCCA is the determination of the service life of the bridge and/or its components. Usually the end of the service life of a bridge is determined by [3.70]: (i) no longer needed; or (ii) unsafe, obsolete or unable to provide the services expected of it, even with repairs. Eurocode 1990 [3.75] specifies the service life of new bridges to be 100 years; other codes specify other time periods. The condition of a bridge deteriorates with time from its initial high level to an unacceptable level C_f (see Figure 3.6). The service life (SL) of a bridge represents the period between the time when the bridge is placed in service (T_0) and the time it reaches an unacceptable condition level (C_f). As already referred, other reasons may accelerate the end of the service life of a bridge. Reasons like obsolescence, resulting from a change in the requirements or expectations of a bridge and thus leading to a reduction of its service life, even if it is still in an acceptable condition.

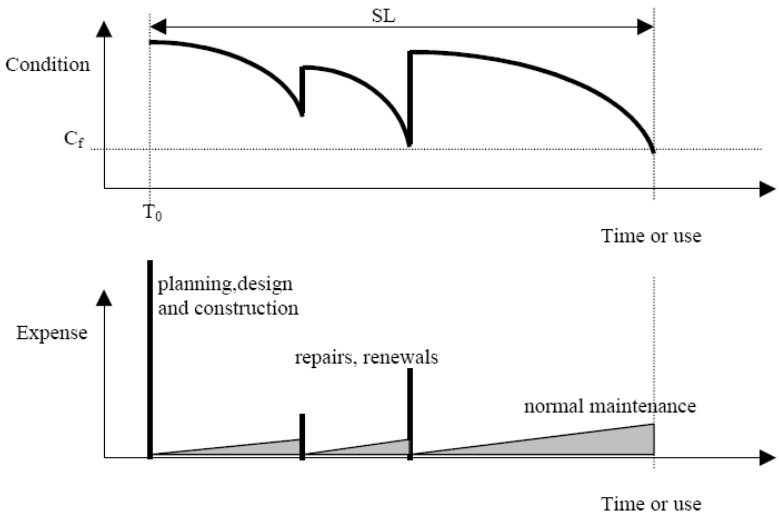

Figure 3.6. Service life and relative costs (from [3.70])

During the service life of a bridge, at least some normal or routine maintenance is expected. Under conditions of normal maintenance only, without major repairs, the service life of a typical highway bridge can be substantially less than 75 to 100 years [3.70]. Naturally, the entity responsible for a bridge undertakes the necessary actions (repairs, rehabilitation or renewals) in order to return its condition to a higher level and extend the service life. In fact, the challenge of bridge managers is to specify an economically efficient set of actions, and respective timing, so that bridges can achieve the intended service life. Great efforts in research have been devoted to the topics of service life prediction and deterioration models. A review of models can be found in the final deliverables of research projects BRIME [3.76] and LIFECON [3.77]. Without being exhaustive, additional information can be found in [3.78][3.79][3.80][3.81][3.82][3.83][3.84].

Apart from scientific data, the past experience of highway agencies in bridge maintenance and rehabilitation can provide statistical data for the value of the service life of a bridge and for the activities, and respective timing, needed to fulfil that period of time. According to [3.70], there is no particular reason to assume that SL is equal to or different from the "design lifetime" that designers use in their projects according to some design code. However, in a LCCA the analysis period should generally be set as equal to the best estimate of SL for the bridge, or bridge element, that is the focus of the analysis.

3.4.4.2. Economic data

Among the most important parameters in a LCCA is the discount rate [3.70][3.73]. A review of various criteria proposed in the literature for the selection of the discount rate may be found in [3.73].

The present value of future costs, as given by expression (3.4), reduces rapidly over time for different discount rates. For example, from Figure 3.7, the present amount of 1000€, ten years into the future, drops from 613€ at a discount rate of 5% (point A), to 161€ at a discount rate of 20% (point B). Assuming a same discount rate (for example 5% in Figure 3.7), 1000 € in 10 years worth 619€ in present value (point A). This value decreases to 482€ if a time span of 15 years is considered (point C).

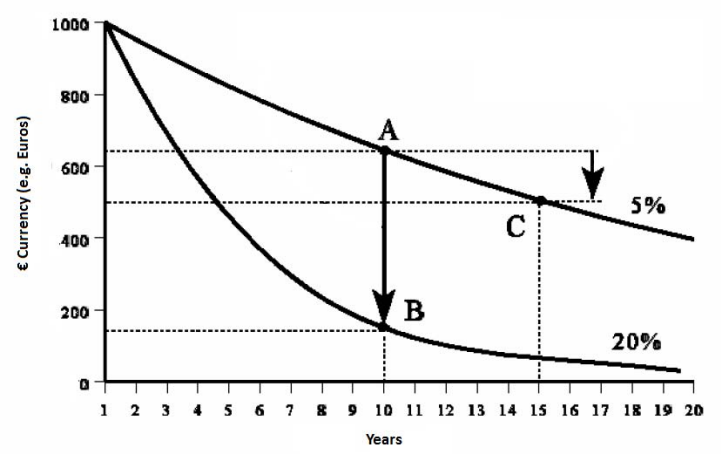

Figure 3.7. Present value of future costs (from [3.63])

The selection of a suitable discount rate is thus crucial in a LCC analysis. A high discount rate will tend to favour options with low capital cost, short life and high recurring costs, whilst a low discount rate will have the opposite effect. Usually, government agencies publish discount rates to be used in the economic analysis of government projects. In the private sector, discount rates are usually determined by the investor's minimum acceptable rate of return for investments. The use of two discount rates is recommended [3.71] and a sensitivity analysis should be conducted in order to assess the differences in the results. Buildings and construction assets, such as bridges, have long service lives. Due to the difficulty in predicting inflation in long term, the use of real costs and real discount rate is also recommended [3.71]. Over a long period of time, the real discount rate is usually 0-2%. At low discount rates, long-term future costs and savings are immediately meaningful, and therefore, investment for a better future would look more rewarding.

Inflation or deflation is another economic parameter that may needs attention in LCCA. Price inflation/deflation causes a reduction/increase in the purchasing power of current currency over time. Some authors [3.71] recommend to use constant-currency analysis since it eliminates the need to estimate the rate of inflation over the time period of analysis. Inflation may also be used in LCCA to convert existing past data on costs to present values.

3.4.4.3. Cost data

Cost data are of many types, depending on the cost breakdown scheme chosen for the LCCA. Some authors [3.70] make a distinction between costs that are directly measurable and those that must be inferred from other observations. Another distinction may be made in terms of costs associated with the normal maintenance of the bridge and costs due to the occurrence of extraordinary events (e.g., collisions, earthquake, etc). Nevertheless, costs are inevitably associated with the time they accrued, and unless the discount rate is set to zero, the prediction of its occurrence has a major influence in the result of a LCCA.

3.4.5. Advanced LCCA analysis

LCCA addresses the life cycle of a system or product; hence, predictions are needed to account for future events. If the system is a building or a bridge, then the life span can be about 100 years, or more, which makes predictions even more difficult to be made. There are many sources of uncertainty in LCCA, e.g., the service life of the bridge or its components, future operating and maintenance costs, disposal costs, etc. Also, other important variables, such as the discount rate and inflation rate, further increase the uncertainty level in LCCA.

The proper treatment of these uncertainties is fundamental for the successful implementation of a LCCA. Several approaches have been developed to address this problem. The most common approaches found in the literature are: (i) sensitivity analysis [3.85][3.86][3.87]; (ii) probabilistic analysis [3.88][3.89][3.90]; and (iii) fuzzy analysis [3.91][3.92][3.93]. An integrated framework to handle uncertainties was proposed by Kishk and Al-Hajj [3.94], which combines probabilistic and subjective data as represented by probability density functions and fuzzy numbers, respectively.

A European research project EUROLIFEFORM [3.95] aimed to develop a probabilistic approach to predict WLCC and performance of buildings and civil infrastructures. The focus of this approach was the integration of deterioration algorithms of structural components in a stochastic WLCC.

A comprehensive procedure and software tool for bridge life-cycle cost analysis including the explicit introduction of uncertainty and vulnerability risk was developed in the US [3.70] to be used by US transportation agencies. In this approach uncertain parameters are represented by probability distributions and analysis are carried out by Monte Carlo simulations.

3.5. LIFE CYCLE SOCIAL ANALYSIS (LCSA)

3.5.1. Introduction

Among the three common known pillars of sustainability, the social aspect is the one at the earliest stage of development. Most of the authors reviewed in this work acknowledge that the

social component of sustainability is fundamental to complete the holistic picture of sustainability, although, its integration in life cycle assessment is still in its infancy [3.4][3.96][3.97].

Societal assessment is commonly referred to as the third pillar of measuring sustainable development and the assessment of life cycle social aspects is a critical future issue for life cycle approaches in general. However social impacts are not easily quantifiable and, contrary to LCC, social LCA is a more recent topic and therefore further research is needed. Nevertheless, several papers have been published over the last years focusing on the problem. O'Brien et al. [3.98] identified social and political factors that contribute to environmental issues and emphasized the connection between them. In order to enhance LCA as a tool for decision-making a framework for Social Life Cycle Impact Assessment (SLCA) is being developed by Dreyer et al., [3.97]. This new framework is intended to support informed business decisions in a company which aims at minimizing harmful impacts on peoples' lives from the activities in the company's product chains. Hunkeler [3.99] suggests a preliminary methodology for mid-point based societal life cycle assessment for comparative product assertions and applies it to a case study comparing two detergents in terms of labour hours. Input-output modelling may also be used to characterize the effects of changes in economic demands on social indicators [3.100] and the methodology is applied to a case study regarding a change in a supplier in the US and the corresponding effect in a social indicator - the infant mortality.

Furthermore, the concept of Corporate Social Responsibility (CSR) also recognizes the importance of the social dimension of sustainability. "CSR is the continuing commitment by business to behave ethically and contribute to economic development while improving the quality of life of the workforce and their families, as well as of the local community and society at large" [3.101]. A business aiming to operate according to the principles of sustainability or CSR must consider its entire supply chain, and not only the links which belong to its own sphere of legal responsibility [3.96]. This requires the considerations of environmental, economic and social aspects through a life cycle approach. The International Organization for Standardization (ISO) launched the development of an International Standard providing guidelines for social responsibility (SR). This standard is expected to be published in 2010 as ISO 26000 and to be used in a voluntary basis.

Contrary to the life cycle environmental and economic analysis, which were addressed in the previous sections, a framework for a life cycle social analysis is presently not addressed in any specific standard nor there's a general consensus in the scientific community in regard of the way to do it. A general methodological framework for LCSA was proposed by the UNEP-SETAC Life Cycle Initiative [3.102], in order to integrate social aspects in life cycle analysis similar to the framework for environmental LCA laid out by ISO 14044 [3.14]. The suite of standards under development by the European Committee for Standardisation (CEN) on Sustainability of Construction works includes social performance and covered in the draft standard prEN 15643 – Part 3 [3.103].

A more comprehensive review of life cycle social analysis is provided in Kloepffer [3.4] and Jørgensen et al. [3.104].

3.5.2. LCSA framework

There are two major trends of thinking in regard of the integration of social aspects in the general framework of life cycle analysis according to ISO 14044 [3.14]. Some authors advocate that it is feasible, and others don't [3.105]. According to Spillemaeckers [3.97][3.105] there are two major reasons for making the life cycle framework inadequate to perform the life cycle social assessment. The first reason is that an environmental LCA employs an input-output model, making an inventory of the flows of raw materials, energy and emissions without taking much account of what happens within the companies involved in each process along the life cycle. Since essential social criteria, such as working hours and discrimination, are characteristics within each unit process and related companies, this is a major drawback of the LCEA framework. In other words, the object of a LCEA are elementary flows, while in LCSA the object are relations. The other limitation refers to the characteristics of societal indicators. Key societal indicators such the ones referred in the previous paragraph, are very much local dependent thus requiring the establishment of regionally-specific databases. This is not the case in LCEA, where indicators are usually homogenised, with continental or global averages often assumed.

Due to these two reasons a twofold approach was developed [3.105]. This model makes a clear distinction between aspects closely related to the product and organization-specific aspects (see Figure 3.8). The assessment of environmental aspects is based on the LCEA method, which analyses the product's process tree. For the assessment of social and economic aspects the model uses an approach that considers the organizations involved in the production chain. This latter approach was adopted for the development of the Belgian social label [3.105], which is a governmental label for products and services that are bought and sold in Belgium.

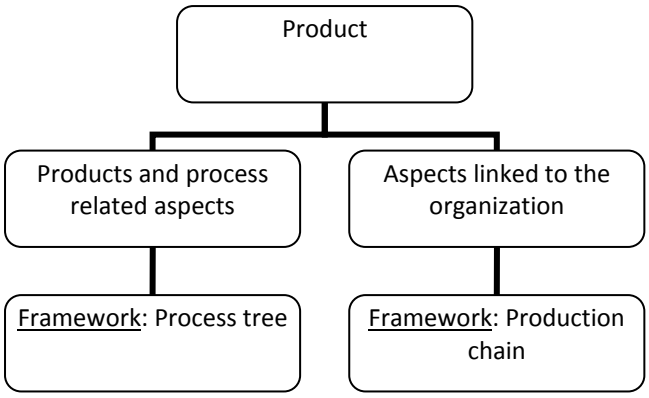

Figure 3.8. Integrated approach to chain analysis (adapted from [3.105])

Dreyer et al. [3.97] also shares the opinion that most social impacts have no relation to the processes themselves, but rather to the conduct of the companies performing processes.

In these approaches the inventory analysis is therefore focused on the conduct of the companies engaged in the life cycle, thus leading to the problem of quantifying how much of the company´s total social impacts should be allocated to the process included in the assessed product. To address this problem, Dreyer et al. [3.97] proposes the use of a share factor, representing the weight that is given to a company's social profile along the total product chain, to allocate the impacts created by the company involved in the product system to the assessed product. The share factor can be calculated, for example, by the number of working hours spent at the company per functional unit of the product. Spillemaeckers et al. [3.105], on the other hand,

avoids the need for allocation as each company, involved in the life cycle of the product or service, is globally assessed, regardless of the fact that some of the company's processes might not be involved in the life cycle.

To overcome the problem of relating social impacts to the functional unit, Hunkeler [3.99] proposed an approach derived from life cycle inventory data. In his approach only a single impact category is used: the working hours spent to produce each unit process. The time needed is calculated as part of the societal life cycle inventory.

The importance of the availability of local data is acknowledged by most authors. Dreyer et al. [3.97] argues that country or region-specific information about the product chain may enable a crude assessment, although a conclusive assessment must be based on company-specific information, at least for the most important companies in the product chain. Spillemaeckers et al. [3.105] suggest to use in a first attempt a desktop screening based on literature, internet and various databases, in order to gather the company specific information. This preliminary analysis allows to identify the chain actors more vulnerable to problems and then visits to those specific locals may be considered. Other authors cited by Jørgensen et al. [3.104], although acknowledging the importance of local data for accurate analysis, argue that generic data from country and industry databases or statistics can give a rough estimate on several social impacts.

According to the general framework of LCEA [3.14], the impact assessment stage converts inventory information into impacts, through classification and characterization. In LCSA there are currently two classification systems [3.104]: a classification system similar to the approach used in LCEA and a classification system according to the impacted stakeholders. According to Grießhammer et al. [3.102] these two approaches are complementary. In both cases, impact categories are chosen to support the interpretation phase. In LCSA there is presently no consensus regarding the use of mid-point or end-point categories, and the trend is to simplify the inventory flows rather than a characterization step according to the LCEA methodology [3.104]. A review of the main approaches is given by Jørgensen et al [3.104]. A different approach is given by Hutchins and Sutherland [3.96]. In this latter approach an input-output analysis is introduced as a method for considering social impacts.

3.5.3. Further developments in LCSA

The assessment of the social dimension of sustainability is the lesser developed aspect. There are presently a great variety of approaches in order to deal with the different stages of the LCSA methodology, which reflects its immature stage. There are still a great number of important issues that have not been solved. Kloepffer [3.4] lists the following main issues: the problem of relating societal impacts with the functional unit of the system; the problem of obtaining site specific data; and the problem of the selection and proper quantification of social indicators.

3.6. SYNOPSIS OF THE CHAPTER

This chapter reviewed current methodologies and tools for the evaluation of environmental, economical and social criteria based in life cycle approaches.

The implementation of the concept of Sustainable Development in general terms lead to an increased concern about environmental problems, disregarding economical and social aspects. This is reflected in the availability of methods and tools to address the environmental aspect in comparison with the availability of methods and tools for the evaluation of economical and social criteria.

Moreover, a comprehensive approach in the context of Sustainable Development implies the integration of, at least, the three main aspects referred in the last paragraph. Currently such methodology is not available, particularly, for the assessment of a construction asset.

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CHAPTER 4. SUSTAINABILITY INDICATORS

4.1. INDICATORS FOR A SUSTAINABLE DEVELOPMENT

4.1.1. Introduction

Indicators have long been used to monitor systems that need care or need to be controlled (e.g., being pale is a sign or a indicator that something could be wrong with someone, a high body temperature is a indicator for doctors of a problem, etc). An indicator can be defined [4.1] *"as something that helps us to understand where we are, what we are going and how far we are from the goal. (...) Indicators are presentations of measurements. They are bits of information that summarize the characteristics of systems or highlight what is happening in a system".* Indicators are thus part of the information needed to understand the world and make decisions.

Indicators are needed to fulfil the aims of Sustainable Development. This is clear from Agenda 21 [4.2]: "(…) *indicators of Sustainable Development need to be developed to provide solid bases for decision making at all levels, and to contribute to a self-regulating sustainability of integrated environmental and development systems*".

Sustainable Development is a multidimensional concept and should be observed in a holistic sense. The understanding of the individual dimensions and the relationships between them is essential for the development of an integral approach. Indicators are useful to integrate environmental, economic and social science knowledge into decision-making. Furthermore, they can lead to better actions by simplifying, clarifying and making aggregated information available for decision-makers. Indicators are useful tools to measure and balance progress towards Sustainable Development.

Care should be taken in regard of what kind of development is being measured. One thing is to measure or monitor the development of a certain aspect and another thing is to measure the development of an aspect in a sustainable perspective. Usually development is associated with growth. For instance, the development of an economy may be analysed by the growth in the GDP per capita. However, growth simply means getting bigger, not necessarily getting better. A high GDP growth may also be associated with higher energy consumption, exploitation of natural resources and negative impacts on environmental resources. The growth of the population may indicate the development of a country, but is it an indicator of a sustainable development of the country? Sustainability indicators should be more than growth indicators, they should be about efficiency, sufficiency, equity and quality of life [4.3]. An environmental indicator becomes a sustainability indicator with the addition of time, limit or target (e.g., the emission of air pollutants, per year, to the atmosphere has little meaning to common people; however, the amount released to the atmosphere relative to the amount that atmosphere can absorb without causing damage to people is easily understood).

Indicators are often developed based on historical practices, regulations or through dialogue among a wide range of stakeholders, such as government representatives, experts and civil

society representatives. Often indicators are selected in order to give answers to specific problems individually rather than how they jointly provide an answer to a problem.

Conceptual frameworks for indicators help to focus and clarify what to measure, what to expect from measurement and what kinds of indicators to use. Diversity of core values, indicator processes and sustainable development theories have resulted in the development and application of different frameworks. The main differences among them are the ways in which they conceptualize the key dimensions of sustainable development, the inter-linkages among these dimensions, the way they group the issues to be measured, and the concepts by which they justify the selection and aggregation of indicators [4.4].

A standard framework for evaluating progress towards sustainability does not exist [4.5]. The existing frameworks can be categorised into (i) causal-chain frameworks, (ii) impacts-based frameworks, and (iii) influence-oriented frameworks.

Due to general awareness regarding the issue of sustainability, over the last years, an increased number of environmental reports have been developed making use of environmental indicators. These reports are usually based on causal chain frameworks. Conceptual causal chain frameworks links indicators of the environmental driving forces, to pressure indicators, to environmental state indicators, to impact indicators and, finally, to indicators of societal response [4.6].

The most common causal chain frameworks used in the selection of a set of indicators are the Pressure-State-Response (PSR), the Driving force-State-Response (DSR), and the Driving force-Pressure-State-Impact-Response (DPSIR). In each framework a causal chain is identified and a distinction is made between (i) forces that act on the environment, (ii) changes that, as a consequence, take place in the environment and (iii) the societal reaction to those changes. The main difference between these frameworks, which are represented in Figure 4.1, is in the degree in which they subdivide the steps in the causal chain. These frameworks will be described further on the next sections.

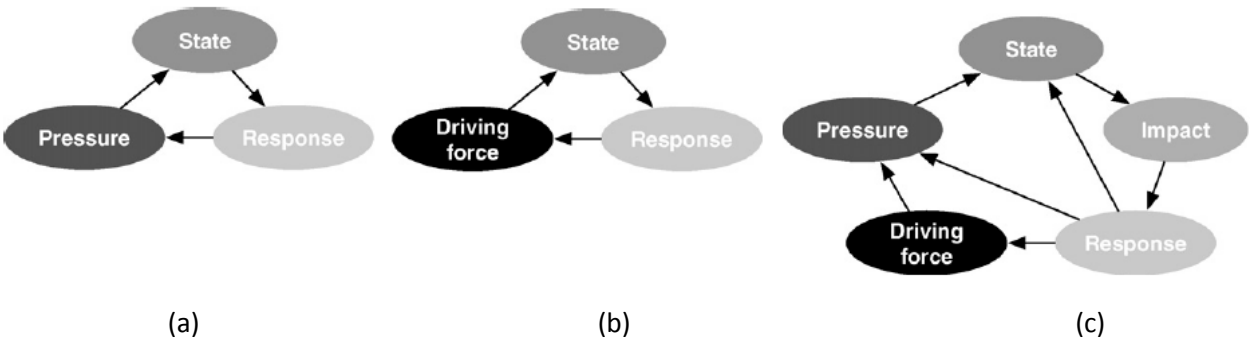

Figure 4.1. Causal chain frameworks (a) PSR; (b) DSR; (c) DPSIR [4.7]

Recently, an enhanced DPSIR was proposed [4.7] in which causal networks are used instead in order to take into account the interactions between the individual causal chains.

In most reports, although the indicators are presented in the framework of causal chains, the choice of indicators is based on individual criteria and not on how they are related through causality. Naturally, the selection of indicators is very much dependent of the purpose and scope

of the indicator set. However, common criteria are found in reports relative to the development of indicator sets:

- relevant to assessing sustainable development progress;
- broad in coverage all aspects of sustainable development;
- limited in number but sufficiently comprehensive to capture the multidimensional nature of sustainable development;
- the set of indicators should remain open-ended in order to adapt to future needs;
- understandable, clear and unambiguous;
- conceptually sound and theoretically well founded in technical and scientific terms;
- representative of an international consensus to the extent possible;
- provide a basis for international comparisons;
- data to support the indicator should be made available at a cost/benefit ration and of know quality.

4.1.2. Indicators by the United Nations Commission on Sustainable Development (UN CSD)

The United Nations Commission on Sustainable Development (CSD) was created by the UN General Assembly, in 1992, to ensure an effective follow-up of United Nations Conference on Environment and Development (UNCED). Since then, the commission has been responsible for monitoring the progress towards the implementation of Agenda 21 and the Rio Declaration on Environment and Development, and to provide guidance on the implementation of Earth Summit agreements at the local, national and international levels.

In this regard, and recognizing the importance of indicators in helping countries in decision making processes toward Sustainable Development, in 1995, the CSD approved its work programme on indicators of Sustainable Development. The first two sets of indicators were developed between 1994 and 2001. The third revised set of CSD indicators was finalised in 2006 and published in 2007 [4.4]. The revised edition contains 96 indicators, including a subset of 50 core indicators. The aim of these sets on indicators is to support countries in developing and implementing national indicators for Sustainable Development for policy making.

The initial set of indicators was organised in a DSR framework, in which driving force indicators were defined to describe processes or activities that have a positive or a negative impact on sustainable development; state indicators were defined to describe the situation at the time; and response indicators were used to reflect societal actions aimed at moving towards sustainable development. These indicators were further grouped into four dimensions of sustainable development: social, economic, environmental and institutional. The revision of the CSD indicators, in 2001, changed this framework mainly because it was unable to address the complexity of relationships between the issues and the relation between indicators and policy issues. Thus, the second set of indicators followed a more flexible theme/sub-theme framework, also considering the four dimensions of sustainable development. In this framework, indicators were grouped into themes, which were determined on the basis of policy relevance.

The most recent list of CSD indicator themes, which follows the same theme/sub-theme framework adopted in 2001, is presented in Table 4.1.

Table 4.1. CSD indicator themes [4.4]

Poverty	Natural hazards	Economic development
Governance	Atmosphere	Global economic partnership
Health	Land	Consumption and production patterns
Education	Oceans, seas and coasts	
Demographics	Freshwater	
	Biodiversity	

In this new set the relation between indicators and the main dimensions of sustainability is not explicit and some themes are transversal in order to better translate the multidimensional and integrative nature of Sustainable Development.

4.1.3. Indicators by the Organisation for Economic Cooperation and Development (OECD)

In order to support the measurement of the environmental performance and to report on progress towards Sustainable Development in OECD Member countries, a list of environmental indicators to be used at the international and national levels has been developed by the OECD [4.8]. This set of indicators aims to harmonise environmental indicators in Member countries and to assist in further developments and use of those indicators. Indicators were developed based on the PSR model. Therefore, indicators of environmental pressures, environmental conditions and societal responses were defined. Indicators of environmental pressures are used to characterize production and consumption patterns, and they often reflect emission or resource use intensities. Indicators of environmental conditions aim to give an overview of the situation (state) concerning the environment and its development over time. Finally, indicators of societal responses show the extent to which society responds to environmental concerns.

The set of indicators developed by OECD includes several categories of indicators, each corresponding to a specific purpose and framework [4.8]:

- Core environmental indicators are designed to help track environmental progress and the factors involved in it, and analyse environmental policies. The OECD Core Set is a set commonly agreed upon by OECD countries for OECD use. It is published regularly. The Core Set, of about 50 indicators, covers issues that reflect the main environmental concerns in OECD countries.
- Key environmental indicators endorsed by OECD Environment Ministers, are a reduced set of core indicators, selected from the OECD Core Set, that serve wider communication purposes. They inform the general public and provide key signals to policymakers.
- Sectoral environmental indicators are designed to help integrate environmental concerns into sectoral policies. Each set focuses on a specific sector (transport, energy, household consumption, tourism, agriculture). Indicators are classified following an adjusted PSR model reflecting: sectoral trends of environmental

significance; their interactions with the environment (including positive and negative effects); and related economic and policy considerations.

- Indicators derived from environmental accounting are designed to help integrate environmental concerns into economic and resource management policies. Focus is on: environmental expenditure accounts; physical natural resource accounts, related to sustainable management of natural resources; and physical material flow accounts, related to the efficiency and productivity of material resource use.
- Decoupling Environmental Indicators (DEIs) measure the decoupling of environmental pressure from economic growth. In conjunction with other indicators used in OECD country reviews, they are valuable tools for determining whether countries are on track towards sustainable development. Most DEIs are derived from other indicator sets and further broken down to reflect underlying drivers and structural changes.

Each of these sets of indicators is closely related to each other. The Core set of indicators represents a common minimum set and countries are encouraged to adapt them according to national circumstances. The main issues covered in the Core set of indicators are presented in Table 4.2. For each of those issues, indicators of environmental pressure, environmental conditions and societal responses were defined.

Table 4.2. Major environmental issues in the Core set of indicators

Climate change	Water resources	Socio-economic, sectoral and general indicators
Ozone layer depletion	Forest resources	
Eutrophication	Fish resources	
Acidification	Soil degradation	
Toxic contamination	Material resources	
Urban environmental quality		
Biodiversity		
Cultural landscapes		
Waste		

4.1.4. Indicators by the European Environmental Agency (EEA)

The EEA uses several types of indicators, based in the DPSIR framework, in its reporting activities. According to this system [4.9], social and economic developments exert Pressure (P) on the environment and, as a consequence, the State (S) of the environment changes (e.g. provision of adequate conditions for health, resources availability, etc). This leads to Impacts (I) on human health, ecosystems and materials that may elicit a societal Response (R) that feeds back on the Driving forces (D), or on the state or impacts directly. Environmental indicators reflect all elements of the causal chain that links human activities to their ultimate environmental impacts and the societal responses to these impacts. The DPSIR is also useful in describing the links between DPSIR elements.

Thus, for example, the relationship between the “driving forces” and the “pressure” is a function of the eco-efficiency of the technology and related systems in use. Similarly, the relationship between the “impacts” on humans or eco-systems and the “state” depends on the carrying capacities and thresholds for these systems. Whether society “responds” to impacts depends on

how these impacts are perceived and evaluated; and the results of "responds" on the "driving forces" depends on the effectiveness of the Response.

The EEA classifies indicators into 4 categories: descriptive indicators, performance indicators, efficiency indicators and total welfare indicators.

Descriptive indicators address the question "What is happening to the environment and to humans?". They describe the actual situation, with regard to the main environmental issues, as it is. In this group of indicators, other types are defined:

- driving forces indicators describing the social, demographic and economic developments in societies and the corresponding changes in life styles, overall levels of consumption and production patterns;
- pressure indicators describing developments in release of substances (emissions), physical and biological agents, the use of resources and the use of land (e.g., CO_2 emissions per sector);
- state indicators giving a description of the quantity and quality of physical, biological and chemical phenomena in a certain area (e.g., level of noise in the neighbourhood of airports);
- impact indicators describing the impacts on the social and economic functions on the environment;
- response indicators referring to responses by groups (and individuals) in society, as well as government attempts to prevent, compensate, ameliorate or adapt to changes in the state of the environment.

Performance indicators address the question "Does it matter?". This set of indicators compare actual conditions with a specific set of reference conditions. They measure the "distance" between the current environmental situation and the desired situation (target).

Efficiency indicators aimed to answer the question "Are we improving?". These indicators reflect whether or not society is improving the quality of its products and processes in terms of resources, emissions and waste per unit output.

Finally, total welfare indicators address the question "Are we on the whole better off?". These indicators have a much broader scope, aiming at measuring the total sustainability.

First reports on the State of the Environment, from EEA Member countries, made use mainly of descriptive indicators. However, since then the EEA encouraged the use of other types of indicators. Thus, a core set of 37 indicators was identified in 2004 by the EEA [4.10]. The main purpose of this set were to improve the quality and coverage of data flows, to streamline contributions with other European initiatives and to provide a manageable and stable basis for indicator-based assessments of progress against environmental policy priorities.

The core set of indicators covers six environmental themes and four sectors (see Table 4.3), all topics addressing EU policy priorities. Each indicator in the core set can be positioned in the DPSIR framework and all the indicators are either descriptive or performance based. Future indicators of eco-efficiency, policy effectiveness and welfare are foreseen.

Table 4.3. Main themes in the Core set of indicators

Air pollution and ozone depletion	Agriculture
Biodiversity	Energy
Climate change	Fisheries
Terrestrial	Transport
Waste	Water

4.2. INDICATORS FOR A SUSTAINABLE CONSTRUCTION

4.2.1. Introduction

This section addresses indicators for the assessment of the sustainability of the construction sector. As stated before, indicators are figures or other measurements which enable information on certain phenomenon (e.g. environmental impacts) to be simplified and easier to understand. Indicators can also be used for signs that one can observe and express with help of classification criteria. The classification criteria for sustainable construction can be based both on quantitative as well as on qualitative matters.

The assessment of the construction sector is a complex task as it involves multiple sub-sectors and stakeholders. The construction sector comprehends public and private housing, non-residential public property (e.g. schools, hospitals, etc), industrial buildings, infrastructures (e.g. roads, bridges, tunnels, water systems, sewer systems, etc). Moreover, the construction sector also includes the planning and development of transportation networks, etc. Therefore, in order to assess the sustainability of the sector, different types of indicators are needed to address the specific characteristics of each sub-sector.

On the other side, the sustainability may be evaluated from a different point of view depending on the interested party. In the construction sector a large number of parties are involved: public bodies, owners of real estate, contractors, planners, developers, designers, facility managers, users of buildings and facilities, etc. Thus, the selection of indicators should also address the main users of the indicators and their needs.

As referred in Chapter 1, this work focuses on the selection of indicators for designers of bridges, so that decisions may be made in early stages of construction projects. However, in this chapter, an overview of existing indicators and framework for the assessment of the global built environment is given.

4.2.1.1. Construction indicators in the EU

In order to implement and monitor the success of European policies towards Sustainable Development, several European initiatives have been financed over the last years in order to develop a set of indicators for the assessment of the sustainability in the construction sector. One of these initiatives was the CRISP project. CRISP was a European thematic network (ended in 2003) on Construction and City Related Sustainability Indicators [4.11], created with the aim of defining a framework and general methodology for indicators for the assessment of built environment and to gather those indicators within a database. The CRISP indicator database is available on the public website [4.12] and contains more than 500 indicators and 40 systems of indicators. In this database indicators are classified according to the sustainable development

issue (environmental, economic and social) and to the construction category they refer to (urban, infrastructure, buildings, building's products and processes). The statistical analysis of the indicators led to two main conclusions [4.11]: (i) with respect to category, indicators for buildings are very well represented, while only few indicators addresses infrastructures; and (ii) with respect to the sustainability issue, the environmental aspect is dominant, followed by social and economic aspects.

More recently, the need for further development of sustainability indicators, in relation to production, consumption and waste, was acknowledged as an outcome of the Life Cycle Thinking Workshop coordinated by the European Commission's Directorate General Joint Research Centre (DG JRC) [4.13]. Furthermore, it was stressed out that indicators should be based on a life cycle approach. In this regard, it is foreseen, by 2020, the development of life cycle based environmental indicators covering areas of production, consumption and waste.

Currently, Green Public Procurement (GPP) is being promoted by the EU in order to include environmental criteria in tender documents for construction works by contracting authorities. On this purpose, key environmental impacts were identified [4.14], although methodologies for the quantification of the indicators representing the environmental impacts are not provided.

4.2.1.2. Indicators in Life Cycle Analysis

In the impact assessment step of a Life Cycle Analysis environmental indicators are used to assess the potential of possible environmental problems in relation to a product or system functional unit. Indicators in LCA are not used to quantify actual impacts or risks.

Usually only environmental indicators are used, however other indicators such as noise, accidents, etc, may also be found in some methodologies. In Table 4.4 [4.15], indicators representing impact categories at midpoint level are indicated for some well-known LCA methodologies.

Table 4.4. Midpoint impact categories in LCA methodologies (adapted from [4.15])

	CML 2002	Eco-indicator	EDIP97	EDIP2003	IMPACT 2002(+)	LIME	LUCAS	RECIPE	SWISS ECO SCARCITY	TRACI	MEEuP	USEtox
Climate change	x	x	x	x	x	x	x	x	x	x	x	
Ozone depletion	x	x	x	x	x	x	x	x	x	x	x	
Photochemical ozone creation	x	x	x	x	x	x	x	x	x	x	x	
Acidification	x	x	x	x	x	x	x	x	x	x	x	
Eutrophication	x	x	x	x	x	x	x	x	x	x	x	
Ecotoxicity	x	x	x	x	x	x	x	x	x	x	x	x
Human toxicity	x	x	x	x	x	x	x	x	x	x	x	x
Ionising radiation	x	x			x			x	x			
Land use	x	x			x			x	x	x		
Resource consumption	x	x	x	x	x	x	x	x	x	x	x	
Noise				x								
Accidents					x							

Life cycle analysis can be applied both to buildings and infrastructures, although indicators should be chosen according to the system under analysis. Therefore, indicators for life cycle analysis of buildings are not necessarily the same as the ones for infrastructures. For instance,

the impact “indoor air quality” is very much appropriate for buildings but it does not apply to bridges.

4.2.1.3. Construction indicators in other organisations

Several international organisations (e.g., U.S. Green Building Council, iiSBE – International Initiative for Sustainable Built Environment, etc) are developing and implementing systems, which provide a list of indicators to measure the environmental performance of buildings and infrastructures. These systems are mainly developed for buildings and they will be described in more detail over the next section.

4.2.2. Sustainability Indicators for Buildings

This section introduces approaches that have been developed for the sustainability of buildings. Taking into consideration the three main themes of sustainability, environment, economy and society, the environmental aspect of buildings is the one that is found in most current approaches.

Currently, several methods are available for the evaluation of the environmental quality of buildings. Each of these methods proposes different types of indicators in order to measure (qualitatively or quantitatively) the environmental performance of a building, although in some cases other aspects are also covered. These methods intend to provide an environmental label to buildings.

In the next sub-sections indicators provided in standards, rating systems and other approaches are described.

4.2.2.1. Indicators in standards

4.2.2.1.1. ISO TC 59 – Building construction SC17 – Sustainability in building construction

The ISO standard ISO/TS 21929-1 [4.16] provides a framework and guidelines for the development and selection of appropriate sustainability indicators for buildings. This standard addresses the economic, environmental and social impacts of a building.

With respect to environmental indicators, a distinction is made between indicators that can be presented in terms of environmental loadings (e.g. total CO2 emissions) and impacts (e.g. contribution to global warming), and consequential environmental impacts which address aspects that influence the amount of loadings or impacts (e.g. adaptability of a building, durability, etc). It is recommended that environmental indicators of buildings should consider the life cycle of the building. Furthermore, a distinction of the life cycle stages, to which indicators are related, should be maintained.

ISO/TS 21931-1 [4.17] provides a set of environmental indicators that can be used for the assessment of environmental performance of buildings, which are indicated in Table 4.5.

In ISO/TS 21929-1 economic indicators indicate monetary flows connected to the building and they may be assessed based on life-cycle economy. Some economic flows related to the life cycle of a building are represented in Table 4.5. Also in this case, it is referred that economic indicators can be consequential.

Table 4.5. Indicators in each sustainability theme

Environment [4.17]	Economic [4.16]	Social [4.16]
Climate change	Investment	Quality of buildings
Destruction of the ozone layer	Use (energy consumption, water consumption, etc)	Building related effects on health and safety of users
Acidification	Deconstruction and waste treatm.	Barrier-free use of buildings
Eutrophication	Development of the economic value of a building	User satisfaction
Formation of photochemical oxidant	Revenue generated by the building	Architectural quality of buildings
Depletion of non renewable resour.		
Formation of pollutants		Protection of cultural heritage

Social indicators of buildings describe how buildings interact with issues of concern related to sustainability at the community level [4.16]. Examples of social aspects on the building level are also indicated in Table 4.5.

It is further recommended that sustainability should be described on the basis of a comprehensive set of indicators describing the essential environmental, economic and social impacts of a building, and their inter-relationship.

4.2.2.1.2. CEN TC 350

The future set of standards [4.18][4.19][4.20], which are currently being developed under the Technical Committee CEN/TC 350, will also provide a set of possible indicators for the assessment of buildings.

Table 4.6 indicates the indicators that have been proposed for the assessment of the environmental, economic and social aspects of buildings. These indicators are meant to be used on a life cycle approach.

Table 4.6. Indicators in each sustainability theme

Environment [4.21]	Social [4.22]	Economic [4.23]
Climate change	Thermal indoor climate	Life cycle costs due to construction, operation, maintenance and end-of-life
Destruction of the stratospheric ozone layer	Indoor air quality	
Acidification of land and water sources	Lighting	
Eutrophication	Acoustics	
Formation of ground level ozone expressed as photochemical oxidants	Accessibility	
Depletion of non renewable resources	Safety	
Depletion of non-renewable resources other than primary energy	Toxic or irritating human load	
Depletion of non-renewable primary energy		
Use of freshwater resources		
Non-hazardous waste to disposal		
Hazardous waste to disposal		
Nuclear waste (separate from hazardous waste)		
Use of renewable resources other than primary energy		
Use of renewable primary energy		
Biodiversity		
Land use		

4.2.2.2. Rating systems

Indicators in rating systems differ from the previous ones in three main aspects: (i) they may be either quantitative or qualitative, (ii) usually they are not based on a life cycle approach, (iii) in some cases, they intend to cover the three main pillars of sustainability. Table 4.7 indicates the categories addressed in four rating systems.

Table 4.7. Categories in rating systems

	Categories	GREENSTAR	ECOHOMES	SBTOOL	LEED
Environment	Energy	x	x	x	x
	Transport	x	x	x	x
	Pollution	x	x	x	x
	Materials	x	x	x	x
	Water	x	x	x	x
	Land use and ecology	x	x	x	x
Social	Health and well being (indoor quality)	x	x	x	x
Economic	Economics			x	
Management	Management	x	x	x	
	Innovation	x			x
	Quality of services			x	

From the four approaches in Table 4.7, only SBTool addresses the economic aspect of buildings. All these approaches include several environmental categories, while the social aspect is addressed only in one category.

4.2.2.3. Indicators in other approaches

4.2.2.3.1. LEnSE project

LEnSE is a European research project (2006-2007) created with the aim to develop a methodology for the assessment of the sustainability performance of buildings. The methodology is aimed to be applied to existing, new and renovated buildings. The LEnSE methodology [4.24] encompasses a list of 57 sustainability issues in the three pillars of sustainable construction. The list was grouped into 11 categories, as represented in Table 4.8.

Table 4.8. Categories in each sustainability theme [4.24]

Environment	Social	Economic
Climate change	Occupants' well being	Whole life value
Biodiversity	Accessibility	Financing and Management
Resource use and waste	Security	Externalities
Environmental management and geophysical risk	Social and cultural value	

For each category a list of sub-issues and corresponding examples of potential indicators are provided.

4.2.3. Sustainability Indicators for Infrastructures

The assessment of the sustainability of infrastructures is not at the same level as for buildings. In spite of this, some authors have proposed a set of indicators for the assessment of infrastructures [4.25][4.26].

In this section, the main methodologies for the assessment of infrastructures are described.

4.2.3.1. Environmental Impact Assessment (EIA) studies

Environmental Impact Assessment (EIA) studies are mandatory for major infrastructures projects, such as the construction of roads and bridges.

EIA is a framework for identifying, predicting, evaluating and mitigating the biophysical, social, and other effects of proposed projects or plans and physical activities [4.27]. In contrast with LCA, EIA is generally a site-specific procedure and it concentrates on the assessment of actual, local environmental problems [4.28]. Thus, impact assessment categories in EIA studies do not correspond to impact assessment categories in LCA. The former categories address actual events and environmental concentrations are often used to estimate the likelihood or probability of specific events to occur, while the latter works with potential environmental problems.

One of the steps in an EIA is the impact identification and preparation of a description of the affected environment. This can be accomplished by the use of matrices, networks and checklists [4.29]. Matrices are used to relate project actions or activities with appropriate environmental factors. Networks integrate impact causes and consequences through identifying interrelationships between causal actions and the impacted environmental factors. Checklists range from simple checklists listing environmental factors to complex approaches involving importance weightings for factors. EIA vary from study to study; however, an example of the topic areas covered are listed in Table 4.9.

Table 4.9. List of topic areas in EIA (adapted from [4.30])

Land use, landscape and visual quality
Geology, topography and soils
Hydrology and water quality
Air quality and climate
Ecology: terrestrial and aquatic
Noise
Transport
Socio-economic impact
Interrelationships between effects

4.2.3.2. Rating systems

Contrary to buildings, rating systems for the assessment of infrastructures are more rare. However, a methodology developed by CEEQUAL Ltd [4.31], provides an assessment framework suitable for any civil engineering project, mainly infrastructures. This methodology is being used for assessing, benchmarking and labelling the environmental performance of projects.

The methodology assesses 12 aspects of sustainability, which can be divided in the three main categories of Table 4.10.

Table 4.10. Assessed categories in CEEQUAL [4.31]

Environment	Social	Management
Energy	Archaeology and cultural heritage	Project Environmental Management
Transport	Nuisance to neighbours	
Material use	Community relations and joy in use	
Water issues	Landscape issues	
Land use		
Ecology and biodiversity		
Waste management		

4.2.4. Economic indicators

As referred in the previous chapter, in this dissertation, focus is mainly given to indicators for life cycle based approaches.

ISO 15686-5 [4.32] provides some examples of costs to be included in the LCC analysis of buildings, as indicated in Table 4.11.

Table 4.11. Life cycle costs for new or refurbishment buildings

Construction	Operation	Maintenance	End-of-life
Professional fees; Temporary works; Construction; Initial adaptation or refurbishment of asset; Taxes, others.	Rent (if applicable); Insurance; Regulatory costs (e.g., fire, access inspections) Utilities (e.g., energy costs for heating, cooling, etc); Taxes, and others.	Maintenance management; Adaptation or refurbishment of asset; Repairs and replacement; Cleaning; Ground maintenance; Redecoration; Taxes, and others.	Disposal inspections; Disposal and demolition; Reinstatement to meet contractual requirements; Taxes, and others.

4.3. INDICATORS FOR THE ASSESSMENT OF BRIDGES

4.3.1. Life cycle impacts of bridges

At the project-level, a bridge designer faces several options that will influence the sustainability of his/her work. For instance, the choice of a main material is responsible for more or less impacts on the material production stage depending on the characteristics of the raw materials and the transformation processes needed to produce it. Also, it can influence the long-term behaviour of the bridge and restrain the reuse of materials after demolition. Hence, different choices imply different impacts in each process.

In this work, impacts are categorized into environmental, economic and social impacts, for which individual indicators are needed. Environmental indicators address an environmental aspect of the bridge in terms of loadings or impacts. Environmental loadings (e.g., use of resources, waste production, emissions, etc) are related to environmental impacts, which can be expressed as environmental categories [4.16]. Economic indicators address the monetary flows connected to the bridge, and social indicators address the impacts of the bridge on its users and surrounding community. Monetary flows related to a bridge are usually divided into agency costs and user costs (see Chapter 3). In the scope of this research, agency costs are addressed as economical indicators while user costs are addressed as social indicators. The impacts occurring over the bridge life cycle differ in the intensity and type; Table 4.12 summarizes the main impacts of a bridge over its life cycle.

Table 4.12. Life cycle impacts of a bridge

Stage	Processes	Category	Impacts
Material production and distribution	Raw materials acquisition; Raw materials transformation; Transportation	Environmental	Loss of eco-systems Natural resource depletion Energy consumption Water consumption Visual effects Dust Emissions to air, water and soil
		Economic	Costs of raw materials and transformation processes
		Social	
Construction	On-site materials production; Use of equipment; Transportation; Traffic interruption and congestion	Environmental	Land-use Loss of eco-systems Energy consumption Water consumption Dust Emissions to air, water and soil
		Economic	Costs of mechanical and auxiliary equipment
		Social	Time delays Noise Visual effects Safety and accidents
Operation	Materials production; Use of equipment; Transportation; Traffic interruption and congestion	Environmental	Energy consumption Water consumption Dust Emissions to air, water and soil
		Economic	Costs due to maintenance and rehabilitation processes
		Social	Time delays Noise Safety and accidents
End-of-life	Use of equipment; Traffic interruption and congestion Waste management	Environmental	Energy consumption Water consumption Dust Emissions to air, water and soil
		Economic	Costs of demolition and waste management
		Social	Time delays Noise Safety and accidents

The technical solution of the bridge, i.e. the solution which meets the requirements of strength and safety according to structural codes, implies economic, environmental and social impacts as listed in Table 4.12. Furthermore, the holistic concept of sustainability implies that these impacts are inter-related (see Figure 4.2). The proper choice of a set of indicators shall take this inter-relationship into account [4.16].

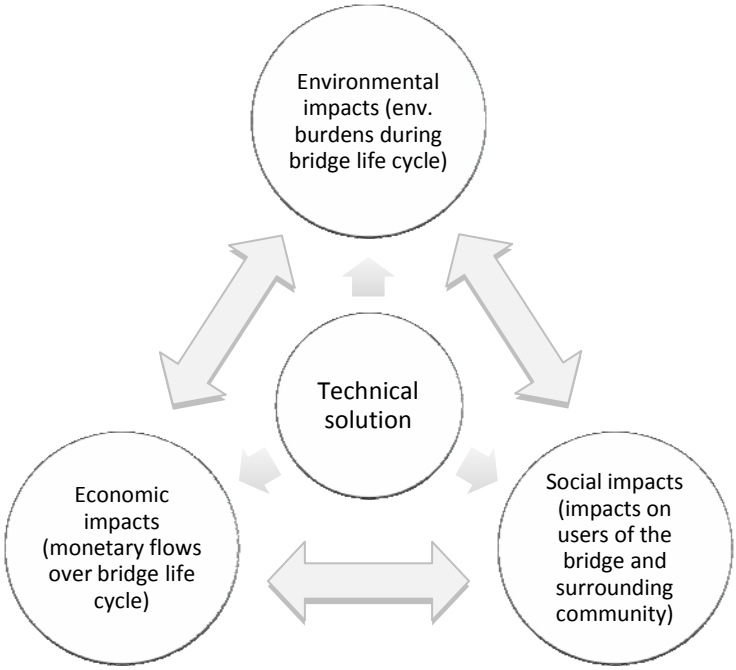

Figure 4.2. Inter-relation between impacts (adapted from [4.16])

4.3.2. Criteria for the selection of indicators

This section describes the criteria to be used for the selection of the indicators to characterize the environmental, economic and social categories. First, some assumptions are needed.

As referred in Chapter 1, the goal of the integral methodology for the assessment of bridge design is to guide the design engineer through the design process in order to guarantee an efficient design in terms of environmental, economic and social criteria, over the complete life cycle of the structure.

In the context of this research, it is assumed that the decision regarding the construction of the bridge is already taken. The design of the bridge is part of a major infrastructure project (a highway or a major roadway), and the location of the bridge is usually dictated by the constraints of the infrastructure design, either the over passing or under passing of a highway, for instance. This assumption is very important for the selection of the indicators, as described in the following paragraphs.

Accordingly to this assumption, all the environmental impacts due to the construction of the bridge in the selected place are not taken into consideration on the analysis. Naturally, this should have been taken into consideration during the general planning of the infrastructure project, in which the bridge is included. The same applies to the economical and social impacts. The cost/benefit relation of the bridge and the impacts of the bridge to the surrounding population are not considered, as these impacts are usually taken into consideration during the decision process concerning the major project.

Moreover, this assumption applies to all stages over the life cycle of the bridge. Hence, during the operation stage, the impacts (environmental, economic and social) due to the normal functioning of the bridge are not considered.

The object of assessment in the integral analysis developed in this research are all the processes that the bridge designer can influence and/or make a choice between alternatives. Thus, the set of indicators chosen for the assessment of bridges shall give the designer a clear idea about the effects of his/her choices on the sustainability of his/her work. Those choices regard the use of different types of construction materials, the adoption of a construction process, the maintenance and rehabilitation strategies and the planning for demolition and waste management.

In this research, the main criteria for the selection of indicators are:

i) indicators shall provide a measure of the essential environmental, economical and social impacts of the bridge;

ii) indicators should be preferably quantifiable and based on a life cycle approach, i.e., they shall take into account all the stages over the life cycle of the bridge;

iii) double counting of indicators shall be avoided; the simultaneous consideration of the three categories can lead to the measurement of the same issue in different aspects (e.g., environmental costs and environmental impacts).

iv) indicators shall enable to consider the quality of its information: the quality of the information provided by an indicator in the construction stage (which is usually quantified based on available data) is usually higher than the quality of the information provided by the same indicator but for the operation and/or end-of-life stages (which is usually quantified based on estimated data).

4.3.3. Selection of indicators for bridge life cycle assessment

The use of a system of indicators is more effective than an individual indicator for the assessment of the sustainability of a construction system [4.16].

In this section three sets of indicators are selected and structured in order to make an effective sustainable assessment of a bridge system. The system of indicators is selected according to the criteria listed in the previous section.

4.3.3.1. Environmental indicators

In this work the environmental indicators chosen are the set of indicators defined in the Operational Guide to the ISO standards [4.33] developed by the Centre of Environmental Sciences (CML) at the University of Leiden. The choice of a single set of indicators from a single methodology is preferred to a choice of individual indicators from different methodologies. In each methodology the indicators are developed in a systematic way taking into account the inter-dependency between indicators. For instance, the characterization factors developed in the Guide for each impact category take into account the fact that a certain emission can contribute simultaneously to several impact categories.

The Guide distinguishes between “baseline”, “study-specific” and “other” impact categories, depending on the environmental relevance in relation to the analysis and the availability of adequate characterization methods. The baseline impact categories recommended by the Guide comprehend the impacts that are included in most life cycle environmental analysis, and these are the indicators chosen to make part of the methodology developed in this research. For each impact category, as illustrated in Table 4.13, the Guide suggests a characterization model and characterization factors derived from those models are provided.

Table 4.13. Environmental indicators

Indicator	Space scale	Time scale	Areas of protection (*)
Global warming	Global	20, 100, 500 yrs	NE, ME, HH
Acidification	Local/continental	∞	NE, ME, NR, HH
Eutrophication	Local/continental	∞	NE, ME, NR
Photo oxidant formation	Local/continental	5 days (?)	NE, ME, NR, HH
Ozone depletion	Global	5, 10, 15, 20, 25, 30, 40 yrs and ∞	NE, ME, NR, HH
Ecotoxicity	Local/regional/ continental/global	20, 100, 500 yrs and ∞	NE, NR
Human toxicity	Continental/global	20, 100, 500 yrs and ∞	HH
Abiotic depletion	Global	-	HH, NE, NR

(*) Human Health (HH), Natural Environment (NE), Man-made Environment (ME) and Natural Resources (NR)

The choice of this particular set of indicators and respective impact categories has been made for several reasons:

i) the set is based on the best available models developed by the SETAC-Europe Working Group on impact assessment;

ii) the impact categories are defined according to the requirements of ISO standards 14040 series;

iii) the impacts cover most of the environmental problems currently assessed by life cycle environmental approaches;

iv) the characterization models have been developed based on European data (which is particularly relevant for impacts that are local dependent);

v) the definition of several models for the same impact category enables to consider same of the uncertainty and variability in the calculation of the indicators.

There are two major environmental problems related to the promotion of sustainable activities in construction: the safeguard of natural resources and the reduction of Construction and Demolition Waste (C&DW). In order to promote these two aspects, indicators are needed to provide a trend on its performance. The safeguard of natural resources is covered under the impact category abiotic depletion. The reduction of the construction and demolition waste has two major advantages, the protection of natural resources and the minimization of waste sent to landfill. The first advantage is covered under the impact category abiotic depletion, while the second advantage is covered in the remaining impact categories listed in Table 4.13. Thus, in order to avoid double counting, an indicator for the quantification of the C&DW is important to be considered in the analysis. However, it should only be informative and not considered in the same analysis together with the other indicators. All these indicators will be further discussed in Chapter 6.

4.3.3.2. Economical indicators

In Chapter 3 different cost breakdown structures were referred for life cycle cost analysis. The set of economic indicators adopted in this work refer to the time when costs occur. Thus, 3 indicators are defined: (i) initial cost; (ii) cost of operation, maintenance and repair (OM&R); and (iii) end-of-life cost. Initial cost includes all for the costs due to the construction of the bridge. All the costs occurring over the life cycle of the bridge are quantified by the indicator of cost of OM&R, while the costs inherent to the demolition of the bridge and disposal of demolition waste are included in the indicator of end-of-life cost. In a concession motorway these costs are borne by the concessionaire. These indicators will be further discussed in Chapter 7.

4.3.3.3. Social indicators

The construction of a bridge has naturally impacts on the society, in general, and in the surrounding population, in particular. In the goal of the integral analysis developed in this dissertation two categories of indicators are adopted: indicators describing the direct impacts of the bridge on its users and indicators describing the impacts of the bridge on the surrounding population. In the first category three indicators are selected: the driver delays' cost due to work activity in the bridge, the corresponding cost due to the operation of the vehicle and the costs of accidents. The second category of indicators comprehends the noise due to work activity and the aesthetics of the bridge. All these indicators, except aesthetics, may be quantify over the complete life cycle of the bridge. Further discussion on these indicators is provided in Chapter 8.

4.4. SYNOPSIS OF THE CHAPTER

In this chapter an overview of indicators for the evaluation of Sustainable Development and, in particular, of Sustainable Construction was provided.

The selection of the indicators depends on the goals of the analysis, but in the framework of sustainability, they should cover at least the three main dimensions: environment, economy and society.

In this context, a set of criteria were defined for the selection of indicators covering the three main dimensions of sustainability. Avoiding double counting of impacts is an important criterion to take into account when integrating different aspects in the same analysis.

Based on the proposed set of criteria, indicators were introduced for the evaluation of a particular construction asset: bridges. This set of indicators, covering environmental, economical and social criteria, are intended to be quantify based on a life cycle approach.

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CHAPTER 5. INTEGRAL LIFE CYCLE ANALYSIS OF BRIDGES

5.1. FRAMEWORK FOR INTEGRAL LIFE CYCLE ANALYSIS

5.1.1. Introduction

An integral life cycle approach for bridges is introduced in this chapter and further developed in the following chapters. The presumption of being an integral analysis is reflected in the simultaneous consideration of environmental, economical and social aspects in the assessment of the performance of a construction system, in this case a bridge, over its life cycle.

Furthermore, the aim of the approach is the life cycle assessment of the system in the context of sustainable development and, in particular, in the context of sustainable construction. Therefore, the approach aims at balancing environmental, economical and social aspects.

Two different purposes, considering two different perspectives, are pursued in this approach. The first purpose is a detailed accounting of the environmental, economical and social impacts of a bridge over its life cycle, in view of the identification of improvement possibilities of the processes contributing with major impacts. The second purpose is to help in the decision making process of choosing between different construction solutions. Thus, the first case considers an accounting perspective and the second case considers a decision making perspective. It should be emphasized here that a life cycle analysis is not a decision making approach; however, it can provide valuable information for decision makers in the process of decision making.

Currently, there is not a standardized methodology providing guidance for an integral life cycle analysis of a construction system. As described in the previous chapters, the current development of the three main categories is not at the same level. The life cycle environmental analysis has currently the most well established standardized framework, although there is still no generalized acceptable methodology in the scientific community. In a decreasing order of development follow the life cycle economic analysis and the life cycle social analysis. For this reason, for the development of the general framework for the integral life cycle analysis, it was decided to adopt and extend the standardized framework for Life Cycle Environmental Analysis (LCEA), according to the series of ISO standards 14040 [5.1][5.2], to Life Cycle Cost Analysis (LCCA) and to Life Cycle Social Analysis (LCSA).

In the literature, Life Cycle Analysis (LCA) is usually related to the environmental criterion. However, hereafter in this thesis, LCA is used to refer to life cycle analysis integrating environmental, economical and social criteria, unless otherwise noted.

Therefore, the generalized framework proposed in this chapter entails the four main steps of the ISO standard 14040 [5.1]: the goal and scope step; the inventory step; the impact assessment step; and the interpretation step (see Figure 5.1). However, as it will be described over the next sub-chapters, each step of the analysis will be adapted in order to allow the integration of the economical and social aspects in the life cycle analysis.

The integration of the three criteria is based on the condition that the evaluation of the three criteria share the same goal and scope and they are based on the same inventory analysis.

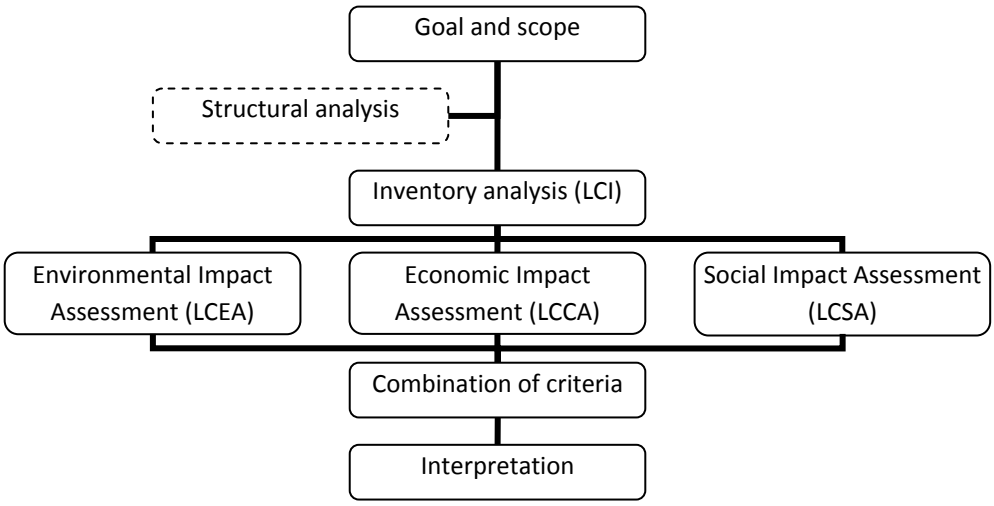


Figure 5.1. Flowchart of the Life Cycle Integral Analysis

The impact assessment stage of the three main categories is made separately for each criterion although based on the same assumptions. The following step, the combination of criteria, depends on the perspective considered. In the decision making perspective, the balance between the individual performances is achieved by a multi-criteria decision analysis; in the accounting perspective the performances are interpreted individually and/or aggregated into a single index.

The two perspectives referred in the previous paragraphs share most of the steps in the framework of the integral analysis represented in Figure 5.1. In the case of the accounting perspective, the analysis is concluded in the impact assessment stage and the interpretation of the outcome of the analyses is made at this level. In the decision making perspective, the criteria are combined in order to enable comparisons between alternative options and interpretation is made after this additional stage.

The traditional design of a construction system is based on the requirements of codes and regulations that have been developed for that purpose. These requirements relate to the safety of the structure (e.g. Eurocodes) and usually include rules for resistance, durability and serviceability. In this approach, the initial safety of the structure, according to the requirements of the Structural Eurocodes, is assumed to be fulfilled. However, in a life cycle analysis, this is not enough. Bridges start to deteriorate immediately after it enters into service. The rate of deterioration depends on many factors for different types of bridges. In order to keep the bridge above the required condition, maintenance and rehabilitation of the bridge is required. Each time an intervention in needed on the bridge, it originates environmental, economical and social impacts that need to be considered in a life cycle analysis. Hence, the life cycle environmental, economical and social analysis of bridges are directly dependent on the lifetime structural performance and this relationship should be addressed in the methodology. This issue is further discussed in sub-chapter 5.2.

The design of a sustainable construction system is not a straightforward process. As referred in the last paragraph, the way a structure is designed implies environmental, economical and social

impacts and vice-versa, that is, the minimization of these criteria depends on the way the structure is designed. Therefore, a sustainable design implies an iterative approach and the approach developed in this dissertation allows to take this iteration into account.

A life cycle analysis implies a time span associated with the analysis. In the case of a construction system, the life span may comprehend decades or even a century. Many assumptions and scenarios are therefore needed in order to make a life cycle analysis operational. This and other reasons regarding the current development of the methodologies introduce a high level of variability and uncertainty in the analysis. Thus, the analysis of these uncertainties, its propagation throughout the analysis and its influence in the results are also addressed in the proposed methodology.

This chapter introduces the general framework for the integral life cycle analysis of bridges, with a main focus on the inventory step of the overall analysis. The environmental, economical and social analysis will be developed in chapters 6, 7 and 8, respectively. Finally, the decision making perspective is dealt with in chapter 12.

5.1.2. Goals and scope

5.1.2.1. Aims of the approach

The general aim of the approach introduced in this chapter is the integral life cycle analysis of bridges taking into consideration, apart from traditional aspects of safety and resistance, the environmental, the economical and the social aspects; thus contributing to a more sustainable construction sector.

The developed approach has two main perspectives: an accounting perspective and a decision making perspective. Both cases share a general purpose: the improvement of a construction system, in this case a bridge, in the context of sustainable construction.

The aim of the accounting perspective is to quantify, as much as possible, all the potential impacts of a bridge over its life cycle; in order to understand which is(are) the process(es) contributing with major share to those impacts. The identification of such process(es) enables the definition of improvement possibilities leading to a more efficient performance. This perspective may be taken by a design-engineer or a team of designers willing to improve the design of a bridge.

The second perspective aims to provide valuable information to a decision making process. During the design process of a bridge, the designer is often facing decisions regarding, for instance, the use of different materials, the use of different construction systems, the choice of different construction and demolition waste treatment, etc. As already referred, a life cycle approach is not a decision making tool, however, it can be used as a decision-support tool guiding the decision maker in his/her choices over the design of a bridge. Although, this perspective was developed to assist planners of bridges, it can also be used with other purposes. For instance, it can also be used to aid the selection of alternative projects of bridges, in a bidding process in the context of green procurement. This second perspective allows also the identification of critical processes and thus the definition of improvement measures, as in the former perspective.

Albeit the developed methodology enables the two described perspectives, some adaptations are needed in each case, as will be described in the following sub-sections.

5.1.2.2. Scope of the life cycle analysis

The life cycle analysis covers all stages from raw material acquisition to deposition of demolition waste, through construction and operation of the bridge, and the transportation of materials and equipment between stages, as illustrated in Figure 5.2. Each box in Figure 5.2 represents a unit process. In fact, each box involves a number of sub-unit processes (e.g. the production of cement for input to the production of concrete); however, for simplification, the boxes represented in Figure 5.2 are assumed to be the main unit processes. The rules that determine which unit processes are included in the life cycle study are the cut-off rules and this issue is further described in sub-section 5.4.1.1.

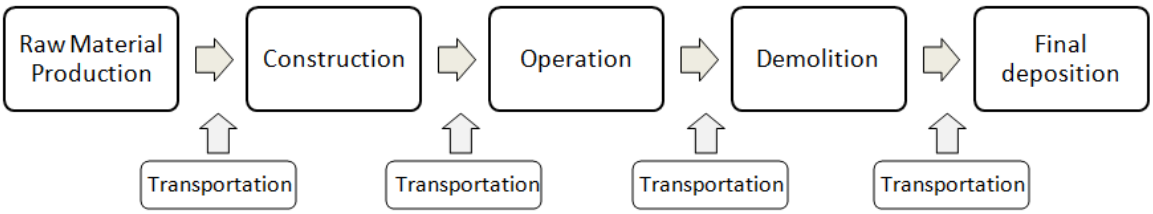


Figure 5.2. System Boundary of the integral analysis

The scope of the analysis depends also on the respective goal. In the case of the accounting perspective all the stages in Figure 5.2 are taken into account. However, in case a comparison between two or more alternatives is made then all the processes not affected by the changing of alternative may be left out of the study. For instance, in the case of a bridge, if the aim of the study is to analyse the consequences of changing the treatment of the demolition waste in the end-of-life stage, than all the remaining stages apart from the one(s) affected by the waste treatment, which may also include the stage of material production in case of recycling, may be left out of the scope of the analysis.

As referred before, it is assumed that the construction system is designed according to the corresponding Eurocode. In the case of bridges, the Eurocode specifies a service life of 100 years. In this approach the time period of analysis coincides with the design service life of the structure, thus 100 years. Furthermore, it is assumed that material production and construction of the bridge occur in the first year and that the demolition and deposition of the structure will occur in the 100th year.

5.1.2.3. Functional equivalent

The functional equivalent of a product system enables the comparison between two product systems. In case of bridges, a comparison between the assessment results of two or more bridges can only be made on the basis of their functional equivalency.

The functional equivalent adopted in this dissertation is a bridge overcrossing a motorway, designed for a service life of 100 years.

The functional equivalent defined in the last paragraph is not unique as bridges can performed other functions (e.g. a bridge can also be designed to become a landmark: in this case, the

aesthetics of the bridge could also be added to the functional equivalent); depending on the goal of the study, additional functions can be added to the one defined for this approach.

5.1.3. Inventory analysis

The inventory analysis entails the quantification of the inventory flows for a product system. In traditional life cycle environmental analysis the inventory flows include inputs of water, energy, and raw materials, and releases to air, land, and water. Taking into consideration the aims of the approach, the production of waste is also included in the inventory (this aspect will be discussed in Chapter 6). As referred in the first section of this chapter, economic analysis and social analysis are also based on this inventory analysis. This implies that input and/or output flows relevant for these analyses need also to be collected. A summary of inventory flows for each unit process is represented in Figure 5.3.

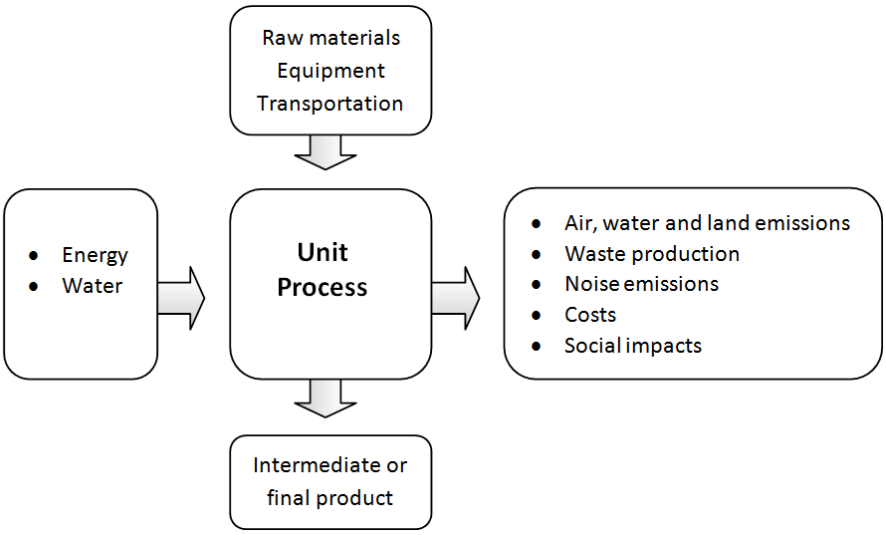


Figure 5.3. Inventory data of a general unit process

The life cycle inventory analysis, commonly denominated LCI, is often the most time-consuming task in life cycle analysis. Currently, databases are available providing environmental data for materials and processes. Nevertheless, in many cases data is currently not available, particularly for processes in relation to construction. Moreover, for the economical and social analyses, no databases are currently available.

Another important aspect that should be addressed by LCI is the allocation of input/output flows of materials with recycling content. This issue is particularly important in a construction system where the reuse and recycling of construction materials are usually acknowledged as contributing to the sustainability of the sector.

All these aspects will be further detailed in sub-chapter 5.4.

5.1.4. Impact assessment

In the impact assessment stage the inventory data collected in the previous stage are processed according to the selected indicators for the environmental, economic and social analyses.

The set of indicators for each analysis were chosen according to the goals of the integral approach. The indicators adopted for the environmental, economic and social analysis are represented in Table 5.1; these indicators will be further developed in Chapters 6, 7 and 8, respectively.

Table 5.1. Indicators for environmental, economic and social assessment

Environmental	Abiotic depletion	Economic	Initial costs	Social	Vehicle operation costs
	Acidification				
	Eutrophication				
	Global warming		Operation, Maintenance and repair costs		Driver delay costs
	Ozone layer depletion				Safety costs
	Human toxicity				Noise
	Terrestrial ecotoxicity		End-of-life costs		Aesthetics
	Photochemical oxidation				
	Waste production				

5.2. LIFE CYCLE STRUCTURAL ANALYSIS

5.2.1. Considerations about lifetime

The integral life cycle analysis developed in this dissertation aims at the evaluation of three main criteria: environmental, economic and social. Their evaluation is however dependent on the structural behaviour of the structure over the time period considered in the life cycle analysis, which considers all the stages and inter-linked stages of a structure, from extraction of natural resources to the final disposal of all materials. In this dissertation, the time period considered in the life cycle analysis is defined as lifetime.

Thus, a major step in life cycle analysis is the definition of the lifetime. According to the general framework for life cycle analysis in the ISO standards [5.1][5.2], the functional unit and boundary conditions should be associated with a reference period of time, although no fixed values are provided. The practitioner has some freedom to decide about the reference time period, whether to make it coincident or not with the service life. Moreover, no guidance is provided in case the lifetime is shorter than the service life or in the case of extended service life.

A structural system is designed according to the corresponding structural code for a design working life or service life. In this work the definition of design working life is taken from EN1990 [5.3], which states that “design working life is the assumed period of time for which the structure is to be used for its intended purpose with anticipated maintenance but without major repair being necessary”. In the case of bridges this period of time is 100 years. In reality, the service life of bridges may be less than 100 years or can be extended far beyond the 100 years if major rehabilitation is considered. The estimated service life of a bridge can be assumed to be the lifetime of the life cycle analysis. This, however, may introduce some difficulties when comparing two systems with different services lives. Furthermore, the bridge may reach the end-of-life stage even without reaching the end of its service life, if obsolescence is considered. Obsolescence is here understood as the inability of the structure to satisfy changing functional, economic, environmental or cultural requirements; and it’s the cause of demolition in about 50% of all demolition cases [5.4].

Whether making the lifetime coincident with the service life or not, it is necessary to predict the service life of the structure and the frequency of maintenance in order to keep the structure above the minimum required, as discussed in the next section.

5.2.2. Prediction of structural behaviour

Bridge structural behaviour deteriorates with time. Maintenance and rehabilitation are needed in order to keep it in a safe condition during its entire service life or to extend the service life. In general, three types of maintenance can be distinguished [5.5]: routine maintenance, which refers to minor work carried out on a regular bases (e.g. cleaning of drains); preventive maintenance, which leads to a delay in the rate of deterioration and may enhance the strength of the structure to some extent (e.g. steelwork painting, minor concrete repairs, expansion joint replacement, etc); and essential maintenance, referring to rehabilitation work when a structure is considered to be structurally inadequate (e.g. major concrete repairs, replacement of structural elements, etc).

The prediction of the service life of structures or components and the prediction of maintenance frequency have been recognised as critical issues in the research community, and thus addressed in many thesis and research programmes. It is not the aim of this dissertation to provide a state-of-art on the available models and methodologies addressing one or both aspects. However, without being exhaustive, many interesting references may be found in [5.6][5.7][5.8].

However, given the aim of this thesis, an approach is needed to deal with the above questions and to provide guidance during the operation stage of the bridge in order to quantify different criteria. Two different approaches are hereby considered: a lifetime probabilistic-based analysis and a lifetime scenario-based analysis. These two approaches are detailed in the following sub-sections.

5.2.2.1. Lifetime reliability-based approach

A model developed by Frangopol et al. [5.9] enables to consider different types of maintenance of the bridge service life. In this model, a reliability index is used as a measure of performance of deteriorating structures under the effect of maintenance actions. The proposed model considers linear deterioration under no maintenance. The effects of maintenance actions are modelled through an improvement in reliability immediately after application of maintenance and a reduction of the deterioration rate for a period of time after application.

The model, represented in Figure 5.4, is defined by eight random variables: initial reliability index (β_0); time of damage initiation (TI); reliability deterioration rate without maintenance (α); time of first application of preventive maintenance (TPI); time of reapplication of preventive maintenance (TP); duration of preventive maintenance effect on bridge reliability (TPD); reliability deterioration rate during preventive maintenance effect (γ); and improvement of reliability index (if any) immediately after the application of preventive maintenance (θ).

Based in this model the distribution of the rehabilitation time or rate (i.e., time at which the reliability index down crosses the target value) may be determined considering preventive maintenance (T_{RP}) or without preventive maintenance (T_R).

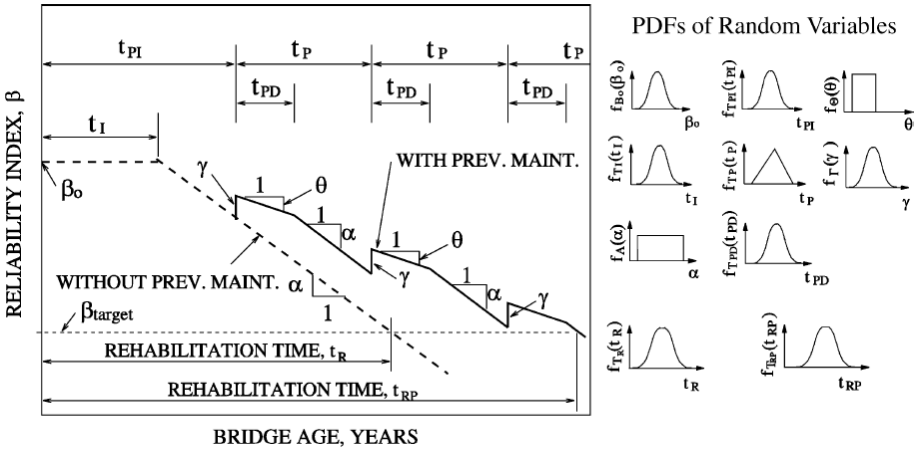
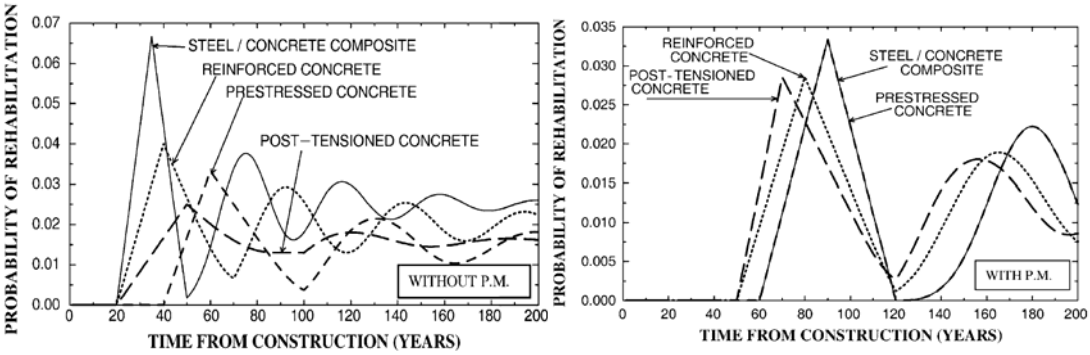


Figure 5.4. Reliability-based model for bridge deterioration [5.9]

The probability of rehabilitation has been computed for four bridge types assuming that no preventive maintenance has been done and preventive maintenance has been done [5.10]. The results are presented in Figure 5.5(a) and Figure 5.5(b), respectively.



(a) (b)

Figure 5.5. Probability of rehabilitation of four bridge types (a) assuming no preventive maintenance, and (b) assuming preventive maintenance [5.10]

The computation of these distributions was based on triangular distributions predicted by experts [5.9] and assuming a triangular distribution for the application of preventive maintenance with the minimum, mode and maximum values given by 10, 20 and 25, respectively.

The main advantage of this model is that it takes into account several types of uncertainties influencing the service life of a structure, and in this regard, this approach is similar to the approach being developed in this research, although in this case the main criteria are environmental, economic and social.

The model proposed by Frangopol et al. [5.9] can also be coupled with optimization algorithms in order to find the maintenance strategy resulting in lower present value of mean cumulative cost, respecting reliability thresholds. This issue will not be addressed here as it is beyond the scope of the life cycle analysis developed in this dissertation; however, application examples may be found in [5.11][5.12][5.13][5.14].

The main drawback of this approach is the amount of data needed to perform such type of analysis. Moreover, the results obtained by Frangopol et al. [5.9] are related to specific sets of bridges and they cannot be generalized to all types of bridges. Therefore, another approach is hereby considered, based in the estimate service life of different bridge's components and relative scenarios for maintenance as described in the following sub-section.

5.2.2.2. Lifetime scenario-based approach

In this sub-section a scenario-based approach is proposed to considerer different maintenance types and frequencies over the service life of the structure.

For simplicity, the structure is hereby sub-divided into structural elements and equipment. Structural elements include the sub-structure and superstructure, while equipment include all the other elements. Table 5.2 provides examples of each kind.

Table 5.2. Components of bridge structures

Superstructure	Concrete deck
	Steel girders
	Cross-beam elements
Sub-structure	Piers
	Abutments
	Foundations
	Piles
Equipment	Bearings
	Expansion joints
	Safety guards
	Edge beams/cornice
	Parapet/railing
	Waterproof layer
	Drainage system
	Road asphalt layer

Through the consultation of equipment catalogues available online, available literature and current practices in motorway agencies it is possible to draw scenarios in regard of the service life of bridge equipments. Naturally, the service life of an equipment depends of many factors like the way they are placed in the construction, the environmental characteristics, etc.

While the frequency of maintenance and replacement of equipment may be considered as described in the previous paragraph, the maintenance and rehabilitation of structural elements is not that simple. However, in this approach it is assumed that bridges are used for its intended purpose over a period of 100 years, provided that appropriate maintenance and rehabilitation is taken into account. This assumption is validated by the work of Frangopol et al. [5.9] referred in the previous sub-section.

Hence, in the proposed approach scenarios will be established for the maintenance and rehabilitation of a bridge over a period of 100 years. These scenarios are established based on the estimated service life of the major components of the bridge and on the estimated service life of the equipment.

The scenario-based approach adopted in this work will be further developed in the case studies.

5.3. UNCERTAINTY IN LIFE CYCLE APPROACHES

5.3.1. Introduction

Uncertainties are unavoidable in a life cycle approach. A methodological procedure of life cycle analysis has to deal with several sources of uncertainties in every step of the analysis. These uncertainties should be properly addressed otherwise the outcome of the analysis might lead to incorrect or biased conclusions [5.15][5.16][5.17]. Moreover, to be used as an aid tool for decision making, the quality of the decision-support information should be clear [5.18] in order to ensure that sound decisions are made.

In general, the sources of uncertainty may be classified into two broad types [5.19]: aleatory and epistemic. Aleatory uncertainty is the uncertainty associated with the randomness of the underlying phenomenon that is exhibit as variability in the observed information; whilst epistemic uncertainty is the uncertainty associated with imperfect models of the real world due to insufficient or imperfect knowledge of reality. Both types of uncertainty are usually present in life cycle analysis.

Given the current development of LCEA in relation to LCCA and LCSA, many authors have explicitly addressed the problem of uncertainties in LCEA over the last years, while in relation to LCCA and LCSA the problem has not gathered the same interest so far.

Therefore, in relation to LCEA, Huijbregts [5.20] distinguished between uncertainty and variability to address the epistemic and aleatory uncertainties, respectively. Moreover, according to the author, uncertainty in LCEA is divided into: (i) parameter uncertainty due to imprecise, incomplete or outdated measurements and lack of data; (ii) model uncertainty due to the use of simplified models for environmental problems; and (iii) uncertainty due to choices (e.g., choice of allocation procedures or weighting factors); while variability addresses: (i) spatial and temporal variability (the lack of spatial and temporal data and integration in the models); and (ii) variability between objects and sources (e.g., the weighting of environmental impacts may introduce variability between human preferences). In the context of LCEA, other classifications of uncertainties have been suggested in the literature [5.18]. However, as emphasised by Heijungs and Huijbregts [5.18] more important than classifying uncertainties is to distinguished between sources and sorts of uncertainties and it is the sorts of uncertainty that determine the choice of the approach to deal with uncertainty.

In the following text and throughout the next chapters, the term “uncertainty” is used to refer both the aleatory and epistemic uncertainty in life cycle analysis, unless otherwise indicated.

As already referred, the evaluation of the types of uncertainty, and to what extent the outcome of a life cycle analysis is affected by them, is an issue that has been addressed over the last years by several authors, in particular, in relation to LCEA.

Most studies focus on specific types of uncertainty in individual stages of LCEA. For instance, the evaluation and discussion of uncertainties in the LCI stage may be found in [5.21][5.22][5.23][5.24][5.25]. Many authors discussed the outcome of a LCEA based on the use of different LCIA approaches [5.26][5.27][5.28][5.29].

Only a few studies attempt to assess the simultaneous effect of several types of uncertainties in the result of a LCEA. A methodology taking into account simultaneously parameter, scenario and model uncertainties was proposed by Huijbregts et al. [5.15], although the weighting and normalisation steps of LCEA were not considered in their analysis. The evaluation of uncertainties in the LCI and Life Cycle Impact Assessment (LCIA) stages were also performed by Geisler et al. [5.31] and discussed based on a case study. More recently, Hung and Ma [5.30] proposed a methodology to analyse the uncertainties involved in the LCI, LCIA, normalisation and weighting steps of LCEA. In their study, uncertainties in the LCI stage were considered by the introduction of probabilistic distributions, whilst the uncertainty in the remaining stages was evaluated by the use of different available methodologies for LCIA and relative values of normalization and weighting.

The explicit introduction of uncertainties in LCEA may be accomplished by the use of different statistical approaches [5.18]: (i) scenario analysis, where different data sets, models and/or choices are used; (ii) sampling methods, like Monte-Carlo Simulation or Latin-hypercube Simulation; (iii) analytical methods based on mathematical expressions; and (iv) non-traditional methods such as fuzzy sets, Bayesian methods, neural networks. etc. Examples and references of the application of each approach to LCEA are provided in [5.18].

Different authors have different opinions regarding the appropriateness of the approach for processing uncertainties. Heijungs [5.32] argues that analytical methods are efficient and easily operationalized although requiring complex mathematical expressions. Steen [5.33], on the other side, says that the complexity involved in the mathematical models make the use of analytical methods almost impractical and suggests the use of stochastic modelling. The same opinion is expressed by Lloyd and Ries [5.16] saying that the use of complex numerical solutions for solving analytical methods may not provide reliable estimates for tails of output distributions leading to inaccurate approximations.

The increasing availability of software providing the tools to deal with more complex analysis allow the use of more sophisticated models such as intervals, fuzzy sets and stochastic modelling, and this explains the more recent trend in processing uncertainties. Tan et al. [5.34] argue that the use of fuzzy sets are more appropriate than stochastic modelling because imprecision in LCI data is caused by ambiguity that cannot be described in probabilistic terms. Fuzzy sets are effective for quantifying imprecise language in uncertainty analysis, although they may overestimate results as correlation between variables is not considered [5.35].

Uncertainty in normative choices and model formulations may, in some cases, be more appropriate modelled using scenarios. Furthermore, if probabilities can be assigned to each scenario, nonparametric bootstrapping can be used to sample from the set of scenarios [5.16].

In a survey of quantitative approaches for propagating and analyzing uncertainty in LCEA [5.16]. most of the surveyed studies (about 67%) used stochastic modelling, in which, Monte Carlo simulation shown to be the most popular sampling approach.

Stochastic modelling is an effective method for assessing the probability outcome in LCEA [5.16]. Best performance is clearly established only by stochastic dominance, that is, when the cumulative distribution functions of alternatives do not cross. A disadvantage of the approach is

pointed out to be the amount of data needed for the characterization of uncertainty and the time needed for computation [5.34][5.17].

5.3.2. Framework to deal with uncertainties

5.3.2.1. General framework

In this dissertation, three main types of uncertainties are taken into account for the LCEA, LCCA and LCSA: (i) the uncertainty in the input data (parameter uncertainty); (ii) the uncertainty in the choices (scenario uncertainty); and (iii) the uncertainty in the mathematical models (model uncertainty). Table 5.3 presents these three types of uncertainties for the various stages of the life cycle analysis.

It is the purpose of the proposed integral methodology to analyse the uncertainties in several stages of the life cycle analysis. Moreover, the proposed methodology aims to assess the simultaneously effect of the different uncertainties listed in Table 5.3 and the propagation of uncertainty throughout the integral life cycle analysis.

Table 5.3. Types of uncertainties in life cycle analysis

Stage of analysis	Inventory stage	Impact Assessment	Normalisation	Weighting
Types of uncertainties	Uncertainty in data; Uncertainty in the choice of allocation procedure.	Parameter uncertainty in models; Space variability (in LCEA); Temporal variability (in LCEA).	Uncertainty in data (in LCEA); Uncertainty in choices (in LCEA).	Uncertainty about preferences.
Tool to deal with uncertainties	Probabilistic analysis (MCS[(1)] & LHS[(2)]) , Scenario analysis	Scenario analysis, Probabilistic analysis (MCS[(1)], LHS[(2)] & Bootstrap)	Probabilistic Analysis (MCS[(1)] & LHS[(2)])	Probabilistic Analysis (MCS[(1)] & LHS[(2)])

[(1)] Monte Carlo Simulation; [(2)] Latin-Hypercube Simulation

The techniques for quantifying uncertainty in this research work include Monte Carlo numerical techniques of simple random sampling and bootstrap analysis. Monte Carlo techniques for analysing and evaluating mathematical problems and models have become increasingly ubiquitous with the advancement of computer technology.

Monte Carlo simulation is a repeated process of generating deterministic solutions to a given problem; each solution corresponds to a set of deterministic values of the underlying random variables [5.19].

In simple random sampling Monte Carlo, the randomized variables are simply generated based on distributions. More sophisticated methods of Monte Carlo exist, such as Latin hypercube sampling and the use of Markov chains to determine the accuracy of the distributions used.

Bootstrap methods are used to determine the precision of a given set of data by generating simulated datasets of the same size as the original [5.36]. The simulated datasets can be sampled with replacement from the actual data, the resampling or non-parametric method; or sampled from a distribution fit to the data, the parametric method. A powerful application of

the bootstrap is the construction of confidence intervals for any parameter of the underlying distribution [5.37]. In this research work bootstrap will be used to construct confidence intervals for the mean of an unknown distribution using small sample sizes.

5.3.2.2. Parameter uncertainty

Parameter uncertainty can be found in all stages over the life cycle analysis, from inventory stage to weighting processes. In the inventory analysis, a large amount of data is needed. Data may be collected or measured directly for the ongoing study, or taken from literature or from available databases. In each case, the chance to introduce uncertainty in the inventory is huge. Imprecise or incomplete measurements, lack of data, geographical representation and outdated data are the main sources of uncertainty in the collected data.

In some cases, data for a same product is collected from several sources and an average of the collected data is made. In this case, the mean value is subjected to a high level of uncertainties (e.g., data for steel production from the world steel organization).

The quantification of the uncertainties is, nevertheless, another problem to be solved. Moreover, in many cases there are not enough data to make statistical studies and in this case, simplified procedures may be adopted as described in section 5.4.3.

In this framework, parameter uncertainty will be evaluated from the inventory stage to the normalisation stage of life cycle analyses. The uncertainty will be introduced by the use of probabilistic distributions assigned to main parameters.

5.3.2.3. Uncertainty in choices

As already referred, choices are unavoidable in life cycle analysis. They are needed for the selection of the functional unit, the selection of allocation procedures, the selection of the characterisation models, the selection of the normalisation and weighting values, etc. The standardization of procedures is useful for reducing uncertainty due to choices to a broadly accepted level.

In this framework, uncertainty due to choices, over the different stages of the life cycle analyses, are addressed by the use of scenario analysis and probabilistic analysis.

5.3.2.4. Model uncertainty

Model uncertainty will only be addressed in LCEA. In this case, spatially and temporally variation in emissions and characterisation factors is generally disregarded, introducing uncertainties in the models and subsequently in the results of the analysis. Another model uncertainty in LCEA is the lack of suitable characterisation factors for sum emissions.

These types of uncertainties are addressed in this thesis by means of scenario analysis together with a probabilistic analysis (Monte Carlo Simulation and Latin-Hyper cube Simulation).

5.4. LIFE CYCLE INVENTORY ANALYSIS

5.4.1. Data in relation to system boundary

Life cycle inventory analysis comprises the quantification of relevant inputs and outputs for all unit processes within the system boundary of the construction system (see Figure 5.2).

According to ISO 14040 [5.1], inventory analysis is an iterative process in which along the process of data collection, new data requirements or limitations may be identified requiring a change in the data collection procedures and in the system boundaries, so that the goal(s) of the study will still be met. Moreover, decisions regarding data to be included shall be based on sensitivity analysis to determine their significance to the results of the study [5.2].

Data quality requirements are established in ISO 14044 [5.2] to enable the goal and scope of the life cycle analysis to be met. Hence, data quality should be specified in terms of:

- the time-related coverage, as the age of data and the minimum length of time over which data should be collected;

- the geographical area from which data for unit processes should be collected to satisfy the goal of the study;

- the technology coverage: specific technology or technology mix;

- the precision of the data values for each data expressed (e.g. variance);

- the completeness, as a percentage of flow that is measured or estimated;

- the representativeness, as a qualitative assessment of the degree to which the data set reflects the true population of interest (i.e. geographical coverage, time period and technology coverage);

- consistency, as a qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis;

- reproducibility, as a qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study;

- sources of the data;

- uncertainty of the information (e.g. data, models and assumptions).

The quality of data used in this approach is further discussed in section 5.4.3.

To meet the goals of the integrated approach, economic and social data are collected in this stage together with environmental data. As referred in sub-chapter 5.1, the same system boundary shall be use for the evaluation of environmental, economical and social criteria. However, in spite of the previous condition, the unit processes considered for the evaluation of environmental data do not have to be the same as for the evaluation of economical data or social data. For instance, considering the production of a composite material, the quantification of environmental data takes into account all the environmental burdens due to the production of the material and all the upstream burdens (e.g. production of the raw materials, transportation, etc.). However, in a LCCA, considering the cost of a composite material at the

level of the material manufacturer (price 1 in Figure 5.6), it includes the costs of all upstream processes necessary for the its production. Therefore, in this case, the cost of the composite material provides a measure of the aggregated upstream costs.

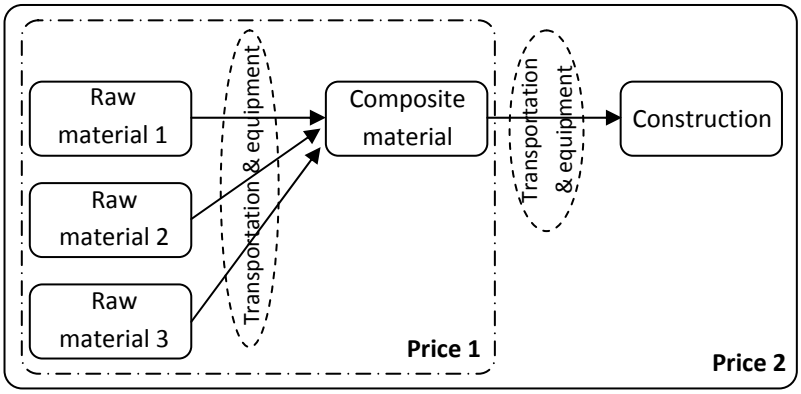


Figure 5.6. Aggregation of unit processes for LCCA

Moreover, considering the cost at the level of the product user (price 2 in Figure 5.6) then this composite price usually includes the production of material(s), the use of equipment, the man-power and eventually the cost of transportation from the production site to the construction site. Therefore, in general, for construction materials and for LCCA the unit processes of "raw material production" and "construction" in Figure 5.2 may be aggregated, without violating the condition of using the same system boundary of the other life cycle analysis.

5.4.1.1. Cut-off rules

In a life cycle analysis cut-off rules are necessary in order to make life cycle analysis possible. Without them, the whole world needs to be considered due to relations between unit processes and flows. According to ISO 14044 [5.2], cut-off rules may be based on: (i) mass, (ii) energy and (iii) environmental significance. Extending this rule to economical and social analysis then cost and social significance may also be included.

Often data for an unit process is not available. Therefore, the lack of information in relation to a unit process may also be a cut-off rule. However, in this case, data from a similar unit process can be adopted to fill the gap. Naturally, this should be acknowledged and taken into consideration in the results of the analysis.

5.4.1.2. Capital equipment

The energy and resources that are required to build construction equipment and the cost of using the equipment should be considered in life cycle analysis. In relation to life cycle cost analysis, the cost of equipment is usually included in the composite prices of materials (as referred before) or provided as individual items in the bill of quantities.

For the environmental analysis, the problem is more complex. However, for most systems, capital expenditures are allocated to a large number of products manufactured during the lifetime of the equipment. Therefore, the resource use and environmental effluents produced are usually small when attributed to the system of interest. The energy and emissions involved with capital equipment can be excluded when the manufacture of the item itself accounts for a minor fraction of the total product output over the life of the equipment [5.38].

Currently, environmental data in relation to the fabrication of construction equipment is seldom available. Thus, capital equipment will not be considered in the LCEA.

5.4.1.3. Data Sources

The collection of data for life cycle analysis is usually acknowledged as one of the most difficult and time consuming tasks. The main reason for this is the amount of data needed and the availability of such data. According to the framework introduced in this chapter, three main categories of data are needed in order to estimate the environmental, economical and social performances of the a product system.

The current trend in the practice of life cycle environmental analysis led to an increasing number of available databases. Thus, for LCEA, a list of available Life Cycle Inventory (LCI) databases around the world (including public and private, or restricted-access, databases) is provided in [5.39]. In relation of LCCA and LCSA, the problem is more complicated. The creation of databases implies a generic data format, which in case of LCCA and LCSA does not currently exist. The requirements of the data for LCCA and LCSA are very much dependent of the goal and scope of the analysis.

A summary of some environmental databases related with construction materials and processes is indicated in Table 5.4.

Table 5.4. Summary of environmental databases for construction

Name of database	Contents	Geographic coverage	Date of last update
World steel Life Cycle Inventory [5.40]	Long steel products (sections, rebar, engineering steel), Flat steel products (plate, hot rolled coil, cold rolled coil	Europe, East Asia, Canada, Czech Rep., Slovak Rep., Turkey, South Africa, Mexico, US	2010
Life Cycle Inventory of Portland Cement Concrete [5.41]	Ready mixed concrete, Concrete masonry units, Precast concrete	US	2006
ETH-ESU 96 libraries [5.42]	Focus on energy (data on electricity generation and related processes like transport, processing and waste treatment)	Western Europe	1996
Ecoinvent [5.42]	Energy , Transport, Building Materials, Chemicals, Washing agents, Paper & board, Agriculture, Waste Management	Switzerland/Europe/ Global	2010
Franklin US [5.42]	Energy, transport, steel, plastics and processing	US	1998
BEES Database [5.43]	Building construction materials and processes	US	2007
IVAM LCA Data [5.44]	Materials, transport, energy and waste treatments	Netherlands	2005
IDEMAT [5.42]	Materials (metals, alloys, plastics, wood), energy and transport	Western Europe	2001
US LCI Database [5.45]	Transportation, metals, wood, energy, waste management	US	2008
European Reference Life Cycle Data (ELCD) System [5.46]	Materials, energy carriers, transport, end-of-life treatment, systems	Europe	2005

Two of the most common materials used for bridge construction are concrete and steel. For this reason in section 5.4.3 a special focus will be given to the data used for these two materials. In addition, an introduction to the database used for other construction materials is also provided.

5.4.2. Allocation

5.4.2.1. Introduction

Most industrial processes are multifunctional, i.e., their output entails more than one product and the inputs for the production of products often include intermediate or discarded products. An allocation problem occurs when an appropriate decision is needed in order to allocate the input/output flows to the functional unit provided by the product system under study.

Allocation in defined in ISO 14040 [5.1] as "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product system". An allocation process addresses the partition of flows between unit processes or product systems.

According to ISO 14044 [5.2], allocation should be avoided either by dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes or by expanding the product system to include the additional functions related to the co-products (system expansion). Dividing unit processes helps to reduce the relevance of the allocation problem by further refining the multifunctional process and by setting the system boundaries; while, by expanding the product system, allocation may be avoided by redefining the functional unit and system boundaries [5.47]. System expansion includes the avoided burden approach, which eliminates surplus-functions from the multifunctional process by subtracting equivalent mono-functional processes to obtain a mono-functional process.

When neither subdivision of processes nor system expansion are feasible for the scope and goal of the study, then allocation is unavoidable. In this case, one of two alternatives is recommended by ISO 14044 [5.2]. In the first alternative, the partition of inputs and outputs of the system is based on physical (or chemical or biological) causal relationships. When a physical relationship cannot be established, the second alternative prescribes allocation based on other relationships (e.g. economic value of the products).

Reuse and recycling of construction materials is a very important issue in the pursuit of sustainable construction, as referred in the previous chapters. The consideration of reuse and recycling within Life Cycle Assessment is a multi-functionality issue, implying the use of allocation processes. The allocation principles and procedures mentioned above also apply to recycling and reuse situations, although in this case, the changes in the inherent properties of materials shall be taken into consideration when choosing the allocation procedure to be used [5.2]. In this case, three main situations may occur [5.47]:

i) the material's inherent properties are not changed over the considered product system and the material is to be reused in the same application;

ii) the material's inherent properties are changed over the considered product system and the material is to be reused in the same application;

iii) the material's inherent properties are changed over the considered product system and the material is to be used in other applications.

In the first case, there is a closed-loop situation in which the substitution of primary material is assumed to be complete and therefore, no environmental burdens from primary material production or final disposal are allocated to the product system. The second case corresponds to an open-loop approach assuming a closed-loop situation. In this case, the changed material properties are considered irrelevant and recycling is addressed as a closed-loop situation. Finally, in the last case, there is an open-loop situation where the substitution of primary material is assumed to be partial. In this case, environmental burdens due to primary material production or final disposal have to be partially allocated to the system under study.

According to ISO 14044 [5.2], in the case of a closed-loop situation allocation is avoided since the use of secondary material replaces the use of virgin materials.

In an open-loop situation the allocation may be based in one of the following parameters [5.2]: physical properties (e.g. mass, resistance, etc), economic value (e.g. market price of the recycled material) and the number of subsequent uses of the recycled material.

Allocation procedures for open-loop recycling are exemplified in following sub-section.

5.4.2.2. Allocation procedures for open-loop recycling

Modelling open-loop recycling is a problem of where the system boundaries are set. A recycling process can be both a waste treatment and a secondary material production. Hence, the impacts of recycling are attributable to at least two product systems in sequence: product system 1, the system providing the recycling material; and product system 2, the system receiving the recycling material. Three possible locations for setting system boundaries can be distinguished [5.47]:

i) after the use phase/after demolition and before recycling (line 1 in Figure 5.7);

ii) during the recycling process (line 2 in Figure 5.7);

iii) after reprocessing the material before the production of intermediate products (line 3 in Figure 5.7).

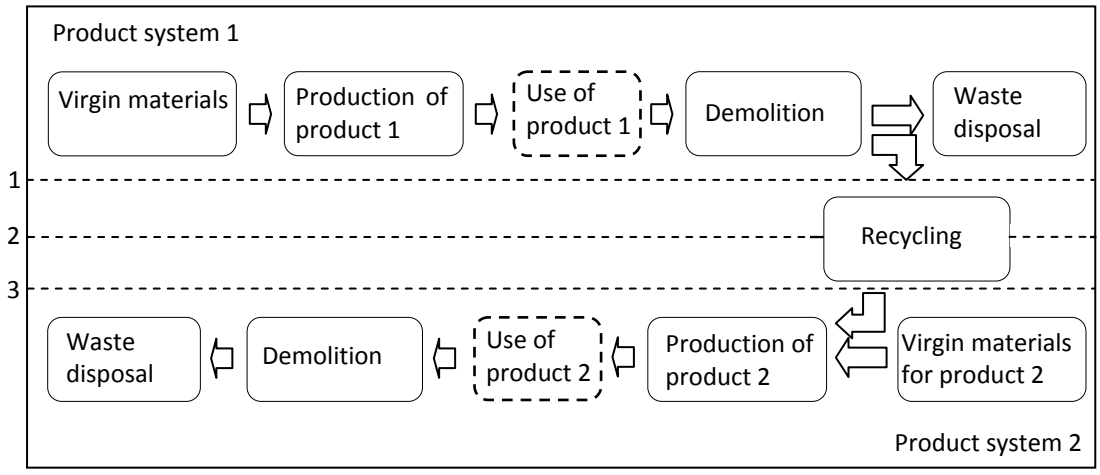


Figure 5.7. Open-loop recycling

Werner [5.47] argues that in the case of a recycling process, the attribution criteria stated in ISO standard 14044 [5.2] are not enough for decisions regarding the setting of the system boundaries. In this case, a third criterion has to be applied: "the range of the decision-maker's responsibility defining the life cycle steps and processes that the decision-maker feels responsible". Furthermore, the range of responsibility should be chosen so that LCA supports best decision-making according to the general and material specific management rules for sustainable development.

Independently of the allocation procedure, it should be kept in mind that a recycling process is not free of burdens and the efficiency of the recycling process depends of the material being processed [5.48]. Therefore, first it is necessary to quantify the benefits and burdens in relation to the whole recycling process. The benefits of recycling a material are: (i) the decrease of the amount of solid waste sent to landfill (C_1), and (ii) the safeguard of raw materials necessary to produce virgin materials (C_2). The recycling process itself and the production of the new material from the recycled material, including transportation, are burdens that need also to be considered (*D*). In relation to Figure 5.7, considering all the burdens associated with the life-cycle of product 1 (*A*), from its production from virgin raw material to its disposal, and all the burdens associated with the life-cycle of product 2 (*B*), from its production from virgin raw material to its disposal, then all the net inputs and outputs associated with the system $N_{I/0}$ may be expressed by the following expression [5.49]:

$$N_{I/0} = A + B - RR \times C_1 - Y \times RR \times C_2 + RR \times D + E \tag{5.1}$$

where, RR is the recycling rate of product 1, Y represents the efficiency of the recycling process and E represents any inputs and outputs due to the fact that product 2 is made of recycled materials instead of virgin materials. Expression (5.1) represents all credits and debits given to the system that produces the recycling material (product system 1) and to the system receiving the recycled material (product system 2) (see Figure 5.7). The differences among allocation procedures regards the way credits and debits are allocated between the two systems.

Over the next paragraphs three of the most popular allocation procedures are described, considering two product systems in a sequence, as illustrated in Figure 5.7. Many other allocation approaches for open-loop recycling have been proposed by several authors [5.47][5.50][5.51][5.48][5.52].

The choice of the most appropriate approach in regard of life cycle analysis of construction systems will not be discussed here as it depends on the type of material(s) involved; therefore, this issue will be further developed in section 5.4.3.

5.4.2.2.1. Cut-off rule

The cut-off procedure is one of the most traditional allocation procedures for reuse and recycling. It is usually the procedure adopted in LCA softwares (e.g. SimaPro). This procedure is based on the assumption that each product system should be assigned with the impacts directly caused by that system [5.53]. Hence, considering the two product systems in Figure 5.7, the environmental burdens of all stages from raw material extraction to the disposal of non-recyclable wastes are included in product system 1, while the environmental burdens of

collecting and recycling are considered burdens to the next product system (product system 2). The expressions for the net input and output for the two systems are given by [5.53]:

$$N_{i/o}(\text{Product } 1) = A - RR \times C_1 \tag{5.2}$$

$$N_{i/o}(\text{Product } 2) = B - Y \times RR \times C_2 + RR \times D + E \tag{5.3}$$

The cut-off method is easily applied and due to its conservative nature it allows estimating the relative importance of an alternative allocation method [5.54]. Another advantage of this procedure is that by allocating the impacts of the upgrading activities to the new product (product 2), the uncertainty associated with future recycling or reuse technologies is reduced.

The main drawback of the method is that no credits due to the safeguard of virgin raw materials are given to the system that produces the recycling material. In this regard, no incentives are given to the party that makes the effort to promote the use of materials with recycling potential. Also, the quality of the secondary material at the end of the life cycle is neglected [5.54].

5.4.2.2.2. The partition rule

This allocation procedure is based on assigning an arbitrary ratio between the two systems (e.g. 100:0, 0:100 or 50:50). The most popular method is the 50:50 rule, in which environmental interventions caused or omitted by recycling are equally distributed by product system 1 and product system 2. In this case, the inputs and outputs for each system are calculated according to the following expressions [5.49]:

$$N_{I/0}(product\ \ 1) = A - 50\% \times [RR \times C_1 + Y \times RR \times C_2 - RR \times D - E] \tag{5.4}$$

$$N_{I/0}(product\ \ 2) = B - 50\% \times [RR \times C_1 + Y \times RR \times C_2 - RR \times D - E] \tag{5.5}$$

This approach is based on the assumption that both products systems are equally necessary to enable recycling [5.47]. According to Klöpffer [5.48] the main advantages of this procedure is that it avoids double counting of burdens related to recycling and it provides an equal incentive for producers and users of secondary raw materials.

5.4.2.2.3. Economic allocation

Economic allocation is based on the primary assumption that market prices depict the qualitative degradation of a material over a product system [5.54][5.55]. According to this procedure, the environmental burdens of primary and secondary materials are weighted according to their price relation. Economic allocation is advised in the handbook on LCA [5.51] as the baseline method for most allocation situations in a detailed life cycle analysis.

Borg et al. [5.55] proposed an economic allocation procedure for building-related LCA based on the additional following assumptions:

i) the system producing the recycling material (product system 1) has to take responsibility for the upgrading of the recycled material to the required level;

ii) only loads corresponding to the recycling fraction (*RF*) are allocated to the system receiving the recycling material (product system 2);

iii) the recyclability of the building material , i.e. the potential recycled content of the material based on its characteristics in combination with the context the material is built into, is expressed by a design factor.

According to this principles, a part of the burdens due to primary production is allocated to the system receiving the secondary material, while the environmental loads due to the recycling and upgrading processes are allocated to the primary system. Hence, following the terminology used in expression (5.1), and considering the market price of primary material (*€PM*) and the market price of secondary material (*€SM*), the inputs and outputs for both product systems are given by [5.55]:

$$N_{I/0}(\text{Product } 1) = A - RF \times C_1 - (€SM/€PM) \times [RF \times C_2] + RF \times D + E \tag{5.6}$$

$$N_{I/0}(\text{Product } 2) = (1 - RF) \times B + (€SM/€PM) \times [RF \times C_2] - RF \times D - E \tag{5.7}$$

where, the relation (*€SM/€PM*) represents the quality reduction of the material between product system 1 and product system 2. Furthermore, to be a fair procedure, the primary and secondary materials are compared on an equivalent level in the upgrading system [5.55]. This is particularly important in the case of secondary materials with different market values according to its upgrading level.

In this approach a design factor is proposed to take into account the potential losses in the recyclable material due to its application in the construction system, its use and its demolition. This factor is an approximation of the recyclable fraction (*RF*) used in expressions (5.6) and (5.7).

The same method is applied in the case of a new product (P_2) made from recycling material (RM_1) from product P_1 that is further recycled into a new product (P_3), see Figure 5.8. In this case, there's an exchange of loads between the product system under study and the previous and the following product system [5.55].

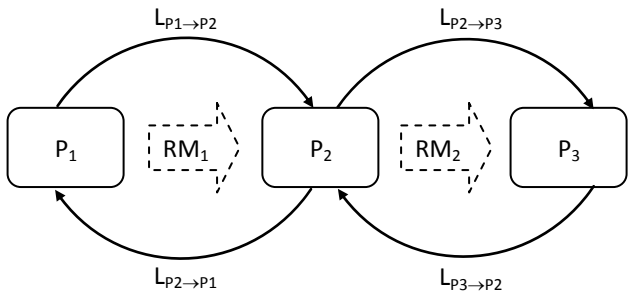


Figure 5.8. Allocation between different product cycles (adapted from [5.55])

Thus, considering the product system P_2, the system receives a share of the environmental loads from P_1 caused by virgin production ($L_{P1\to P2}$), but may also be released of a share of the environmental loads from the upgrading and recycling process of material RM_1 ($L_{P2\to P1}$). In the same way, considering the recycling of material RM_2, then product system P_2 may allocate part of the received load from virgin production to product P_3 ($L_{P2\to P3}$), and, at the same time, receive a load due to the upgrading process of secondary material RM_2 ($L_{P3\to P2}$).

The total loads allocated to product system P_2 are therefore [5.55]:

$$L_{Allocated \rightarrow P2} = L_{P1 \rightarrow P2} - L_{P2 \rightarrow P1} + L_{P3 \rightarrow P2} - L_{P2 \rightarrow P3} \tag{5.8}$$

Hence, considering the market prices of secondary materials RM_1 and RM_2, respectively $€SM_{RM1}$ and $€SM_{RM2}$, and the market price of primary material (€PM),

$$L_{Allocated \rightarrow P2} = (1 - RF) \times C_2 \times \left(\frac{€SM_{RM1} - RF \times €SM_{RM2}}{€PM} \right) + RF \times D_{RM2} - D_{RM1} \tag{5.9}$$

where, RF is the recycling fraction of material RM_2 (to account from losses in the recycling process), C_2 is the load due to the production of material from virgin raw materials, and D_{RM1} and D_{RM2} are the loads relating to the upgrading and recycling processes of secondary materials RM_1 and RM_2, respectively.

In case the material RM_1 is recycled into material RM_2 with the same quality or value ($€SM_{RM1}$ = $€SM_{RM2}$ = $€SM$), and assuming the impacts from the recycling processes are also the same (D_{RM1} = D_{RM2} = D), then from the previous expression:

$$L_{Allocated \rightarrow P2} = (1 - RF) \times C_2 \times \left(\frac{€SM}{€PM} \right) - (1 - RF) \times D \tag{5.10}$$

This allocation procedure assumes that there is a stable price relation between primary and secondary materials [5.54]. This represents a major drawback in the case of secondary materials with emerging recycling markets or with no prices on which to base allocation [5.51].

5.4.2.2.4. Remarks regarding the choice of the allocation procedure

Recycling plays a very important role in the pursuit of the aims of Sustainable Development in the construction sector. However, as illustrated in the previous paragraphs, there is much freedom left to the LCA practitioner regarding the choice of the allocation procedure to be used in the case of open-loop recycling.

Some criteria, in which allocation methods should be based, are suggested by Klopffer [5.48]: (i) mathematical balance, avoiding double counting; (ii) justice and incentive for both producers and users of secondary materials; and (iii) feasibility within the framework of a LCA.

Ekvall and Tillman [5.53] added that the choice of the open-loop allocation procedure should be consistent with the goal of the study. Moreover, the choice should reflect the characteristics of the studied system and the context of the allocation [5.55].

For instance, in the case of consequential LCAs (see sub-chapter 3.2 for distinction between LCA types), open-loop recycling may have important consequences for the environmental burdens of activities outside the life-cycle of the product; for instance, the reaction of the market for a recycled material due to a change in the supply/demand for the recycled material [5.50][5.56]. Ekvall [5.50] suggests to model these effects through system expansion, in order to include the activities that are affected, and to model the way markets react to changes by determining the price elasticity (i.e. relation between the price and quantities of a product being traded in the market and the corresponding change in the quantity supplied or demanded caused by a change of its price) of the products involved. However, since most activities are interrelated in the global technological system, it makes it difficult to identify which activities are significantly affected by

any change. To overcome this problem, Vieira and Horvath [5.56] proposed the use of a hybrid LCA (combination the LCA process-based and LCA economic I/O – based), to eliminate the burden of modelling individually all the economic sectors affected by changes in the construction industry. This approach was applied to a case study comparing the attributional and consequential LCA of the end-of-life impacts of a concrete building. However, they've concluded that no significant differences were obtained between the two analysis and the choice between the use of one or the other approach for buildings was not a critical point.

In this dissertation, open-loop recycling is dealt within the level of the product life cycle, and although in the decision making perspective, changes or alternatives in the system are taken into account, no consequences outside the systems are considered. Therefore, the approaches referred in the above paragraph will not be further discussed in this text.

5.4.2.3. Allocation procedures in construction-related LCA

5.4.2.3.1. Time allocation

An allocation procedure implies a trade-off between current and future impacts. This can be a critical issue, particularly in the case of construction systems with long lifetime spans [5.56]. By assigning credits to the use of materials with recycling content or reusing potential in a design of a construction system it is assumed that at the end-of-life stage they will effectively be recycled or reused. This may lead to bias results as in fact the recycling or reuse may not happen and even if it happens the changes in future technologies may give completely different impacts when compared with current technologies. To value impacts differently at different points in time by discounting is an issue of great controversy in LCA [5.57][5.58]. Applying temporal cut-offs is a special case of discounting, in which a discount rate of zero is applied for the time horizon considered and a discount rate of infinity thereafter, and it is a procedure often proposed to deal with long-term landfill emissions [5.59].

Vieira and Horvath [5.56] proposed a discounting approach by allocating the impacts of the upgrading activities to the secondary product and the impacts of end-of-life activities to the primary product; thus avoiding the need for forecasting the technologies that could be used for recycling or reuse.

On the other end, Borg et al. [5.55] allocated the burdens of upgrading activities to the primary system. The allocation of burdens is based on the price relation between recycled materials and new materials. Due to the difficulty in predicting these values at the time of the recycling process, they proposed to use, as a best estimate, the price relation of today. This proposal is based on the assumption that a relative increase in the price of virgin materials leads to a relative increase in the price of recycled materials, thus keeping a constant relation. Moreover, they proposed also to use the values of today in relation to the environmental loads, thus avoiding the need to predict historical (when receiving environmental loads from the past) and future data (when allocating loads forwards) of recycling processes. This implies a "load trade" between the producers of primary and secondary materials in the same time period. The main drawbacks of this approach are the assumptions of a constant relation in the market prices and a constant relation between the amount of primary and secondary material production over time.

5.4.2.3.2. Design for deconstruction

Although many construction materials are recognized for having a high recycling content, the way they are placed or used in the construction system makes it difficult to take advantage of their recycling potential. For instance, plaster boards can be recycled; however the recycling rate of plaster boards in a building is very much dependent of the way they are accessible during the demolition of the building.

Morgan and Stevenson [5.60] claimed that usually only a small fraction of construction elements are reclaimed and reused for their original purpose. Thus, the solution for reducing construction waste is to reduce it at its source.

Deconstruction is a process of selectively and systematically dismantling buildings or other construction systems to reduce the amount of waste created and generate a supply of high value secondary materials that are suitable for reuse and recycling [5.61].

Thus, designing details for deconstruction at the start of a project enables a construction system, at the end of its useful lifespan, to be the resource for the next and helps closing the loop for resource use. This aspect should be taken into account in the allocation procedure selected for the life cycle analysis of a construction system, as it affects the fraction of materials that can be recycled, in spite of its potential for recycling. This problem was addressed by Borg et al. [5.55] by the use of a design factor expressing the ability of a material incorporated in a building to be recycled at the end of its useful lifespan.

This issue is particularly important for buildings, which are structures usually composed of several kinds of materials and complex assemblages; for bridges, the way they are assembled and the lesser complexity of this kind of structure enable an easier disassembling.

5.4.2.3.3. Sustainable management rules of construction and demolition waste

In the perspective of sustainable construction two of the major problems in the construction sector, as referred in Chapter 1, are the depletion of natural resources and the production of construction and demolition waste. In general, a recycling process contributes to a more sustainable construction as it allows to reduce both problems.

In fact, as discussed in Chapter 2, current European policies for waste management promote the recycling of construction and demolition waste and its use as a resource in new material. The waste hierarchy established by the European Directive for waste management (see Chapter 2) clearly prioritizes reusing and recycling of materials over land filling. Moreover, the polluter-pays principle, laid down by the Directive, enhances the producer responsibility in order to support the design and production of goods taking into account the efficiency use of resources during their whole life-cycle including their repair, re-use, disassembly and recycling.

Therefore, the way construction and demolition waste is managed is very important in the context of sustainable construction. The allocation of impacts due to construction and demolition waste should address this problem and, furthermore, should reflect the use of good practices in regard of waste management.

5.4.3. Data Collection

5.4.3.1. General data for construction materials and processes

In this dissertation, the main sources of data are indicated in Table 5.5. In the following text, more detailed information about the sources of environmental data will be provided.

Table 5.5. Sources of data for environmental, economical and social analysis

Environmental data	Economic data	Social data
Public databases (mainly for materials); Site-specific measured or calculated data (for some processes); Literature sources.	Data from design project; Data from construction site; Literature sources.	Data from motorway concessionaire; Public statistics; Site-specific calculated data; Literature sources.

The sources of data for economical and social analysis will be further referred in the case studies, as data were collected specifically for them.

5.4.3.2. Environmental data

The database that is going to be used for the collection of environmental data for general construction materials and processes is Ecoinvent v2.1 [5.62]. The Ecoinvent database was developed by the Swiss Centre for Life Cycle Inventories and it provides generic LCI data for construction material production and related processes. The geographical scope of the data is Switzerland or Europe and the reference year is 2000, although in 2004 some processes were reviewed and a few other were added.

5.4.3.2.1. Waste disposal of construction materials

The Ecoinvent database [5.62] provides data for three disposal options: (i) direct recycling (path 1 in Figure 5.9), (ii) recycling after sorting (path 2 in Figure 5.9), and (iii) direct final disposal without sorting (path 3 in Figure 5.9). However, for the recycling process a cut-off rule is used: only the burdens of the processes inside the dashed box in Figure 5.9 are considered in each case. Thus, option (i) includes only the burdens from dismantling, whilst option (ii) includes dismantling, the sorting plant process and the final disposal of non-recycled fractions. The last option, (iii), comprehends dismantling and final disposal of all waste materials.

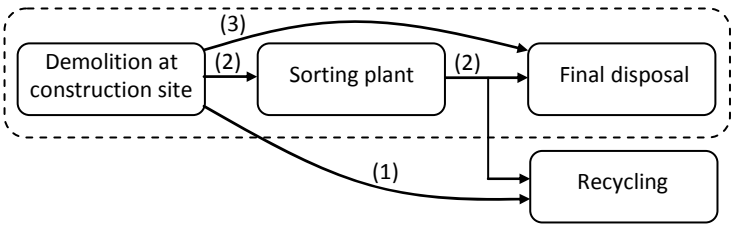


Figure 5.9. Disposal options in the Ecoinvent database (adapted from [5.62])

Waste materials can be sent to an inert material landfill or to a sanitary landfill. For the inert material landfill no landfill emissions are inventoried, since they are considered to be negligible.

5.4.3.2.2. Uncertainties in data

In the Ecoinvent database all inputs and outputs are described by single figures. Different types of uncertainties are present in a LCI process. In Ecoinvent, to take into account the variability and parameter uncertainty in the inputs and outputs due, for instance, to measurement uncertainties, process specific variations, temporal variation, etc, a probabilistic characterization of these values is provided. Thus, a lognormal distribution is attributed to each parameter and the single figure referred above represents the corresponding mean value.

In cases where enough samples are available, uncertainty distribution and standard deviation are determined by statistical methods; however, this is not always the case. Very often the source of information is very limited. In case where there's only one source of information, only the mean value is obtained without any knowledge about its uncertainty. To overcome this problem, in Ecoinvent, a simplified procedure was adopted to quantify the uncertainty for these cases. This simplified approach entails a qualitative assessment of data quality indicators based on a pedigree matrix developed by Weidema and Wesnaes [5.21]. Therefore, data sources are assessed according to six data quality indicators of "reliability", "completeness", "temporal correlation", "geographic correlation", "further technological correlation" and "sample size".

The indicator of reliability relates to the sources, acquisition methods and verification procedures used to obtain the data (e.g., data based on measurements, data based on assumptions, etc) . The indicator of completeness aims to assess the statistical properties of the data (e.g., size of the sample, representative of the sample, etc). The temporal and geographical correlation indicators represent, respectively, the time correlation between the year of the study and the year when the data was obtained and the geographical correlation between the defined area of the study and the area related to the obtained data. The indicator further technological correlation represents all other aspects of correlation not covered in temporal and geographical, such as the relation between the processes, technology used, materials, etc, under study and the corresponding processes, technology used, materials, etc, of the collected data. Finally, the indicator sample size relates to a specific characteristic of the statistical data: the sample size behind the figure reported in the information source.

Each indicator is divided into five quality levels (scored from 1 to 5) and hence, a set of six indicator scores is attributed to each input and output flow in ecoinvent. Furthermore, an uncertainty factor (expressed as a contribution to the square of the geometric standard deviation) is attributed to each of the score of the six indicators. These factors were determined based on expert judgements and are represented in Table 5.6 [5.63].

Table 5.6. Uncertainties factors applied in conjunction with the pedigree matrix [5.63]

Indicator score	1	2	3	4	5
Reliability	1.00	1.05	1.10	1.20	1.50
Completeness	1.00	1.02	1.05	1.10	1.20
Temporal correlation	1.00	1.03	1.10	1.20	1.50
Geographical correlation	1.00	1.01	1.02	-	1.10
Further technological correlation	1.00	-	1.20	1.50	2.00
Sample size	1.00	1.02	1.05	1.10	1.20

The square of the geometric standard deviation is calculated according to the following expression:

$$SD_{g95} = \exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_b)]^2}} \quad (5.11)$$

where, U_1, U_2, U_3, U_4, U_5 and U_6 are the uncertainty factors of reliability, completeness, temporal correlation, geographic correlation, other technological correlation and sample size, respectively; and U_b is a basic uncertainty factor that is emission specific.

Basic uncertainty factors (U_b) are specific for the input and output considered. Table 5.7 indicates some examples of this kind of factors [5.63] applied for technosphere inputs and outputs. These factors are also based on expert judgements.

Table 5.7. Examples of basic uncertainty factors [5.63]

Input/output	c (*)	p (*)	a (*)
Resources			
Prim. energy carriers, metals, salts	1.05	1.05	1.05
Land use, occupation	1.50	1.50	1.50
Land use, transformation	2.00	2.00	2.00
Pollutants emitted to air:			
CO_2	1.05	1.05	
SO_2	1.05		
NMVOC total	1.50		
NO_x, N_2O	1.50		1.40
CH_4, NH_3	1.50		1.20
Individual hydrocarbons	1.50	2.00	
PM>10	1.50	1.50	
PM10	2.00	2.00	
PM2.5	3.00	3.00	
PAH	3.00		
CO, heavy metals	5.00		
Inorganic emissions, others		1.50	
Radionuclides		3.00	
Pollutants emitted to water:			
BOD, COD, DOC, TOC, inorganic compounds		1.50	
Individual hydrocarbons, PAH		3.00	
Heavy metals		5.00	1.80
Pesticides			1.50
NO_3, PO_4			1.50
Pollutants emitted to soil:			
Oil, hydrocarbon total		1.50	
Heavy metals		1.50	1.50
Pesticides			1.20
Demand of:			
Thermal energy, electricity, semi-finished products, working material, waste treatment	1.05	1.05	1.05
Transport services	2.00	2.00	2.00
Infrastructure	3.00	3.00	3.00

(*) c: combustion emissions; p: process emissions; a: agricultural emissions

5.4.3.3. Data for steel

5.4.3.3.1. Steel production

In this work data for steel production is gathered from the database of the World Steel organization [5.41]. The reason for this choice is mainly the availability of detailed information regarding the contents of the database. The LCI study was undertaken according to ISO 14040 series of standards and it has undergone a critical review from an independent panel of specialists. This database was last updated in 2010; the reference year for the data is for 2005 to 2007, depending on each company providing data. Some upstream data is based on 2008 data.

Data for the inventory study was collected from companies around the world: western Europe (EU-15), Asia (Japan, Korea and Taiwan) and rest-of-the-world (Canada, Czech Republic, Slovak Republic, Turkey, Mexico, South Africa and US). The companies included in the study account for about 39.7% of global steel production and the contributing sites are among the largest of the principal producer countries. Inventory data was calculated for each site and the resulting values average across the contributing sites.

The two major routes to produce steel are the Blast Furnace (BF) and the Electric Arc Furnace (EAF). The main difference between these two routes is the input of virgin materials into the production process. The BF route is primary ore based with up to 25% scrap input, while the EAF route is mainly a 100% scrap based steelmaking process. Both routes cast products that feed into hot and cold rolling processes. The database provides data for both processes depending of the type of product. Data available for flat products are from the BF route whilst for long products there are data available from both routes. This is due to the fact that by the time data was collected flat products were mainly produced from the BF route and thus no significant data for flat products was collected from the EAF route.

The LCI study includes all significant inputs and outputs from the steel production route and provides data for fourteen steel products including hot rolled coil, cold rolled coil, hot dip and electrically galvanized sheet, painted sheet, tinplate and tin-free sheet, tubes, sections, plate, rebar/wire rod, and engineering steels. The functional unit of the study is one kilogram of steel at the factory gate. The system boundary, illustrated in Figure 5.10, includes all production stages from raw material acquisition to finished products ready to be shipped from the steelworks (“cradle to gate” approach). It also includes the production and transportation of raw materials, energy sources and consumables used on the steelworks. It does not include the manufactured of downstream products, their use and end-of-life treatment.

The following cut-off criteria were set out in this study: (i) at least 99% of material inputs to each process were included; (ii) all non-mass inputs were recorded (including energy carriers and water); and (iii) wastes with less than 1% of total waste tonnage were not recorded.

The production of steel generates important quantities of valuable by-products (particularly the BF route). In this study, the allocation of by-products (except scrap) was avoided by the system expansion methodology.

This study does not include upstream data for scrap collection, sorting and processing. Also, no allocation procedure was applied to the use of scrap for reuse and recycling.

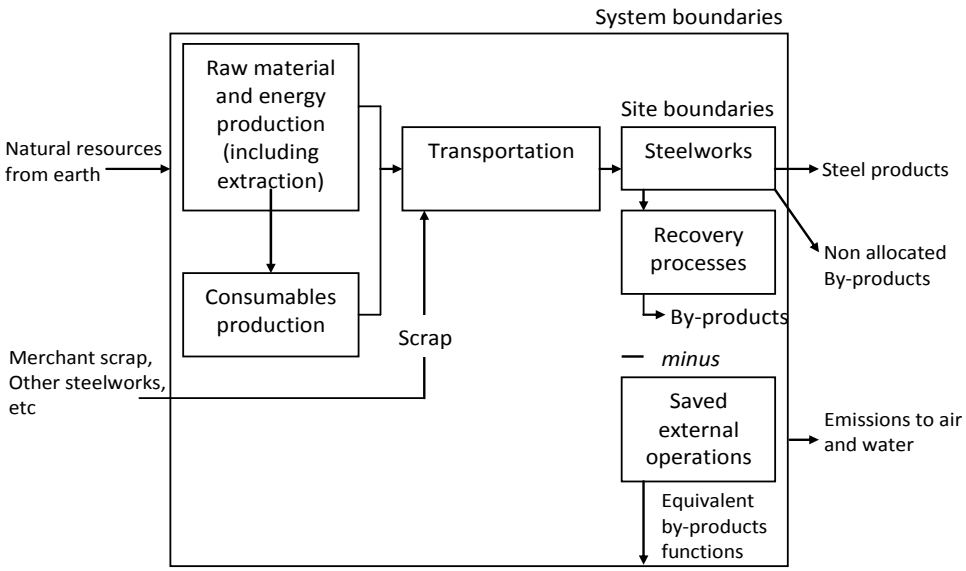


Figure 5.10. System boundary for steel production [5.41]

5.4.3.3.2. Steel fabrication

Data from the previous section regards the production of finished steel products at the gate of the factory. Downstream processes into manufactured products are not included. Some products, however, need further processing in order to be used in construction. That is the case of steel plates, which are used to fabricate I girders for bridge construction or any other applications.

In this dissertation, data for the fabrication of I girders from steel plates was obtained from a fabrication site in Portugal. Although several alternatives could have been considered for this study, it was decided to adopt the factory layout of Martifer S.A., as a representative example of a large European steelwork fabricator. Martifer S.A. is the leading Portuguese steelwork fabricator and one of the largest in Europe, with factories in Portugal and Poland, and a largely automated production line equipped with Computer Numeric Control (CNC) machines remotely fed by CNC data directly generated by the preparation office.

The main inputs and outputs relative to the fabrication of steel products are presented in Figure 5.11. The inventory of data is relative to the system boundary represented in Figure 5.11 by a dashed line. Data regarding the production of electricity in Portugal was obtained from the Ecoinvent database [5.42].

The inputs may be divided into three categories: category I corresponds to materials needed for the steel finished products such as plates, connectors and paint; category II relates to the elements used for the fabrication of the finished products such as welding consumables, steel grit and electric energy used by the machines; category III comprises the indirect elements needed for the fabrication of finished products that are part of the normal functioning of the facilities such as electric energy, gas and water. The input values are presented in Table 5.8, for the base years of 2005 and 2006.

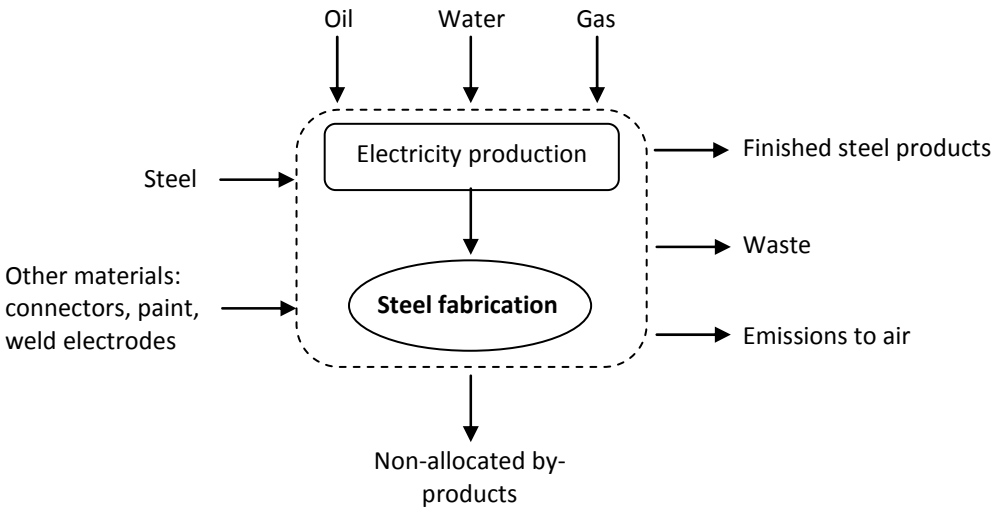


Figure 5.11. System boundary of steel factory

Table 5.8. Total inputs of steel fabrication (categories I to III)

Category I	2005	2006
Steel (tonnes)	16133	20466
Paint (liters)		228206
Category II	2005	2006
Welds (tonnes)		52
Steel grit (tonnes)		72
Category III	2005	2006
Electric energy (GWh)	2.6	3.1
Gas (tonnes)	60.8	88.2
Water (m^3)	6334	7248
Diesel (tonnes)	-	16.2

The main output is the finished steel product. Simultaneously, other outputs are produced which can be classified into four categories: category I corresponds to waste to be recycled and/or reused; category II comprises ordinary waste sent to landfill; category III includes all contaminated waste sent to landfill of dangerous waste; and category IV represents the emissions to the atmosphere. In the first category are the steel waste generated by the cutting of the plates or parts of steel profiles that are not used in the fabrication of the girders. This steel waste is sent for recycling. This category also includes steel grit used in the process of cleaning and fillings created by the cutting of the plates. The former is reused while the latter is recycled. Also the waste produced in the remaining activities in the facility, which are not directly involved in the fabrication of the girders, may be quantified and include paper, plastic and metal packages which are sent for recycling. Category II comprises the ordinary waste which does not need any special treatment and therefore is sent to a sanitary landfill. Category III involves waste with toxic content and thus it is sent to special landfills prepared to receive this kind of waste. Most of this waste is generated by the painting process. Finally in Category IV are the emissions to the atmosphere.

The output values, corresponding to the years 2005 and 2006, are presented in Table 5.9 and Table 5.10, respectively for categories I, II and II and IV. In what concerns emissions, Martifer does not have permanent measurement of daily emissions.

Table 5.9. Total outputs of steel fabrication (categories I, II and III)

Category I (ton)	2005	2006
Scrap	1332.70	1961.80
Grit	117.7	108.26
Metal packaging	20.8	17.02
Filings	56.4	43.34
Paper	9.30	8.67
Plastic	3.40	3.34
Glass	-	1.24
Category II (ton)	2005	2006
Ordinary waste	96.50	139.62
Category III (ton)	2005	2006
Contaminated waste	159.20	98.15

The frequency of the measurements depends on the maximum values obtained, according to Portuguese standards. In the case of Martifer, as the values obtained are small, usually two series of measurements are made every two or three years, depending of the sector being measured. The cumulative value of emissions per year is thus estimated by the average daily emissions per hour and by the total number of hours of fabrication in each sector.

Table 5.10. Total outputs of steel fabrication (category IV)

Category IV (ton)	2005 (I)	2005 (II)	2005 (I + II)/2	2006
VOC	4.232	13.959	9.095	-
PM	1.816	1.822	1.819	1.42
CO	0.004	0.002	0.003	-
NOx	0.290	0.536	0.413	-
Cd	-	0.001	0.001	-
Ni-As	-	0.003	0.003	-
Cr-Cu-Pb	-	0.017	0.017	-

In 2005, 16133 tonnes of steel (see Table 5.9) were necessary to fabricate 14 800 tonnes of steel finished products, while in 2006, 20 466 tonnes of steel were necessary to fabricate 18 504 tonnes of steel finished products. Thus, every year, approximately 10% of the steel entering the factory results in scrap, which is then sent for recycling.

The measurements obtained in Martifer are very limited; however, for the sake of completeness, it is better to include this process in the life cycle of steel, than simply to neglect it. The relative importance of steel fabrication in the life cycle of steel, from raw material production to the gate of the factory, is illustrated in Box 5.1, considering the fabrication of 1 kg of steel in relation to the production of steel plate girders.

Box 5.1. Contribution of steel fabrication to the cradle-to-gate analysis of steel

Figure 5.12 illustrates the complete system boundary for the fabrication of 1kg of steel girders ready to be transported for the construction site. It comprises four major processes: (i) steel production in a steel plant (including the transportation of raw materials); (iii) transportation from the steel plant to the steel workshop; and (ii) steel fabrication.

The transportation of steel from the production site to the workshop may vary. Martifer usually receives steel plates from three main sites: Luxembourg, Spain, India or China. In each case, except Spain, the transportation of steel is done by sea. From Spain, steel is transported by road. Therefore, four different scenarios for steel transportation are considered: (i) scenario 1 -

assuming that the production site is located in Luxembourg and a travelling distance, by sea, of approximately 2500 km; (ii) scenario 2 - assuming that the production site is located in India and a travelling distance, by sea, of approximately 21000 km; (iii) scenario 3 - assuming that the production site is located in China and a travelling distance, by sea, of approximately 26000 km, and (iv) scenario 4 - assuming that the production site is located in Spain and a travelling distance, by road, of approximately 700 km. When the transportation is made by sea, an additional distance by road of 60 km is included corresponding to the distance between Martifer and the nearest sea port (in Aveiro). Data for sea and road transportation of steel from the production site to the workshop, is obtained from the Ecoinvent database [5.22], considering a transoceanic tanker and a diesel-truck, respectively.

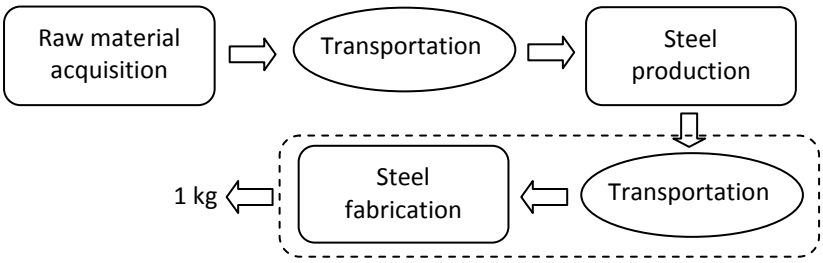


Figure 5.12. System boundary for the fabrication of 1 kg of steel ready to be transported for the construction site

For the fabrication of 1 kg of steel at the gate of the workshop it is necessary no produce 1.1 kg of steel. Table 5.11 indicates the amounts of some selected emissions for the production of 1.1 kg of steel, from both routes Blast Furnace and Electric Arc Furnace (85% of scrap), and the amounts of the same emissions for its fabrication according to the scenarios described.

Table 5.11. LCI data of 1 kg of plate steel at the gate of the factory

	Units	Plate prod. from BF	Plate prod. from EAF	Steel fabrication			
				Scen. 1	Scen. 2	Scen. 3	Scen. 4
Carbon Dioxide (CO_2)	kg	2.55E+00	1.32E+00	9.22E-03	3.46E-03	1.18E-02	9.17E-02
Carbon Monoxide (CO)	kg	3.20E-02	1.29E-02	3.31E-05	6.72E-05	9.00E-05	1.41E-04
Particulates	kg	1.85E-03	9.82E-04	1.37E-04	1.37E-04	1.37E-04	1.46E-04
Sulphur Oxides (SO_x as SO_2)	kg	4.01E-03	2.64E-03	1.83E-06	3.08E-06	4.48E-06	1.05E-05
Nitrogen Oxides (NO_x as NO_2)	kg	3.52E-03	2.58E-03	9.24E-05	7.21E-05	1.03E-04	3.99E-04

The last four columns in the previous table include the processes inside the dashed box in Figure 5.12, while the first two columns include all the remaining processes in the same figure. Scenarios 1 to 3 relate to sea transportation, and in this case, the worst scenario is scenario 3 with the longest distance. However, comparing to scenario 4, the latter presents the worst result. The comparison between scen. 3 and 4 with steel production is indicated in Table 5.12,

Table 5.12. Relation between steel fabrication and steel production

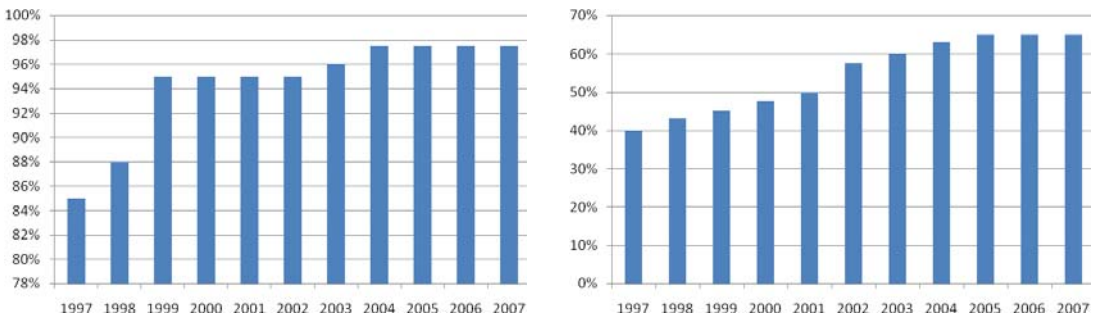
	Scen.3/prod. (BF)	Scen.3/prod. (EAF)	Scen.4/prod. (BF)	Scen.4/prod. (EAF)
Carbon Dioxide (CO_2)	0.46%	0.89%	3.59%	6.94%
Carbon Monoxide (CO)	0.28%	0.70%	0.44%	1.09%
Particulates	7.43%	14.00%	7.90%	14.88%
Sulphur Oxides (SO_x as SO_2)	0.11%	0.17%	0.26%	0.40%
Nitrogen Oxides (NO_x as NO_2)	2.93%	4.00%	11.34%	15.44%

These results, although relating only to some selected emissions, indicate that the fabrication of steel has a small contribution (less than 16% in the worst case) to the cradle-to-gate data of steel.

The conclusion of the analysis presented in Box 5.1 is corroborated by the outcome of a project [5.64] developed in Europe with the aim to collect full life cycle inventory data on steel products. In this project data was collected for 17 finished products, for each life cycle stage, downstream of steel production, in order to produce full inventory datasheets and to enable the comparison of the relative environmental importance of the different life cycles stages analyzed. In relation to the relative importance of downstream phases, the major conclusion of this study was that, for all studied products, the overall contribution of the steel production phase was dominant. In fact, in relation to energy consumption, steel production accounts for about 75% of the whole life cycle. Moreover, the study concludes that all life-cycle stages, downstream of steel production, have a relatively minor contribution (typically a few percent) to environmental impacts.

5.4.3.3.3. Steel recycling

Steel is 100% recyclable and scrap can be converted to the same quality of steel depending upon the metallurgy and recycling route [5.65]. Therefore, in the end-of-life of a steel structure, the structure is most probably dismantled and steel is sent for recycling or reusing (partially or completely). According to data from the Steel Recycling Institute [5.66], in north America, the recycling rate of structural steel is about 97.5%. Graphs represented in Figure 5.13, show the trend of the recycling rates of structural steel and reinforcement steel in the construction sector, respectively.



(a) (b)

Figure 5.13. Recycling rates of (a) structural steel and (b) reinforcement steel [5.66]

5.4.3.3.4. Avoiding scrap allocation

During the life cycle of steel, scrap arises from the manufacture phase, the final processing phase and the end-of-life phase (see Figure 5.14). Thus, an allocation procedure has to be taken into account for scrap outputs from the whole life system. Furthermore, as it was referred in paragraph 5.4.3.3.1, steel is processed via different production routes, and the allocation of scrap inputs to steelmaking is another issue to be considered.

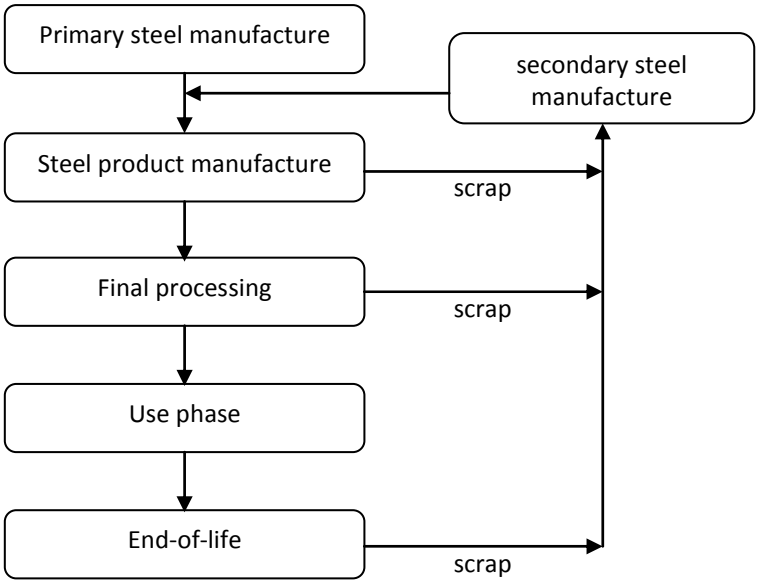


Figure 5.14. System boundary of LCI including end-of-life data on scrap [5.41]

Finally, steel can be recycled or reused many times and an appropriate allocation method is needed to address multiple recycling and reuse of steel components.

The methodology adopted in this dissertation to address the allocation problem of steel is the closed material loop recycling approach developed by the worldsteel association [5.41]. This methodology was developed in order to generate LCI data of steel products, accounting for end-of-life recycling. The adoption of a closed-loop approach is justified by the fact that scrap is re-melted to produce new steel with little or no change in its inherent properties. In this case, following the guidance of ISO standard 14044, the need for allocation is avoided since the use of secondary material replaces the use of virgin (primary) materials.

Thus, considering the two main routes for steel processing, and assuming the LCI data for steel production via the BF route (assuming 100% virgin material) given by X_{pr} and the LCI data for steel production via the EAF route (assuming 100% secondary steel) given by X_{re}, then the LCI data associated with scrap is given by expression (5.12)

$$LCI_{scrap} = Y\left(X_{pr} - X_{re}\right) \tag{5.12}$$

where, Y is the metallic yield, representing the efficiency of the secondary process in converting scarp into steel. According to the worldsteel association [5.41], about 1.05 kg of scrap is required to produce 1 kg of secondary steel.

Considering the primary route, assuming 100% input of virgin material and a recovery rate (fraction of steel recovered as scrap over the life cycle of a steel product) of RR, then, at the end of the life-cycle, the net scrap produced is given by RR. Therefore, the LCI for 1 kg of steel, including the end of life, is given by the LCI for primary manufacture with a credit for the scrap produced, as given by expression (5.13)

$$LCI = X_{pr} - RR\left[Y\left(X_{pr} - X_{re}\right)\right] \tag{5.13}$$

On the other end, assuming that 1 kg of secondary steel is used to produce new steel via the secondary route, and at the end of life RR kg of steel is recovered for recycling, then, the net scrap consumed is given by (1/Y – RR). In this case, the LCI for 1 kg of steel, including the end of life, is given by the LCI for secondary manufacture with a debit for the scrap consumed, as expressed by (5.14)

$$LCI = X_{re} + (1/Y - RR)[Y(X_{pr} - X_{re})] \tag{5.14}$$

Rearranging expression (5.13) it leads to expression (5.14), indicating that the LCI of the system does not depend upon the source of the material. It depends on the recycling ratio of steel at the end of life and the process yield associated with the recycling process. Hence, expression (5.13) allows to allocate steel scrap independently of the production route of steel.

The closed loop methodology described in the previous paragraphs can also be applied in the case of multiple recycling and reuse of steel. Assuming a steel product in a close loop, recycled throughout *n* life cycle stages, in the same application, with the same recycling rate and yield at each stage; then, the LCI, per kg of steel, for the whole system is given by expression (5.15) [5.41]:

$$LCI = (X_{pr} - X_{re})\left[\frac{(1 - RR \times Y)}{(1 - (RR \times Y)^n)}\right] + X_{re} \tag{5.15}$$

For a system in which a material is continually recycled (n $\rightarrow \infty$), then $[1 - (RR \times Y)^n] \rightarrow 1$. Hence, from expression (5.15),

$$LCI = (X_{pr} - X_{re})(1 - RR \times Y) + X_{re} = X_{pr} - RR[Y(X_{pr} - X_{re})] \tag{5.16}$$

Expression (5.16) is the same expression as (5.13), meaning that for an infinite loop recycling the result is the same as considering one cycle. Furthermore, the result shows also that the methodology takes into account the ability of steel to be recycled many times.

The previous expressions were derived assuming 100% primary production or 100% secondary production. In reality, steel products produced via the primary route may also include some scrap consumption and products from the EAF may also include a small percentage of virgin materials. In this case, the debit or credit given by expression (5.12) may be re-written as

$$LCI_{scrap} = (RR - S) \times Y(X_{pr} - X_{re}) \tag{5.17}$$

where, *(RR - S)* represents the net scrap at the end-of-life. Considering the LCI data of a finished steel product given by *X'*, then the LCI for the product, including the end-of-life recycling, is given by,

$$LCI = X' - [(RR - S) \times Y(X_{pr} - X_{re})] \tag{5.18}$$

Expression (5.18) is currently being used by the worldsteel organisation to generate LCI data for steel products, including recycling at the end-of-life. Thus, attention should be given to LCI data

provided by the worldsteel organisation, whether it includes or not the end-of-life recycling. This is illustrated with an example in Box 5.2.

Box 5.2. LCI data for steel accounting for end-of-life recycling

The LCI data for the production through the BF route of 1 kg of plate steel, at the gate of the factory, is shown in the first column of Table 5.13, for some of the most important air emissions. Data in this column does not consider allocation for recycling, only the production stage is included.

Table 5.13. LCI data of 1 kg of plate steel at the gate of the factory (data from worldsteel [5.65])

	Units	Plate production	Plate with end-of-life recycling (RR = 85%)
Inputs			
Coal	kg	0.832	0.312
Iron	kg	1.586	0.542
Outputs			
Carbon Dioxide (CO_2)	gr	2319	1201
Carbon Monoxide (CO)	gr	29.12	11.77
Nitrogen Oxides (NO_x)	gr	3.182	2.355
Particulates	gr	1.682	0.893
Sulphur Oxides (as SO_2)	gr	2.183	1.304

The second column represents LCI data for steel production including production and end-of-life phases, assuming a recovery rate (RR) of 85%. Allocation for end-of-life recycling was modeled according to the recycling methodology described in the previous paragraphs.

Table 5.13 emphasizes a clear distinction between data with and without consideration of end-of-life. In a LCA of a product system it is important to acknowledge whether the credits or debits due to recycling are given in the first stage of the analysis or in the end-of-life stage, in order to avoid double-counting.

5.4.3.3.5. Alternative scrap allocation

The closed-loop procedure described in the previous sub-sections avoids allocation by system-expansion. Some authors claim [5.51]that this procedure should not be used when comparisons between alternative systems are made; thus, in this paragraph an alternative procedure is proposed based on economic allocation.

Consider a general case of steel production with a percentage of scrap input (S) and a recycling rate (RR) at the end-of-life stage, as indicated in Figure 5.16

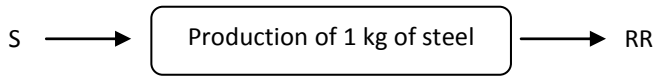


Figure 5.15. General case of steel production

Then, in relation to Figure 5.9, this system is equivalent to product system P_2, receiving a secondary material from product P_1 and providing a secondary material to product P_3. In relation to product systems 1 and 2, product system 2 receives a share of the environmental loads from the preceding product system, caused by virgin production ($L_{P1\rightarrow P2}$), but allocates loads from upgrading and recycling process of material (S) to the preceding product ($L_{P2\rightarrow P1}$):

$$L_{P1\rightarrow P2} = S \times C_2 \times \frac{€SM(S)}{€PM} \tag{5.19}$$

$$L_{P2\rightarrow P1} = -S \times D \tag{5.20}$$

Considering product systems 2 and 3, product 2 receives a credit due to the production of secondary material ($L_{P2\rightarrow P3}$), but is responsible for the upgrade of secondary material ($L_{P3\rightarrow P2}$),

$$L_{P2\rightarrow P3} = -RR \times C_2 \times \frac{€SM(RR)}{€PM} \tag{5.21}$$

$$L_{P3\rightarrow P2} = RR \times D \tag{5.22}$$

The total loads allocated to product system P_2 are therefore:

$$L_{allocted\rightarrow P2} = L_{P1\rightarrow P2} + L_{P2\rightarrow P1} + L_{P2\rightarrow P3} + L_{P3\rightarrow P2} \tag{5.23}$$

$$\Leftrightarrow L_{allocted\rightarrow P2} = S \times C_2 \times \frac{€SM(S)}{€PM} - S \times D - RR \times C_2 \times \frac{€SM(RR)}{€PM} + RR \times D$$

$$\Leftrightarrow L_{allocted\rightarrow P2} = \left(S \times \frac{€SM_S}{€PM} - RR \times \frac{€SM_{RR}}{€PM} \right) \times C_2 + (RR - S) \times D$$

In the case of steel, the quality of steel made from primary materials is equivalent to the quality of steel made from secondary materials [5.65], thus the market prices: $€SM_S = €PM$ and $€SM_{RR} = €PM$. Introducing these values in (5.23) yields,

$$L_{allocted\rightarrow P2} = (S - RR) \times C_2 + (RR - S) \times D = -(RR - S) \times (C_2 - D) \tag{5.24}$$

Moreover, considering the nomenclature used in the previous paragraphs, $C_2 = X_{pr}$ and $D = X_{re}$, then

$$L_{allocted\rightarrow P2} = -(RR - S) \times (X_{pr} - X_{re}) \tag{5.25}$$

Considering the loads to the production of P_2 given by X', then the LCI of product system P_2 is given by,

$$LCI = X' - (RR - S) \times (X_{pr} - X_{re}) \tag{5.26}$$

This expression coincides with expression (5.18) obtained by the closed-loop methodology (with Y = 1.0). Given that the market of steel does not differentiate between the price of steel made from virgin materials and steel made from scrap, then the outcome of the economic allocation provides the same result as the closed-loop approach.

5.4.3.3.6. Uncertainties in steel data

Contrarily to the Ecoinvent database, the worldsteel organisation does not provide uncertainty information about the data for steel. However, in order to perform a probabilistic analysis, uncertainty information about steel production and fabrication is needed.

Therefore, the procedure adopted by Ecoinvent, the Pedigree Matrix [5.21] in conjunction with basic uncertainty factors [5.63], will be used in the case of steel data. Thus, first, data source quality is assessed by the use of six quality indicators: reliability, completeness, temporal correlation, geographic correlation, further technological correlation and sample size. Then, basic uncertainty factors, were taken from Table 5.7.

The quality assessment of data for steel production, based on the uncertainty factors applied in conjunction with the Pedigree matrix, is represented in Table 5.14. The score for each indicator was based on information from the report provided by worldsteel [5.41].

Table 5.14. Pedigree matrix and uncertainty factors for steel production

Indicator	Score	Uncertainty factor	Remarks
Reliability	2	1.05	Most of the data is obtained from measurements but some data is based on assumptions.
Completeness	3	1.05	Data was collected from sites relevant to the market considered, however, the representative data is less than 50%.
Temporal correlation	1	1.00	The reference year of the data provided is 2005-2007 (some data is from 2008), thus, less than 3 years to the reference year (2008).
Geographic correlation	1	1.00	There are two data sources for steel data: Europe and world. Steel is imported to Portugal from Europe and other countries in the world; so, it is considered that data is from area under study.
Further technological correlation	1	1.00	Data from processes and materials correspond to processes and materials under study.
Sample size	5	1.20	The sample size is unknown.

The square of the geometrical standard deviation (95% interval), according to expression (5.11), is indicated in Table 5.15 for some of the most important emissions in the process of plate steel production via the blast furnace route.

Table 5.15. SD_{g95} for emissions in the production of 1 kg of plate steel via the blast furnace route

Emissions to air (kg)	U_b	SD_{g95}
Carbon dioxide (CO_2)	1.05	1.223
Carbon monoxide (CO)	5.00	5.059
Sulphur oxides (SO_2)	1.05	1.223
Nitrogen oxides (NO_x)	1.50	1.568
Chromium (Cr)	5.00	5.059
Lead (Pb)	5.00	5.059
Mercury (Hg)	5.00	5.059

It should be noted that CO_2 emissions have usually a lower uncertainty when compared with other emissions, namely CO. This is due to the fact that CO_2 emissions are usually generated from fuel input, while CO emissions depends on many factors such as engine characteristics and maintenance, load factors, etc.

The same approach is used for the quality assessment of data for steel fabrication and the results are indicated in Table 5.16.

Table 5.16. Pedigree matrix and uncertainty factors for steel fabrication

Indicator	Score	Uncertainty factor	Remarks
Reliability	1	1.00	Most of the data is obtained from validated measurements, which are published in official reports
Completeness	4	1.10	Data is representative from only one site relevant for the market considered.
Temporal correlation	2	1.03	The reference year of the data provided is 2005-06, less than 6 years to the reference year (2008).
Geographic correlation	3	1.02	Data is provided from only one region.
Further technological correlation	1	1.00	Data from processes and materials correspond to processes and materials under study.
Sample size	5	1.20	The sample size is unknown.

In this case, the square of the geometrical standard deviation (95% interval), according to expression (5.11), is indicated in Table 5.17 for some of the emissions in the process of steel fabrication.

Table 5.17. SD_{g95} for selected emissions in the fabrication of 1 kg of steel

Emissions to air (kg)	U_b	SD_{g95}
Cadmium (Cd)	5.00	5.068
Carbon monoxide (CO)	5.00	5.068
Nitrogen oxides (NOx)	1.50	1.578

5.4.3.4. Data for concrete

5.4.3.4.1. Concrete production

In this thesisdissertation, data for concrete production was provided by the Portland Cement Association (PCA) [5.40]. The database of the PCA was developed according to ISO 14040 standards and it provides LCI data for ready mixed concrete, concrete masonry and precast concrete. In this section emphasis will be given to ready mixed concrete and precast concrete. Furthermore, the database differentiates data between concretes mixes, both for ready mixed and precast concrete. Thus, seven representative concrete mixes are provided for ready mixed concrete (five mixes with 28-day compressive strength of 20 MPa and different contents of fly ash and slag cement, and two mixes with 28-day compressive strength of 25 MPa and 35 MPa), and three mixes for precast concrete (with 28-day compressive strengths of 20 MPa, 50 MPa and 70 MPa). The database is updated regularly (the last update was in 2007); the major drawback of this database is the geographic area covered, which regards only the United States. The functional unit for the LCI study is the production, in the United States, of 1 m^3 of concrete at the gate of the factory ("cradle to gate" approach). The system boundary for concrete production is illustrated in Figure 5.16 and it includes cement and slag cement production, aggregate production, transportation and plant operations. The system boundary does not include the upstream profiles of fuels and electricity.

The cut-off rule used in this study eliminated energy, materials and emissions associated with construction of concrete plant equipment and buildings, as these have a negligible contribution to the final products. No allocation was considered for fly ash and silica fume, although they are inputs to the system, as they were considered industrial waste materials from other product systems.

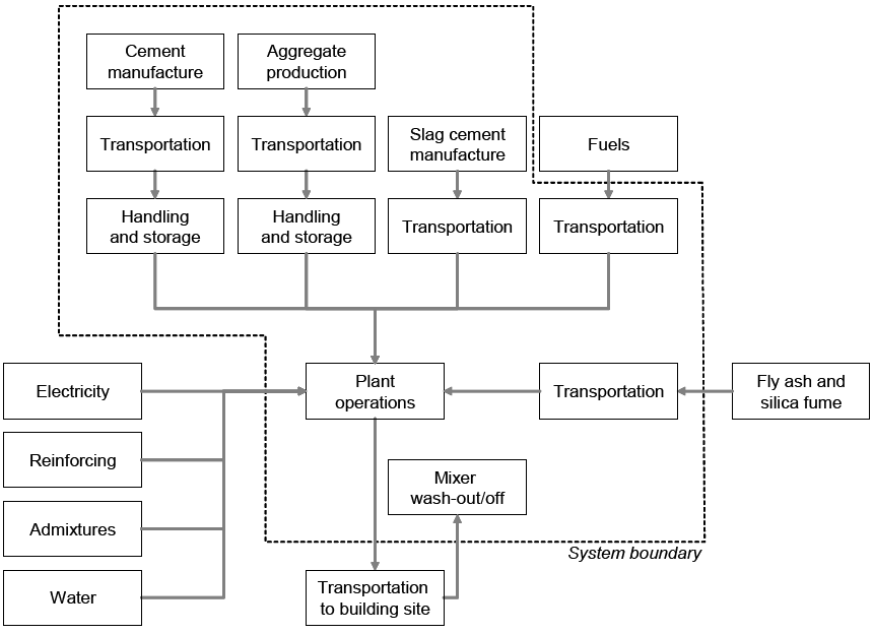


Figure 5.16. System boundary for concrete production [5.40]

The LCI study was based on data provided by US national surveys and existing databases; the environmental flows were calculated as production-weighted averages to account for the fact that new cement and concrete plants have higher production rates and are cleaner and more efficient that older plants.

5.4.3.4.2. End-of-life of concrete

Concrete is a very popular construction material. It is estimated that approximately 25 billion tonnes of concrete are manufactured globally each year. At the same time, almost 900 million tonnes of Construction and Demolition Waste (C&DW) is created annually, in which, the concrete content varies from 20% to 80% [5.67]. Except for a few countries the demolition waste of a concrete structure is typically disposed in landfills. However, since environmental concerns are given special attention, concrete recycling is becoming increasingly popular. According to the US Construction Materials Recycling Association [5.67], in the US 140 million tons of concrete are recycled each year. The use of recycled concrete aggregate varies from aggregate base course to ready mix concrete. Aggregate base course are untreated aggregates used as foundation for roadway pavements. This is the major market in the US and it represents the simplest and easiest use of recycled concrete. Contrary to the recycled aggregates' market, the market for ready mix recycled concrete is still in its infancy but with a huge potential for growing. Recycled concrete is an accepted source of aggregate into new concrete by the American Society for Testing and Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO); however, the inexperience with recycled aggregate products due to lack of exposure still remains a barrier to the recycled concrete market.

Plants for production of recycled concrete aggregates are not very different from conventional plants. The process of recycled aggregates involves crushing, pre-sizing, sorting, screening and contaminant elimination. Crushing and screening systems start with primary jaws, cones and/or large impactors taking rubble from 30 inches to 4 feet. A secondary cone or impact may be run and primary and secondary screens may be used, depending on the final product desired. A

scalping screen removes dirt and foreign particles. A fine harp deck screen removes fine material from coarse aggregate. Further cleaning is necessary to ensure the recycled concrete product is free from dirt, clay, wood, plastic and organic materials. This is done by water floatation, hand picking, air separators and electromagnetic separators.

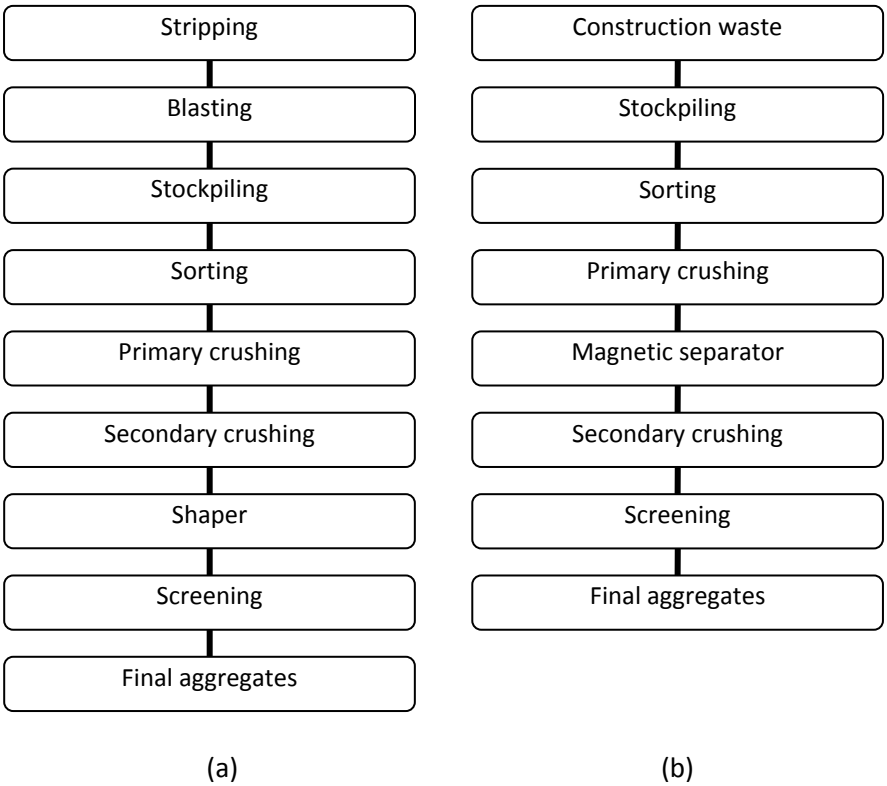


Figure 5.17.(a) Production of natural aggregates and (b) Production of recycled aggregates (adapted from [5.67])

The differences between the characteristics of recycled aggregate concrete and conventional concrete are mainly due to the characteristics of recycled aggregates [5.67], namely, the water absorption of recycled concrete aggregates which is much higher than that of the virgin aggregates. This is due to the large amounts of old mortar and cement paste attached to recycled aggregates. Absorption values range from 2% to 6% for coarse recycled aggregates and 4% to 8% for fine aggregates. However, the same principles used to design concrete mixtures with conventional aggregates should be used when recycled aggregates are used. Naturally, because of the high absorption of recycled aggregates, some deviations in trial batch weights may be necessary. The water-cement ratio may be assumed to be the same, provided that the recycled concrete contains recycled coarse aggregate and natural sand. The cement content for recycled-aggregate concrete will be somewhat higher than the cement content of a conventional concrete because of the higher free water requirements of recycled concrete mixtures. At least 5% extra cement would be required in mixtures using coarse recycled aggregates and virgin fines, at least 15% extra would be needed if both coarse and fine recycled aggregates were used. The density of recycled aggregate concrete is lower because of the large amount of old mortar and cement paste adhering to recycled aggregates. The density of new concrete may be 5% to 15% lower than that of concrete made with conventional aggregates. According to [5.68], the

mechanical properties of the new concrete are not significantly affected if conventional aggregate in concrete is replaced by recycled aggregates in a proportion up to 20%- 30%.

5.4.3.4.3. Allocation of recycled concrete

Recycling of concrete is a necessary step towards the aims of Sustainable Construction, as it may brings economic and environmental benefits.

In contrast to steel, the recycling of concrete recycling should not be addressed in a closed-loop approach. As discussed in section 5.4.2, the process of concrete recycling implies a change in the inherent properties of the material being recycled; or, considering the use of recycled aggregates as base course, its use in another application. Therefore, an open-loop allocation procedure is more appropriate to address concrete recycling, although some authors used a close-loop approach [5.68].

Therefore, in this paragraph, the most appropriate approaches to deal with concrete recycling are discussed based on the life cycle analysis of 1 m^3 of concrete from its production to its disposal; the use phase is not considered as, in this case, it has no influence on the study.

First two scenarios are considered for the disposal of concrete at the end-of-life stage without recycling, thus, avoiding the need for allocation. These are then used for comparison with the other scenarios where allocation is considered.

The first scenario assumes that in the end-of-life, concrete waste is going to be disposed directly into a landfill for inert materials. This corresponds to path (3) in Figure 5.9. The second scenario is similar to the previous one, except that concrete waste is first going through a sorting plant before being disposed into a landfill for inert materials. This corresponds to path (2) in Figure 5.9, considering the recycling fraction equal to zero.

In the environmental data of concrete mixes from PCA, the most significant airborne emissions are CO_2, CO, NO_x and SO_2, which account for about 90% of all airborne emissions [5.40]. The emissions of CO_2 and other combustion gases are primarily due to the cement content in the concrete mixes, as illustrated in Table 5.18 for the production of 1 m^3 of concrete mix, with 25 MPa [5.40].

Table 5.18. LCI data for the production of 1 m^3 of concrete at the gate of the factory [5.40] (in kg/m^3)

	Portland cement	Natural aggregates	Crushed aggregates	Plant operations	Transport	Total
Inputs						
Cement	279					279
Coarse aggregate		878	309			1187
Fine aggregate		771				771
Outputs						
Carbon Dioxide (CO_2)	2.52E+02	1.50E+00	4.40E-01	1.76E+00	5.95E+00	2.62E+02
Carbon Monoxide (CO)	2.98E-01	3.21E-03	1.01E-03	6.59E-04	2.93E-02	3.32E-01
Nitrogen oxides (NO_x)	6.24E-01	9.18E-03	2.80E-03	1.72E-03	5.95E-02	6.97E-01
Sulfur dioxide (SO_2)	3.60E-01	-	-	1.04E-08	-	3.60E-01

The results of the life cycle analysis, considering both end-of-life scenarios, are indicated in Table 5.19. The results are presented for the most significant airborne emissions in concrete production (in kg/m^3). Two additional indicators are also presented: (i) the safeguard of raw materials (in case of recycling or reuse), and (ii) the production of waste over the life cycle. The

first column corresponds to the production stage only (cradle-to-gate); while the two other columns correspond to the stages of production plus the end-of-life scenario. In both end-of-life scenarios a transportation process was included assuming a distance of 20 km from the demolition place to the disposal place. Data for the processes of transportation, sorting and disposal into a landfill for inert material was taken from Ecoinvent.

Table 5.19. Air emissions (in kg/m^3) for different end-of-life scenarios (without recycling)

	Concrete production	Concrete production + end-of-life scenario	
		Direct disposal without sorting	Disposal after sorting
Air emissions (kg/m^3)			
Carbon Dioxide (CO_2)	2.62E+02	2.93E+02 (+12%)	2.95E+02 (+12%)
Carbon Monoxide (CO)	3.32E-01	4.18E-01 (+26%)	4.22E-01 (+27%)
Nitrogen oxides (NO_x)	6.97E-01	9.71E-01 (+39%)	9.92E-01 (+42%)
Sulfur dioxide (SO_2)	3.60E-01	4.03E-01 (+12%)	4.06E-01 (+13%)
Other indicators (kg/m^3)			
Safeguard of raw materials	-	0	0
Waste production	-	2300	2300

It is clear from Table 5.19 that the disposal phase of concrete cannot be considered a negligible contribution to the life cycle. The consideration of the end-of-life scenario increased the amount of the initial emissions from 10% to approximately 50%.

There is no recycling of materials in any of the scenarios considered; thus, there's no safeguard of raw materials.

Also, in both scenarios the total amount of concrete waste (considering that 1 m^3 of concrete is about 2300 kg) is sent to a landfill, although in the second scenario the waste is going through a sorting plant. Naturally, this led to an increase on the amount of emissions in relation to the first scenario. According to current legislation (see Chapter 2) mixed construction waste must be sorted first before disposal; thus, in the case of a real application, this would be the most appropriate process.

Next, the production of recycled concrete aggregates is considered from the recycling of concrete. The process of production of recycled concrete aggregates hereby considered is the crushing of concrete, no other upgrading process is included. However, considering the recycling of concrete at the end-of-life stage implies, as previously referred, an allocation procedure. In this case, three allocation procedures are selected for comparison: (i) "cut-off" rule, (ii) "50:50" rule, and (iii) economic allocation.

As illustrated in Figure 5.18, all scenarios include all the processes from the production of 1 m^3 of concrete, through demolition, until the production of recycled aggregates. In each scenario it is assumed that only a fraction of concrete is going to be recycled (80%) and the remaining concrete waste is sent to a landfill for inert materials. A transportation process was included assuming a distance of 50 km from the demolition place to the disposal place. In the case of the 50:50 allocation and economic allocation, an additional transportation process was included, representing the transport of the waste from the demolition place to the recycling plant, considering a distance of 10 km or 20 km.

Data for the production of recycled aggregates is not currently available in databases. However, as illustrated in Figure 5.14, the production of recycled aggregates is not very different from the

production of crushed aggregates. In this work, data for the production of recycled aggregates was provided from two sources: average data for crushing concrete provided from Ecoinvent and data from SUSA, a concrete recycling company in Serbia [5.69].

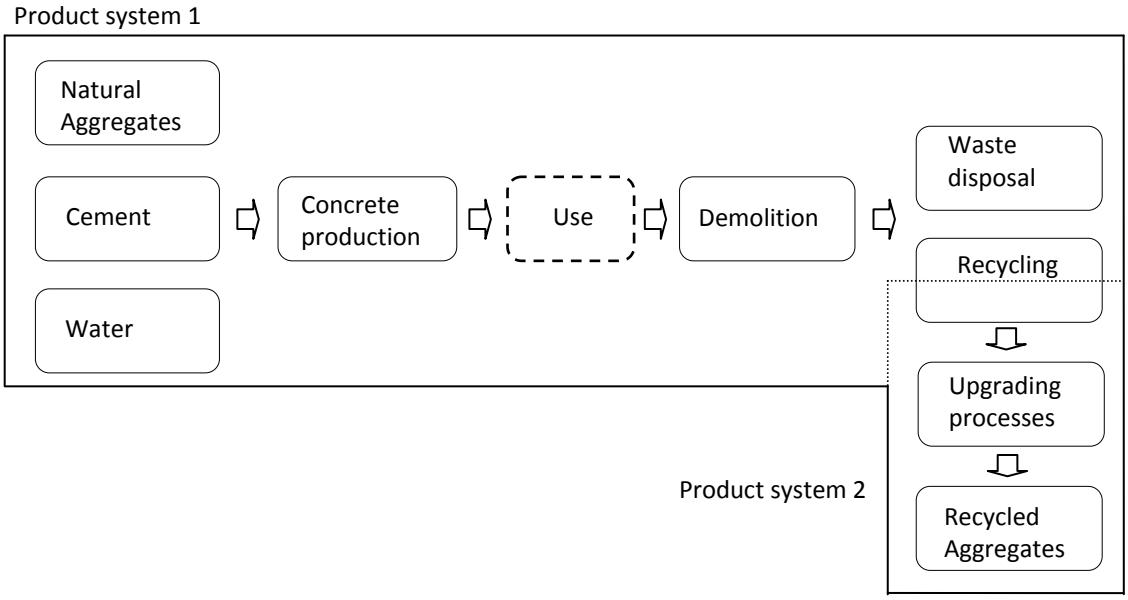


Figure 5.18. Allocation between two product systems

From expression (5.1) all the inputs and outputs associated with the life-cycle of concrete, from the production of 1 m^3 of concrete from virgin material to the disposal of 1 m^3 of concrete waste, are expressed by the following expression:

$$N_{I/0} = A - RR \times C_1 - Y \times RR \times C_2 + RR \times D \tag{5.27}$$

where, RR is the fraction of concrete that is recycled and Y represents the efficiency of the recycling process. Moreover, according to clause 5.4.3.4.2, 1 m^3 of recycled concrete produces 0.6 m^3 of recycled aggregates. Hence, in the following, the efficiency of the recycling process is considered to be 60%.

In the first case, a cut-off rule is used, eliminating all the burdens due to concrete recycling from the system, as illustrated in Figure 5.19.

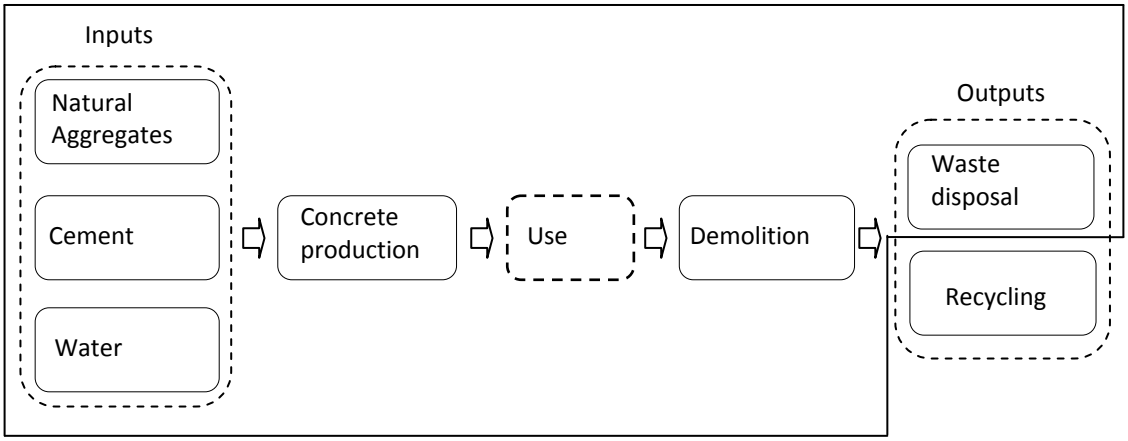


Figure 5.19. System boundaries in the cut-off procedure

Considering the "50:50" rule, 50% of the credits and debits are allocated to product system 1, whilst the remaining 50% are allocated to product system 2. Thus, from expression (5.17):

$$N_{I/0}(product\ \ 1) = A - 1/2\left[RR \times C_1 + Y \times RR \times C_2 - RR \times D\right] \tag{5.28}$$

The outcome of both life cycle analyses are indicated in Table 5.20. The variation of total air emissions is related to the production of concrete (in the first column). From the above expression, the safeguard of raw materials is assumed to be equivalent to the fraction of the concrete waste that is recycled, considering the efficiency of the recycling process, as given by the following expression:

$$SRM = -1/2 \times Y \times RR \times (concrete_waste) \tag{5.29}$$

In this calculation it is considered that 1 m^3 of concrete is about 2300 kg.

Table 5.20. LCI data of 1 m^3 of concrete including end-of-life recycling

	Concrete production	Cut-off rule		50:50 rule	
		10 km	20 km	10 km	20 km
Air emissions (kg/m^3)					
Carbon Dioxide (CO_2)	2.62E+02	2.77E+02 (+6%)	2.81E+02 (+7%)	2.90E+02 (+11%)	2.92E+02 (+11%)
Carbon Monoxide (CO)	3.32E-01	3.77E-01 (+14%)	3.82E-01 (+15%)	4.05E-01 (+22%)	4.06E-01 (+22%)
Nitrogen oxides (NO_x)	6.97E-01	8.51E-01 (+22%)	8.69E-01 (+25%)	9.21E-01 (+32%)	9.26E-01 (+33%)
Sulfur dioxide (SO_2)	3.60E-01	3.82E-01 (+6%)	3.85E-01 (+7%)	4.00E-01 (+11%)	4.02E-01 (+12%)
Other indicators (kg/m^3)					
Safeguard of raw materials	-	0	0	552	552
Waste production	-	460	460	1748	1748

It is noted from Table 5.20 that the longer the distance to the recycling plant, the higher are the emissions due to transportation of waste. This leads to the natural conclusion that sorting and recycling of materials in the site of demolition is the most efficient process. Comparing the "cut-off" rule to the "50:50" rule, and in contrast to what some authors argue (see clause 5.4.2.2.1), the "cut-off" approach is not always a conservative approach. By neglecting all the burdens/credits due to recycling processes and in the case this burdens are higher than the respective credits, then the approach provides a better environmental "score" than if the recycling process was included. This is noted from the comparison of the two approaches in terms of air emissions and waste production. By ignoring the efficiency of the recycling process, the "cut-off" rule does not take into account that, although 80% of concrete is recycled, due to the efficiency of the recycling process only 60% of the recycling fraction is effective, the remaining material is waste and has to be sent for disposal.

The loss of quality in the properties of recycled aggregates comparing with virgin aggregates is not considered in the previous approaches. As already referred, this can be taken into account by the ratio between the market price of recycled aggregates (€RA) and the market price of natural aggregates (€NA), as given by expression (5.29).

$$N_{I/0} = A - RR \times C_1 - (€RA/€NA) \times Y \times RR \times C_2 + RR \times D \quad (5.30)$$

Three different situations were considered for the ratio between the market prices of recycled and virgin aggregates: a ratio of 0.5, a ratio of 0.7 and a ratio of 1. The results obtained for each case are indicated in Table 5.21, considering the same indicators as in Table 5.20. In this case the safeguard of raw materials (*SRM*) is assumed to be given by,

$$SRM = (€RA/€NA) \times Y \times RR \times (concrete_waste) \quad (5.31)$$

Table 5.21. LCI data of 1 m^3 of concrete including end-of-life recycling (economic allocation)

Distance (*)	10 km			20 km	
(€RA/€NA)	0.5	0.7	1.0	0.5	1.0
Air emissions (kg/m^3)					
Carbon Dioxide (CO_2)	2.85E+02 (+9%)	2.85E+02 (+9%)	2.85E+02 (+9%)	2.88E+02 (+10%)	2.88E+02 (+10%)
Carbon Monoxide (CO)	3.85E-01 (+16%)	3.85E-01 (+16%)	3.85E-01 (+16%)	3.90E-01 (+17%)	3.90E-01 (+17%)
Nitrogen oxides (NO_x)	8.65E-01 (+24%)	8.64E-01 (+24%)	8.62E-01 (+24%)	8.75E-01 (+26%)	8.71E-01 (+25%)
Sulfur dioxide (SO_2)	3.96E-01 (+10%)	3.96E-01 (+10%)	3.96E-01 (+10%)	3.99E-01 (+11%)	3.99E-01 (+11%)
Other indicators (kg/m^3)					
Safeguard of raw materials (SRM)	552	773	1104	552	1104
Waste production	1196	1196	1196	1196	1196

(*) distance from the demolition place to the recycling plant

The same conclusion in relation to the distance of the recycling plant from Table 5.20 is valid for this table.

In this case, three different market price ratios were considered. It is noted that assuming the ratio equal to 1, implies that the quality of secondary and primary materials is the same, and thus a closed-loop may be assumed. This is not a realistic ratio for the case of recycled concrete aggregates, particularly since no other upgrading process apart from crushing was considered. A ratio of 1 was considered to analyse its influence on the outcome of the analysis and should be considered as an extreme situation. However, from the analysis of the previous table and in relation to air emissions, one may conclude that the ratio has a minor influence on the outcome of the life cycle analysis. On the other end, in respect of the safeguard of raw materials the situation is different; and in this case, the ratio has clearly a major influence. This apparent inconsistency is due to the reason that, in case of air emissions, the production of aggregates from recycled (or secondary) materials is similar to the production of aggregates from virgin (or primary) materials; and in comparison with the other processes involved (transportation and deposition in landfill) their contribution is very small. Therefore, thus they have a very small influence in the result of the life cycle analysis.

A summary of the life cycle analysis, considering the worst case in each end-of-life scenario, is provided in Table 5.22. The variation of air emissions is relative to the production of 1 m^3 of concrete (cradle-to-gate).

Table 5.22. Influence of end-of-life scenario for concrete recycling

End-of-life scenario	No recycling		Recycling		
	Disposal	Sorting	Cut-off	50:50	Economic
Air emissions					
CO_2	+12%	+12%	+7%	+11%	+10%
CO	+26%	+27%	+15%	+22%	+17%
NO_x	+39%	+42%	+25%	+33%	+26%
SO_2	+12%	+13%	+7%	+12%	+11%
Other indicators (kg/m^3)					
Safeguard of raw materials	0	0	0	552	552
Waste	2300	2300	460	1748	1196

From this table it is noted that recycling of concrete is beneficial in comparison with the simple disposal of concrete waste in a landfill. Comparing the results of the scenarios considering recycling and no-recycling, the former have lower values for air emissions, lower amount of waste produced and naturally, they promote the safeguard of natural resources.

In relation to the allocation procedures, the “cut-off” rule, as already mentioned, neglects the impacts due to recycling and underestimates the amount of waste produced as it doesn´t take into account the inefficiency of the recycling process. Therefore, this rule is not in agreement with current waste management legislation as referred in Chapter 2. Also, no credits are given to the production of secondary materials, thus it doesn’t promote the safeguard of raw materials.

The “50:50” rule provides values slightly higher than the economic approach. In this case, this is due to the reason that the outcome of the life cycle analysis is more dependent on the processes of transportation and landfill of inert materials than the processes of production and recycling of aggregates. Thus, as in the case of the “50:50” rule the amount of waste produced is higher than in the case of economic allocation, the corresponding impacts are also higher and the final outcome reflects this.

The economic allocation approach should only be used in case of well-established markets for secondary materials, which is not the present case for recycled concrete aggregates. However, in the above calculations it was noted that the relation between the market prices of aggregates materials was not very important taking into account the remaining processes involved. Thus, this process will be adopted for the allocation of concrete recycling in the case studies.

It should be emphasized, however, that in an economic allocation approach the comparison of primary and secondary material should be carried out for materials on an equivalent level in the upgrading system. In this case it was chosen to base the comparison at the level of aggregates and the comparison was made between virgin aggregates and recycled concrete aggregates. The same approach may be used for the recycling of concrete, comparing the production of concrete from virgin materials and the production of concrete from recycled aggregates; however, in order to enable such comparison major changes in the processes involved are needed and thus the conclusions presented in the previous paragraphs are not valid. Also, at the present there is no data to perform such analysis.

5.4.3.4.4. Uncertainties in data for concrete

The environmental inventory data for concrete production [5.40] does not provide uncertainty information about the data. Thus, once again, the procedure adopted by Ecoinvent, the Pedigree

Matrix [5.21] in conjunction with basic uncertainty factors [5.63], will be used in the case of concrete data.

The quality assessment of data for concrete production is represented in Table 5.14. The score for each indicator was based on information from the report provided by PCA [5.40].

Table 5.23. Pedigree matrix and uncertainty factors for concrete production

Indicator	Score	Uncertainty factor	Remarks
Reliability	2	1.05	Most of the data is obtained from measurements but some data is based on assumptions.
Completeness	3	1.05	Data was collected from sites relevant to the market considered, however, the representative data is less than 50%.
Temporal correlation	1	1.00	The reference year of the data provided is mainly 2006, thus, less than 3 years to the reference year (2008).
Geographic correlation	5	1.10	Data is only related to the U.S.A.
Further technological correlation	1	1.00	Data from processes and materials correspond to processes and materials under study (assuming similar technology in the U.S.).
Sample size	5	1.20	The sample size is unknown.

In the case of the data related to the production of 1 m^3 of concrete with 28-day compressive strength of 35 MPa, the square of the geometrical standard deviation (95% interval), according to expression (5.8), is indicated in Table 5.24, for some of the most important emissions in the process.

Table 5.24. SD_{g95} for emissions in the production of 1 m^3 of concrete (35 MPa)

Emissions to air (kg)	U_b	SD_{g95}
Carbon dioxide (CO_2)	1.05	1.249
Carbon monoxide (CO)	5.00	5.073
Sulphur oxides (SO_2)	1.05	1.249
Nitrogen oxides (NO_x)	1.50	1.584
Chromium (Cr)	5.00	5.073
Lead (Pb)	5.00	5.073
Mercury (Hg)	5.00	5.073

5.4.3.5. Data for the use of construction equipment

Construction equipment used over the different stages in the life cycle of a bridge is a non-road source of emissions. Non-road engines contribute significantly to anthropogenic emissions inventories, with U.S. estimates for various pollutants ranging from 14% to 22% [5.70].

Modelling non-road emissions is essential in estimating the total impacts of bridge design, and in this work the NONROAD model [5.71] developed by the U.S. Environmental Protection Agency's (EPA) was selected as a tool to estimate fuel use and emissions from construction equipment based on vehicle class and horsepower rating. The NONROAD model estimates non-road emissions for any area in the United States at the national, state or county levels for several pollutants.

The last version of the model is the NONROAD2008. This model calculates emission estimates for hydrocarbon (HC), oxides of nitrogen (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), primary particulate matter with an aerodynamic diameter less than or equal to 10 micrometers

(PM-10), and primary particulate matter with an aerodynamic diameter less than or equal to 2.5 micrometers (PM-2.5) and carbon dioxide (CO_2), for all gasoline, diesel, compressed natural gas (CNG) and liquefied petroleum gas (LPG) nonroad equipment. The model comprehends various HC species, including volatile organic compounds (VOCs), and breaks out the HC emissions according to exhaust and evaporative components. PM-10 is assumed to be equivalent to total PM, and PM-2.5 is assumed to be 92% of PM-10 for gasoline and diesel-fueled engines and 100% of PM-10 for LPG and CNG-fueled engines. This model covers a wide range of construction, agricultural and industrial equipment.

The calculation of the emissions is based in expression (5.32) and takes into account the equipment population data, activity surveys and emission testing results [5.70],

$$Emissions = (population) \times (rated_power) \times (load_factor) \times (activity) \times (emission_factor) \quad (5.32)$$

In this work, only emission factors for diesel fuelled engines are of interest, as these will be used to compute emissions due to the construction equipment used in the various stages of the bridge life cycle.

5.4.3.5.1. Methodology for calculation of emission factors in NONROAD

The NONROAD model calculates emission factors for diesel engines based in Tier 1 and Tier 2 engine test certification data.

For HC, CO, and NO_x, the exhaust emission factor for a given diesel equipment type in a given model year/age is calculated as follows [5.72]:

$$EF_{adj(HC,CO,NOx)} = EF_{SS} \times TAF \times DF \quad (5.33)$$

where, EF_{adj} is the final emission factor used in model, after adjustments to account for transient operation and deterioration (g/hp-hr); EF_{ss} is the zero-hour, steady-state emission factor (g/hp-hr); TAF is the transient adjustment factor (dimensionless); and DF is the deterioration factor (dimensionless).

The zero-hour, steady-state emission factors (EF_{ss}) are mainly a function of model year and horsepower category, which defines the technology type. The transient adjustment factors (TAFs) vary by equipment type. The deterioration factor (DF) is a function of the technology type and age of the engine.

Since PM emissions are dependent on the sulfur content of the fuel the engine is burning, the equation used for PM is slightly modified from previous equation, as follows [5.72]:

$$EF_{adj(PM)} = EF_{SS} \times TAF \times DF - SPM_{adj} \quad (5.34)$$

where, SPM_{adj} is the adjustment to PM emission factor to account for variations in fuel sulfur content (g/hp-hr). PM and SO_2 are the only diesel pollutants that are dependent on fuel sulfur content.

For Brake-Specific Fuel Consumption (BSFC), there is no deterioration applied, so the equation is simplified to [5.72]:

$$EF_{adj(BSFC)} = EF_{SS} \times TAF \tag{5.35}$$

Emission factors for CO_2 and SO_2 are calculated based on BSFC; therefore, the model does not require CO_2 or SO_2 emission factor input files.

5.4.3.5.2. Emission factors generated from NONROAD2008

The emission factors considered in this work are obtained from NONROAD2008 model. The VOC emission factors include exhaust and evaporative emissions. Some examples of emission factors for diesel-fueled construction equipment are provided in Table 5.25 [5.71].

Table 5.25. Emission factors for diesel-fueled construction equipment [g/(hp-hr)] [5.71]

Equipment	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
Cement & Mortar mixers	0.514	1.943	6.374	0.365	0.354	0.114	529.484
Cranes	0.304	0.907	4.377	0.208	0.202	0.114	530.121
Dumpers	1.108	3.989	7.060	0.851	0.826	0.134	623.186
Excavators	0.278	1.224	3.653	0.253	0.245	0.115	535.989
Paving equipment	0.337	1.509	4.463	0.299	0.290	0.115	535.810
Rollers	0.310	1.348	4.159	0.278	0.269	0.115	535.891
Scrapers	0.291	1.264	3.888	0.263	0.256	0.115	535.947
Other	0.341	1.537	4.514	0.303	0.294	0.115	535.797

The emission factors represented in Table 5.25 correspond to construction equipment with horsepower category comprehended between 175 hp and 300 hp, except dumpers, which horsepower category is comprehended between 100 hp and 175 hp.

5.4.3.5.3. Uncertainties in emission factors from NONROAD model

The calculation of non-road emissions is subject to many sources of uncertainty. A major source of uncertainty is the lack of data and, in general, there are much less data for non-road emissions than for either on-road mobile or stationary sources [5.70]. A sensitivity analysis of the model showed that estimated emissions are significantly sensitive to increases in equipment population, activity, load factor and emission factor [5.70]. In this case, however, only uncertainties in emission factors are considered.

Uncertainties in emission factors were calculated by Chi [5.70] based on bootstrap analysis and expert elicitation. The work focussed on the exhaust THC, NO_x, CO and PM pollutant emissions. Bootstrap analysis were performed for data from models years 1996 to 1998 using both a resampling technique and a parametric method. The test data were grouped by engine horsepower and per year. Table 5.26 presents the emission factor uncertainty results (95% confidence intervals about the mean) of the resampling bootstrap and the parametric bootstrap analysis. These results were averaged over model years and horsepower grouping.

Table 5.26. Uncertainties of diesel engine certification emission test [5.70]

Emission	Resampling bootstrap	Parametric bootstrap
THC	± 30 %	± 20 %
NO_x	± 6 %	± 3.5 %
CO	± 25 %	± 16 %
PM	± 15 %	± 10 %

Both cases showed that the mean emission factors were relatively less uncertain for NO_x than for any of the three other pollutants. VOC uncertainties were 5 to 6 times greater than NO_x uncertainties.

The uncertainties resulting from the bootstrap methods took only into account the variability of engine test results. They didn't reflect the uncertainty due to the representativeness of the data nor the certification test and other variables. Thus, expert elicitation was also performed aiming to capture uncertainties in model parameters not accounted for in bootstrap analysis.

The result from the expert elicitation suggested that PM data were generally the most uncertain pollutant, with uncertainties varying from -29% and +52%. The largest specific emission factor uncertainty was -29% and +96% for CO emissions, and the most certain at ±15% for NO_x emissions.

As expected, expert opinion of emission factor uncertainties were more conservative than the average values from either bootstrap method; however, all results showed lower uncertainties for NO_x.

The 95% confidence intervals about the mean of the non-road emission factors adopted in this work are indicated in Table 5.27. These values correspond to the most conservative values in the bootstrap analysis of Chi [5.70]. The values adopted to SO_2 and CO_2 are conservative as they are only estimations. Moreover, lognormal distributions are adopted in order to avoid negative values.

Table 5.27. Uncertainties in non-road emission factors

Emission	Resampling bootstrap
THC	± 30 %
NO_x	± 6 %
CO	± 25 %
PM	± 15 %
SO_2	± 50 %
CO_2	± 50 %

5.4.3.6. Data for road traffic

5.4.3.6.1. Introduction

Road traffic is responsible for major potential impacts in the environment, in the economy and in society. Mobile sources, particularly, motorway vehicles generate more pollution than any other source and traffic congestion can lead to substantial time losses and can limit worker productivity [5.73].

The traffic flow passing under and above a bridge on a daily basis is not affected by the bridge and does not depend on the type of bridge. Thus, in this dissertation the traffic flow under normal conditions is not of concern. However, when the bridge is built, maintained or demolished, traffic congestion usually results from delays in the construction work zone. Hence, in this dissertation the focus is on the traffic flow related to construction activity. Construction related delays result in additional fuel consumption and related emissions, as well as economic and social impacts. The aim is therefore to estimate the additional impacts related to traffic when there is work activity in the bridge. This difference represents the interaction between the bridge and the traffic.

To quantify traffic related impacts it is necessary to model the traffic under and above the bridge. The impact of construction activities on traffic flow is given by a comparison between the flow congestion modelled during construction activity and the flow modelled under non-construction activity.

Several models are available for the analysis of traffic flows affected by work zones: QUEWZ, MicroBENCOST, KyUCP traffic model, etc. More complex models, such as QuickZone and VISSIM, allow to additionally estimate the impact of the work area and the lane closure on adjacent roadways including any alternate route [5.74].

QuickZone was jointly developed in the U.S. by the Office of Research, Development, and Technology in the FHWA and Mitretek Systems, and it allows to estimate user delays in work zones. This model can evaluate the traffic impacts for work zone mitigation strategies and estimates the costs, traffic delays, and potential backups associated with these impacts. However, the model requires a significant amount of data to accurately model the roadway system. As QuickZone is a network flow model that analyzes individual segments in specified time steps, the model relies on a network composed of links and nodes. Hourly and daily demand patterns are needed to populate the links with traffic flow.

VISSIM is a microscopic, behaviour-based, multi-modal traffic simulation model. It was developed by PTV AG in Karlsruhe, Germany. It is capable of modelling traffic and public transport operations in a network integrating street and freeway systems. The program can analyze traffic operations under constraints such as different lane configurations, traffic compositions, and traffic signals, thus making it a useful tool for the evaluation of various traffic control alternatives based on measures of effectiveness such as delay, queue length, and throughput.

All the referred models have advantages and disadvantages. The model selected to be integrated in the approach developed in this dissertation is the Queue and User Cost Evaluation of Work Zones (QUEWZ). Although this model has several limitations, as will be described in the following paragraphs, the model was chosen mainly for two reasons: the ability of the model to establish construction strategies (e.g. time schedules) to reduce the corresponding impacts and the availability of an algorithm that could be implemented in a Microsoft excel datasheet, allowing an easy compatibility with the integral life cycle approach.

5.4.3.6.2. The QUEWZ model

The Queue and User Cost Evaluation of Work Zones (QUEWZ) model [5.73] was developed at the Texas Transportation Institute (TTI) for the Texas State Department of Highways and Public Transportation in 1982. The model has been upgraded numerous times, the most recent version is QUEWZ-98. The model analyzes traffic flows through motorway work zones and allows to estimate the traditional road user costs and air pollution on various lane closure strategies. It can be applied to basic motorway segments having as many as six lanes in each direction, and can analyze any number of lanes closed in one or both directions. The model first estimates speeds and queuing characteristics both with and without the work zone and then estimates the additional air pollution and road user costs generated by the work zone.

The traffic flow in a work zone of a motorway is unique to the extent that it needs to be described by a combination of free-flowing traffic and stop-and-go traffic. When traffic volumes

are not great enough to cause congestion and queuing, the traffic can be characterized entirely by the volume and speeds. When congestion occurs, additional information (such as queue lengths) is needed to characterize the traffic.

A traffic model for analysing a work zone should be able to comprehensively define the work zone characteristics. Traffic passing through a work zone is characterized in three ways, from the viewpoint of emission prediction and user impacts [5.73]:

- Vehicles proceeding undelayed through the work zone: when the capacity of the work zone is sufficiently greater than the demand, the vehicles passing through the work zone are processed without any delay. This scenario does not contribute toward excess emission levels, nor user costs;
- Vehicles proceeding through the work zone at a reduced speed: as the traffic demand at the work zone approaches the capacity of the work zone, the rate at which vehicles are processed through the work zone decreases, lowering the overall speeds of vehicles. This implies a deceleration from the approach speed to a minimum speed near the work zone, an acceleration to the work zone average speed, travel at an average speed through the work zone and finally, an acceleration from the work zone speed to pre-work zone speed. During acceleration and deceleration, vehicles emit more pollutants, however, the lower average speeds in the work zone might result in lesser pollution when compared to cases where vehicles proceed unhindered at higher average speeds. The characteristics of this traffic behaviour are indicated in Figure 5.20, neglecting the queue zone;
- Vehicles stopping near the work zone as a result of queue formation: when the traffic demand at the work zone exceeds the capacity of the work zone, several things occur:
  - queue formation upstream of the work zone involving deceleration from the approach speed to idling at the end of the queue,
  - short acceleration-deceleration movements (creeping motion) through the queue,
  - acceleration to work zone speed at the beginning of the work zone,
  - passage through the work zone at the average work zone speed, and
  - acceleration to pre-work zone speed at the end of the work zone.

  The characteristics of this traffic behaviour are illustrated in Figure 5.20 [5.73].

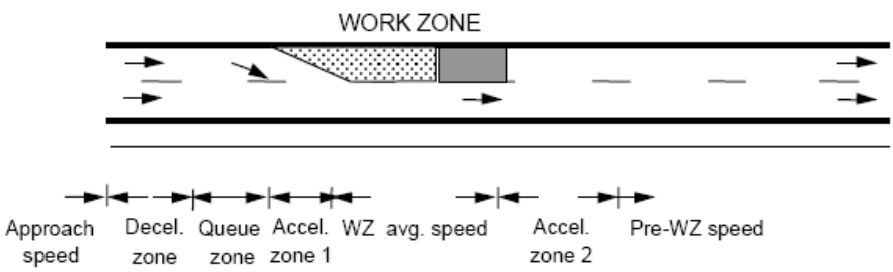


Figure 5.20. Traffic behaviour associated with queue formation near a work zone [5.73]

If the speeds at the beginning and end of the zones described in Figure 5.20 are known, the time spent by the vehicle in these zones can be calculated by assuming constant acceleration and deceleration rates for the vehicles. Thus, the traffic analysis model requires the following data:

- work zone capacity,
- speed-flow relationship,
- length of work zone,
- average length of the queue,
- average vehicle speeds in the queue,
- vehicle mix,
- acceleration and deceleration rate of vehicles.

The normal approach speed and average speed through the work zone are computed from relationships between speed and volume-to-capacity ratios presented in the Highway Capacity Model [5.75]. The use of the same speed-volume relationship applied both with and without the work zone limits the model somewhat, since research suggests that the speed-volume relationships may well differ substantially with and without work zones [5.76].

However, the model user has the option of modifying the parameters of the relationship between speed and volume-to-capacity ratio to more accurately represent the road segment under analysis.

In the model, the capacity of the work zone with no ongoing activity is considered to be 90% of the normal capacity of 2000 vphpl; thus a value of 1800 vphpl is considered [5.76]. The capacity of the work zone when work activity is present is given by the following equation [5.74]:

$$C = (1600 + I - R) \times H \times N \tag{5.36}$$

where, C is the estimated capacity of the work zone (vph); I represents the effect of work intensity (-160 to +160 vehicles; default value is 0); R represents the effect of entrance ramps (0 to 160 vehicles; default value is 0); H represents the effect of heavy vehicles; and N is the number of open lanes through the work zone.

Borchardt et al. [5.74] argue that QUEWZ model tends to underestimate the work zone capacity. However, its performance was on average the same as the other simplified models reviewed by the authors.

The minimum speed through the work zone is estimated using a linear regression model developed at TTI. In a queue, the minimum speed is presumed to be zero and the average speed is estimated using a model also developed at TTI. When approach volumes exceed the capacity of the work zone, the length of queue and vehicle hours of delay are computed using the approach presented in the 1985 Highway Capacity Manual [5.77].

This model allows to estimate additional air pollution and user costs related with traffic congestion in work zones. In this chapter, only the estimation of air pollution is further developed. The calculation of user costs based on this model is further developed in Chapter 8.

5.4.3.6.3. Predicting Work Zone Mobile Emissions

The major contributors of air pollution and their sources are indicated in Table 5.28, which shows that motor vehicles, hereafter denominated mobile sources, are principal contributors of carbon monoxide (CO), a product of the incomplete burning of fuel, nitrogen oxides (NOx), a product of high-compression internal combustion engines; and hydrocarbons (HC), resulting from incomplete burning or evaporated gasoline [5.76].

Table 5.28. Source and proportion of air pollutants in the U.S (data from 1982) [5.76]

Source	Pollutant (% of total)				
	CO	HC	NOx	SO	PM
Mobile sources	72.5	33.3	47.8	4.1	18.0
Motorway vehicles	63.0	26.7	38.7	2.2	14.0
Gasoline					
Cars	38.1	16.7	16.6	0.7	7.1
Light trucks	11.2	5.6	5.7	0.2	2.1
Heavy trucks	12.4	2.8	2.9	0.1	0.9
Motorcycles	0.3	0.4	< 0.05	0.0	0.1
Diesel					
Cars	< 0.05	< 0.05	0.1	< 0.05	0.3
Light trucks	< 0.05	< 0.05	< 0.05	< 0.05	0.1
Heavy trucks	0.9	1.2	13.3	1.2	4.2
Other transportation modes	9.5	6.6	9.1	1.8	3.3
Industrial processes	6.5	39.2	3.0	14.5	31.7
Power plants	0.4	0.0	30.8	66.9	13.2
Other fuel combustion	8.5	11.0	16.9	14.5	18.5
Solid waste disposal	2.9	3.3	0.5	0.0	5.3
Miscellaneous	9.2	13.2	1.0	0.0	13.2

Vehicle emissions vary according to the type of engine, the mode of operation, the fuel composition, presence and working condition of emission control devices, atmospheric conditions and engine tuning [5.73].

Table 5.29. Emission characteristics in relation to operating mode [5.73]

Operating mode	Emission concentration		
	CO	HC	NOx
Idle	High	High	Very low
Acceleration			
Moderate	Low	Low	High
Heavy	Moderate	High	Moderate
Deceleration	Very high	High	Very low
Cruise			
Low speed	Low	Low	Low
High speed	Very low	Very low	Moderate

Emissions data required to model the above variations is usually collected from emission testing programs. Models are then applied to predict emissions from an aggregate fleet containing different types of vehicles, ages and operating characteristics, which operate under different conditions from those of the tests. QUEWZ uses the model MOBILE4.1 [5.78], developed by the U.S. Environmental Protection Agency, to address these problems.

Therefore, based on this model modal emissions rates for each pollutant are given by the following expressions [5.73]:

i) Calculation of CO emissions (in grs/h)

$m_{CO\ i}$ = Hot stabilized idle emission rate from the default MOBILE 4.1 scenario,

$m_{CO\ d} = 1.5 \times m_{COi}$,

$m_{CO\ cr1}$ = 16.2 mph MOBILE 4.1 scenario rate x 16.2 x $(0.494 + 0.000227 \times S^2)$,

$m_{CO\ a1}$ = MOBILE 4.1 scenario rate at speed S x S x $[0.182 - 0.0079776 \times (aS) + 0.00036227 \times (aS)^2]$,

$m_{CO\ a2}$ = MOBILE 4.1 scenario rate at speed S x S x [0.182 - 0.0079776 x aS + 0.00036227 x $(aS)^2$],

ix) Calculation of HC emissions (in grs/h)

$m_{HC\ i}$ = $m_{HC\ d}$ = $m_{HC\ cr1}$ = Hot stabilized idle emission rate from the default MOBILE 4.1 scenario;

$m_{HC\ a1}$ = MOBILE 4.1 scenario rate at speed S x S x [0.018 – 5.266x10^{-4} x (aS) + 6.1296x10^{-6} x $(aS)^2$];

$m_{HC\ a2}$ = MOBILE 4.1 scenario rate at speed S x S x [0.018 – 5.266x10^{-4} x (aS) + 6.1296x10^{-6} x $(aS)^2$];

x) Calculation of NOx emissions (in grs/h)

$m_{NOx\ i}$ = $m_{NOx\ cr1}$ = Hot stabilized idle emission rate from the default MOBILE 4.1 scenario

$m_{NOx\ d}$ = MOBILE 4.1 scenario rate at speed S x S x [0.00143 – 1.7005 x 10^{-4} (aS)],

$m_{NOx\ a1}$ = MOBILE 4.1 scenario rate at speed S x S x [0.00386 + 8.1446 x 10^{-4} (aS)],

$m_{NO\ a2}$ = MOBILE 4.1 scenario rate at speed S x S x [0.00386 + 8.1446 x 10^{-4} (aS)]

The modal emissions defined by the previous expressions are a function of the MOBILE 4.1 scenario rate, which would imply to run the Mobile model for each speed at which acceleration and deceleration were needed. To overcome this problem and to implement the model in a excel sheet, equivalent models [5.73] were used based on regression analysis.

To calculate the total emission of a pollutant *p* (in grs) in a work zone the time spent by each vehicle in each mode of operation (acceleration (t_{ai}), deceleration (t_d), cruise (t_{wz}), queue (t_q)) is first computed. The average emission rate for each mode and for each pollutant is then multiplied by the time spent in that mode to obtain the emission values. These emission values, when multiplied by the total number of vehicles (*V*) in the time period of analysis (*T*), give the total mass of pollutants, as indicated by the following expression [5.73]:

$$E_{p_wz} = \left(m_{pd} \times t_d + m_{pi} \times t_q + m_{pa1} \times t_{a1} + m_{pcr1} \times t_{wz} + m_{pa2} \times t_{a2}\right) \times V \times T \qquad (5.37)$$

where, m_{pd} is the emission rate of pollutant *p* emitted under deceleration at an average speed v_d, m_{pai} is the emission rate of pollutant *p* emitted under acceleration at an average speed v_{ai}, m_{pi} is the emission rate of pollutant *p* emitted while idling, and m_{pcri} is the emission rate of pollutant *p* emitted while cruising at an average speed v_{cri}.

On the other end, the emission of a pollutant *p* (in grs) if the vehicles were travelling over the affected length in the absence of the work zone is given by,

$$E_{p_n} = m_{pcr2} \times t \times V \times T \qquad (5.38)$$

where, *t* is the total time to cross the affected length at normal approach speed in the absence of the work zone.

Hence, excess vehicle emissions of pollutant *p* (in grs) at a work zone is defined as the difference between the total emissions produced at and near the work zone minus those produced if traffic had cruised unimpeded through the work zone:

$$DE_p = E_{p_wz} - E_{p_n} \tag{5.39}$$

Box 5.3. Calculation of work zone mobile emissions

The QUEWZ model allows to establish a strategy leading to an optimal time schedule in relation to air emissions and fuel consumption. To exemplify this feature, 6 scenarios are considered for a motorway with two carriageways with four lanes in each direction. The ADT is 70287 vehicles/day. The percentage of heavy vehicles is assumed to be 12%. The traffic distribution per day and per day is represented in Figure 5.21, showing a peak hour at 8 hrs and a peak hour at 18 hrs.

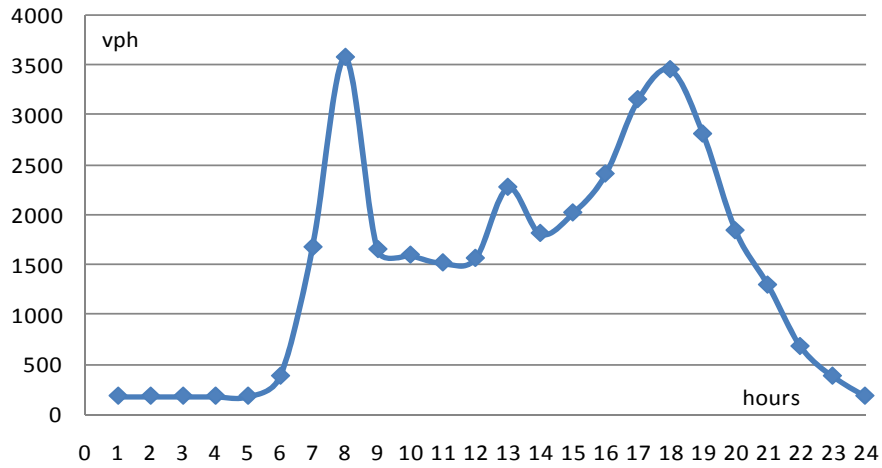


Figure 5.21. Traffic distribution per hour and per day

The maximum flow per lane before work activity is 2000 vehicles per hour per lane (vphpl). The restricted capacity per lane of the work zone, without activity, is 1800 vphpl and 1650 vphpl, respectively for night (22 – 6) and day (6 – 22) periods. The capacity per lane of the work zone during work activity is 1485 vphpl from 22 – 6 hours and 1450 vphpl from 6 – 22 hours. The differences between different scenarios are related to the number of lanes open and the time periods of closure. The characteristics of the work zone in each scenario are indicated in Table 5.30.

Table 5.30. Emissions (per day and per carriageway) in a motorway work zone

Scen.	No. of lanes	No. of open lanes	WZ length (km)	Restricted WZ capacity		Hours of restricted. activity	Hours of WZ activity
				Inactivity (vph)	Activity (vph)		
1	4	4	1	7200	6600	0 - 24	6 - 20
2	4	3	1	6600	4455	0 - 24	22 - 6
3	4	3	1	7200	4350	0 - 24	6 - 22
4	4	2	1	6600	2970	0 - 24	22 - 6
5	4	2	1	7200	2900	0 - 24	6 - 22
6	4	2	1	6600	2900	6 – 9; 18 - 22	9 - 18
				7200		22 - 6	

The emissions and fuel consumption, per day and per carriageway, corresponding to each scenario are indicated in Table 5.31.

Table 5.31. Emissions and fuel consumption (per day and per carriageway) in a motorway work zone

Scen.	Max. queue (km)	CO (kg/day)	HC (kg/day)	NO_x (kg/day)	Fuel (kg/day)	
					Gasoline	Diesel
1	0	68.56	0.76	0.61	390.07	699.35
2	0	68.56	0.77	0.62	391.09	700.51
3	0	68.56	1.26	0.73	485.91	808.29
4	0	68.53	0.78	0.62	391.90	701.42
5	2.3	478.89	39.47	9.07	1528.41	2195.24
6	1.6	225.51	15.71	3.85	963.57	1467.13

Scenario 1 is a reference scenario in which all lanes are open despite some work activity during the period of 6 - 20 hrs. In scenarios 2 and 3 there's the closure of a lane in different time periods. However, the volume of traffic is lower than the capacity of the work zone, and thus the difference between the night closure (scenario 2) and the day closure (scenario 3) is not very significant.

Scenarios 4 to 6 correspond to the situation in which two lanes of traffic are closed although at different time periods. When the closure is made during the night (scenario 4) the results are similar to the previous scenarios due to the same reasons. However, in scenarios 5 and 6 there's a queue with lengths of 2.3 km and 1.6 km, respectively. In both scenarios the closure is made during the day, although in scenario 6 the time period was reduced in comparison with scenario 5. This reduction result in a significant benefit, both in terms of emissions and fuel consumption.

This example shows that bad strategies in the management of the traffic flow in the work zone may result in very significant impacts and the simple arrangement of the time schedule for the closure of lanes can lead to significant benefits in terms of environmental burdens and user costs (as will be discussed in Chapter 8).

5.4.3.6.4. Uncertainties in work zone mobile emissions

Mobile emission data is not directly comparable to non-road mainly due to differences in emission standards, fuel characteristics, control technologies and operating modes. However, basic engine construction and behaviour is often similar for the two source categories [5.70].

No data is available in the literature in relation to the uncertainty in the emission factors used in the QUEWZ model and there's no detail data about the models used for its calculation, which could allow to perform such uncertainty analysis. Therefore, the values adopted for the 95% confidence interval of mobile emissions are indicated in Table 5.32, and they correspond to the values adopted for the non-road emissions indicated in Table 5.27. Also in this case lognormal distributions are adopted in order to avoid negative values.

Table 5.32. Uncertainties in mobile emission factors

Emission	95% confidence interval about the mean
HC	± 30 %
NO_x	± 6 %
CO	± 25 %

5.5. SYNOPSIS OF THE CHAPTER

This chapter introduced the general framework for the integral life cycle analysis. The proposed approach has two different purposes: (i) a detailed accounting of the environmental, economical and social impacts of a bridge over its life cycle, and (ii) to help in the decision making process of choosing between different construction solutions.

The proposed framework is based on the standardized framework for LCEA as specified in ISO 14040 series of standards. The evaluation of the environmental, economical and social criteria follow the same sequence of analysis and share the first steps of the approach: the goal and scope definition and the inventory stage. The focus of this chapter was on the common steps of the integral approach.

Although the lifetime structural performance of bridges is not directly included in the present framework, a scenario-based approach was proposed as an alternative approach.

In the inventory stage, a description was made of the type of data needed and databases or other sources of data were provided. One important aspect addressed in the inventory stage is the allocation of input/output flows of materials with recycling content. This issue is particularly important in a construction system where the reuse and recycling of construction materials are usually acknowledged as contributing to the sustainability of the sector. Therefore, allocation procedures were discussed in this chapter and an allocation procedure was proposed for the recycling of steel and concrete.

Uncertainties are unavoidable in life cycle analysis. Different types of uncertainties, occurring at different stages of life cycle analysis, were introduced in this chapter. However, this chapter addressed only uncertainties in relation to the inventory stage . Uncertainties in the other stages of life cycle analysis will be addressed in the following chapters.

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CHAPTER 6. LIFE CYCLE ENVIRONMENTAL ANALYSIS

6.1. INTRODUCTION

The evaluation of the environmental criteria over the life cycle follows the guidance from ISO standards ISO 14040 [6.1] and 14044 [6.2]. According to this set of standards, the evaluation comprehends four main steps, as represented in Figure 6.1. However, in this work, two additional steps are added: normalization and weighting. These two steps are considered to be optional in ISO standards, although they have a relevant role in a decision making process. Thus, the complete flowchart for the environmental life cycle analysis is represented in Figure 6.1.

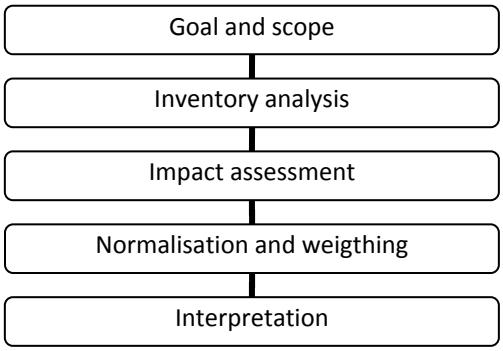


Figure 6.1. Scheme of the environmental life cycle analysis

The first and second steps in the flowchart of Figure 6.1 are shared with the other two criteria of the integral analysis and were discussed in the previous chapter. This chapter develops the remaining steps of the environmental analysis. In relation to the impact assessment analysis, the selected indicators are further described and calculation methods are introduced for its evaluation. Normalisation and weighting are here considered as two procedures of the same goal. In a decision making process, taking any decision based only in the results of the impact assessment analysis is a very complex task. Normalisation is in itself a process of weighting, as the result of an impact category is compared with a reference value of the same impact category. By means of a normalisation process, the relative importance of each impact is therefore enhanced. However, the comparison between impact categories is not taken into account in a normalisation procedure. Thus, weighting is further introduced to fulfil this aim. These two processes are developed in the same sub-chapter.

Finally, in the interpretation step, the results of the environmental analysis are reviewed and complementary analyses are performed to check the consistency of the results.

Furthermore, in this chapter uncertainties are discussed in the steps of impact assessment, normalization and weighting. Several types of uncertainties are identified and a methodology is proposed to address and operationalize those uncertainties in the life cycle analysis.

6.2. LIFE CYCLE IMPACT ASSESSMENT

6.2.1. Introduction

In this sub-chapter the list of indicators chosen to describe the impacts on the environment are presented. For each indicator, a general description of the impact category is made, followed by a detailed analysis of the methodologies used in each case for the quantification of the impacts. Furthermore, the aim of this sub-chapter is to identify the sources of uncertainty of each indicator in order to quantify them and make them operational in a Life Cycle Environmental Analysis (LCEA).

Each life cycle approach currently available works with a different set of indicators, as indicated in Chapter 4. According to the ISO standards [6.1][6.2], the choice of a particular set of impact categories shall be consistent and form a comprehensive set of environmental issues related to the goal and scope of the LCA study.

In this work, the main environmental indicators selected are the set of indicators defined in the Operational Guide to the ISO standards [6.3] developed by the Centre of Environmental Sciences (CML) in the University of Leiden. The choice of a single set of indicators from a single methodology is better than to choose partial sets of indicators from different methodologies as each approach developed a set of coherent indicators that takes into account the inter-dependency of the impacts. For instance, the characterization factors suggested by the Guide [6.3] for each impact take into consideration the fact that a certain emission can contribute simultaneously to several impact categories.

The choice of this particular set of impact categories and respective indicators has been made for several reasons:

i) the set is based on the best available models developed by the SETAC-Europe Working Group on Impact Assessment;

ii) the impact categories are defined according to the requirements of ISO standards 14040 and 14044;

iii) the set of impacts covers most of the environmental problems assessed by current Life Cycle Approaches;

iv) the impact indicators are defined at a mid-point level on the cause-effect chain; and

v) the characterization models have been developed based on European data (this is particularly important for impact categories that are location dependent).

The Guide distinguishes between “baseline” impact categories, “study-specific” impact categories and “other” impact categories, depending on the environmental relevance in relation to LCA and the availability of adequate characterization methods. The baseline impact categories comprehend the impacts that are included in most LCEA studies. The impacts that are going to be considered in this work belong to this category. The Guide recommends for each impact category a characterization method and characterization factors derived from the model.

Apart from the set of environmental indicators recommended by the Guide, one additional indicator is hereby considered: waste production.

The production of construction and demolition waste is one of the major impacts of the construction sector; hence, this indicator is introduced to address this problem.

However, this indicator will not be considered in the life cycle analysis in order to avoid double counting of impacts. The waste produced in each stage over the life cycle is quantified and the impacts due to its transportation and final destination is considered (either recycled or land filled). Thus, the aim of this indicator is essentially to call the attention to the problem.

The selected impact categories, which are going to be treated individually in the following section, are summarized in Table 6.1.

Table 6.1. Environmental impact categories

Indicator	Space scale	Time scale
Global warming	Global	20, 100, 500 yrs
Acidification	Local/continental	∞
Eutrophication	Local/continental	∞
Photo oxidant formation	Local/continental	-
Ozone depletion	Global	5, 10, 15, 20, 25, 30, 40 yrs and ∞
Ecotoxicity	Local/regional/continental/global	20, 100, 500 yrs and ∞
Human toxicity	Continental/global	20, 100, 500 yrs and ∞
Abiotic depletion	Global	-
Waste production	Local/regional	-

6.2.2. Indicators of environmental performance

6.2.2.1. Global warming

6.2.2.1.1. Introduction

The impact category “Global warming” is also referred to as “Climate change”. However, this is not accurate as both concepts refer to different phenomena. When discussing about “Global warming” and “Climate change”, two relationships must be addressed: (i) the relationship between the increase in CO_2 emissions in the atmosphere, since the industrial period, and global warming; and (ii) the relationship between global warming and climate change.

While the first relationship finds a more general world wide acceptance, the second is subject of great controversy, in part due to the complexity of the phenomena that rule the climate on Earth. Both relations will be analyzed in the following paragraphs.

In this dissertation the impact category indicator is referred to as “global warming”, as this is the mid-point effect in the impact pathway of CO_2 emissions and “climate change”. However, first the “natural” greenhouse effect is introduced.

The “Greenhouse effect”, represented in Figure 6.2, is due to the Infrared (IR) active gases, which are naturally present in the Earth’s atmosphere (e.g. H_2O, CO_2 and O_3), that absorb the terrestrial (infrared) energy (or radiation) leaving the Earth and reflect some of this heat back to earth, contributing to warm the surface and the lower atmosphere. The earth's climate is driven by the balance of energy or heat added by the sun and lost by the earth. Since the industrial period, increased concentrations of these gases, also known as greenhouse gases, are enhancing the natural Earth’s greenhouse effect, causing a temperature rise at the Earth’s surface and giving rise to concern over potential resultant climate changes.

The enhanced greenhouse effect is also called climate forcing (or radiative forcing) and can be quantified in terms of the amount of extra energy trapped in the atmosphere (measured in Watts per square meter).

Figure 6.2. Global Warming [6.4]

6.2.2.1.2. Green house gases

i) Carbon dioxide (CO_2)

CO_2 is a gas naturally produced through respiration, decay of plants and animals, and natural forest fires. Anthropogenic or manmade sources of CO_2 include fossil fuel combustion, land use changes, biomass burning and manufacture of cement. The main removal processes is absorption by the oceans and terrestrial biota, especially forestry.

The concentration of CO_2 in the atmosphere has increased from 280 parts per million (ppm) in the preindustrial period to about 367 ppm in 1999, being the highest value over the last 160000 years. This increase has come mainly from fossil fuel combustion and cement production, approximately 6.5 Pg CO_2/yr. Land changes produced a contribution of about 1.6 ± 1.0 Pg CO_2/yr [6.5]. These anthropogenic sources of CO_2 exceed the estimated uptake of CO_2 by the atmosphere and oceans, implying a significant but as yet unidentified terrestrial sink. Today CO_2 emissions will influence its atmospheric concentration in the years to come, since the time taken for atmospheric CO_2 to adjust to changes in sources or sinks is of the order of 50-200 years [6.5].

CO_2 is the largest individual contributor to the enhanced greenhouse effect, having a forcing value of about +1.56 Wm^{-2} (meaning an additional 1.56 Wm^{-2} of energy is trapped in the atmosphere as a result of the build up of CO_2) over the period 1765 to 1999.

ii) Methane (CH_4)

CH_4 is naturally formed in the wetland regions during the decay of organic material and by termites. The major sink for CH_4 is the chemical reaction with hydroxyl (OH) radicals in the lower atmosphere.

The concentration of CH_4 in the atmosphere has increased from about 0.80 ppm in the preindustrial times to about 1.75 ppm in 1998. Over this period CH_4 has contributed a forcing value of +0.48 Wm^{-2}. The main causes are due to fossil fuel related sources, approximately 70-120 Tg CH_4/yr, and from rice cultivation, animal husbandry, biomass burning and landfills, contributing about 300-350 Tg CH_4/yr [6.5].

iii) Nitrous Oxide (N_2O)

N_2O is naturally produced by oceans and rainforests. Anthropogenic sources include nylon and nitric acid production, agricultural practices, cars with catalytic converters and biomass burning. The major sinks for N_2O are photolytic reactions in the atmosphere.

The atmospheric concentration of N_2O has increased from about 275 ppb in the preindustrial period to about 314 ppb in 1998. N_2O is responsible for a forcing of about +0.15 Wm^{-2} since 1765 [6.5].

iv) Chlorofluorocarbons (CFCs)

CFSc are a group of anthropogenic compounds containing chlorine, fluorine and carbon. These compounds were not significantly present in the atmosphere before 1950. However, since then they have been widely used as refrigerants and in spray propellants and foam manufacture. There are no sinks for CFCs in the lower atmosphere. As a result they are transported to the stratosphere where they are broken down by UV radiation, releasing free chlorine atoms which cause significant ozone depletion.

In 1998 the atmospheric concentration of CFC-11 was 268 ppt. The total forcing value of CFCs is about +0.30 Wm^{-2}. This includes CFC-11, 12, 113, 114, 115, methylchloroform and carbon tetrachloride [6.5].

Because of their role in catalyzing decomposition of stratospheric ozone, production of these compounds has been dramatically reduced in response to the Montreal Protocol and subsequent international agreements. However, atmospheric concentrations of these compounds will remain significant into the next years because of their relatively long lifetimes.

6.2.2.1.3. The carbon cycle and atmospheric CO_2

The carbon cycle model presented in the following paragraphs was developed in the framework of the Intergovernmental Panel on Global Climate Change (IPCC).

The IPCC is a scientific body established in 1988 by the UNEP (United Nations Environmental Programme) and WMO (World Meteorological Organisation) with three main objectives: (i) to assess the available scientific information on climate change; (Iii) to assess the environmental and socio-economic impacts of climate change; and (iii) to formulate response strategies. The group played a large part in the formulation of a UN framework convention on climate change, signed in 1992, and have produced four major assessment reports; the first in 1990, the second in 1995, the third in 2001, the fourth and more recent in 2007.

The main components of the natural carbon cycle are represented in Figure 6.3 [6.6]. The two most important fluxes in regard of the balance of CO_2 in the atmosphere are the gross primary production and respiration by the land biosphere and the physical air-sea exchange (denoted by thick arrows in Figure 6.3). These fluxes are approximately balanced each year.

Additional natural fluxes of carbon, important on longer time-scales, comprehend the flux of 0.4 Pg CO_2/yr from atmospheric CO_2 via plants to inert soil carbon, which is approximately balanced on a time-scale of several millenia by export of dissolved organic carbon (DOC) in rivers; and a flux of 0.4 PgC/yr dissolved inorganic carbon (DIC) derived from the weathering of $CaCO_3$, which takes up CO_2 from the atmosphere in a 1:1 ratio [6.6]. These fluxes of DOC and DIC together comprise the river transport of 0.8 PgC/yr. In the ocean, the DOC from rivers is respired and released to the atmosphere, while $CaCO_3$ production by marine organisms results in half of the DIC from rivers being returned to the atmosphere and half being buried in deep-sea sediments – which are the precursor of carbonate rocks.

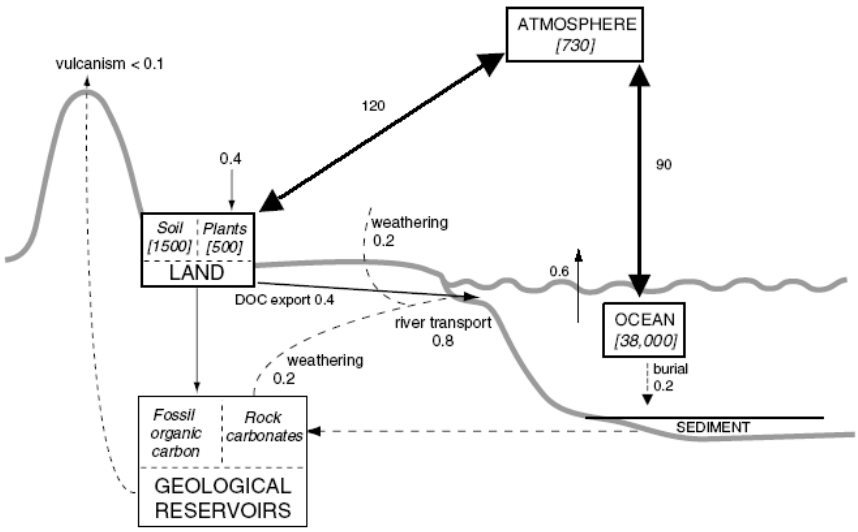


Figure 6.3. Main components of the natural carbon cycle (from [6.6])

Fluxes with even longer time-scales include the burial of organic matter as fossil organic carbon (including fossil fuels) and outgassing of CO_2 through tectonic processes (volcanism).

The main anthropogenic processes that release CO_2 to the atmosphere, fossil fuel burning and land-use change, are represented in Figure 6.4. Only a part of this CO_2 stays in the atmosphere; the rest is taken up by the land (plants and soil) or by the ocean. These uptake components represent imbalances in the large natural two-way successful fluxes between atmosphere and ocean and between atmosphere and land [6.6].

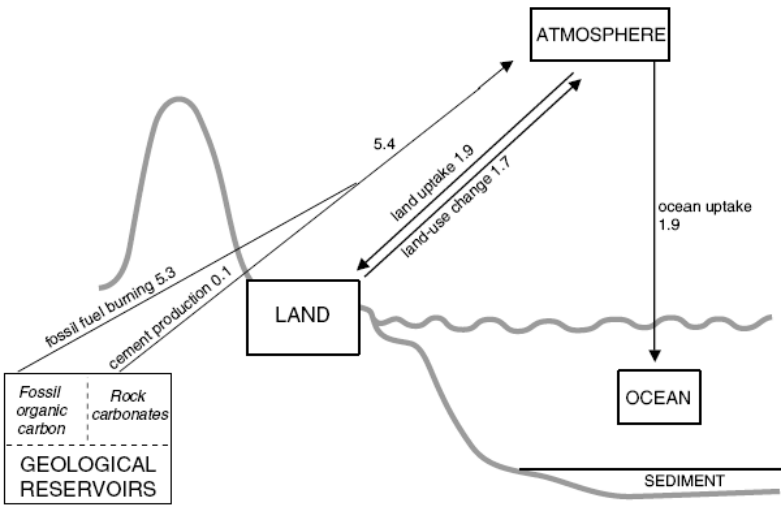


Figure 6.4. Human perturbation of the carbon cycle (from [6.6])

6.2.2.1.4. Lifetime of greenhouse gases

Prediction of future persistence of anthropogenic greenhouse gases in the atmosphere is based on mathematical models that simulate future additions and removals. The greenhouse gas concentrations predicted by these models are subject to large uncertainties in the effects of both natural processes and human activities. For some greenhouse gases persistence can be estimated from "mean residence times", which are obtained with simple linear models and represent the time that would be necessary for removal of 63% of the anthropogenic excess of the material in the atmosphere, if anthropogenic sources were abruptly diminished to zero. This approach yields a rough measure of the persistence in the atmosphere of anthropogenic additions of CH_4 with an estimated mean residence time of 10 years; N_2O, 100 years; and CFC-11 and CFC-12, 50 and 102 years, respectively [6.6].

The persistence of anthropogenic CO_2 in the atmosphere cannot be estimated with such a simple model because exchange with the ocean and sediments leads to a more complex behaviour. Model simulations of oceanic CO_2 uptake provide response times associated with CO_2 gas exchange at the ocean surface of approximately 10 years and downward mixing of surface waters on the order of decades to centuries. But even when these oceanic CO_2 removal processes are allowed sufficient time in the models to reach their maximum capacity, they can remove only about 70 to 85% of the anthropogenic CO_2 added to the atmosphere. Additional CO_2 might be removed by burial in soils or deep sea sediments through mechanisms that, although poorly understood, are generally believed to require times extending to thousands of years. Therefore, of the several anthropogenic greenhouse gases, CO_2 is the most important agent of potential future climate warming because of its large current greenhouse forcing, its substantial projected future forcing, and its long persistence in the atmosphere.

6.2.2.1.5. Trend of greenhouse gases

Total greenhouse gas emissions in the EU-27, excluding emission and removals from land-use, land use change and forestry (LULUCF), decreased by 0.3% between 2005 and 2006 and by 7.7% between 1990 and 2006 [6.7]. During the 1990s, emissions decreased strongly in the Member States that joined the EU since 1st May 2004 (EU-12). Between 2000 and 2005, trends were similar in the pre-2004 EU Member States (EU-15) and in the EU-12. However between 2005 and 2006, emissions decreased in the EU-15 while they increased in the EU-12.

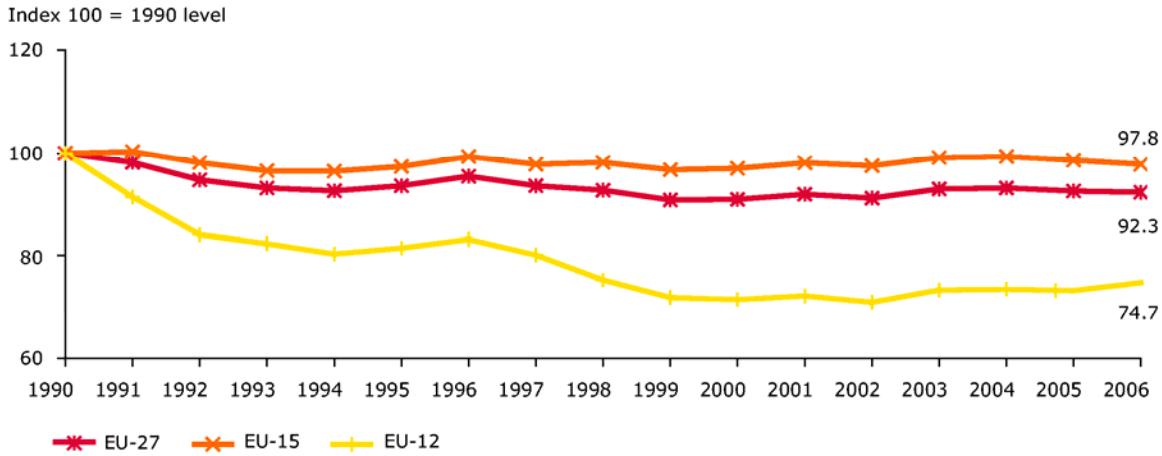


Figure 6.5. Greenhouse emissions trends for EU-27, EU-15 and EU-12, 1990-2006 (from [6.7])

Between 1990 and 2006, greenhouse gas emissions in the EU-27 decreased in all main emitting sectors except in the transport sector, where they increased considerably. In the EU-15, CO_2 emissions from public electricity and heat production also increased.

In 2006, total EU-15 greenhouse gas emissions (excluding LULUCF) had decreased by 2.7% compared to the Kyoto base year. 2006 emissions of all EU-12 Member States that have a Kyoto target were well below their Kyoto target, except in Slovenia.

According to the most recent inventory of greenhouse gas emissions, published by the EEA [6.8], emissions have continued their downward trend in 2008. The EU-27's emissions stood 11.3% below their 1990 levels, meaning that EU-27 has already achieved more than half of its unilateral reduction target of 20% by 2020 through domestic emission reductions alone.

The EU-15 emissions achieved a reduction of 6.9% compared to Kyoto base-year levels. This means the EU-15 has achieved more than 3/4 of the total reduction needed to reach its 8% reduction commitment by 2008-2012 under the Kyoto Protocol.

6.2.2.2. Ozone Depletion

6.2.2.2.1. Introduction

High in the earth's atmosphere (the stratosphere), chemical processes maintain a balanced concentration of ozone. The ozone layer acts like a shield in the upper atmosphere to protect the earth by absorbing much of the harmful ultraviolet radiation (UV) from the sun [6.9]. If a gas can stay in the atmosphere long enough to reach the stratosphere, and if the gas carries bromine or chlorine atoms, the ozone balance may be threatened as free bromine and chlorine can accelerate the breakdown of ozone.

In 1974, emissions of chlorofluorocarbons or CFCs were associated with the depletion of ozone in the stratosphere. In the 1980s, a thinning of the ozone layer over Antarctica was observed; although additional research shown that ozone depletion occurs over every continent [6.9].

To address this problem, in 1987, the Montreal Protocol on substances that deplete the ozone layer was signed. Today, more than 190 countries have ratified the treaty. These countries were committed to take measures to limit or phase-out production and consumption of ozone depleting substances in order to protect the stratospheric ozone layer against depletion.

This protocol was one of the most successful protocols ever made, as described in the following clause.

6.2.2.2.2. Trends of ozone-depleting substances (ODSs)

Consumption and production of ozone-depleting substances (ODSs) in EEA member countries has gone down markedly, particularly in the first half of the 1990s [6.10]. Before the Montreal Protocol was signed in 1987, the production of ODSs in the EEA stood at about 516616 ODP (i.e. ozone depletion potential) tonnes. Implementation of the Montreal Protocol has led to a decrease in the atmospheric burden of ODSs in the lower atmosphere and in the stratosphere. The total production and consumption of ODSs in EEA member countries has decreased strongly since the Montreal Protocol as illustrated in Figure 6.6. In 2006, production was down to 114 OPD tonnes, and in 2007 it was actually negative, as illustrated in Figure 6.6. Negative numbers are possible because 'production' is defined under Article 1(5) of the Montreal Protocol as

production minus the amount destroyed minus the amount entirely used as feedstock in the manufacture of other chemicals. Therefore, calculated production may be negative if destroyed amounts and/or feedstocks (e.g. from a carry-over stock) exceed production. Consumption is defined as production plus imports minus exports of controlled substances under the Montreal Protocol. As with calculated production, the consumption of ODS can be negative.

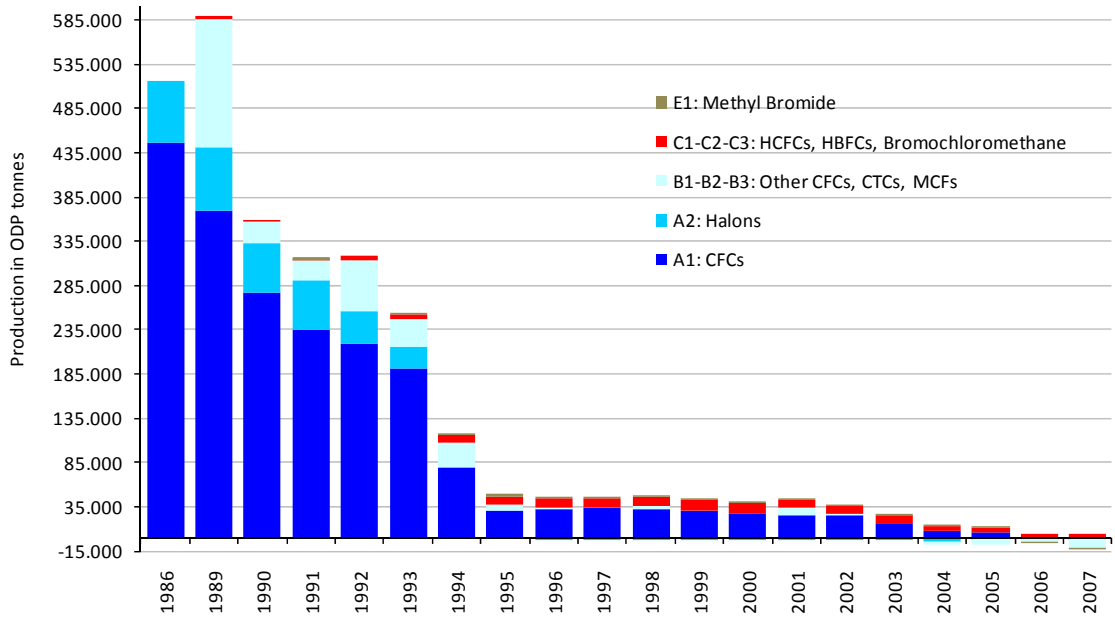


Figure 6.6. Production of ozone depleting substances in EEA member countries, 1986-2007 [6.10]

Globally, the 2006 UNEP Synthesis Assessment under the Montreal Protocol on Substances that Deplete the Ozone Layer [6.11] showed there is clear evidence of a decrease in the atmospheric burden of ozone-depleting substances (ODSs) in the lower atmosphere and in the stratosphere; as well as some early signs of an onset of the expected stratospheric ozone recovery.

Nevertheless, according to the EEA [6.10], in spite of the current optimistic situation, the ozone hole expanded in 2008 to 27 million square kilometres, equivalent to about six times the territory of the EU.

6.2.2.3. Photo oxidant formation

6.2.2.3.1. Introduction

Photo-oxidant formation is the formation of reactive chemical compounds such as ozone by the action of ultraviolet (UV) light on certain primary air pollutants. Photo-oxidant formation, also known as “summer smog” or “photochemical smog”, constitutes a major part of the smog above many cities and industrialized areas. Ground-level ozone is among the most serious air pollutants in Europe today [6.12]. Elevated levels of ozone cause health problems, premature deaths, reduced agricultural crop yields, changes in biodiversity and damage to materials.

Nitrogen oxides (NO_x), carbon monoxide (CO) and volatile organic compounds (VOCs) are emitted into the atmosphere from many natural and anthropogenic processes. In the lowest portion of Earth’s atmosphere, the troposphere, and under the influence of UV-light, photo-

oxidants are formed through photochemical oxidation of VOCs and CO in the presence of NOx. These reactions lead to the formation of ozone (O3), peroxyacetyl nitrate (PAN), peroxybenzoyl nitrate (PBN) and a number of other substances.

Photochemical compounds are toxic to humans, animals and plants and are the cause of many degradation processes on materials. In the plants, tropospheric ozone is absorbed by plants through the leafs. In the leaves, ozone degrades chlorophyll, which leads to the incapability of the photosynthesis process to occur and consequently affecting the growth of the plant. In humans, low concentrations of photochemical smog can cause reduced functionality of the lungs, chest constriction and eye, nose and throat irritation. At higher concentrations, it may cause coughing and decreased ability to concentrate. In regard of materials, ozone attacks natural rubber, cellulose, synthetic polymers, etc., and reduces the lifetime of many materials (textiles, car tires, etc.)

6.2.2.3.2. Trends of tropospheric (ground-level) ozone precursors

The National Emission Ceilings Directive (NECD) [6.13] and Gothenburg protocol under the United Nations Convention on Long-Range Transboundary Air Pollution (LRTAP Convention) [6.14] set for each of the EU-27 Member States ceilings (i.e. limits) for two ozone precursors, NO_x and NMVOC, which must be met by 2010. According to the EEA, data from 2007 shows that slightly more than half of the 27 Member States are not on track towards meeting their combined target for the two ozone precursor pollutants. Similarly, the EU-27 as a whole is also not on track to achieve its aggregated ceiling for these pollutants [6.15].

Aggregated emissions of tropospheric (ground-level) ozone precursors have reduced by 39% across the EEA-32 region between 1990 and 2007 (Figure 6.7). Within most countries reductions have occurred for the aggregated emissions of the two ozone precursors (NO_x and NMVOC). The largest reductions have occurred in Liechtenstein (-60%), Switzerland (-60%) and Germany (-55%), but the emissions of these two pollutants have increased in six countries (Romania, Greece, Portugal, Spain, Cyprus and Turkey).

Emissions of NO_x (51 % of the total aggregated emissions) and NMVOC (36 %) are the most important pollutants that contributed to the formation of tropospheric ozone in 2007. Carbon monoxide and methane contributed 12% and 1%, respectively. However emissions of both these pollutants have been significantly reduced since 1990 - NO_x has contributed 37% and NMVOC 40% of the total observed reduction of precursor emissions. This reduction of emissions is mainly due to the introduction of three way catalytic converters for cars and increased penetration of diesel-fuelled vehicles. The introduction of other European legislative measures has also contributed to the reduction, such as the implementation of the Solvent Emissions Directive in industrial processes.

On an individual pollutant basis, other EEA analysis indicates that many Member States anticipate that, without implementing additional measures to reduce emissions, they will miss one or any of their respective 2010 NECD ceilings. The 2010 emission ceiling for NO_x is the most difficult ceiling for many Member States to meet. Twelve Member States have reported that they anticipate missing their NO_x ceiling (Austria, Belgium, France, Germany, Ireland, Luxemburg, the Netherlands, Poland, Slovenia, Spain, Sweden and the United Kingdom). Five Member States

report they anticipate missing their NMVOC ceiling (Denmark, France, Poland, Portugal and Spain).

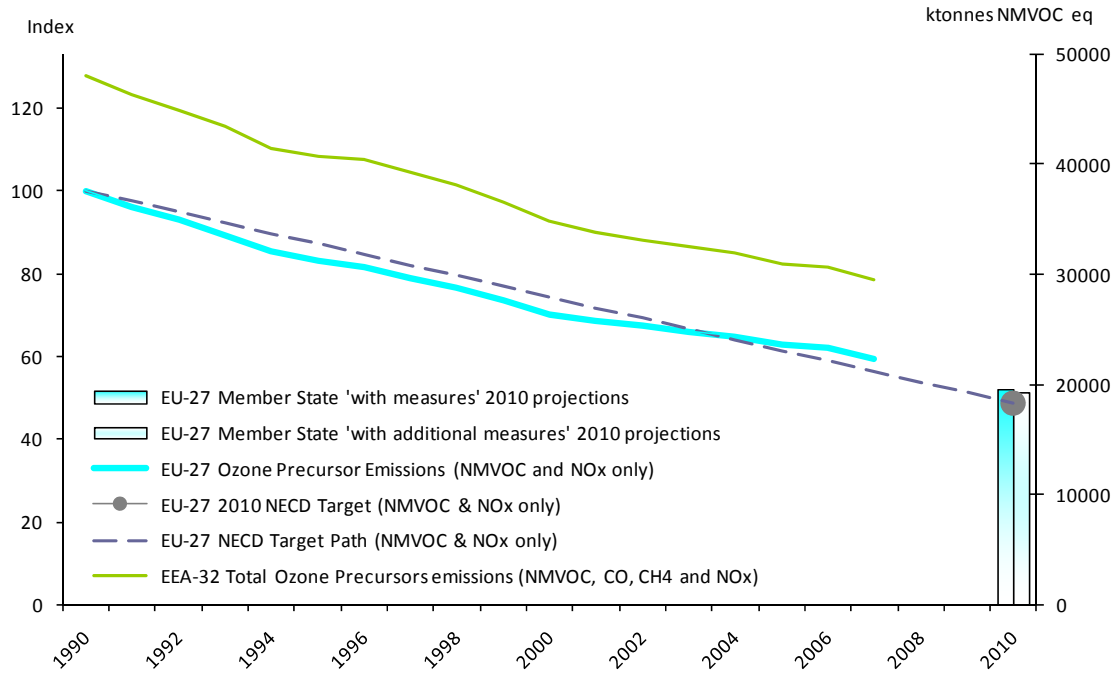


Figure 6.7. Emissions of ozone precursors (EEA member countries) [6.15]

6.2.2.4. Acidification

6.2.2.4.1. Introduction

Acidification is the process where air pollution (mainly ammonia (NH_3), sulphur dioxide (SO_2) and nitrogen oxides (NO_x)) is converted into acid substances. Acidifying compounds emitted into the atmosphere are transported by wind and deposit as acidic particles or acid rain or snow hundreds or thousands of km away from the source. Acid rain is considered to be an example of transboundary (international) pollution.

Acid deposition may occur as wet precipitation (mist, snow, or rain) or in the form of particles of gases as dry deposition or is absorbed directly by lakes, plants, and masonry as gases.

Acidic precipitation is mainly caused by the release into the atmosphere of sulphur dioxide and oxides of nitrogen, which dissolve in pure rainwater making it acidic. Sulphur dioxide is formed by the burning of fossil fuels, such as coal, that contain high quantities of sulphur; nitrogen oxides are produced by various industrial activities and are present in car exhaust fumes.

Some soils contain natural alkalinity, such as chalk or lime, which neutralizes the effects of acidification; however, this effect is limited. Acidification occurs when the capacity of the soil or water bodies to resist or neutralise acidifying atmospheric deposition begins to decline. Ecosystems may eventually lose their neutralising or buffering capacity completely, if acid deposition rates persistently exceed their levels of tolerance.

Acid substances may attack man-made and natural materials and cause damage to health, human capital and natural values. Materials such as limestone, cement and concrete are sensitive to acid because it may react with their content of chalk and disintegrate the material

structure. Acids can also cause considerable corrosion of metal surfaces. In terrestrial systems, acidification increases the susceptibility of plants and trees to environmental pressures, leading to reduced health and eventually death of whole forests. In aquatic systems (lakes and rivers), acid deposition may change the composition of living organisms in the water (for instance, by reducing the activity and reproduction of photosynthetic algae), leading, in worst cases, to the elimination of all life.

Acidification is one of the impact categories in which local sensitivity plays an important role. In Europe there are different areas of sensitivity according to the concentration of the pollutant in the atmosphere. Figure 6.8 shows the exceedance of the Critical Load (CL) for acidification in Europe [6.16]. The critical load of sulphur and nitrogen acidity is defined as the highest deposition of acidifying compounds that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function.

According to EEA [6.16], 84% of the gridcells with critical loads exceedances in 1990 showed a decline in exceeded area of more than 50% by 2010. The risk of ecosystem acidification in Europe has considerably improved and it is predicted to improve further. Future predictions indicate the problem will only be an issue at some hot spots, in particular at the border area between the Netherlands and Germany.

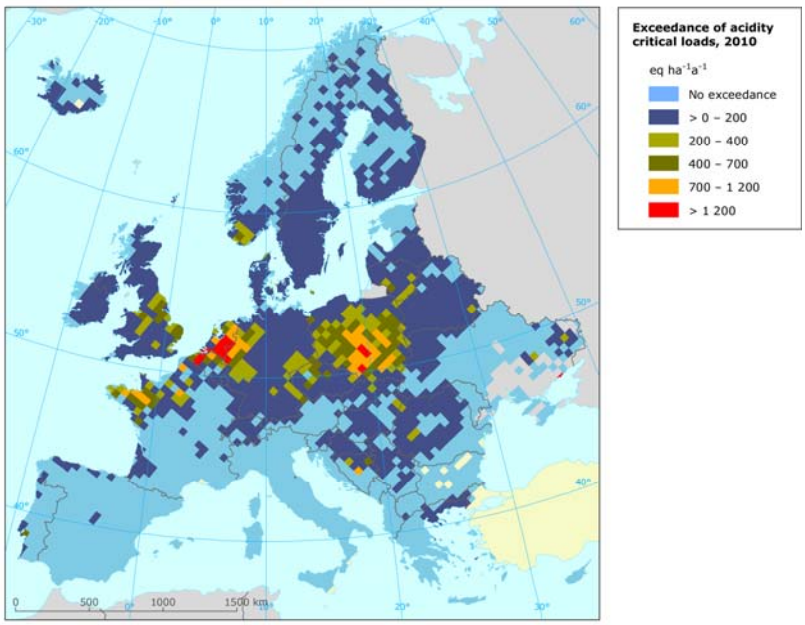


Figure 6.8. Distribution of the magnitude of average accumulated exceedance of the critical load for acidity in 2010 [6.16]

6.2.2.4.2. Trend of acidifying emissions in Europe

According to the latest EEA assessment (in 2008), the overall emissions of acidifying gases (NH_3, NO_x, SO_2) have decreased significantly in most EEA member countries between 1990 and 2005 despite increased economic activity (GDP) [6.16]. Between 1900 and 2005 emission of acidifying pollutants in the EU-15 Member States decreased by 47% from 1025 kt to 539 kt (see Figure

6.9). In the same period, emissions in the New EU-12 countries declined significantly from 503 kt to 206 kt, a reduction of 59%. Both cases are well on track on meeting their 2010 emission targets for acidifying pollutants, under the NECD.

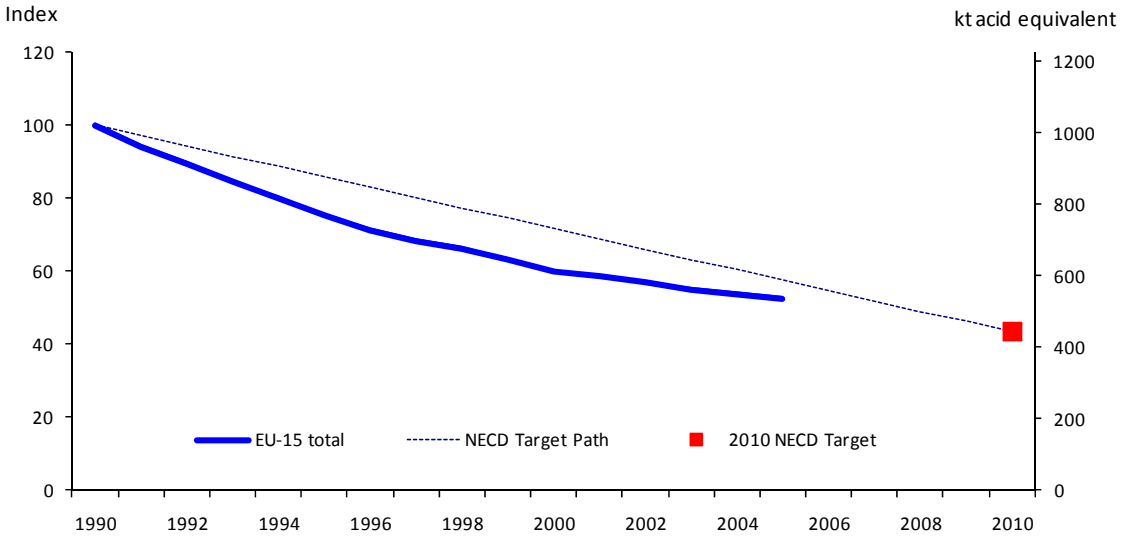


Figure 6.9. Emission trends of acidifying pollutants in EU-15 (ktonnes acid equivalent) [6.16]

6.2.2.5. Eutrophication

6.2.2.5.1. Introduction

Nutrients are usually added to the soil through fertilization to stimulate the growth of plants and agricultural products. When these nutrients end up in sensitive natural water or land areas, this unintended fertilization may result in overproduction of plants or algae, which, in turn, can smother other organisms when they die and begin to decay. This environmental problem, which is illustrated in Figure 6.10, is generally known as nutrient enrichment or eutrophication and it covers all potential impacts of excessively high environmental levels of nutrients, the most important of which are nitrogen (N) and phosphorus (P).

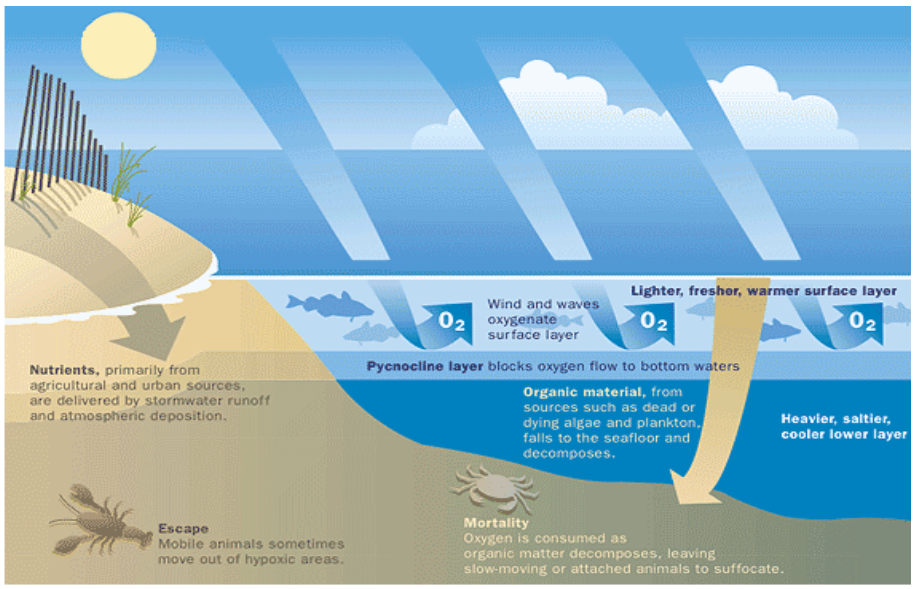


Figure 6.10. The eutrophication process [6.17]

Nutrient enrichment may be a problem both in the aquatic environment and in the terrestrial environment. In the aquatic environment (such as lakes, rivers, estuaries, shallow seas, etc.) the nutrient enrichment results in the increased growth of algae which leads to increased oxygen consumption in the water, due to increased decomposition of dead algae in the bottom waters and increased respiration of living algae during the night. The increased growth of algae also causes a reduction in the penetration of light into the water, limiting the photosynthesis of plants at the bottom, and a reduction in the visibility of the water.

In the terrestrial environment, sensitive land areas with low concentration of nutrients in the soil (oligotrophic land) may disappear when exposed to nutrient enrichment.

Figure 6.11 represents the exceedance of the Critical Load (CL) for eutrophication in Europe, showing different sensitive areas across Europe [6.16]. The critical load of nutrient nitrogen is defined as the highest atmospheric deposition of nitrogen compounds below which harmful effects in ecosystem structure and function do not occur, according to present knowledge.

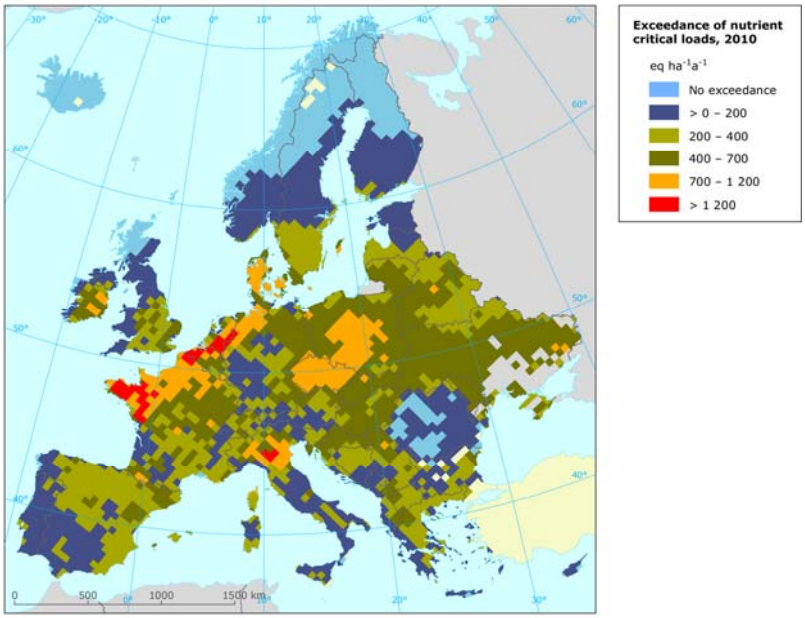


Figure 6.11. Distribution of the magnitude of average accumulated exceedance of the critical load for eutrophication in 2010 [6.16]

According to the EEA, the magnitude of the risk of ecosystem eutrophication and its geographical coverage has diminished only slightly over the years. However, future predictions indicate that the risk is still widespread over Europe.

6.2.2.5.2. Trend of eutrophication emissions in Europe

According to the European Environmental Agency [6.16], there have been limited improvements, since 1980, in the exposure of European ecosystems to eutrophication. Figure 6.12 indicates the percentage of the area in the broader European continent (A = 5 918E+03 km^2) and in the countries of the EU-25 (A = 1 655E+03 km^2) where there is an average accumulated exceedance of critical loads for eutrophication.

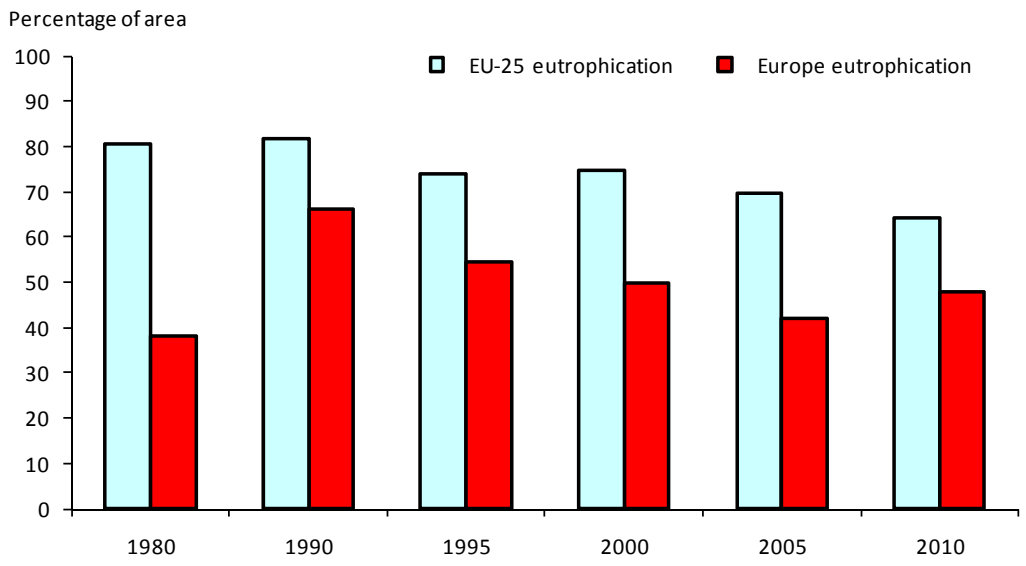


Figure 6.12. EU-25 and European-wide ecosystem damage area (average accumulated exceedance of critical loads) [6.16]

It is noted from the previous figure that the broader European continent has a lesser problem than the countries of the EU-25.

6.2.2.6. Air pollution and toxicity

6.2.2.6.1. Introduction

Air pollution includes all contaminants found in the atmosphere, either in the form of gases or particles, and can have serious consequences on the health of human beings and on natural ecosystems. The sources of this problem are both natural and human-based.

Air pollution is a local but also a transboundary issue; as pollutants released in one country may be transported in the atmosphere and harm the environment and human health elsewhere.

In Europe, as a result of the increasing implementation of environmental policies and regulations, emissions of many air pollutants have fallen substantially since 1990. However, since 1997, measured concentrations of particulate matter and ozone in the air have not shown any significant improvement despite the decrease in emissions. The situation is particularly serious for Europe's urban population living in cities, where certain EU air quality limits (set for the protection of human health) are exceeded [6.16]. Also, as referred in the previous clauses, some countries are likely to miss one or more legally binding 2010 emission ceilings of important air pollutants. The need to reduce exposure to air pollution remains an important issue.

Another important type of pollutant harming the human health and the environment are heavy metals. Heavy metals (such as cadmium, lead and mercury) are recognised as being toxic substances to humans and environment. All have the quality of being progressively accumulated higher up the food chain, such that chronic exposure of lower organisms to much lower concentrations can expose predatory organisms, including humans, to potentially harmful concentrations. In humans they are also of direct concern because of their toxicity, their potential to cause cancer and their potential ability to cause harmful effects at low concentrations. The relative toxic/carcinogenic potencies of heavy metals are compound

specific. Specifically, exposure to heavy metals has been linked with developmental retardation, various cancers and kidney damage. Metals are persistent throughout the environment, and cadmium, lead and mercury are among those heavy metals that are already a focus of international and EU action. These substances tend not just to be confined to a given geographical region, and thus are not always open to effective local control. For example, in the case of cadmium, much is found in fine particles which do not readily dry deposit, rather having long residence times in the atmosphere and hence are subject to long-range transport processes.

6.2.2.6.2. Trend of toxic emissions in Europe

The trend in some air pollutants were presented in the previous clauses (see Figure 6.7 and Figure 6.9). It is noted that certain non-methane volatile organic compounds (NMVOCs), such as benzene and 1.3 butadiene, are hazardous to human health.

In relation to the emission of heavy metals and according to EEA [6.16], across the EEA-32 countries, emissions of lead have decreased by 88%, mercury by 57% and cadmium by 56% between 1990 and 2007, as represented in Figure 6.13. For each substance, the most significant sources in 2007 are from energy-related sources associated with fuel combustion, particularly from public power and heat generating facilities and in industrial facilities.

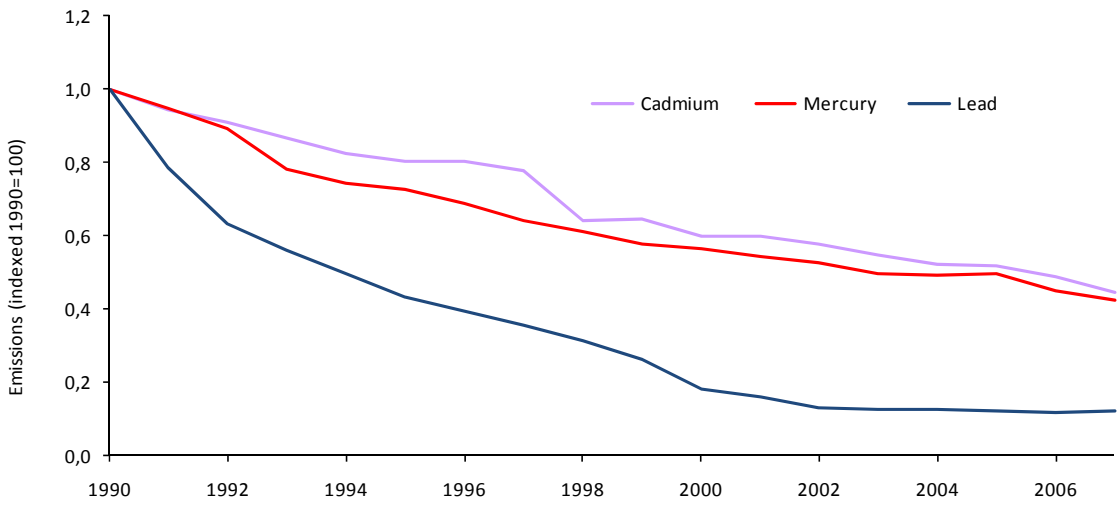


Figure 6.13. Emission trends of selected heavy metals (EEA member countries - indexed 1990 = 100) [6.16]

Much progress has been made since the early 1990s in reducing point source emissions of cadmium and lead (e.g. emissions from industrial facilities). This has been achieved through improvements in for example abatement technologies for wastewater treatment, incinerators and in metal refining and smelting industries, and in some countries by the closure of older industrial facilities as a consequence of economic re-structuring.

In the case of mercury, the observed decrease in emissions may be largely attributed to improved controls on mercury cells used in industrial processes (e.g. in the chlor-alkali process) including the replacement of old mercury cells by diaphragm or membrane cells, and the general decline of coal use across Europe as a result of fuel switching.

Although the promotion of unleaded petrol within the EU and in other EEA member countries has been a particular success story, the road transport sector still remains an important source of lead, contributing around 25% of total lead emission in the EEA-32 region. However over the last 5 year period little progress has been made in reducing emissions further; total emissions of lead have remained largely constant.

6.2.2.7. Natural resources depletion

6.2.2.7.1. Introduction

The Earth's natural resources are vital to the survival and development of the human population. Some of these resources, such as minerals, species, and habitats, are finite — once they have been exhausted or destroyed, they are gone forever [6.18]. Others, such as air, water, and wood, are renewable — although we generally rely on the Earth's natural systems to regrow, renew, and purify them for us. Although many effects of over-exploitation are felt locally, the growing interdependence of nations and international trade in natural resources make their management a global issue.

The main driving forces of resource depletion are population and economical growth. The estimated 50% growth in the global population over the next 50 years will put an ever higher pressure on the environment.

In Europe, the main driving forces for resource depletion are economy growth and the pattern of development. The European model of development is based on a high level of resource consumption, including materials and energy. Current material consumption in industrialized countries is between 31 and 74 tonnes/person/year [6.18].

6.2.2.7.2. Trends in resources consumption

Earth has a limited source of supplies. The availability of some non-renewable resources, including many metals and construction materials, does not currently give cause for too much concern.

In the EU-15 (see Figure 6.14), domestic material consumption of construction minerals increased somewhat during the 1990s, to around 2.6 billion tonnes (about 7.0 tonnes per capita) per year [6.18].

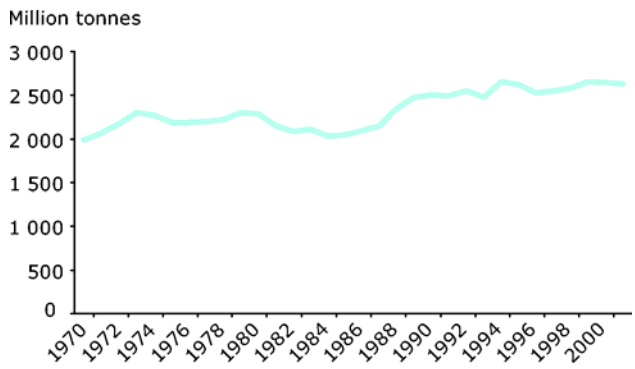


Figure 6.14. Annual domestic consumption of construction minerals, EU15 1970-2001 [6.18]

The volumes of construction minerals comsumed per year are very high, which make them environmental significant. The extraction of construction minerals, apart from emissions and

energy consumption due to the processes of extraction and consequent processing, tends to be very damaging to landscapes, generate noise, and have negative impacts on biodiversity [6.18]. Moreover, the increasing consumption of construction minerals is related to the transformation of land into built-up area, leading to significant losses of its basic natural functions.

6.2.2.8. Waste production

Waste production is a global problem and includes several flows. In this work, waste production relates to the waste generated in construction and demolitions activities.

According to a report from the European Environmental Agency [6.19], about 850 million tonnes of construction and demolition waste is generated in the EU per year. This represents 31% of the total waste generation in the EU.

In order to comply with the objectives of the new EU Waste Framework Directive (see Chapter 2), Member States shall take the necessary measures designed to achieve the following targets:

(a) by 2020, the preparing for re-use and the recycling of waste materials such as at least paper, metal, plastic and glass from households and possibly from other origins as far as these waste streams are similar to waste from households, shall be increased to a minimum of overall 50% by weight.

(b) by 2020 the preparing for re-use, recycling and other material recovery, including backfilling operations using waste to substitute other materials, of non-hazardous construction and demolition waste excluding naturally occurring material defined in category 170504 in the European Waste Catalogue (EWC) shall be increased to a minimum of 70% by weight."

The Directive does not include targets for individual waste types belonging to municipal waste and construction and demolition waste, but does demand an overall target of 50% and 70% respectively. Further, the overall target for the municipal waste requires that at least glass, metal, paper and plastic are included, although it can include other waste streams.

The production and intended reduction of construction and demolition waste is thus an indispensable indicator for the goal of the integrated approach proposed in this thesis.

6.2.3. Calculation methods

6.2.3.1. Introduction

In this dissertation, the impact categories are chosen at a mid-point level and thus, a problem-oriented methodology is used for the calculation of the indicators, except "waste production". Hence, each category indicator has a characterization model from which characterization factors are derived. According to this method impact categories are linear functions, i.e. characterization factors are independent of the magnitude of the environmental intervention, as given by expression (6.1):

$$impact_{cat} = \sum_i m_i \times charact_factor_{cat,i} \tag{6.1}$$

where m_i is the mass of the inventory flow *i* and $charact_factor_{cat,\,i}$ is the characterization factor of inventory flow *i* for the impact category.

As already referred in Chapter 3, a problem-oriented approach is mass oriented; emissions are taken into consideration independently of the site or the time they are released. Therefore potential environmental impacts are evaluated instead of "real" impacts.

Thus, as referred in the first paragraph, the problem-oriented approach is going to be used for all indicators except "Waste production". This indicator is calculated directly from the use of Inventories. In this case, the impact assessment step is skipped, and the life cycle inventory results are directly used in the final interpretation step.

The following sections describe the characterization models and characterisation factors for the selected impact categories.

6.2.3.2. Global Warming Potential (GWP)

The Global Warming indicator measures the impact of human emissions on the radiative forcing of the atmosphere.

Global Warming Potentials (GWPs) are intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas. However, the impact of greenhouse gas emissions upon the atmosphere is related not only to radiative properties, but also to the time-scale characterizing the removal of the substance from the atmosphere. Radiative properties control the absorption of radiation per kilogram of gas present at any instant, but the lifetime controls how long an emitted kilogram is retained in the atmosphere and hence is able to influence the thermal budget [6.20].

GWPs are though a measure of the relative radiative effect of a given substance compared to another, integrated over a chosen time horizon. The choice of the time horizon depends in part upon whether the intention is to emphasize shorter-term processes (e.g. response of cloud cover to surface temperature changes) or longer-term phenomena (such as sea level rise). In addition, if the speed of potential climate change is of greatest interest (rather than the magnitude), then a focus on shorter time horizons can be useful.

GWPs are defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas [6.20].

The generally accepted authority on GWPs is the Intergovernmental Panel on Climate Change (IPCC), and in their definition of GWPs the reference gas is Carbon Dioxide (CO_2). Therefore, the global warming potential of substance *i* (GWP_i) is given by the ratio between the increased infrared absorption due to the instantaneous emission of 1 kg of the substance and that due to an equal emission of carbon dioxide (CO_2), both integrated over time, as given by [6.20],

$$GWP_{T,i} = \frac{\int_0^T a_i \left[c_i(t)\right] dt}{\int_0^T a_{CO_2} \left[c_{CO_2}(t)\right] dt} \qquad (6.2)$$

where, a_i is the radiative forcing per unit concentration increase of greenhouse gas *i* (in $W.m^{-2}.kg^{-1}$), $c_i(t)$ is the concentration of greenhouse gas *i* at time *t* after the release (in $kg.m^{-3}$), *T* is the time over which integration is performed (in yr) and the corresponding quantities for the reference gas in the denominator.

GWPs were calculated for three time horizons of 20, 100 and 500 years. Table 6.2 indicates the GWPs of three of the most important greenhouse gases for the three time horizons.

Table 6.2. GWPs for given time horizons [6.20] (in kg CO_2 eq./kg)

	20 years	100 years	500 years
Carbon Dioxide (CO_2)	1	1	1
Methane (CH_4)	62	23	7
Nitrous oxide (N_2O)	275	296	156

Hence, according to expression (6.1), the determination of the indicator "Global Warming" is given by,

$$Global\,Warming = \sum_i GWP_i \times m_i \tag{6.3}$$

where, m_i is the mass of substance *i* released (in kg). This indicator is expressed in *kg of CO_2 equivalents*.

6.2.3.3. Ozone Depletion Potential (ODP)

An ozone depletion indicator is derived through several properties of a gas, which include its stability to reach the stratosphere and the amount of bromine or chlorine the gas carries. These properties are then compared to CFC-11 (although CFC-11 is now banned by the Montreal Protocol in industrialized nations, it is still manufactured in many developing economies). The properties of each gas are then compared to the properties of CFC-11 and converted into CFC-11 equivalents. Then the individual equivalents are added together for the overall ozone depletion indicator score, which represents the total quantity of ozone depleting gases released. The ozone depletion potential of substance *i* (ODP_i) is given by [6.3],

$$ODP_i = \frac{\delta[O_3]_i}{\delta[O_3]_{CFC-11}} \tag{6.4}$$

where, $\delta[O_3]_i$ represents the change in the stratospheric ozone column *i* the equilibrium state due to annual emissions of substance i (in $kg.yr^{-1}$), and $\delta[O_3]_{CFC-11}$ the change in this column in the equilibrium state due to annual emissions of CFC-11.

OPDs were compiled by the World Meteorological Organisation (WMO). These OPDs are steady-state and they describe the integrated impact of an emission of a substance on the ozone layer compared with CFC-11 [6.3]. These ODPs are recommended for situations in which the time span of interest is eternity. In other cases, time-dependent ODPS are recommended [6.3]. Some of th OPDs are indicated in Table 6.3 for selected substances.

Table 6.3. Time-dependent *OPDs* for some substances [6.3] (in kg CFC-11 eq./kg)

	Steady-state ($t \approx \infty$)	40 years	30 years	25 years	20 years	15 years	10 years	5 years
CFC-11	1	1	1	1	1	1	1	1
CFC-10	1.2	1.14	1.2	1.22	1.22	1.23	1.25	1.26
Halon 1211	5.1	7.1	8.0	8.5	9	9.7	10.5	11.3
Halon 1301	12.0	10.8	10.7	10.6	10.5	10.5	10.4	10.3

Thus, the determination of the indicator Ozone Depletion is given by,

$$Ozone \quad Depletion = \sum_i ODP_i \times m_i \tag{6.5}$$

where, m_i is the mass of substance *i* released (in kg). This indicator is expressed in *kg of CFC-11 equivalents*.

6.2.3.4. Photochemical Ozone Creation Potential (POCP)

Photo-oxidants may be formed in the troposphere under the influence of ultraviolet light, through photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) [6.3]. This chemical reaction is "non-linear," meaning that sometimes the NO_x concentration will drive the reaction, an other times, it's the VOC that drive the reaction. Various indicators take low, average and high NO_x concentrations to calculate an overall score. Photochemical ozone creation potentials assess various emission scenarios for VOCs. Therefore, the photochemical ozone creation potential of a VOC (POCP) is given by the ratio between the change in ozone concentration due to a change in the emission of that VOC and the change in the ozone concentration due to a change in the emission of ethylene (C_2H_4) [6.3], as expressed by,

$$POCP_i = \frac{a_i / b_i}{a_{C_2H_4} / b_{C_2H_4}} \tag{6.6}$$

where, a_i represents the change in ozone concentration due to a change in the emission of VOC *i*; b_i represents the integrated emission of VOC *i*, up to that time; and $a_{C_2H_4}$ and $b_{C_2H_4}$ the respective parameters for the reference substance, ethylene.

POCPs were calculated for two scenarios (i) a scenario with a relatively high background concentration of NO_x; and (ii) a scenario with a relatively low background concentration of NO_x. These two characterization factors are indicated in Table 6.4 for some selected substances.

Table 6.4. *POCPs* for different concentration of NO_x and for some substances [6.3] (in kg C_2H_4 eq./kg)

	High-NO_x POCPs	Low-NO_x POCPs
Acetaldehyde (CH_3CHO)	0.641	0.200
Butane (C_4H_{10})	0.352	0.500
Carbon monoxide (CO)	0.027	0.040
Ethyne (C_2H_2)	0.085	0.400
Methane (CH_4)	0.006	0.007
Nitrogen oxide (NO_x)	0.028	no data
Propene (C_3H_6)	1.123	0.600
Sulphur oxide (SO_x)	0.048	no data
Toluene ($C_6H_5CH_3$)	0.637	0.500
Non-methane volatile organic compounds (NMVOCs)	0.150	0.150

Thus, the determination of the indicator Photo-oxidant formation is given by,

$$Photo-oxidant \quad formation = \sum_i POCP_i \times m_i \tag{6.7}$$

where, m_i is the mass of substance *i* released (in kg). This indicator is expressed in *kg of ethylene (C_2H_4) equivalents*.

6.2.3.5. Acidification potential (AP)

As referred in sub-section 6.2.2.4 acidification in one of the impact categories in which local sensitivity plays an important role. The characterisation factors adopted in this work are based in the model RAINS-LCA, which takes fate, background depositions and effects into account [6.21]. Based in this model, Huijbregts [6.21] developed characterisation factors for 44 regions in Europe and average European factors, by a weighted summation of the regional factors for each acidifying emission, as given by the following expression [6.3]:

$$AP_{x,r} = \frac{\sum_{e \in Europe} A_{e \in j} \times \frac{t_{r,x,j}}{CL_{e \in j}}}{\sum_{e \in Europe} A_{e \in j} \times \frac{t_{r,ref,j}}{CL_{e \in j}}} \tag{6.8}$$

where, $AP_{x,r}$ is the regional acidification potential of substance x in region r, A_e represents the ecosystem e (in grid cell $_j$), $CL_{e\epsilon j}$ is the critical load for ecosystem e (in grid cell j), $t_{r,x,j}$ represents a transport factor (the fraction of $E_{r,x}$ deposited on j), and $E_{r,x}$ is the emission of substance x in region r.

The average European characterisation factors for acidification are represented in Table 6.5, and they are compared with the values calculated for Western and Eastern Europe and Portugal [6.21]. The reference area is Switzerland.

Table 6.5. Acidification potentials (in kg Swiss SO_2 eq.) [6.21]

	Ammonia (NH_3)	Nitrogen Oxide (NO_x)	Sulfur Oxide (SO_2)
Average Europe	1.60	0.50	1.20
West Europe	1.30	0.41	0.79
East Europe	1.80	0.70	1.60
Portugal	0.28	0.08	0.18

Thus, the determination of the indicator acidification is given by,

$$Acidification = \sum_i AP_i \times m_i \tag{6.9}$$

where, m_i is the mass of substance i released (in kg). This indicator is expressed in *kg of SO_2 equivalents.*

6.2.3.6. Eutrophication Potential (EP)

The eutrophication indicator is given by the aggregation of the potential contribution of emissions of N, P and C (given in terms of Chemical Oxygen Demand, COD) to biomass formation [6.3]. The Eutrophication Potential of substance i reflects its potential contribution to biomass formation and it's given by the relation,

$$EP_i = \frac{\nu_i / M_i}{\nu_{ref} / M_{ref}} \tag{6.10}$$

where, ν_i and ν_{ref} are the potential contributions to eutrophication of one mole of substance i and one mole of the reference substance, respectively; and M_i and M_{ref} are the mass of i and the

mass of reference substance, which in this case is PO_4^{3-}. Some characterization factors for selected substances are indicated in Table 6.6

Table 6.6. Eutrophication potentials (in kg PO_4^{3-} eq./kg) [6.3]

	Ammonia (NH_3)	Nitrogen Oxide (NO_x)	Nitrate (N)	Phosphate (P)
EPi	0.35	0.13	0.10	1.00

The eutrophication indicator is given by,

$$Eutrohication = \sum_i EP_i \times m_i \tag{6.11}$$

where, m_i (kg) is the mass of substance *i* released to the air, water or soil; and EP_i is the Eutrophication Potential of the substance *i,* expressed in *kg* PO_4^{3-} *equivalents*.

The approach to calculate EPs (expression 6.10) aims to obtain global characterization factors (independent of local differences) and in order to outline the fact that it is unknown which medium (freshwater, salt water, groundwater or soil) an emitted substance will be deposed. This approach aggregates all emissions of N and P to air, water and soil into a single measure, allowing assessing terrestrial and aquatic eutrophication. However, it disregards the media of emission as well as the sensitivity of the receiving environment and the limiting nutrient [6.3].

Therefore, an alternative approach [6.21] including fate and site or region-dependent effect modelling is also adopted in this work. Based in the model RAINS-LCA, which was referred in the previous sub-section, regional and European eutrophication factors for air emissions of ammonia and nitrogen oxide were calculated [6.21]. These factors are indicated in the following table, including characterisation factors for Portugal.

Table 6.7. Eutrophication potentials (in kg Swiss NO_x eq./kg) [6.21]

	Ammonia (NH_3)	Nitrogen Oxide (NO_x)
Average Europe	4.30	1.20
West Europe	3.70	0.99
East Europe	5.00	1.70
Portugal	2.40	0.49

A drawback of this approach is that these factors account only for eutrophication of terrestrial ecosystems due to air emissions; direct emissions to soil and water are not included.

6.2.3.7. Human Toxicity Potential (HTP)

The indicator human toxicity covers the impacts on human health of toxic substances present in the environment.

The calculation of human toxicity potential is based in the model USES-LCA, already referred in the previous sub-sections. This model is a nested model with five spatial scales: regional, continental and global (global is tripartite to reflect the arctic, temperate and tropical climate zones of the Northern hemisphere). To calculate a single characterisation factor for each emission compartment, the four factors calculated at the global and continental scales are aggregated on a population basis: the larger the exposed population, the greater the weight of the associated factor. Hence, the Human Toxicity Potential (*HTP*) of substance *i* emitted to emission compartment *ecomp*, is given by [6.3],

$$HTP_{i,ecomp} = \frac{\sum_r \sum_s PDI_{i,ecomp,r,s} \times E_{i,r} \times N_s}{\sum_r \sum_s PDI_{1.4-dichlorobenzene,air,r,s} \times E_{1.4-dichlorobenzene,r} \times N_s} \quad (6.12)$$

where, N_s is the population density at scale *s*, $PDI_{i,ecomp,r,s}$ is the Predicted Daily Intake via exposure route *r*, at scale *s*, for substance *i* emitted to emission compartment *ecomp* (in day^{-1}), and $E_{i,r}$ is the effect factor, representing the human-toxic impact of substance *i*, (in day). In this model the reference substance is 1.4 dichlorobenzene. Thus, $PDI_{1.4\text{-}dichlorobenzene,r,s}$ is the Predicted Daily Intake resulting from the emission of 1000 kg of 1.4 dichlorobenzene to air (in day^{-1}), and $E_{1.4\text{-}dichlorobenzene,r}$ represents the human-toxic impact of 1.4 dichlorobenzene (in day).

The indicator result for human toxicity for a specific time horizon *t* can be calculated using the following expression:

$$human\ \ toxicity_t = \sum_i \sum_{ecomp} m_{i,ecomp} \times HTP_{i,ecomp,t} \quad (6.13)$$

where, $HTP_{i,ecomp,t}$ is the human toxicity potential of substance *i* emitted to emission compartment *ecomp* for time horizon *t*, and $m_{i,ecomp}$ is the emission of substance *i* to compartment *ecomp* (kg).

The human toxicity potentials adopted in this work take into account the time horizons of 20, 100 and 500 years and infinity, at the global scale [6.21], and are represented in Table 6.8 for some selected air emissions:

Table 6.8. Human toxicity potentials for different time horizons and global scale (in kg 1,4-DB eq./kg)

	20 years	100 years	500 years	∞
Ammonia (NH_3)	0.10	0.10	0.10	0.10
Barium (Ba)	172	175	181	756
Cadmium (Cd)	1.45E5	1.45E5	1.45E5	1.45E5
Cobalt (Co)	1.72E4	1.73E4	1.74E4	1.75E4
Lead (Pb)	24.2	29.1	48.2	467
Mercury (Hg)	212	264	416	6010
Nitrogen oxide (NO_x)	1.20	1.20	1.20	1.20
Particulates (PM)	0.82	0.82	0.82	0.82
Sulphur oxide (SO_x)	0.096	0.096	0.096	0.096

6.2.3.8. Ecotoxicity Potential (EcP)

This impact category covers the impacts of toxic substances on aquatic, terrestrial and sediment ecosystems.

The model adopted in this work for the calculation of ecotoxicity potentials is the same model as the one used for human toxicity potentials, which was described in the previous sub-section. Moreover, this model was used to calculate five subcategories of ecotoxicity potentials: freshwater aquatic, marine aquatic, freshwater sediment, marine sediment and terrestrial; each of them for different time horizons [6.21]. However, in this work, only terrestrial ecotoxicity is taken into account, in order to avoid giving undue weight to the category of ecotoxicity. In this case, the Terrestrial Ecotoxicity Potential (*TETP*) of substance *i* emitted to emission compartment *ecomp*, is given by:

$$TETP_{i,ecomp} = \frac{PEC_{i,ecomp,terrestrial} \times E_{i,terrestrial}}{PEC_{1.4-dichlorobenzene,terrestrial,terrestrial} \times E_{1.4-dichlorobenzene,terrestrial}} \quad (6.14)$$

where, $PEC_{i,ecomp,terrestrial}$ is the predicted concentration of substance *i* on earth due to the emission to compartment *ecomp*, $PEC_{1.4\text{-}dichlorobenzene,terrestrial}$ is the same predicted concentration but for 1.4-dichlorobenzene; $E_{i,r}$ is the effect factor, representing the toxic impact of substance *i* on terrestrial ecosystems and $E_{1.4\text{-}dichlorobenzene,terrestrial}$ is the same factor but for 1.4-dichlorobenzene . The indicator result for terrestrial ecotoxicity is calculated using the following expression:

$$terrestrial \quad e\cot oxicity = \sum_{i} \sum_{ecomp} m_{i,ecomp} \times TETP_{i,ecomp} \quad (6.15)$$

where $m_{i,ecomp}$ is the emission of substance *i* to compartment *ecomp*.

The terrestrial ecotoxicity potentials adopted in this work for time horizons of 20, 100 and 500 years and infinity, at the global scale [6.21], are represented in Table 6.8 for some selected air emissions:

Table 6.9. Terretrial ecotoxicity potentials for different time horizons and global scale (in kg 1,4-DB eq./kg)

	20 years	100 years	500 years	∞
Barium (Ba)	0.359	1.55	4.12	4.86
Cadmium (Cd)	2.48	11.7	43.6	81.2
Cobalt (Co)	11.9	47.6	102	109
Lead (Pb)	0.0288	0.144	0.707	15.7
Mercury (Hg)	669	3170	12300	28300

6.2.3.9. Abiotic Depletion Potential (ADP)

The indicator abiotic depletion aims to evaluate the environmental problem related to the decreasing availability of natural resources. By natural resources it is understood the minerals and materials found in the earth, sea, or atmosphere and biota, that have not yet been industrially processed [6.22].

The model [6.22] adopted for abiotic depletion in this work, assumes that ultimate reserves and extraction rates together are the best way to represent the seriousness of resource depletion. This model is a global model based on ultimate reserves in the world combined with yearly depletion on a world level. Therefore, the Abiotic Depletion Potential of resource *i* (ADP_i) is given by the ratio between the quantity of resource extracted and the recoverable reserves of that resource, expressed in kg of a reference resource, as given by expression (6.16):

$$ADP_i = \frac{DR_i}{(R_i)^2} \times \frac{(R_{ref})^2}{DR_{ref}} \quad (6.16)$$

where, DR_i is the extraction rate of resource *i* (in kg/yr), R_i is the ultimate reserve of resource *i* (in kg), R_{ref} is the ultimate reserve of the reference resource (in kg), and DR_{ref} is the extraction rate of R_{ref} (in kg/yr). The reference resource is antimony.

Thus, the determination of the indicator Abiotic Depletion is given by,

$$Abiotic\ \ Depletion = \sum_i ADP_i \times m_i \tag{6.17}$$

where, m_i is the quantity of resource *i* extracted (in kg). This indicator is expressed *in kg of antimony* (the reference resource).

The abiotic depletion potentials developed from this model and adopted in this work are represented in Table 6.10 for some selected resources.

The abiotic depletion indicator as described in the previous paragraphs is recommended in the Guide [6.3] for LCEA. This indicator is one of the most controversial indicators in LCEA, and currently there's no general consensus about the best indicator to describe this environmental problem (even within standardization bodies like CEN and ISO); therefore, it was decided to adopt this approach in the analysis. However, currently there are not sufficiently production and reserve data for some common abiotic resources, which could lead to some problems in the impact assessment stage of some inventory data.

Table 6.10. Abiotic depletion potentials for some resources (in Sb eq./kg)

Resource	ADs
Aluminium (Al)	1.00E-08
Calcite ($CaCO_3$)	2.83E-10
Coal	1.34E-02
Copper (Cu)	1.94E-03
Gas natural	1.87E-02
Iron ore (Fe)	4.80E-08
Lead (Pb)	1.35E-02

6.2.3.10. Summary of characterization factors

In the previous sub-sections, several characterization factors were referred for each impact category. In this work, two types of indicators are considered for each impact category, except abiotic depletion: the baseline indicators and the alternative indicators. For abiotic depletion only a baseline indicator is considered using the characterization factors provided in Table 6.10.

The baseline indicators are the ones that will be used in the deterministic LCEA, whereas the alternative indicators will be used for the probabilistic analysis. Both indicators and respective characterization factors are provided in Table 6.11.

Table 6.11. Baseline and alternative environmental indicators

Impact category		Characterization factor
Acidification	Baseline indicator	Acidification potential for average Europe
	Alternative indicator	Acidification potential for Portugal
Eutrophication	Baseline indicator	Eutrophication potential for average Europe
	Alternative indicator	Eutrophication potential for Portugal
Global warming	Baseline indicator	GWP for a time horizon of 100 years
	Alternative indicator	GWP for a time horizon of 20 years
	Alternative indicator	GWP for a time horizon of 500 years
Ozone depletion	Baseline indicator	ODP for a steady-state
	Alternative indicator	ODP for a time horizon of 5 years
	Alternative indicator	ODP for a time horizon of 10 years
	Alternative indicator	ODP for a time horizon of 15 years
	Alternative indicator	ODP for a time horizon of 20 years
	Alternative indicator	ODP for a time horizon of 25 years
	Alternative indicator	ODP for a time horizon of 30 years
	Alternative indicator	ODP for a time horizon of 40 years
Human toxicity	Baseline indicator	HTP for a time horizon of 100 years
	Alternative indicator	HTP for a time horizon of 20 years
	Alternative indicator	HTP for a time horizon of 500 years
	Alternative indicator	HTP for a time horizon for ∞
Terrestrial ecotoxicity	Baseline indicator	EcP for a time horizon of 100 years
	Alternative indicator	EcP for a time horizon of 20 years
	Alternative indicator	EcP for a time horizon of 500 years
	Alternative indicator	EcP for a time horizon for ∞
Photochemical oxidation	Baseline indicator	POCP for high-NO_x
	Alternative indicator	POCP for low-NO_x

6.2.4. Uncertainties in life cycle impact assessment

The models used for the calculation of the impact categories, as described in the previous section, involve several assumptions and simplifications, which introduce uncertainties in the calculation of the indicators. The reliability and robustness of the analysis requires dealing with these uncertainties in the analysis.

It was not the goal of this dissertation to further develop the models for calculation of environmental indicators as it would imply a more specific knowledge of the several environmental phenomena involved. However, in order to make the results of the analysis more reliable, this section addresses scenario and model uncertainties in the impact assessment stage.

The consideration of a particular time horizon may result in considerably different characterization factors; for instance, the characterization factors of methane for global warming considering time horizons of 20 and 500 years differ by about ten times (see Table 6.2).

On the other hand, the consideration of spatial differentiation in the calculation of characterization factors of local dependent impact categories can lead to considerable differences in the results: for instance the characterization factors for eutrophication in Table 6.7.

Therefore, in the first case, several scenarios are considered for different time horizons; whereas, in the second case, scenarios considering different locations and corresponding

characterisation factors are considered. In both cases, a nonparametric boostrap procedure is proposed to quantify the resulting uncertainty.

The aim of bootstrap is to estimate the sampling distribution of the chosen estimator, in this case the sample mean, by using limited information. The bootstrap differs from traditional parametric inference in the way this distribution in obtained. Whereas traditional parametric inference utilizes a priori assumptions about the shape of the estimator distribution, the nonparametric bootstrap is distribution free [6.23].

Thus, using bootstrap sampling it is possible to get the distribution of the estimator and the statistics (such as confidence interval) of the estimator. In the method, the basic sample is treated as the population and a Monte Carlo procedure is conducted on it by randomly drawing a large number of "resamples" of size n from this original sample (also of size n) with replacement and calculating for each one the associated mean. The relative frequency distribution of these mean values is an estimate of the sampling distribution for that statistic. The larger the number of samples of size n the more accurate the relative frequency distribution of these estimates will be. The bootstrapped estimate of the sampling distribution is significantly improved when the number of samples is above 1000 [6.23].

For the application of the bootstrap method several assumptions are made: (i) it is assumed that the original sample is a valid representation of the population, and (ii) each new sample is independent of the other samples, although coming from the same population.

For each scenario formulated as described before, a probability may be assigned, reflecting the preference of the decision-maker for each scenario. However, the sum of propabilities assigned to all the scenarios must be 1. Then, by bootstrap sampling, a scenario is chosen randomly for each case. This procedure is exemplified in Box 6.1 for the environmental categories described in the previous sections.

Box 6.1. Uncertainties in the calculation of environmental impact categories

A LCEA was performed considering several scenarios for time horizons and the results are indicated in Table 6.12 for the impact categories of global warming, ozone layer depletion, human toxicity and terrestrial ecotoxicity.

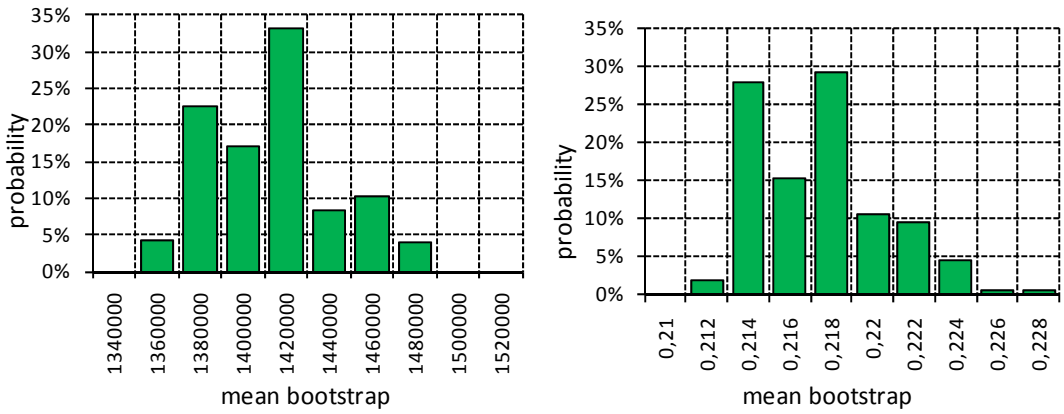
Table 6.12. LCEA results for impact categories considering different time horizons

Impact category	Unit	Total
Global warming 20a	kg CO2 eq.	1477827.50
Global warming 100a	kg CO2 eq.	1385826.10
Global warming 500a	kg CO2 eq.	1354916.50
Ozone layer depletion 5a	kg CFC-11 eq.	0.20979826
Ozone layer depletion 10a	kg CFC-11 eq.	0.21125105
Ozone layer depletion 15a	kg CFC-11 eq.	0.21269771
Ozone layer depletion 20a	kg CFC-11 eq.	0.21226820
Ozone layer depletion 25a	kg CFC-11 eq.	0.21392166
Ozone layer depletion 30a	kg CFC-11 eq.	0.21556278
Ozone layer depletion 40a	kg CFC-11 eq.	0.21692755
Ozone layer depletion steady state	kg CFC-11 eq.	0.23994869
Human toxicity 20a	kg 1,4-DB eq.	195965.43
Human toxicity 100a	kg 1,4-DB eq.	197283.70
Human toxicity 500a	kg 1,4-DB eq.	198103.45
Human toxicity infinite	kg 1,4-DB eq.	279426.66

Table 6.12. (cont.) LCEA results for impact categories considering different time horizons

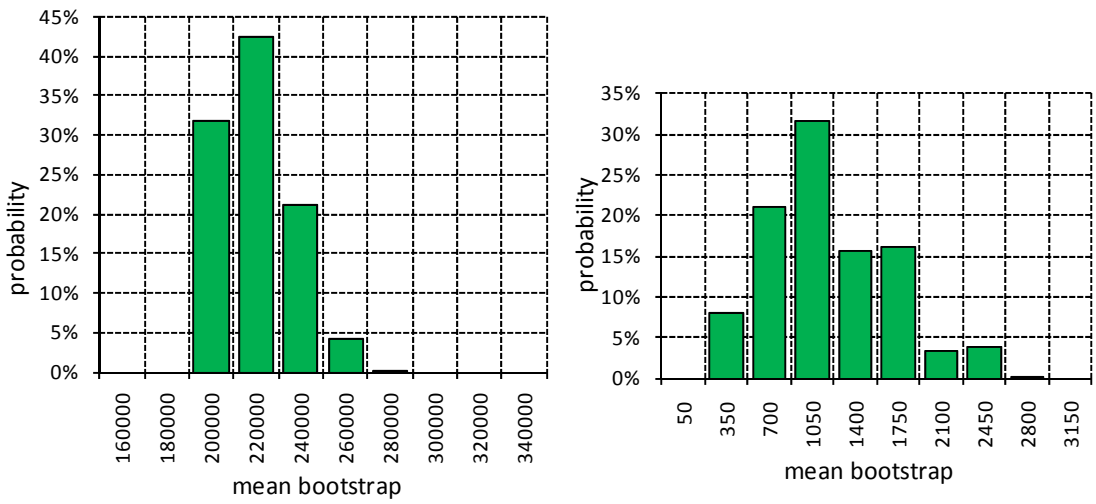
Impact category	Unit	Total
Terrestrial ecotoxicity 20a	kg 1,4-DB eq.	66.98
Terrestrial ecotoxicity 100a	kg 1,4-DB eq.	274.34
Terrestrial ecotoxicity 500a	kg 1,4-DB eq.	1023.52
Terrestrial ecotoxicity infinite	kg 1,4-DB eq.	2719.20

Based in the results obtained for each scenario a nonparametric bootstrap sampling was performed, assuming equal probability for each scenario. For each impact category 1000 bootstrap samples were obtained. The frequency diagrams of the mean values obtained for each impact category are represented in Figure 6.15 and Figure 6.16.



(a) (b)

Figure 6.15. Frequency diagrams for (a) Global Warming and (b) Ozone Layer Depletion



(a) (b)

Figure 6.16. Frequency diagrams for (a) Human Toxicity and (b) Terrestrial Eco-toxicity

In the same LCEA, the impact category of photochemical oxidation was calculated based in a scenario with a relatively high background concentration of NO_x and a scenario with relatively low background concentration of NO_x.

Table 6.13. LCEA results photochemical oxidation (high and low NO_x concentration)

Impact category	Unit	Total
Photochemical oxidation (high NO_x)	kg C_2H_4 eq.	1159.08
Photochemical oxidation (low NO_x)	kg C_2H_4 eq.	1395.70

A bootstrap sampling was performed and the frequency diagram obtained is represented in Figure 6.17.

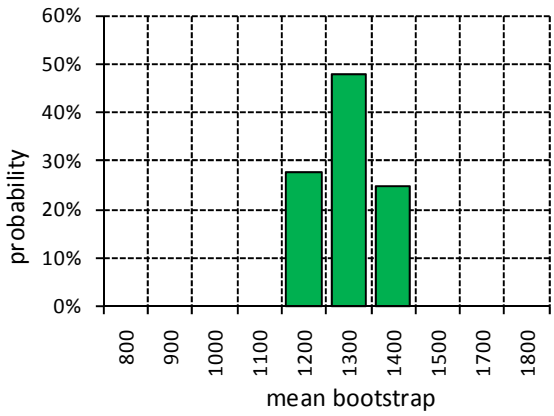


Figure 6.17. Frequency diagram for photochemical oxidation

Finally, the impact categories of acidification and eutrophication were calculated for different regions (countries) in Europe, based on the characterization factors developed by Huijbregts [6.21]. The results obtained for each country are represented in Table 6.14.

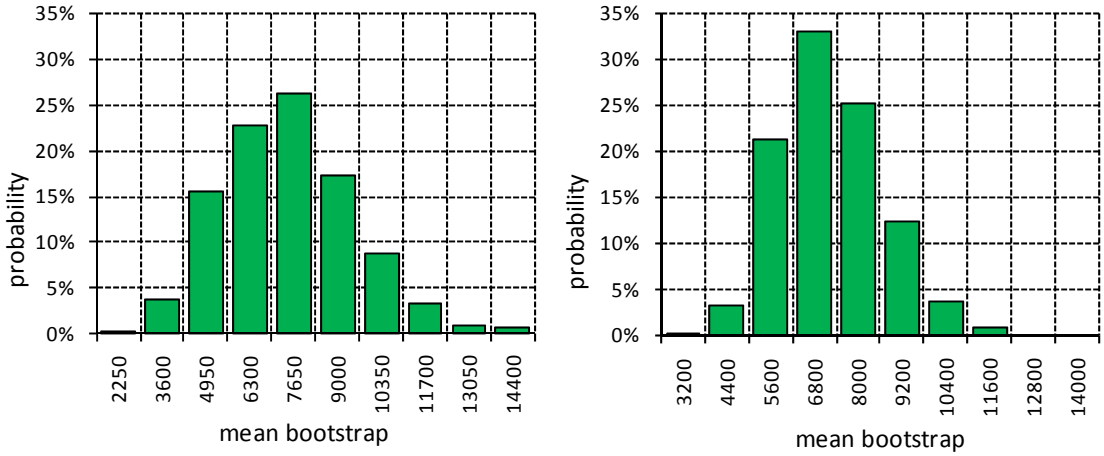
Table 6.14. LCEA results for impact categories considering different regions in Europe

Impact category	Acidification	unit	Eutrophication	unit
Albania	636.63	kg SO_2 eq.	2560.26	kg NO_x eq.
Austria	4356.76	kg SO_2 eq.	4548.93	kg NO_x eq.
Belarus	11225.61	kg SO_2 eq.	10169.79	kg NO_x eq.
Belgium	5466.98	kg SO_2 eq.	6104.00	kg NO_x eq.
Bosnia	1252.66	kg SO_2 eq.	3118.03	kg NO_x eq.
Bulgaria	1156.15	kg SO_2 eq.	2863.92	kg NO_x eq.
Croatia	1973.88	kg SO_2 eq.	3406.80	kg NO_x eq.
Czech republic	5864.09	kg SO_2 eq.	6623.92	kg NO_x eq.
Denmark	9827.26	kg SO_2 eq.	8124.14	kg NO_x eq.
Estonia	19826.91	kg SO_2 eq.	16793.72	kg NO_x eq.
Finland	24566.28	kg SO_2 eq.	17872.91	kg NO_x eq.
France	5471.61	kg SO_2 eq.	6647.32	kg NO_x eq.
Germany	6473.54	kg SO_2 eq.	7640.37	kg NO_x eq.
Greece	385.09	kg SO_2 eq.	1382.41	kg NO_x eq.
Hungary	4551.97	kg SO_2 eq.	5084.36	kg NO_x eq.
Ireland	3425.72	kg SO_2 eq.	2642.34	kg NO_x eq.
Italy	2033.38	kg SO_2 eq.	3066.36	kg NO_x eq.
Latvia	13243.29	kg SO_2 eq.	13236.15	kg NO_x eq.
Lithuania	10633.13	kg SO_2 eq.	11186.24	kg NO_x eq.
Luxembourg	6415.85	kg SO_2 eq.	7132.15	kg NO_x eq.
Macedonia	711.56	kg SO_2 eq.	2403.12	kg NO_x eq.
Moldavia	3751.01	kg SO_2 eq.	4622.50	kg NO_x eq.
Netherlands	5330.09	kg SO_2 eq.	5591.52	kg NO_x eq.
Norway	17447.58	kg SO_2 eq.	8163.49	kg NO_x eq.
Poland	6873.47	kg SO_2 eq.	8162.42	kg NO_x eq.

Table 6.14. (cont.) LCEA results for impact categories considering different regions in Europe

Portugal	943.62	kg SO_2 eq.	2505.40	kg NO_x eq.
Romania	2386.16	kg SO_2 eq.	3820.19	kg NO_x eq.
Russia	25157.32	kg SO_2 eq.	19380.57	kg NO_x eq.
Slovakia	6247.75	kg SO_2 eq.	5609.60	kg NO_x eq.
Slovenia	2564.19	kg SO_2 eq.	3268.80	kg NO_x eq.
Spain	1163.79	kg SO_2 eq.	2652.97	kg NO_x eq.
Sweden	17936.66	kg SO_2 eq.	10688.65	kg NO_x eq.
Switzerland	4407.37	kg SO_2 eq.	5114.14	kg NO_x eq.
Ukraine	6118.26	kg SO_2 eq.	7623.356	kg NO_x eq.
United Kingdom	4751.94	kg SO_2 eq.	3864.415	kg NO_x eq.
Yugoslavia	1672.91	kg SO_2 eq.	3572.456	kg NO_x eq.

Following the same procedure, a nonparametric bootstrap sampling was performed for each impact category. The frequency diagrams are represented in Figure 6.18(a) and Figure 6.18(b) for the impact categories of acidification and eutrophication, respectively.



(a) (b)

Figure 6.18. Frequency diagrams for (a) Acidification and (b) Eutrophication

Based in the bootstrap sampling results calculated above, the 90% confidence interval was estimated for each impact category. The lower and upper bounds of the confidence interval for each impact category are represented in Table 6.15.

Table 6.15. 90% confidence interval of the mean bootstrap

Impact category	Lower bound	Upper bound
Acidification	3 626.30	10 627.88
Eutrophication	4 521.83	9 126.21
Ozone depletion	0.2123	0.2228
Global warming	1 354 916.50	1 447 160.37
Terrestrial ecotoxicity	222.50	1 871.36
Human toxicity	196 624.60	258 561.40
Photochemical oxidation	1 159.08	1 395.70

To make these distributions operational in the life cycle analysis a probabilistic distribution was fitted to each impact category and goodness of fit statistics were applied to determine the accuracy of the fitted distribution. The properties of the fitted distributions are indicated in Table 6.16. Lognormal distributions were used for most impact categories, except photo-chemical oxidation, as it avoids negative values and comprehends a large value range [6.24]. For

the impact category of abiotic depletion, a lognormal distribution was assumed with the mean value equal to the deterministic value obtained in the LCEA (13840.57 kg Sb eq.) and standard deviation of 10% of the mean value.

Table 6.16. Properties of the fitted distributions for impact categories

	Distribution type	Parameters
Global warming	Lognormal	μ = 1414160.0; σ = 31808.2
Acidification	Lognormal	μ = 7708.6; σ = 2159.5
Eutrophication	Lognormal	μ = 7392.3; σ = 1555.5
Photo-oxidant form.	Triangular	μ = 1302.7; σ = 80.0
Ozone depletion	Lognormal	μ = 0.219; σ = 0.005
Ecotoxicity	Lognormal	μ = 1266.0; σ = 524.4
Human toxicity	Lognormal	μ = 220960.0; σ = 20222.4
Abiotic depletion (*)	Lognormal	μ = 13840.57; σ = 1384.1

(*) assumed distribution

For some of the impact categories analysed, such as photochemical oxidation, there are only few values available, therefore an alternative procedure is also considered.

In case data available is not enough to fit a representative distribution, a normal or uniform distribution may be used to enable uncertainty of the results to be incorporated in the analysis. Moreover, in the absence of insufficient data, the probability distribution that is straightforward to endorse is the uniform distribution, where all values have equally probability. Hence, in this case a uniform distribution is also proposed for the impact categories with minimum and maximum values as indicated in Table 6.17.

Table 6.17. Properties of the uniform distributions for impact categories

	Distribution type	Parameters
Global warming	Uniform	max = 1 477 827.50; min = 1 354 916.50
Acidification	Uniform	max = 25 157.32; min = 385.09
Eutrophication	Uniform	max = 19 380.57; min = 1 382.41
Photo-oxidant form.	Uniform	max = 1 395.70; min = 1 159.08
Ozone depletion	Uniform	max = 0.2399; min = 0.2098
Ecotoxicity	Uniform	max = 2719.20; min = 66.98
Human toxicity	Uniform	max = 279 426.66; min = 195 965.43
Abiotic depletion (*)	Uniform	max = 15224.62; min = 12456.51

(*) the maximum and minimum values were considered by +10% and -10%, respectively, of the deterministic value

6.3. NORMALISATION AND WEIGHTING

6.3.1. Introduction

Normalisation and weighting are considered by ISO standards [6.2] as optional steps of a Life Cycle Impact Assessment (LCIA). Other authors [6.3] consider normalisation as a recommended step of LCEA as it provides a better understanding of the relative importance and magnitude of impact categories and thus providing valuable information for the weighting stage.

According to ISO standards normalisation is the “calculation of the magnitude of the category indicator results relative to some reference information”, while weighting is the “process of converting indicator results of different impact categories by using numerical factors based on value-choices”.

Normalisation may also be understood as a weighting process. By introducing normalisation factors the relative importance of each indicator is analysed. While normalisation enhances the relative importance of each indicator within the corresponding impact category, weighting allows setting the relative importance of each indicator against each other. Thus, normalisation and weighting may be assumed as two steps of the same procedure.

For decision making, these two steps are very important as they simplify the interpretation step of the analysis and thus contribute to an easier decision making process. It is agreed that both processes should be very transparent and all the information regarding its calculation should be provided together with the results of the analysis so that everyone can fully understand the extent of the results.

This sub-chapter describes some of the available normalisation and weighting procedures, and the implications and limitations of its use. Moreover, normalisation values referring to Portugal are calculated and a weighting procedure to be applied for life cycle environmental analysis of bridges is proposed.

6.3.2. Normalisation

6.3.2.1. General normalisation values

The main aim of the normalisation procedure is to better understand the relative importance and magnitude of each impact category or indicator for the system under analysis. Furthermore, it can be used to check for uncertainties and to prepare for additional procedures of interpretation and weighting [6.2].

In a normalisation process a reference system may be the aggregate interventions for a given place or area (e.g. a region, country, Europe, etc) over a certain period of time; the per capita interventions for a given area in a reference year; a baseline scenario, etc [6.2].

The normalised factor is the indicator result for a given reference system; thus, it is given by the sum of all interventions related to the reference system multiplied by the corresponding characterization factors [6.3]:

$$N_{cat,ref} = \sum_i m_{i,ref} \times CF_{i,cat} \tag{6.18}$$

where, $N_{cat,ref}$ is the normalisation factor for impact category *cat* and reference system *ref*; $m_{i,ref}$ is the magnitude of intervention *i* associated with the reference system *ref*; and $CF_{i,cat}$ is the characterisation factor for intervention *i* and impact category *cat*.

The normalised category indicator for a given reference system *ref* ($I_{cat,ref}$) is, in turn, given by the ratio between the impact category score (I_{cat}) and the relative normalised factor:

$$I_{cat,ref} = I_{cat} / N_{cat,ref} \tag{6.19}$$

Normalisation can be performed at a single scale level or at different scale levels [6.3]. In the former case the results of each impact category are normalised against reference data from the same reference area, while in the latter, the results for global categories are normalised using

global reference values and local or regional categories use local or regional normalisation values.

In the first case, reference data can be relative to aggregate interventions or per capita interventions, and the most suitable reference area for non site-dependent LCEA is the "world" [6.3].

Normalisation at different scales would be more correct if inventory data and impact assessment are made taking into account spatial differentiation. According to ISO standard 14044 [6.2] the selection of the reference system should take into account the consistency between the spatial and temporal scales of the environmental mechanism and the reference values. However, as currently inventory data and impact assessment are not site dependent, the choice of the "world" as the reference area is more consistent with the spatial scale of the impact scores [6.25].

Table 6.18. Normalisation factors for different regions (per year) [6.25]

Impact category	Units	Western Europe (1995)	The Netherlands (1997)	The world (1990)	The world (1995)
Abiotic depletion	kg (Sb eq.) /yr	1.5×10^{10}	1.7×10^{9}	1.6×10^{11}	1.6×10^{11}
Acidification					
Average Europe	kg (SO_2 eq.) /yr	2.7×10^{10}	6.7×10^{8}	3.2×10^{11}	3.2×10^{11}
Eutrophication					
Average Europe	kg (NO_x eq.) /yr	3.2×10^{10}	1.4×10^{9}	3.6×10^{11}	3.9×10^{11}
Global warming					
TH = 20 yrs	kg (CO_2 eq.) /yr	5.8×10^{12}	3.0×10^{11}	5.7×10^{13}	5.4×10^{13}
TH = 100 yrs	kg (CO_2 eq.) /yr	4.8×10^{12}	2.5×10^{11}	4.4×10^{13}	4.1×10^{13}
TH = 500 yrs	kg (CO_2 eq.) /yr	4.0×10^{12}	2.2×10^{11}	3.4×10^{13}	3.3×10^{13}
Ozone layer depletion					
TH = 5 yrs	kg (CFC-11 eq.) /yr	3.1×10^{8}	1.4×10^{6}	2.6×10^{9}	1.6×10^{9}
TH = 10 yrs	kg (CFC-11 eq.) /yr	1.9×10^{8}	1.2×10^{6}	1.6×10^{9}	9.0×10^{8}
TH = 15 yrs	kg (CFC-11 eq.) /yr	1.5×10^{8}	1.1×10^{6}	1.3×10^{9}	6.9×10^{8}
TH = 20 yrs	kg (CFC-11 eq.) /yr	1.3×10^{8}	1.0×10^{6}	1.2×10^{9}	6.0×10^{8}
TH = 25 yrs	kg (CFC-11 eq.) /yr	1.1×10^{8}	9.9×10^{5}	1.1×10^{9}	5.4×10^{8}
TH = 30 yrs	kg (CFC-11 eq.) /yr	1.1×10^{8}	9.6×10^{5}	1.0×10^{9}	5.0×10^{8}
TH = 40 yrs	kg (CFC-11 eq.) /yr	9.5×10^{7}	9.2×10^{5}	9.2×10^{8}	4.5×10^{8}
TH = ∞	kg (CFC-11 eq.) /yr	8.3×10^{7}	9.8×10^{5}	1.1×10^{9}	5.2×10^{8}
Human toxicity					
TH = 20 yrs	kg (1,4-DCB eq.) /yr	7.5×10^{12}	1.9×10^{11}	5.9×10^{13}	5.7×10^{13}
TH = 100 yrs	kg (1,4-DCB eq.) /yr	7.5×10^{12}	1.9×10^{11}	5.9×10^{13}	5.7×10^{13}
TH = 500 yrs	kg (1,4-DCB eq.) /yr	7.5×10^{12}	1.9×10^{11}	5.9×10^{13}	5.7×10^{13}
TH = ∞	kg (1,4-DCB eq.) /yr	7.6×10^{12}	1.9×10^{11}	6.0×10^{13}	5.7×10^{13}
Terrestrial Ecotoxicity					
TH = 20 yrs	kg (1,4-DCB eq.) /yr	1.9×10^{10}	1.5×10^{8}	1.4×10^{11}	1.3×10^{11}
TH = 100 yrs	kg (1,4-DCB eq.) /yr	2.0×10^{10}	1.7×10^{8}	1.5×10^{11}	1.4×10^{11}
TH = 500 yrs	kg (1,4-DCB eq.) /yr	2.4×10^{10}	2.6×10^{8}	1.8×10^{11}	1.6×10^{11}
TH = ∞	kg (1,4-DCB eq.) /yr	4.7×10^{10}	9.6×10^{8}	2.6×10^{11}	2.7×10^{11}
Photo-chemical oxidation					
High NO_x	kg (C_2H_4 eq.) /yr	8.2×10^{9}	1.8×10^{8}	1.0×10^{11}	9.6×10^{10}
Low NO_x	kg (C_2H_4 eq.) /yr	6.3×10^{9}	1.6×10^{8}	9.2×10^{10}	8.7×10^{10}

In the case of this second approach the normalisation values should referred to the individual ("per capita") instead of the area they referred to. The reason for this is that normalisation factors referring to the world are far higher than normalisations factors referring to smaller

regions, leading to lower normalised results for global impact categories in comparison to regional impact categories [6.3]. Moreover, if regional normalisation factors are used then weighting should also be performed on a regional basis, otherwise the results of the LCEA will be difficult to interpret [6.3].

Normalisation factors may be found in the literature. Normalisation factors for the Netherlands (reference year 1997/98), Western Europe (in 1995) and the world (in 1990 and in 1995) may be found in [6.25] for eight impact categories, as represented in Table 6.18. These values are reproduced here as they are the normalisation factors used in the CML methodology.

ISO 14044 [6.2] recommends the use of several reference systems to assess their influence on the outcome of the LCEA. To illustrate the influence of different normalisation values in the results of a LCEA an example is provided in Box 6.2.

Box 6.2. Influence of different normalisation values in the LCEA result

The results of the LCEA presented in Table 6.12 to Table 6.14 are normalised based on the normalisation values indicated in Table 6.18. The corresponding normalised values are indicated in Table 6.19, together with the variation in relation to the values in the first column (reference area: western Europe), as given by the following expression:

$$\Delta = \left(N_i - N_{Europe}\right) / N_{Europe} \tag{6.20}$$

where, N_i is the normalised value in relation to reference area i and N_{Europe} is the normalised value in relation to western Europe.

Table 6.19. Variation in LCA results due to different normalization values

Impact category	Western Europe (1995)	The Netherlands (1997)	Δ (%)	The world (1990)	Δ (%)	The world (1995)	Δ (%)
Abiotic depletion	9.25E-07	8.16E-06	+782%	8.67E-08	-91%	8.67E-08	-91%
Acidification							
Average Europe	2.43E-07	9.79E-06	+3930%	2.05E-08	-92%	2.05E-08	-92%
Eutrophication							
Average Europe	1.92E-07	4.39E-06	+2186%	1.71E-08	-91%	1.58E-08	-92%
Global warming							
TH = 100 years	2.89E-07	5.55E-06	+1820%	3.16E-08	-89%	3.39E-08	-88%
Ozone layer depletion							
TH = ∞	2.90E-09	2.46E-07	+8369%	2.19E-10	-92%	4.63E-10	-84%
Human toxicity							
TH = 100 years	2.64E-08	1.04E-06	+3847%	3.36E-09	-87%	3.48E-09	-87%
Ecotoxicity							
TH = 100 years	1.37E-08	1.62E-06	+11665%	1.83E-09	-87%	1.96E-09	-86%
Photo-chemical oxidation							
High NO_x	1.25E-07	5.68E-06	+4456%	1.02E-08	-92%	1.06E-08	-91%

Figure 6.19 represents the results obtained using the normalization values for Europe and for the Netherlands.

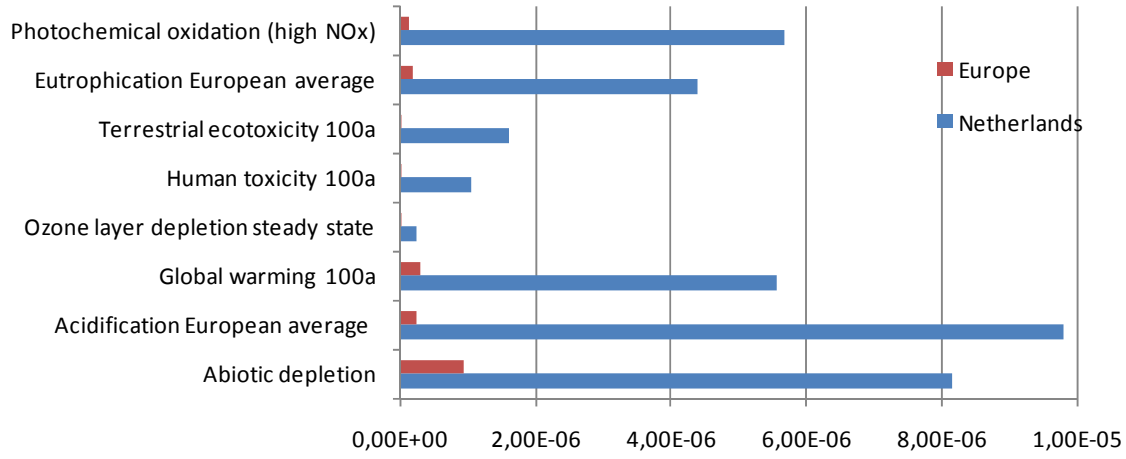


Figure 6.19. Comparison of LCEA normalised results (Europe vs. Netherlands)

Considering "less the better", Table 6.20 compares the scores obtained in the LCEA analysis, with and without normalisation. The impact category with the best performance is assigned 1 and the one with the worst performance is assigned 8. However, it should be noticed that the following table does not provide the best and worst "absolute" environmental performances; the meaning of the scores obtained by each impact category is just to enhance the change of the order given by the relative importance of each impact category considering different reference areas.

Table 6.20. Scores of LCEA results with and without normalization

Impact category	Without normal.	Western Europe	The Netherlands	The world (1990)	The world (1995)
Abiotic depletion	6	8	7	8	8
Acidification	5	6	8	6	6
Eutrophication	4	5	4	5	5
Global warming	8	7	5	7	7
Ozone layer depletion	1	1	1	1	1
Human toxicity	7	3	2	3	3
Ecotoxicity	2	2	3	2	2
Photo-chemical oxidation	3	4	6	4	4

Without normalisation (1st column) the worst score would be obtained by impact category "Global warming" and the best score would be obtained by impact category "ozone layer depletion". Considering normalisation, while the best score is still obtained by the impact category "ozone layer depletion", the worst score changes in relation to the reference area considered. The major difference in relation to the scores obtained with and without normalisation is for the impact category "human toxicity", which gets the 2nd worst score considering the non-normalised values and gets one of the best scores considering the normalised values, no matter the reference area considered. Another example is the impact category "acidification"; considering the Netherlands as the reference area, than this impact category is potentially one the worst environmental problems in the analysis, however, if the reference area is Europe or the world than this impact category is no longer one the major concern. This highlights the importance of normalisation in the interpretation of the results obtained by a LCEA.

6.3.2.2. Portuguese normalisation factors

The aim of this sub-section is to define a set of Portuguese normalisation factors in relation to the impact categories considered in this chapter.

For most impact categories data for the quantification of normalisation values was obtained from national inventories. However, in few cases and due to a lack of national data, it was necessary to use data from other countries, as will be explained in the following paragraphs.

In this work, data for the most important air pollutants is provided from national inventories made by the Portuguese Environmental Agency (*Agência Portuguesa do Ambiente*) [6.26]. These inventories are the basis for the evaluation of Portuguese commitments to international agreements such as the Convention on Long-Range Transboundary Air Pollution (CLRTAP) and the United Nations Framework Convention on Climate Change (UNFCCC).

Therefore, air emissions of green-house gases, gases causing acidification and eutrophication, gases causing photochemical ozone formation, emission of particulates and heavy metals were collected from an inventory with spatial allocation of emission gases [6.27]. The Portuguese Environmental Agency provides this type of data for years 2003, 2005 and 2007, although the complete reports are only available for data related to years 2003 and 2005. Thus, the most recent data is from 2007, although it was published in 2009. However, as no report is available for this year the report from 2005 [6.26], which was published in 2008, is also referred in this study.

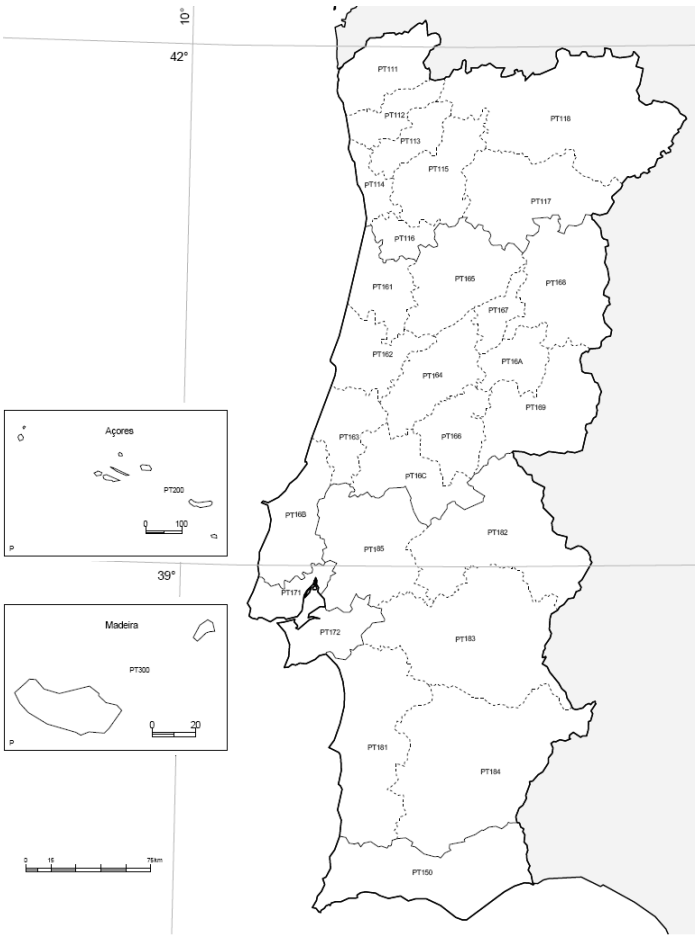


Figure 6.20. Portugal – NUTS level III [6.28]

Data contained in the inventory [6.27] is provided at the municipality level, per unit area (in km^2). However, in this study, data is aggregated according to the Nomenclature of Territorial Units for Statistics (NUTS) level III. The NUTS classification was established by Eurostat and it provides a single uniform breakdown of territorial units for the production of regional statistics at the European level. According to NUTS level III classification, mainland Portugal is divided into twenty-eight regions, plus two more regions corresponding to the archipelagos of Madeira and Azores. These regions and respective codes are represented in Figure 6.20.

The area and mean population for 2008, according to the National Statistics Institute (INE), for each NUTS are given in Table 6.21.

Table 6.21. Portuguese data according to NUTS III (source: INE)

NUTS III code	Name	Area (km^2)	Mean population in 2008
PT111	Minho-Lima	2 219.29	251 002
PT112	Cávado	1 245.67	412 690
PT113	Ave	1 246.16	524 758
PT114	Grande Porto	814.45	1 283 980
PT115	Tâmega	2 619.57	560 850
PT116	Entre Douro e Vouga	862.23	288 933
PT117	Douro	4 107.52	209 894
PT118	Alto Trás-os-Montes	8 167.88	213 998
PT150	Algarve	4 995.76	430 135
PT161	Baixo Vouga	1 802.25	399 919
PT162	Baixo Mondego	2 062.83	330 465
PT163	Pinhal Litoral	1 741.83	267 893
PT164	Pinhal Interior Norte	2 616.57	137 370
PT165	Dão-Lafões	3 488.59	291 297
PT166	Pinhal Interior Sul	1 904.68	40 379
PT167	Serra da Estrela	867.80	47 382
PT168	Beira Interior Norte	4 063.11	108 891
PT169	Beira Interior Sul	3 732.04	72 775
PT16A	Cova da Beira	1 374.56	90 721
PT16B	Oeste	2 220.13	363 879
PT16C	Médio Tejo	2 306.21	231 082
PT171	Grande Lisboa	1 375.89	2 029 438
PT172	Península de Setúbal	1 525.08	770 165
PT181	Alentejo Litoral	5 254.81	95 638
PT182	Alto Alentejo	6 230.14	116 504
PT183	Alentejo Central	7 226.52	169 101
PT184	Baixo Alentejo	8 503.74	125 855
PT185	Lezíria do Tejo	4 276.76	249 763
PT200	Açores	2 322.00	244 739
PT300	Madeira	827.97	255 429

6.3.2.2.1. Normalisation factors for acidification and eutrophication

Portuguese emission data causing acidification and eutrophication were taken from the 2007 inventory [6.27], considering the emission of ammonia (NH_3), nitrogen oxides (NO_x) and sulphur oxides (SO_x). According to the report of 2005 [6.26], the total emission of substances causing acidification and eutrophication were mainly due to the sectors of energy production, road and rail transportation, and agriculture:

- sulphur oxides emissions are mainly caused from energy production (56.8%), combustion in the industry (25.6%) and industrial processes (10.2%);
- nitrogen oxide emissions are mainly due to the sector of transportation (36.2%), energy production (21%) and industrial combustions (20.2%);
- emissions of ammonia are mainly due to agriculture (41.5%) and animal production (39.3%).

The inventory provides these emissions per municipality and per square kilometre. The total emission of a substance per NUT III was determined by the aggregation of the respective emissions per municipality in each NUT.

Two sets of characterisation factors for each impact category were applied in the calculation of normalisation scores. The characterization factors for acidification were taken from Table 6.5, considering the average values for Europe and the corresponding values for Portugal. Likewise, for eutrophication, the characterization factors were taken from Table 6.7, considering the average values for Europe and the corresponding values for Portugal.

The resulting normalisation scores for acifification and eutrophication are indicated in Table 6.22, per NUT and per capita, considering the characterization factors relative to Portugal.

Table 6.22. Normalisation factors for acidification and eutrophication in Portugal (reference area NUTS III)

NUTS III code	Acidification		Eutrophication	
	(kg SO_2 eq./yr)	(kg SO_2 eq./yr.Hab.)	(kg PO_4^{---} eq./yr)	(kg PO_4^{---} eq./yr. Hab.)
PT111	9.09E+05	3.62E+00	5.18E+06	2.06E+01
PT112	1.08E+06	2.63E+00	6.12E+06	1.48E+01
PT113	1.12E+06	2.13E+00	6.03E+06	1.15E+01
PT114	4.56E+06	3.55E+00	1.47E+07	1.14E+01
PT115	1.28E+06	2.28E+00	6.70E+06	1.19E+01
PT116	7.60E+05	2.63E+00	3.47E+06	1.20E+01
PT117	5.87E+05	2.80E+00	4.23E+06	2.01E+01
PT118	1.10E+06	5.12E+00	8.42E+06	3.94E+01
PT150	1.28E+06	2.99E+00	8.53E+06	1.98E+01
PT161	2.16E+06	5.40E+00	1.06E+07	2.65E+01
PT162	3.71E+06	1.12E+01	1.79E+07	5.42E+01
PT163	1.38E+06	5.14E+00	7.28E+06	2.72E+01
PT164	5.66E+05	4.12E+00	2.59E+06	1.88E+01
PT165	1.23E+06	4.22E+00	9.04E+06	3.10E+01
PT166	1.37E+05	3.39E+00	9.11E+05	2.26E+01
PT167	1.27E+05	2.68E+00	8.77E+05	1.85E+01
PT168	6.19E+05	5.68E+00	4.61E+06	4.24E+01
PT169	6.59E+05	9.06E+00	3.93E+06	5.40E+01
PT16A	2.66E+05	2.93E+00	1.87E+06	2.07E+01
PT16B	2.19E+06	6.02E+00	1.21E+07	3.32E+01
PT16C	5.35E+06	2.32E+01	9.83E+06	4.25E+01
PT171	3.67E+06	1.81E+00	2.06E+07	1.01E+01
PT172	8.26E+06	1.07E+01	1.94E+07	2.52E+01
PT181	1.58E+07	1.65E+02	2.07E+07	2.16E+02
PT182	1.10E+06	9.46E+00	8.80E+06	7.55E+01
PT183	1.54E+06	9.13E+00	1.24E+07	7.32E+01
PT184	1.40E+06	1.11E+01	1.12E+07	8.90E+01
PT185	1.53E+06	6.13E+00	1.06E+07	4.25E+01
PT200	2.60E+06	1.06E+00	8.37E+06	3.42E+01
PT300	2.50E+06	9.80E+00	3.51E+06	1.37E+01

6.3.2.2.2. Normalisation factors for human toxicity and ecotoxicity

Emissions of ammonia (NH_3), Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x), Particulates (PM) and heavy metals (mercury (Hg), cadmium (Cd) and Lead (Pb)) were taken from the 2007 national inventory [6.27] for the calculation of human toxicity and terrestrial ecotoxicity. The main sources of NH_3, NO_x and SO_x emissions were already described in the previous paragraph.

The industrial sector is the main source for the emission of particulate matter (PM). According to (6.29), in 2005, 46.1% of PM emissions were due to industrial processes, 20.8% were from industrial combustions, 17.9% from small sources of combustion, 6.1% from transportation (road and rail), 2.8% from agricultural waste, 2% from energy production, 1.5% from the use of solvents and 2.8% from other sources. According to the same report, the emission of heavy metals was related to the use and type of fuels. Emissions of Pb were mainly due to the transportation sector (59%), industrial combustion contributes with 13.2%, small sources of combustion with 12.3%, deposition of debris in soils with 12.3%, energy production with 2.6% and other sources 0.4%. The main source of Cd emissions was point sources (85.5%), while most of Hg emissions (65.7%) occurred in point sources associated with industrial activities.

Table 6.23. Normalisation factors for human toxicity and ecotoxicity in Portugal (reference area NUTS III)

NUTS III code	Human Toxicity		Terrestrial Ecotoxicity	
	(kg 1.4-DCB eq./yr)	(kg 1.4-DCB eq./yr.Hab.)	(kg 1.4-DCB eq./yr)	(kg 1.4-DCB eq./yr. Hab.)
PT111	1.09E+07	4.33E+01	1.57E+05	6.26E-01
PT112	1.58E+07	3.82E+01	1.81E+05	4.38E-01
PT113	1.86E+07	3.54E+01	2.04E+05	3.90E-01
PT114	6.12E+07	4.76E+01	8.30E+05	6.47E-01
PT115	2.31E+07	4.11E+01	2.34E+05	4.16E-01
PT116	1.25E+07	4.33E+01	1.59E+05	5.52E-01
PT117	5.62E+06	2.68E+01	3.73E+04	1.78E-01
PT118	7.05E+06	3.29E+01	3.93E+04	1.84E-01
PT150	1.64E+07	3.80E+01	8.66E+04	2.01E-01
PT161	3.10E+07	7.75E+01	4.72E+05	1.18E+00
PT162	1.25E+08	3.79E+02	6.43E+05	1.95E+00
PT163	3.19E+07	1.19E+02	2.04E+05	7.62E-01
PT164	1.26E+07	9.18E+01	1.05E+05	7.63E-01
PT165	9.31E+06	3.20E+01	1.13E+05	3.90E-01
PT166	1.62E+06	4.02E+01	1.12E+04	2.78E-01
PT167	1.41E+06	2.99E+01	9.74E+03	2.05E-01
PT168	4.49E+06	4.12E+01	2.74E+04	2.52E-01
PT169	5.86E+06	8.05E+01	7.53E+04	1.03E+00
PT16A	2.75E+06	3.03E+01	1.90E+04	2.09E-01
PT16B	3.10E+07	8.53E+01	2.96E+05	8.15E-01
PT16C	2.79E+07	1.21E+02	6.75E+05	2.92E+00
PT171	5.66E+08	2.79E+02	6.52E+05	3.21E-01
PT172	7.87E+07	1.02E+02	1.04E+06	1.35E+00
PT181	5.80E+07	6.06E+02	1.85E+06	1.94E+01
PT182	4.53E+06	3.89E+02	3.19E+04	2.74E-01
PT183	6.25E+06	3.69E+01	3.55E+04	2.10E-01
PT184	5.89E+06	4.68E+01	2.83E+04	2.25E-01
PT185	1.34E+07	5.36E+01	1.15E+05	4.61E-01
PT200	2.48E+07	1.01E+02	2.47E+05	1.01E+00
PT300	2.82E+07	1.11E+02	3.71E+05	1.45E+00

Four sets of characterisation factors, considering different time horizons, were used for the calculation of normalisation scores for human toxicity and terrestrial ecotoxicity. These factors were taken from Table 6.8 and Table 6.9, respectively for human toxicity and terrestrial ecotoxicity. In should be noticed that these characterisation factors were defined at the continental scale.

The normalisation factors for human toxicity and terrestrial ecotoxicity, considering the characterisation factors relative to a time horizon of 100 years, are represented in Table 6.23, per NUT III and per capita.

6.3.2.2.3. Normalisation factors for global warming and photochemical ozone creation

Green house gas emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were provided in [6.27]. In 2005, about 84.5% of Portuguese CO_2 emissions were mainly from three sectors [6.26]: energy production (32.6%), road/rail transportation (27.7%) and industrial combustion (24.1%). Other sources include the sector of small sources of combustion (8.8%) and industrial processes (3.2%).

Table 6.24. Normalisation factors for global warming and photochemical oxidation in Portugal (reference area NUTS III)

NUTS III code	Global warming		Photochemical oxidation	
	(kg CO_2 eq./yr)	(kg CO_2eq./yr.Hab.)	(kg C_2H_4 eq./yr)	(kg C_2H_4 eq./yr. Hab.)
PT111	1.03E+09	4.10E+03	2.37E+06	9.43E+00
PT112	1.53E+09	3.70E+03	2.29E+06	5.55E+00
PT113	1.95E+09	3.71E+03	2.73E+06	5.21E+00
PT114	8.46E+09	6.59E+03	7.87E+06	6.13E+00
PT115	2.08E+09	3.71E+03	3.72E+06	6.63E+00
PT116	1.28E+09	4.44E+03	2.76E+06	9.54E+00
PT117	8.83E+08	4.21E+03	3.25E+06	1.55E+01
PT118	1.15E+09	5.37E+03	6.38E+06	2.98E+01
PT150	2.44E+09	5.67E+03	3.52E+06	8.19E+00
PT161	2.33E+09	5.82E+03	5.63E+06	1.41E+01
PT162	3.72E+09	1.13E+04	3.76E+06	1.14E+01
PT163	2.24E+09	8.35E+03	1.99E+06	7.43E+00
PT164	5.48E+08	3.99E+03	1.12E+06	8.18E+00
PT165	1.25E+09	4.29E+03	2.06E+06	7.09E+00
PT166	2.01E+08	4.98E+03	4.39E+05	1.09E+01
PT167	2.10E+08	4.43E+03	5.19E+05	1.10E+01
PT168	7.12E+08	6.54E+03	3.43E+06	3.15E+01
PT169	5.56E+08	7.64E+03	3.36E+06	4.61E+01
PT16A	4.31E+08	4.75E+03	1.20E+06	1.32E+01
PT16B	4.66E+09	1.28E+04	4.27E+06	1.17E+01
PT16C	4.21E+09	1.82E+04	3.21E+06	1.39E+01
PT171	1.05E+10	5.18E+03	1.06E+07	5.21E+00
PT172	7.88E+09	1.02E+04	7.48E+06	9.71E+00
PT181	1.13E+10	1.19E+05	1.62E+07	1.69E+02
PT182	9.35E+08	8.03E+03	8.28E+06	7.11E+01
PT183	1.36E+09	8.05E+03	1.03E+07	6.11E+01
PT184	1.18E+09	9.39E+03	1.10E+07	8.77E+01
PT185	1.75E+09	7.01E+03	5.31E+06	2.12E+01
PT200	1.60E+09	6.52E+03	4.10E+06	1.68E+01
PT300	1.49E+09	5.82E+03	2.06E+06	8.05E+00

In relation to the emission of CH_4, the major contributing sectors were [6.26]: deposition of waste in soils (47%), sewage water (25.2%) and animal husbandry (12.4%). Finally, the main sources of N_2O emissions are: agriculture (44.7%), animal husbandry (20.1%), industrial processes (9.7%), sewage water (9.2%) and transportation (8.8%).

For the calculation of normalisation scores for the impact category global warming, three sets of characterisation factors, considering different time horizons, were used according to Table 6.2. The normalisation factors for global warming, considering the characterisation factors relative to a time horizon of 100 years, are represented in Table 6.24, per NUT III and per capita.

For the calculation of the normalisation values for the impact category photochemical oxidation, the following emissions were considered: Carbon Monoxide (CO), Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x), Methane (CH_4) and non-methane volatile organic compounds (NMVOC).

In relation to the emissions of non-methane volatile organic compounds (NMVOC), the inventory considers two types emissions [6.27]: natural emissions, due to vegetal land cover and forest wildfires; and anthropogenic emissions, derived from human activities. In 2005, natural emissions of NMVOC account for 58.7% of the total NMVOC emissions; while anthropogenic emissions were mainly caused by the use of solvents (15.3%), road/rail transportation (7.6%), industrial processes (5%), agriculture (3.4%), fugitive emissions (3.2%), small combustion sources (3%), industrial combustion (1.8%) and other sources (2%) [6.26].

In this case, two sets of characterisation factors, considering different background concentration of NO_x, were used according to Table 6.4. The normalisation factors for photochemical oxidation, considering the characterisation factors relative to high background concentration of NO_x, are represented in Table 6.24, per NUT III and per capita.

6.3.2.2.4. Normalisation factor for ozone layer depletion

In spite of the commitments of Portugal to international protocols, such as the Montreal Protocol, no Portuguese data was found regarding the emission of ozone-depletion substances. Therefore, the normalisation values for Portugal were estimated from Dutch values indicated in Table 6.18, by extrapolation. This approach was used by Huijbregts et al. [6.25] assuming a good correlation between emissions and the GDP of the region involved.

The extrapolation method used is based on gross domestic products (GDP) converted to international dollars using Purchasing Power Parity (PPP) rates. Purchasing Power Parity (PPP) rates are currency conversion rates enabling international volume comparisons of GDP by taking into account the differences in price levels between countries [6.29].

Dutch normalisation scores indicated in Table 6.18 were determined based on emission data from 1997 and in the characterization factors from Table 6.3. Therefore, GDP values from 1997, indicated in Table 6.25, were also used to extrapolate data to Portugal.

Table 6.25. GDP based on PPP valuation of country GDP (international dollars) [6.30]

Country	Year 1997	Year 2009
The Netherlands	$ 399 410 000 000	$ 658 230 000 000
Portugal	$ 152 300 000 000	$ 232 660 000 000

The resulting normalisation scores for ozone layer depletion are indicated in Table 6.28, for different time-dependent characterisation.

6.3.2.2.5. Normalisation factor for abiotic depletion

For the impact category abiotic depletion, a Portuguese normalisation value is quantified based on national extraction rates of natural resources. The World Resources Institute [6.31] provides data for the total amount of primary energy consumed in Portugal from the usage of fossil fuels, namely, the use of crude oil and natural gas liquids, coal and coal products, and natural gas. These values are indicated in Table 6.26 for the year 1999.

Table 6.26. Total fossil fuels consumption in Portugal, 1999 [6.31]

	Energy consumption (in toes(*))
Coal and coal products	3 789 000
Crude oil and natural gas liquids	13 757 000
Natural gas	1 939 000

(*) one toe – one ton of oil equivalent (41.868 GJ)

The characterisation factors used for the calculation of the normalisation value, which are indicated in Table 6.27, are based on the same model as described in sub-section 6.2.3.9.

Table 6.27. Abiotic depletion potentials (in Sb eq./MJ)

Resource	ADs
Energy from coal	4.57E-04
Energy from oil	4.90E-04
Energy from natural gas	5.34E-04

The resulting normalization value is indicated in Table 6.28.

6.3.2.2.6. Summary of normalization factors

The normalisation factors for the impact categories of acidification, eutrophication, human toxicity, terrestrial ecotoxicity, global warming and photochemical oxidation were presented in the tables of the previous clauses by NUT III and per capita. The respective normalisation scores considering the entire national territory are summarized in Table 6.28, considering the characterisation factors indicated in the first column. As referred in the previous paragraphs, these values are related to year 2007. For a comparative purpose, the normalisation values obtained by extrapolation from Dutch data, according to the procedure described in clause 6.3.2.2.4, are also provided in brackets. However, it should be noted that data in brackets referred to year 1997, while Portuguese data referred to year 2007.

Table 6.28. Summary of Portuguese normalisation factors (total per year and per capita)

Impact category	Normalisation factors and units			
Global warming				
TH = 20 yrs	kg CO_2 eq./yr	9.76E+10 (1.14E+11)	kg CO_2 eq./ yr.capita	9.19E+03 (1.08E+04)
TH = 100 yrs		7.99E+10 (9.53E+10)		7.53E+03 (8.98E+03)
TH = 500 yrs		6.98E+10 (8.39E+10)		6.57E+03 (7.90E+03)
Ozone depletion				
TH = 5 yrs	kg CFC-11 eq./yr	5.34E+05	kg CFC-11 eq./ yr. capita	5.03E-02
TH = 10 yrs		4.58E+05		4.31E-02
TH = 15 yrs		4.19E+05		3.95E-02
TH = 20 yrs		3.81E+05		3.59E-02
TH = 25 yrs		3.77E+05		3.56E-02
TH = 30 yrs		3.66E+05		3.45E-02
TH = 40 yrs		3.51E+05		3.30E-02
TH = ∞		3.74E+05		3.52E-02
Photo-oxidant formation				
High NO_x	kg C_2H_4 eq./yr	1.41E+08 (6.86E+07)	kg C_2H_4 eq./ yr. capita	1.33E+01 (6.47E+00)
Low NO_x		1.34E+08 (6.10E+07)		1.26E+01 (5.75E+00)
Acidification				
Average Europe	kg SO_2 eq./yr	4.40E+08 (2.55E+08)	kg SO_2 eq./ yr. capita	4.14E+01 (2.41E+01)
Portugal		6.95E+07		6.55E+00
Eutrophication				
Average Europe	kg NO_x eq./yr	5.49E+08 (5.34E+08)	kg NO_x eq./ yr. capita	5.17E+01 (5.03E+01)
Portugal		2.60E+08		2.45E+01
Human toxicity				
TH = 20 yrs	kg 1,4-DB eq./yr	1.24E+09 (7.24E+10)	kg 1,4-DB eq./ yr. capita	1.17E+02 (6.83E+03)
TH = 100 yrs		1.24E+09 (7.24E+10)		1.17E+02 (6.83E+03)
TH = 500 yrs		1.25E+09 (7.24E+10)		1.17E+02 (6.83E+03)
TH = ∞		1.33E+09 (7.24E+10)		1.25E+02 (6.83E+03)
Terrestrial ecotoxicity				
TH = 20 yrs	kg 1,4-DB eq./yr	1.89E+06 (5.72E+07)	kg 1,4-DB eq./ yr. capita.	1.78E-01 (5.39E+00)
TH = 100 yrs		8.96E+06 (6.48E+07)		8.44E-01 (6.11E+00)
TH = 500 yrs		3.48E+07 (9.91E+07)		3.28E+00 (9.34E+00)
TH = ∞		8.21E+07 (3.66E+08)		7.73E+00 (3.45E+01)
Abiotic depletion	kg Sb eq./yr	3.98E+08 (6.48E+08)	kg Sb eq./ yr. capita	3.75E+01 (6.11E+01)

6.3.2.2.7. Remarks about the calculation of national normalisation factors

The calculation of the Portuguese normalisation factors presented in Table 6.28 was based, apart from the impact category ozone layer depletion, on Portuguese data from the reference year of 2007. As a party to the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP), the United Nations Framework Convention on Climate Change (UNFCCC) and related Protocols, Portugal is committed to provide yearly an update of its inventory of air pollutant emissions, considering the guidelines and reporting format specified in each case. The emissions used in this work were based on inventories and reports made under this framework.

However, as referred in the previous paragraph, the inventories are made according to specific formats and include usually a limited number of substances. The inventories are complete in covering the emission sources of the mandatory substances but this does not imply that the range of emissions are fully representative of the environmental impact categories considered in this chapter.

According to Huijbregts et al. [6.25], a limited set of emissions or extractions are dominant contributors to the normalisation scores presented in Table 6.18:

(i) for the impact category global warming, the emissions of CO_2, CH_4 and N_2O contribute to more than 80% of the respective normalisation scores for all time horizons;

(ii) for the impact category acidification, NH_3, NO_x and SO_x emissions have the most significant contributions in all scales; while, NO_x and NH_3 emissions have the most significant contributions to eutrophication (and they contribute with almost the same share);

(iii) in terms of ozone layer depletion, CFCs, methylchloroform and methylbromide are the main contributors to the normalisation score for short time horizon; while for the infinite time horizon CFCs are the dominant contributors;

(iv) for photochemical ozone formation, CO has a significant share; however the major contributors are alkanes, alkenes and aromatics (> 50%);

(v) normalisation scores for human toxicity and dominated by air emissions of non-halogenated hydrocarbons; while for terrestrial ecotoxicity, inorganic and pesticides have the most important contribution in all time horizons;

(vi) finally, for abiotic depletion, the fossil fuels oil, coal and natural gas contribute to more than 99% to the normalisation scores of abiotic depletion in all scales.

Taking the above observations into consideration in the analysis of Portuguese normalisation factors, indicated in Table 6.28, the following conclusions are made:

(i) The emission data used for the calculation of the normalisation values of global warming, acidification and eutrophication are representative of the most dominant emissions in each impact category; it should be noted however that the normalisation score of eutrophication does not cover aquatic eutrophication (see sub-section 6.2.3.6);

(ii) In relation to the normalisation scores for photochemical oxidation, the Portuguese inventory does not provide a detailed list of substances contributing to the impact category. Apart from CO, NO_x, SO_x and CH_4, it provides emissions of NMVOC, which includes a large variety of chemically different compounds. NMVOC emissions were included in the calculation of the normalisation score by the use of the characterization factor indicated in Table 6.4; therefore, it may be assumed that this normalisation score is satisfactory;

(iii) The normalisation score of ozone layer depletion was obtained by GDP extrapolation from Dutch data; therefore, no further comments are made;

(iv) The normalisation scores of human toxicity and terrestrial ecotoxicity were obtained by emission data of only a few inorganic compounds (NH_3, NO_2, SO_2, PM and heavy metals). For human toxicity the major contributors are air emissions of non-halogenated hydrocarbons, which were not considered in the calculation of the respective normalisation score. Moreover, according to [6.25], in this impact category inorganics have a contribution of less than 10% in all time horizons. In relation to ecotoxicity, for a time horizon of 100 years, pesticides have a major contribution although for an infinite time span inorganics have also an important contribution. Thus, the Portuguese normalisation scores indicated in Table 6.28 for human toxicity and terrestrial ecotoxicity may be underestimated; this conclusion is also noted from the comparison

between the Portuguese values and the values obtained from extrapolation from Dutch data (although the latter is referred to year 1997).

(v) Finally, the normalisation score for abiotic depletion considered the production of energy from the three main resources contributing to the impact category.

6.3.2.3. Set of normalisation scores used in the LCEA

Two sets of normalisation scores were discussed in the previous sub-sections: general normalisation scores (Table 6.18) and Portuguese normalisation scores (Table 6.28).

As discussed in sub-section 6.3.2.1, there are two approaches to deal with normalisation: at a single scale or at different scale levels. According to ISO standard 14044 [6.2], the selection of the reference system should be consistent with the spatial and temporal scales of the environmental mechanism and hence, the second approach is more in agreement with the standard.

Table 6.29. Set of normalization factors adopted in this work (per year and per capita)

Impact category	Units		Geographical scale
Abiotic depletion	kg (Sb eq.) /year/capita	2.81E+01	World
Acidification			
Average Europe	kg (SO_2 eq.) / year/capita	4.14E+01	Portugal
Portugal	kg (SO_2 eq.) / year/capita	6.55E+00	Portugal
Eutrophication			
Average Europe	kg (NO_x eq.) / year/capita	5.17E+01	Portugal
Portugal	kg (NO_x eq.) / year/capita	2.45E+01	Portugal
Global warming			
TH = 20 yrs	kg (CO_2 eq.) / year/capita	9.49E+03	World
TH = 100 yrs	kg (CO_2 eq.) / year/capita	7.21E+03	World
TH = 500 yrs	kg (CO_2 eq.) / year/capita	5.80E+03	World
Ozone layer depletion			
TH = 5 yrs	kg (CFC-11 eq.) / year/capita	2.81E-01	World
TH = 10 yrs	kg (CFC-11 eq.) / year/capita	1.58E-01	World
TH = 15 yrs	kg (CFC-11 eq.) / year/capita	1.21E-01	World
TH = 20 yrs	kg (CFC-11 eq.) / year/capita	1.05E-01	World
TH = 25 yrs	kg (CFC-11 eq.) / year/capita	9.49E-02	World
TH = 30 yrs	kg (CFC-11 eq.) / year/capita	8.79E-02	World
TH = 40 yrs	kg (CFC-11 eq.) / year/capita	7.91E-02	World
TH = ∞	kg (CFC-11 eq.) / year/capita	9.14E-02	World
Human toxicity			
TH = 20 yrs	kg (1,4-DCB eq.) / year/capita	1.00E+04	World
TH = 100 yrs	kg (1,4-DCB eq.) / year/capita	1.00E+04	World
TH = 500 yrs	kg (1,4-DCB eq.) / year/capita	1.00E+04	World
TH = ∞	kg (1,4-DCB eq.) / year/capita	1.00E+04	World
Terrestrial Ecotoxicity			
TH = 20 yrs	kg (1,4-DCB eq.) / year/capita	2.29E+01	World
TH = 100 yrs	kg (1,4-DCB eq.) / year/capita	2.46E+01	World
TH = 500 yrs	kg (1,4-DCB eq.) / year/capita	2.81E+01	World
TH = ∞	kg (1,4-DCB eq.) / year/capita	4.75E+01	World
Photo-chemical oxidation			
High NO_x	kg (C_2H_4 eq.) / year/capita	1.69E+01	World
Low NO_x	kg (C_2H_4 eq.) / year/capita	1.53E+01	World

In the present approach, and taking into consideration the case studies that will be performed to validate the proposed life cycle approach, it is proposed to use normalisation values referring to global reference values for global environmental impact categories and Portuguese normalisation factors for local/regional categories. Therefore, for the impact categories of acidification and eutrophication normalisation is performed using the reference values indicated in Table 6.28, using characteristic factors relative to Portugal; for all the remaining categories, normalisation is performed using reference values for the world in 1995 indicated in Table 6.18. In all cases the references values are given by capita, considering the Portuguese population in 2007 as 10 614 927 and the world population in 1995 as 5 689 010 289 [6.32]. The adopted set of normalisation values are indicated in Table 6.29.

The methodological choices made in the calculation of normalisation values should be consistent with the methodological choices made in the calculation of the environmental impact categories [6.3]. Therefore, the same characterisation factors are used for the calculation of impact categories and respective normalisation values.

To make the set of normalisation values more credible, the next sub-section addresses some of the uncertainties in the normalisation values adopted in this LCEA.

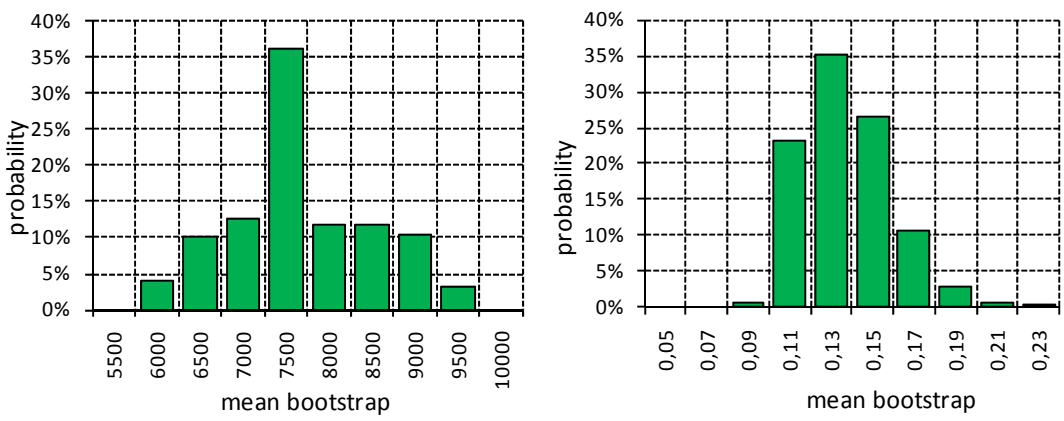
6.3.2.4. Uncertainty of normalization factors

There are two main sources of uncertainties in the normalisation values: (i) the lack of emission data for some substances; and (ii) the modelling behind the characterisation factors.

However, in this sub-section only the latter source of uncertainty is addressed, as the lack of emission data is not feasible within the scope of this work.

For the consistency between the impact assessment stage and the normalisation stage, as referred in the previous sub-section, the same approach to deal with characterisation factors will be used for the normalisation scores.

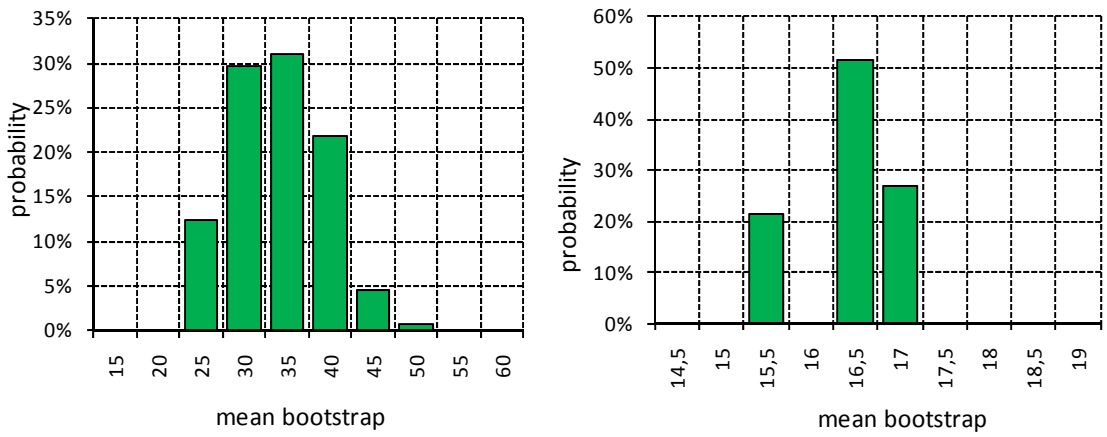
Therefore, for the impact categories of global warming, ozone layer depletion, photochemical oxidation, human toxicity and terrestrial ecotoxicity, a non-parametric bootstrap approach is applied considering different scenarios for diferent time horizons. The frequency diagrams obtained for global warming and ozone layer depletion, considering 1000 resamples from the original sample with replacement, are represented below:



(a) (b)

Figure 6.21. Frequency diagrams for (a) Global Warming and (b) Ozone Layer Depletion

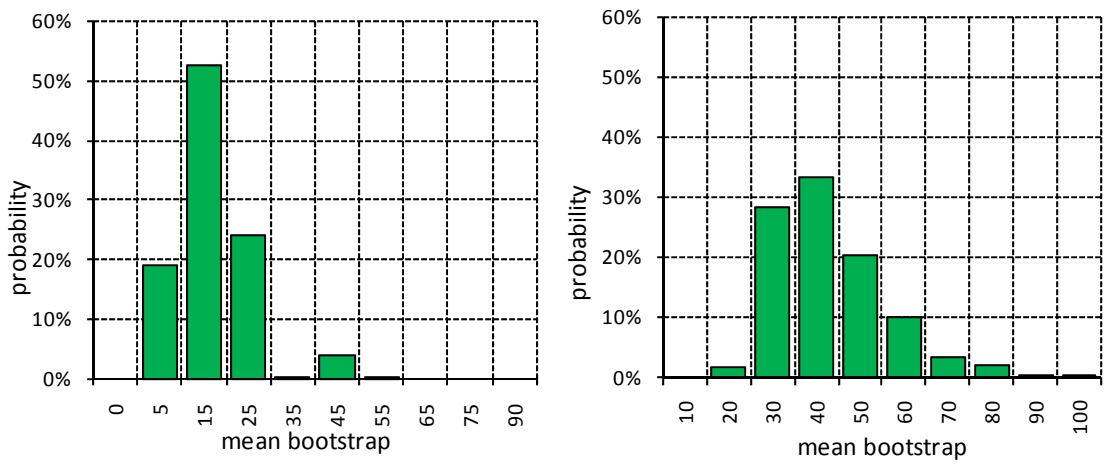
For the impact category human toxicity, there is no change in the normalisation value considering different time horizons (see Table 6.18). Therefore, it is not possible to apply a bootstrap sampling in this case. For the impact categories of terrestrial ecotoxicity and photochemical oxidation, the frequency diagrams, considering 1000 resamples from the original sample with replacement, are indicated in the following picture.



(a) (b)

Figure 6.22. Frequency diagrams for (a) Terrestrial ecotoxicity and (b) photochemical oxidation

For the impact categories of acidification and eutrophication, a non-parametric bootstrap approach is applied considering the original sample composed of the values listed in Table 6.22. The frequency diagrams in this case, considering 1000 resamples from the original sample with replacement, are represented in Figure 6.23.



(a) (b)

Figure 6.23. Frequency diagrams for (a) Acidification and (b) Eutrophication

Based in the bootstrapped estimate of each sampling distribution, the 90% confidence intervals were calculated and the lower and upper bounds are indicated in Table 6.30 in relation to the normalisation scores of each impact category.

Table 6.30. 90% confidence interval of the mean bootstrap

Impact category	Lower bound	Upper bound
Acidification	4.00	35.86
Eutrophication	22.92	61.86
Ozone depletion	0.097	0.165
Global warming	6269.40	8730.28
Terrestrial ecotoxicity	24.17	37.79
Human toxicity	-	-
Photochemical oxidation	15.29	16.87

To make these distributions operational in the life cycle analysis a probabilistic distribution was fitted to each normalisation value and goodness of fit statistics were applied to determine the accuracy of the fitted distribution. The properties of the fitted distributions are indicated in Table 6.31. Lognormal distributions were used for most impact categories. For the normalisation values referring to the impact categories of human toxicity and abiotic depletion, a lognormal distribution was also assumed for both cases.

Table 6.31. Distributions for the fitted normalization values

	Distribution type	Parameters
Global warming	Lognormal	μ = 7731.700; σ = 876.890
Acidification	Lognormal	μ = 18.639; σ = 9.619
Eutrophication	Lognormal	μ = 42.583; σ = 13.280
Photo-oxidant form.	Triangular	μ = 16.352; σ = 0.501
Ozone depletion	Lognormal	μ = 0.136; σ = 0.023
Ecotoxicity	Lognormal	μ = 34.373; σ = 5.676
Human toxicity (*)	Lognormal	μ = 10019.320; σ = 1001.932
Abiotic depletion (*)	Lognormal	μ = 28.12; σ = 2.812

(*) assumed distributions

As an alternative approach, an uniform distribution is also proposed for the normalisation values with minimum and maximum values indicated in Table 6.32.

Table 6.32. Properties of the uniform distributions for normalisation values

	Distribution type	Parameters
Global warming	Uniform	max = 9.49E+03; min = 5.80E+03
Acidification	Uniform	max = 4.14E+01; min = 6.55E+00
Eutrophication	Uniform	max = 5.17E+01; min = 2.45E+01
Photo-oxidant form.	Uniform	max = 1.69E+01; min = 1.53E+01
Ozone depletion	Uniform	max = 2.81E-01; min = 9.14E-02
Ecotoxicity	Uniform	max = 4.75E+01; min = 2.29E+01
Human toxicity (*)	Uniform	max = 1.10E+04; min = 9.02E+03
Abiotic depletion (*)	Uniform	max = 3.09E+01; min = 2.53E+01

(*) the maximum and minimum values were considered by +10% and -10%, respectively, of the deterministic value

6.3.3. Weighting of environmental indicators

6.3.3.1. Introduction

The weighting step of LCEA is usually needed when trade-offs between different environmental impacts are involved. The need to include this step in a life cycle analysis depends on the goal of the analysis. If the goal is to learn from the life cycle analysis the processes and/or stages that most contribute to environmental impacts, considering an attributional perspective, then the weighting step does not add any useful information. On the other side, if the goal of the LCEA is

to aid in a decision making process, then the weighting step may contribute with additional information to the process; however, it cannot replace discussions of environmental values [6.33].

According to ISO 14044 [6.2], weighting is an optional step of LCEA, aiming to convert indicators results of different impact categories by using numerical factors based on value-choices. Different individuals may have different preferences, thus it is possible that different parties will reach different weighting sets based on the same indicator results; therefore, the standard recommends to use different weighting factors and weighting methods and to conduct sensitivity analysis to assess the consequences of the life cycle results of different value-choices. In order to ensure the "transparency" of the results, the standard recommends making available the environmental results obtained prior to weighting, together with the weighting results. Moreover, the standard states that weighting shall not be used for comparative assertions disclosed to the public.

Weighting is a highly controversial issue in the international LCA community. From an ethical point of view, Finnveden [6.34] differentiates between two ethical theories: deontological and teleological. In this respect, for persons holding ethical beliefs in line with deontological theories, in which some rules are given absolute priority, methods involving weighting of different environmental problems against each other may seem unethical. On the other end, according to the teleological group of theories, weighting between good and bad consequences is possible. Moreover, he recognizes that valuation or weighting in LCA requires not only ethical and/or ideological values but also political values. Since a societal consensus on these fundamental values is not possible in an open democratic society, no consensus is possible on valuation of weighting factors or on the valuation method. Thus, it is suggested to explicitly take into account ethical and ideological values in valuation methods for an increased agreement. The construction of several lifestyles-dependent weights by the use of a cultural perspective was also suggested by Hofstetter [6.35].

Other authors [6.36] take a more radical approach and suggest to avoid weighting methods as they yield results with technical, practical and social-political ambiguities, which make them unreliable at a global scale.

In a comparison between alternatives, when all the environmental results of one alternative are superior to the results of the other alternative, then there's no need for weighting. However, in LCEA this situation seldom happens. Nevertheless, weighting is not an exclusive problem of comparisons between different products or services, trade-offs are often needed within the same life cycle; for instance, in the case of recycling, a trade-off between the safeguard of natural resources and other environmental categories (as discussed in the previous chapter) is usually considered.

As referred in the first paragraph, in a situation when it cannot be unambiguously decided if one alternative is environmental preferable to another, then the question of weighting arises.

There are a plurality of environmental values and attitudes towards different kinds of changes in the environment, and this has to be understood and taken into account when using weighting methods in a decision making perspective [6.33]. Hence, Bengtsson and Steen [6.33] proposed to look at weighting as a check of the compatibility between the environmental impacts

associated with a system and different sets of societal preferences. Different people have different conceptions and different attitudes and it is the task of decision makers to say which concerns will be considered in LCEA; naturally, according to the values of the intended audience of the analysis.

In this dissertation it is acknowledged that an unique set of values for weighting is not possible and even not advisable. However, in a decision-making perspective, weighting is needed and thus a consistent procedure for the determination of a set of values to be applied in the LCEA is pursued in this section. The following sub-section describes some of the available approaches for weighting. An approach for the quantification of a weighting set is proposed in the subsequent sub-section.

6.3.3.2. Current approaches to weighting

In this section the main approaches to weighting in LCEA are introduced. A more comprehensive review and discussion on weighting methods may be found in [6.37][6.38][6.39][6.40][6.41][6.42][6.43].

There are three main methods for weighting impact categories in LCEA [6.44]: (i) methods based on distance-to-target, (ii) methods based on monetary values, and (iii) methods based on the judgment of an authoritative panel.

A distance-to-target method is defined by the ratio between the current level of emissions in geographical area and the level that is considered critical, the target level [6.44]. If the level of current emissions is lower than the target level, the weight is lower than in case the emissions are above it, thus indicating how severe a certain kind of emission is. A critical point in this method is the target levels and how they are determined. When policy targets are used, these targets are usually defined in different contexts from that of the LCEA and thus it may distort the analysis [6.33]. Lee [6.45] noted that the ratio between the level of emissions and the respective target only reflects the level of severity of a impact category; it does not provide any information in relation to the relative importance between impact categories. According to Finnveden [6.38] this type of approach is not really a weighting method, it should be considered as a form of normalisation. The EDIP97 method, referred in Chapter 4, is an example of available LCEA approaches using the distance-to-target approach for weighting. In this case, weighting is based on Danish policy targets.

In methods based on monetary values, weighting is made on the basis of costs related to environmental consequences. The significance of the physical impacts is evaluated using monetary considerations; the more significant the monetary value of an environmental category, the greater significance it takes. This type of methods is criticized for several reasons [6.36]. A general criticism is that certain types of environmental damage (e.g. human health) cannot be compensated by money. The EPS method, also referred in Chapter 4, uses a monetary approach for weighting based on the society's willingness to pay to avoid the occurrence of an intervention, threat or damage.

In methods based on the judgment of a panel, a group of people are asked to provide weighting factors on the basis of their specialist knowledge, either by a questionnaire, interviews or group discussions among a group of panellists [6.44]. The panel approach is widely preferred by the LCEA community [6.46], the main reason being the possibility to emphasize value choices

(preference judgment) which are intrinsic to weighting. Value choices can be ordered and facilitated by the help of decision aid criteria and aggregation approaches (e.g., Multi Criteria Decision Approaches). Ecoindicator 99 (referred in Chapter 4) includes damage models and weighting sets based on three different cultural perspectives: individualist, hierarchist and egalitarian. When applying the method, one perspective can be chosen or an average of the three.

Another interesting approach to deal with trade-offs between current and future impacts by discounting was discussed by Hellweg et al [6.47]. In fact, in life cycle cost analysis, future costs are discounted to a present value in order to make them comparable to current costs. The time value of money, represented by a discount rate, depends on several factors such as time preference, productivity of capital and uncertainties. Hellweg et al [6.47] discussed the same factors in the context of environmental problems. Based in their conclusions, discounting due to pure time preference is not acceptable because of ethical reasons, the wellbeing of future generations should be a concern for us; discounting because of capital productivity might be acceptable if damage can be expressed in monetary terms and future generations can be compensated for the damage; finally, in relation to uncertainties, the authors propose to consider them in the modelling of the damage rather than in the discount rate.

Moreover, discounting contradicts sustainability, as in long life spans, the value of future damages becomes negligible when positive rates are used. Future generations have the same right to a good environment as current generations, and thus a discount rate close or equal to zero is suggested [6.47].

Other approaches are suggested by several authors. Seppälä and Hämäläinen [6.48] applied multiattribute value theory (MAVT) to interpret the impact category weights in the context of distance-to-target methods. Moreover, fuzzy sets theory was used to deal with uncertainty and subjectivity in the valuation process by means of distance-to-target methodology [6.49].

Over the last years there has been a growing interest in using multi-criteria analysis (MCA) for life cycle impact assessment. MCA focuses on the ranking of products attributes (e.g., indicators results), with or without weighting, and draws conclusions based on these results. The compensatory or non-compensatory nature of MCA methods will be further discussed in Chapter 12; in the following sub-section a procedure for weighting the environmental categories described in the previous sections is proposed based on the Analytical Hierarchic Process (AHP).

6.3.3.3. Proposed weighting procedure

There is no set of weights directly applicable to the environmental categories selected in this chapter; thus, is its the purpose of this sub-section to propose such a set of values.

There is not a consensual set of requirements to establish good weighting procedures; however, common features are found in the attempts that have been made with that purpose [6.33][6.46]: consistency with the goal and scope of the analysis and transparency; simplicity in application; communicability; and the ability to evaluate all present environmental impacts. Other authors [6.50][6.51] suggested that in the context of aiding the decision maker's preferences, weighting procedures should also take into account the spatial and temporal scale of the environmental mechanisms and the uncertainty of its occurrence.

In order to comply with the above requirements and to clearly identify the ambiguity inherent to the value choices of the decision making process, a methodology based in the Analytical Hierarchic Process (AHP) is hereby proposed. The AHP is a multi-criteria decision making tool that enables to establish weights for selected criteria by means of a series of pair-wise comparisons.

Environmental problems can be discussed over two major perspectives: the geographical scale and the time scale. In this approach environmental categories are pair-wise compared taking into account its relative importance in relation to both perspectives. The two main perspectives are further subdivided. The geographical or space perspective is subdivided into local, regional and global scale. For instance, from a global perspective, greater importance is assigned to global warming, which occurs on a global scale; while local impacts such as toxicity and eutrophication are dominant in a local or regional scales.

On the other hand, time perspective is further divided into short-term horizon, medium-term horizon and long-term horizon. In this case, emissions are relative impacts are compared based on their effects over three time horizons: short-term (between 0-10 years), medium-term (10-100 years) and long-term (> 100 years).

These two perspectives will be further developed in clause 6.4.3.3.2. First an introduction to the AHP is provided in the following paragraph.

6.3.3.3.1. The Analytical Hierarchic Process (AHP)

The Analytical Hierarchy Process (AHP) allows modelling complex problems into a hierarchical structure showing the relationship between the ultimate goal, the objectives (factors), sub-objectives (sub-factors) and alternatives. In allowing the decision makers to derive ratio scale measures through pair wise relative comparisons (opposed to arbitrarily assigning them), AHP not only supports decision makers by enabling them to structure complexity and exercise judgment, but also allows them to incorporate both objective and subjective considerations in the decision process [6.52].

The pair wise comparison process can be performed using words, numbers, or graphical bars, and typically incorporates redundancy, which results in a reduction of measurement error as well as producing a measure of consistency of the comparison judgments. The use of redundancy permits accurate priorities to be derived from verbal judgments even though the words themselves are not very accurate. Thus, words can be used to compare qualitative factors and derive ratio scale priorities that can be combined with quantitative factors, hence allowing the user to make a qualitative, as well as, a quantitative evaluation. By using AHP pair wise comparison process, weights or priorities are derived from a set of judgments (expressed verbally, numerically or graphically). While it is difficult to justify weights that are arbitrarily assigned, judgments and the basis for these judgments (e.g. hard data, knowledge, experience, etc.) can be relatively easy to justify.

This method is a compensatory decision methodology as alternatives that are deficient with respect to one or more objectives (factors) can compensate by their performance with respect to other objectives.

The first step in the AHP is the development of the hierarchy structure of the system. The hierarchy representation of the system has several advantages [6.52]: (i) it can be used to

describe how changes in priority at upper levels affect the priority of elements in lower levels; (ii) it gives detail of information on the structure and function of a system in the lower levels and provide an overview of the factors and their purposes in the upper levels; (iii) natural systems assembled hierarchically evolve more efficiently than those assembled as a whole; (iv) they are stable and flexible; stable in that small changes have small effect and flexible in that additions to a well-structured hierarchy do not disrupt the performance.

Based in the hierarchy structure, comparison matrices are constructed to determine the potency with which the various elements in one level influence the elements on the next higher level, so as to compute the relative strengths of the impacts of the elements of the lowest level on the overall objective. Each element is then evaluated against each of its peers in relation to its impact on achieving the objective of the parent element. These evaluations are termed as pairwise comparisons and take the form of matrices.

The pair-wise comparisons of the elements at each level are made in terms of: (i) their relative importance; (ii) the preference for alternatives with respect to an objective; (iii) the likelihood: when comparing uncertain events or scenarios with respect to the probability of their occurrence.

The values for comparing the elements using the technique of pair-wise comparisons are assigned from a pre-determined scale of relative importance [6.52], which is shown in Table 6.33.

The relative importance (weight) of sub-criteria with respect to the criterion at one level above can be determined by calculating the eigenvector of the matrix [6.52]. The eigenvector solution can be found out by either using computer programs or by manual calculations. Saaty [6.52] developed approximate methods for calculating eigenvectors. However, he recommends the use of average of Normalized Columns for calculating the Eigen vector for the matrices because of its ease of use and it approximates the values of Eigen vector to a satisfactory level.

Table 6.33. Pair-wise comparison judgment scale [6.52]

Intensity of Importance	Definition	Explanation
1	Equal importance of elements	Two elements contribute equally to the objective
3	Moderate importance of one element over another	Experience and judgment slightly favour one element over another
5	Essential or strong importance of one element over another	Experience and judgment strongly favour one element over another
7	Very strong importance of one element over another	An element is strongly favoured and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favouring one element over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two judgments	Used to facilitate compromise between slightly differing judgments

At various stages in the analysis, the consistency of the matrices must be checked to verify the reliability of the judgments of the decision maker. For a consistent positive reciprocal matrix, the largest Eigen value is equal to the order of the matrix (n) and for an inconsistent positive reciprocal matrix, the Eigen value is greater than the order of the matrix. Saaty [6.52] defined a measure of consistency of matrix called the consistency index (CI). The Consistency Index can be defined as:

$$CI = (\lambda_{\max} - n)/(n-1) \tag{6.21}$$

For a perfectly consistent matrix of pairwise comparisons, the CI would be zero, because the Eigen value is equal to the order of the matrix [6.52]. Pairwise comparison based on quantitative judgments results in a consistent matrix. However, it is difficult to maintain this consistency when the judgments are qualitative in nature. E.g.: If we say that criteria A is slightly more important than criteria B for achieving the goal (1:3), and criteria A is strongly more important than criteria C for achieving the goal (1:5), then it can be deduced that criteria B is slightly important as compared to criteria C in achieving the goal (1:3). This analogy might not hold true in all cases. Hence, as a general rule, perfect consistency cannot be expected and is not required by AHP; thus, the computed CI will be greater than zero.

The maximum Eigenvalue required to calculate the consistency index may be estimated by:

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(PW)_i}{nb_i} = \frac{1}{n} \times \sum_{i=1}^{n} \frac{(PW)_i}{b_i} \tag{6.22}$$

where, (PW) is the vector resulting from the multiplication of the original matrix by the weight vector,

The Consistency of judgments in the pair wise comparisons can be calculated by finding the consistency ratio. The Consistency Ratio can be defined as the ratio of Consistency Index and Random Index [6.52]:

$$CR = CI/RI \tag{6.23}$$

The Random Index (RI), for the different order random matrices was calculated by Saaty by randomly creating 500 positive reciprocal matrices of various sizes (1 x 1 to 15 x 15) and calculating the Consistency Index of each matrix. The probability distributions of the CIs were then studied and values for Random Index were recommended. These values are listed in Table 6.34.

Table 6.34. Random index table

Size of Matrix	Random Index (RI)
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

When making judgments concerning a large number of comparisons, it is important to emphasize that the objective in making good decisions is not to minimize the consistency ratio. Good decisions are most often based on consistent judgments, but the reverse is not necessarily true. AHP allows a margin of inconsistency. The acceptable CR range varies according to the size of matrix, for [3 x 3] is 0.05, for [4 x 4] is 0.08 and for all larger matrices ($n \geq 5$) is 0.10. In this case, if the calculated CR is 0.10 or less, the inconsistency is generally considered to be acceptable for the evaluation of the decision hierarchy [6.52]. If the CR is above 0.10, then the values assigned to the pairwise comparison in the given matrix should be re-examined. The whole procedure starting with the pairwise comparisons, matrix calculations, and consistency checks throughout the entire hierarchy should then be repeated.

6.3.3.3.2. Space and time relevance of environmental categories

In setting the hierarchy of the system, in this case, the goal is the achievement of an environmentally preferable alternative. Contributing to that goal are eight decision criteria, the environmental categories indicated in Table 6.1.

Therefore, the hierarchy scheme proposed for the development of the weighting set is represented in Figure 6.24. Three levels are considered. The first level indicates the overall goal of the analysis; the second level indicates the two main criteria; the third level the sub-criteria in each main criteria and finally, the forth level the sub-sub-criteria referred in the previous paragraph.

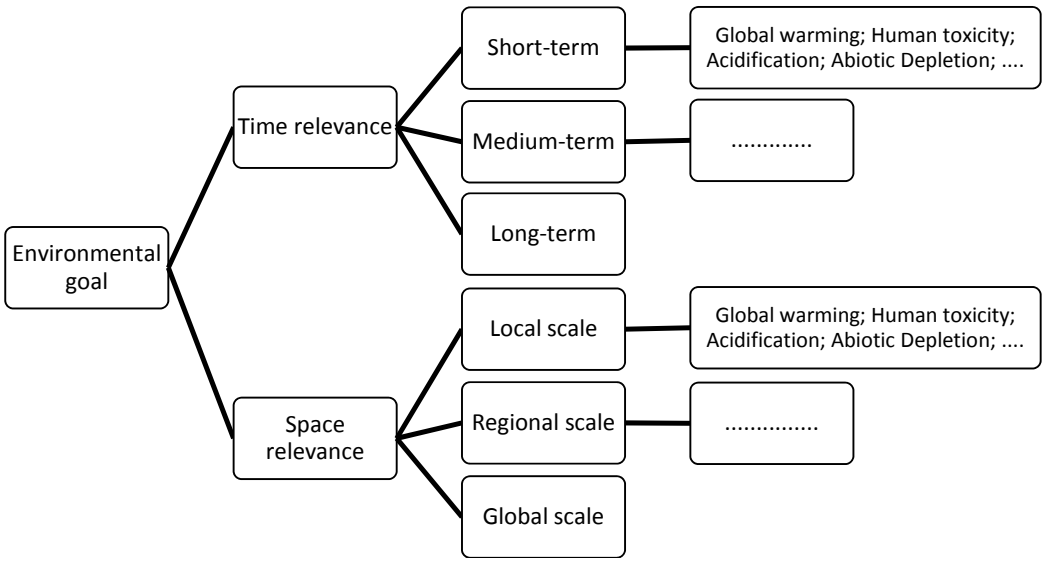


Figure 6.24. Scheme of the decision hierarchy

i) Impact categories in terms of space relevance

The environmental impact categories adopted in this chapter have different importance in relation to the scale in which they are analysed. Hence, in this case impact categories are compared in terms of the relative importance in terms of space.

Some environmental categories are clearly identified as a global problem, such as global warming, for instance. However, other categories may have different effects in relation to the scale they referred to. For instance, acidification and eutrophication may be considered in a local or a regional scale with different effects. In sub-sections 6.2.2.4 and 6.2.2.5, it was noted that local sensitivity played an important role in acidification and eutrophication. Moreover, it was also noted that in the case of Portugal, eutrophication is a more important environmental problem than acidification (see Figure 6.8 and Figure 6.11).

Thus, taking into account these assumptions, Table 6.35 indicates impact categories by a decreasing order of importance for each space perspective.

Table 6.35. Relevance of impact categories in terms of space

Local	Regional	Global
Human toxicity	Eutrophication	Global warming
Photo-oxidant formation	Acidification	Abiotic depletion
Eutrophication	Photo-oxidant formation	Ozone depletion
Acidification	Human toxicity	Acidification
Ecotoxicity	Global warming	Eutrophication
Abiotic depletion	Abiotic depletion	Photo-oxidant formation
Global warming	Ecotoxicity	Human toxicity
Ozone depletion	Ozone depletion	Ecotoxicity

According to the first column of this table, it is assumed that at the local scale “Human toxicity” is considered more important than “Photo-oxidant formation”, and even more important than “eutrophication” emissions, and so on.

The intensity of the importance is given by the preference scale of Table 6.33; for instance, a value of 3 when comparing “Human toxicity” to “Eutrophication” in the same column means that today’s human toxicity emissions are considered to be moderately more important than today’s eutrophication emissions in the local scale. The pair-wise comparison matrices for the local, regional and global perspectives are represented in Table 6.36 to Table 6.38, respectively.

Table 6.36. Pair-wise comparison matrix for local perspective

	GW	AD	OD	AC	EU	Ph	Htox	Eco
GW	1	1/2	2	1/4	1/5	1/6	1/7	1/3
AD	2	1	3	1/3	1/4	1/5	1/6	1/2
OD	1/2	1/3	1	1/5	1/6	1/7	1/8	1/4
AC	4	3	5	1	1/2	1/3	1/4	2
EU	5	4	6	2	1	1/2	1/3	3
Ph	6	5	7	3	2	1	1/2	4
Htox	7	6	8	4	3	2	1	5
Eco	3	2	4	1/2	1/3	1/4	1/5	1

Table 6.37. Pair-wise comparison matrix for regional perspective

	GW	AD	OD	AC	EU	Ph	Htox	Eco
GW	1	2	4	1/3	1/4	1/2	1/2	3
AD	1/2	1	3	1/4	1/5	1/3	1/3	2
OD	1/4	1/3	1	1/6	1/7	1/5	1/5	1/2
AC	3	4	6	1	1/2	2	2	5
EU	4	5	7	2	1	3	3	6
Ph	2	3	5	1/2	1/3	1	1	4
Htox	2	3	5	1/2	1/3	1	1	4
Eco	1/3	1/2	2	1/5	1/6	1/4	1/4	1

Table 6.38. Pair-wise comparison matrix for global perspective

	GW	AD	OD	AC	EU	Ph	Htox	Eco
GW	1	2	3	4	5	6	7	8
AD	1/2	1	2	3	4	5	6	7
OD	1/3	1/2	1	2	3	4	5	6
AC	1/4	1/3	1/2	1	2	3	4	5
EU	1/5	1/4	1/3	1/2	1	2	3	4
Ph	1/6	1/5	1/4	1/3	1/2	1	2	3
Htox	1/7	1/6	1/5	1/4	1/3	1	1	2
Eco	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1

ii) Impact categories in terms of time relevance

In this level impact categories are compared in terms of the relative importance in terms of time horizon. The approach used in this case is based in the preference order of environmental impact defined by a multi-stakeholder panel in NIST [6.53]. A panel of individuals, including producers, users and LCA experts was assembled in order to discuss the weighting of environmental categories in the time perspective. The AHP was applied to derive three sets of weights. The paired comparisons of impacts was based on year's worth of U.S. flows for each pair of impacts and over three time horizons: short term (0 – 10 years), medium term (10 – 100 years) and long-term (>100 years) [6.53].

These sets of weights are not directly applicable to the environmental categories used in the LCEA adopted in this chapter, as there is not a direct equivalency between environmental categories in both approaches. Therefore, a few assumption were needed: (i) the impact category "Human toxicity" in the approach adopted in this chapter includes the categories of "Human health noncancerous", "Human health cancerous" and "Criteria air pollutants" in the approach adopted in [6.53]; (ii) the impact category "Abiotic depletion" in the present approach was considered to be equivalent to the impact category "fossil fuel depletion". The remaining categories could be directly related.

Taking into account this assumptions and the preference order defined by the panel, a new preference order for each time perspective was considered for the impact categories. Table 6.39 indicates impact categories by a decreasing order of importance for each time horizon.

Table 6.39. Relevance of impact categories in terms of time horizon (based in [6.53])

Short-term	Medium-term	Long-term
Human toxicity	Global warming	Global warming
Abiotic depletion	Human toxicity	Human toxicity
Eutrophication	Ecotoxicity	Ecotoxicity
Global warming	Abiotic depletion	Abiotic depletion
Photo-oxidant formation	Eutrophication	Eutrophication
Ecotoxicity	Acidification	Acidification
Acidification	Ozone depletion	Ozone depletion
Ozone depletion	Photo-oxidant formation	Photo-oxidant formation

According to this table, and considering the short-term perspective (1st column), the impact category "Human toxicity" is considered more important than the category "abiotic depletion", even more important than "eutrophication" and so on.

The intensity of the importance is given by the preference scale of Table 6.33; for instance, a value of 3 when comparing "Global warming" to "Human toxicity" in the third column means

that today's global warming emissions are considered to be moderately more important than today's human toxicity emissions in the long term. The pair-wise comparison matrices for the long-term, medium-term and short-term perspectives are represented in Table 6.40 to Table 6.42, respectively.

Table 6.40. Pair-wise comparison matrix for long-term time horizon

	GW	Htox	Eco	AD	EU	AC	OD	Ph
GW	1	5	6	8	8	9	9	9
Htox	1/5	1	2	4	5	6	6	8
Eco	1/6	1/2	1	3	4	5	5	7
AD	1/8	1/4	1/3	1	2	3	3	5
EU	1/8	1/5	1/4	1/2	1	2	2	4
AC	1/9	1/6	1/5	1/3	1/2	1	1	3
OD	1/9	1/6	1/5	1/3	1/2	1	1	3
Ph	1/9	1/8	1/7	1/5	1/4	1/3	1/3	1

Table 6.41. Pair-wise comparison matrix for medium -term time horizon

	GW	Htox	Eco	AD	EU	AC	OD	Ph
GW	1	4	5	6	7	8	8	9
Htox	1/4	1	3	4	5	7	7	8
Eco	1/5	1/3	1	2	3	5	5	6
AD	1/6	1/4	1/2	1	2	4	4	5
EU	1/7	1/5	1/3	1/2	1	3	3	4
AC	1/8	1/7	1/5	1/4	1/3	1	1	2
OD	1/8	1/7	1/5	1/4	1/3	1	1	2
Ph	1/9	1/8	1/6	1/5	1/4	1/2	1/2	1

Table 6.42. Pair-wise comparison matrix for short-term time horizon

	Htox	AD	EU	GW	Ph	Eco	AC	OD
Htox	1	4	5	6	6	7	8	9
AD	1/4	1	3	4	4	6	7	8
EU	1/5	1/3	1	2	2	4	5	6
GW	1/6	1/4	1/2	1	1	3	4	5
Ph	1/6	1/4	1/2	1	1	3	4	5
Eco	1/7	1/6	1/4	1/3	1/3	1	2	3
AC	1/8	1/7	1/5	1/4	1/4	1/2	1	2
OD	1/9	1/8	1/6	1/5	1/5	1/3	1/2	1

6.3.3.3.3. Calculation of the weighting set

The final weighting set is computed based in the pair-wise comparison matrices for space and time perspectives, represented in Figure 6.24 and in the pair-wise comparisons in the upper levels of the hierarchy system. However, in this case, equal importance was assigned to the criteria in the upper levels of the hierarchy.

The weighting sets calculated for each criterion are indicated in Table 6.43, together with the final weighting set. The last row of the table indicates the consistency ratio for each matrix, where it is noted that CR is less than 0.10, indicating a high level of consistency.

Across all scales and time horizons, contributions to global warming (23%) are considered to be the most important environmental problem, closely followed by contributions to human toxicity (22%). Other important concerns include eutrophication (13%) and abiotic depletion (12%). The lowest weight was assigned to ozone depletion (5%), which is consistent with the present lack of

immediate concern, as in this case, remedial actions associated with this impact were already successfully taken.

Table 6.43. Weighting set for environmental impacts

Impact Category	Category weight	Time-relevance			Space-relevance			Final set
		short	medium	long	local	regional	global	
Global warming	CW_1	0.08	0.40	0.44	0.03	0.09	0.33	0.23
Acidification	CW_2	0.03	0.03	0.03	0.11	0.21	0.11	0.09
Eutrophication	CW_3	0.12	0.06	0.05	0.16	0.31	0.07	0.13
Photo-oxidant form.	CW_4	0.08	0.02	0.02	0.23	0.14	0.05	0.09
Ozone depletion	CW_5	0.02	0.03	0.03	0.02	0.03	0.16	0.05
Ecotoxicity	CW_6	0.04	0.13	0.14	0.07	0.04	0.02	0.07
Human toxicity	CW_7	0.39	0.23	0.20	0.33	0.14	0.03	0.22
Abiotic depletion	CW_8	0.23	0.09	0.07	0.05	0.06	0.23	0.12
Consistency ratio (CR)		0.05	0.05	0.06	0.03	0.02	0.03	-

6.3.3.3.4. Sensitivity analysis of the weighting set

In order to evaluate the sensitivity of the final set of weights in relation to the relative importance of criteria in the upper level of the hierarchy, the following sensitivity analysis was performed:

Table 6.44. Parameters in the sensitivity analysis of weightings

Weight set	1st level		2nd level			2nd level		
	Space	Time	Local	Regional	Global	Short	Medium	Long
1	50%	50%	25%	30%	45%	25%	30%	45%
2	50%	50%	45%	30%	25%	25%	30%	45%
3	50%	50%	25%	30%	45%	45%	30%	25%
4	50%	50%	45%	30%	25%	45%	30%	25%
5	40%	60%	25%	30%	45%	25%	30%	45%
6	40%	60%	45%	30%	25%	25%	30%	45%
7	40%	60%	25%	30%	45%	45%	30%	25%
8	40%	60%	45%	30%	25%	45%	30%	25%

The set of weights obtained in each case are represented in Table 6.45, together with the original set, in the first column.

Table 6.45. Sensitivity analysis of weightings

Category weight	Weighting-sets								
	original	1	2	3	4	5	6	7	8
CW_1	0.23	0.26	0.23	0.22	0.19	0.28	0.25	0.23	0.21
CW_2	0.09	0.09	0.09	0.08	0.08	0.07	0.07	0.07	0.07
CW_3	0.13	0.12	0.13	0.13	0.14	0.11	0.12	0.12	0.13
CW_4	0.09	0.08	0.10	0.08	0.10	0.07	0.08	0.08	0.09
CW_5	0.05	0.06	0.04	0.06	0.04	0.05	0.04	0.05	0.04
CW_6	0.07	0.08	0.08	0.07	0.07	0.08	0.09	0.07	0.08
CW_7	0.22	0.20	0.23	0.22	0.25	0.21	0.23	0.23	0.26
CW_8	0.12	0.13	0.11	0.14	0.12	0.12	0.11	0.14	0.13

The results of the sensitivity analysis are illustrated in Figure 6.25, for the scenarios chosen in the sensitivity analysis.

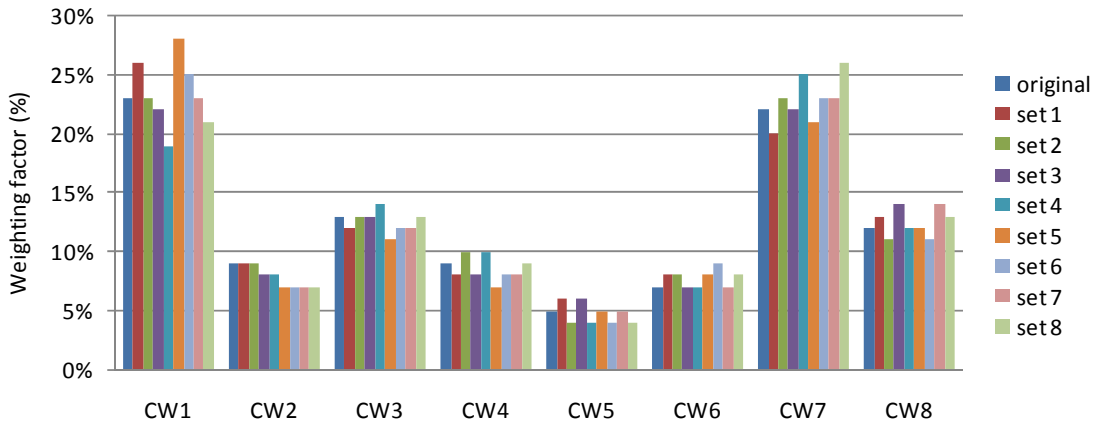


Figure 6.25. Sensitivity analysis of the weighting factors

In all cases the highest weights are for the impact categories of global warming and human toxicity, although global warming has a higher variation than human toxicity. The impact category is the lowest weight, no matter the case, is the ozone layer depletion.

6.3.3.3.5. Uncertainty analysis of the weighting set

To take into account the uncertainty and subjectivity of the decision maker (or decision makers) in regard of his (her) choices or preferences, the preference values can be portrayed by a probabilistic distribution which is fitted to the weighting sets in Table 6.45. Goodness of fit statistics are used to determine how representative the fitted distributions are of the actual sets of weights. The properties of the fitted distributions are indicated in Table 6.46.

Table 6.46. Distributions for the fitted criteria weights

Category weight	Distribution type	Parameters
CW_1	Beta general	$\alpha 1$ = 0.34384; $\alpha 2$ = 0.3518; min = 0.19; max = 0.28
CW_2	Beta general	$\alpha 1$ = 0.12063; $\alpha 2$ = 0.13889; min = 0.07; max = 0.09
CW_3	Beta general	$\alpha 1$ = 0.35434; $\alpha 2$ = 0.346; min = 0.11; max = 0.14
CW_4	Beta general	$\alpha 1$ = 0.29489; $\alpha 2$ = 0.23185; min = 0.07; max = 0.10
CW_5	Beta general	$\alpha 1$ = 0.12886; $\alpha 2$ = 0.17941; min = 0.04; max = 0.06
CW_6	Beta general	$\alpha 1$ = 0.14258; $\alpha 2$ = 0.26773; min = 0.07; max = 0.09
CW_7	Beta general	$\alpha 1$ = 0.33508; $\alpha 2$ = 0.35115; min = 0.20; max = 0.26
CW_8	Beta general	$\alpha 1$ = 0.20138; $\alpha 2$ = 0.2044; min = 0.11; max = 0.14

In case data available is not enough to fit a representative distribution, a normal or uniform distribution may be used to enable uncertainty and subjectivity in the weights to be incorporated in the analysis. Moreover, in the case of insufficient data, the probability distribution that is straightforward to endorse is the uniform distribution, where all weights have equally probability. Hence, in this case a uniform distribution is also proposed for the criteria weights with minimum and maximum values as indicated in Table 6.46.

To determine the relationship between the set of weights, a correlation analysis is undertaken. The correlations between criteria are represented in Table 6.47.

The use of uniform distributions, instead of the distributions of Table 6.46, turns out the uncertainty analysis analogous to traditional sensitivity analysis. However, the uncertainty analysis takes advantage of considering simultaneously the variation of the weights and the correlation between them.

Table 6.47. Criteria weights correlations

	CW_1	CW_2	CW_3	CW_4	CW_5	CW_6	CW_7	CW_8
CW_1	1.000	-0.083	-0.930	-0.763	0.371	0.525	-0.784	-0.178
CW_2		1.000	0.390	0.472	0.287	-0.254	-0.379	-0.185
CW_3			1.000	0.870	-0.321	-0.468	0.619	-0.028
CW_4				1.000	-0.575	-0.232	0.605	-0.351
CW_5					1.000	-0.354	-0.763	0.649
CW_6						1.000	-0.064	-0.573
CW_7							1.000	-0.066
CW_8								1.000

6.4. UNCERTAINTY IN LCEA

In the previous sub-chapters the uncertainties in the steps of impact assessment, normalization and weighting were evaluated individually and probabilistic distributions were assigned for impact categories, normalisation values and weighting set. This sub-chapter addresses the overall uncertainty in LCEA, i.e, considering the uncertainty in all stages of LCEA simultaneously. Moreover, the uncertainty in the inventory data was addressed in the previous chapter but so far has not been included in the LCEA. Therefore, the aim of this sub-chapter is also to include the uncertainty in relation to the inventory stage.

To assess the stage of LCEA that introduces more variability in the outcome of the analysis, several analyses will be performed considering the uncertainty in each stage individually. These results are compared with the results obtained from a complete deterministic analysis, disregarding any type of uncertainty, and a complete probabilistic analysis, considering the assigned distributions. These analyses are summarised in Table 6.48.

Table 6.48. Types of LCE analyses

Stage	Type of data					
Inventory	Fix	Proba.	Fix	Fix	Fix	Proba.
Impact	Fix	Fix	Proba.	Fix	Fix	Proba.
Normalisation	Fix	Fix	Fix	Proba.	Fix	Proba.
Weighting	Fix	Fix	Fix	Fix	Proba.	Proba.
LCEA ref. no.	LCEA1	LCEA2	LCEA3	LCEA4	LCEA5	LCEA6

The probabilistic analyses are performed by Monte Carlo simulations, taking into consideration the correlation between the involved parameters, where needed. To illustrate the procedure, an example is provided in Box 6.3.

Box 6.3. Overall uncertainties in LCEA

The results of the impact assessment analysis provided in Box 6.1 were obtained considering a mean value for all input data. Table 6.49 provides the same results but assuming also the uncertainty in input data. Therefore the results are represented by the mean value and respective interval of confidence.

The deterministic analysis (LCEA1) considered the mean values of the baseline impact categories from Table 6.49, the normalisation values presented in Table 6.29 and the weighting set indicated in Table 6.43. The corresponding results are represented in Figure 6.26.

Table 6.49. LCEA results for impact categories considering data uncertainty

Impact category	Unit	Mean value	2.50%	97.50%
Abiotic depletion	kg Sb. eq.	1.38E+04	1.19E+04	1.71E+04
Global warming 20a	kg CO_2 eq.	1.48E+06	1.31E+06	1.76E+06
Global warming 100a	kg CO_2 eq.	1.38E+06	1.23E+06	1.63E+06
Global warming 500a	kg CO_2 eq.	1.35E+06	1.21E+06	1.60E+06
Ozone layer depletion 5a	kg CFC-11 eq.	0.209	0.103	0.392
Ozone layer depletion 10a	kg CFC-11 eq.	0.210	0.103	0.395
Ozone layer depletion 15a	kg CFC-11 eq.	0.211	0.104	0.398
Ozone layer depletion 20a	kg CFC-11 eq.	0.211	0.103	0.398
Ozone layer depletion 25a	kg CFC-11 eq.	0.213	0.104	0.401
Ozone layer depletion 30a	kg CFC-11 eq.	0.214	0.104	0.405
Ozone layer depletion 40a	kg CFC-11 eq.	0.216	0.105	0.408
Ozone layer depletion ∞	kg CFC-11 eq.	0.239	0.115	0.452
Human toxicity 20a	kg 1,4-DB eq.	1.96E+05	1.43E+05	2.77E+05
Human toxicity 100a	kg 1,4-DB eq.	1.97E+05	1.4E+05	2.80E+05
Human toxicity 500a	kg 1,4-DB eq.	1.98E+05	1.4E+05	2. 1E+05
Human toxicity ∞	kg 1,4-DB eq.	2.80E+ 5	1.92E+05	4.48E+05
Terrestrial ecotoxicity 20a	kg 1,4-DB eq.	66.7	42.8	111
Terrestrial ecotoxicity 100a	kg 1,4-DB eq.	273	169	75
Terre trial ecotoxicity 500a	kg 1,4-DB eq.	1.02E+03	639	1 2E+03
Terrestrial ecotoxicity ∞	kg 1,4-DB eq.	2.70E+03	1.83E+ 3	4.27E+03
Acidification average	kg SO_2 eq.	6.49E+03	5.38E+03	8.48E+03
Acidification Portugal	kg SO_2 eq.	936	767	1.23E+03
Eutrophication average	kg NO_x eq.	6.11E+03	5.42E+03	7.15E+03
Eutrophication ortugal	kg NO_x eq.	2.50E+03	2.22E+03	2.93E+03
Photoch. oxi. (high NO_x)	kg C_2H_4 eq.	1.16E+03	900	1.51E+03
Photoch. oxi. (low NO_x)	kg C_2H_4 eq.	1.40E+03	1.03E+03	1.91E+03

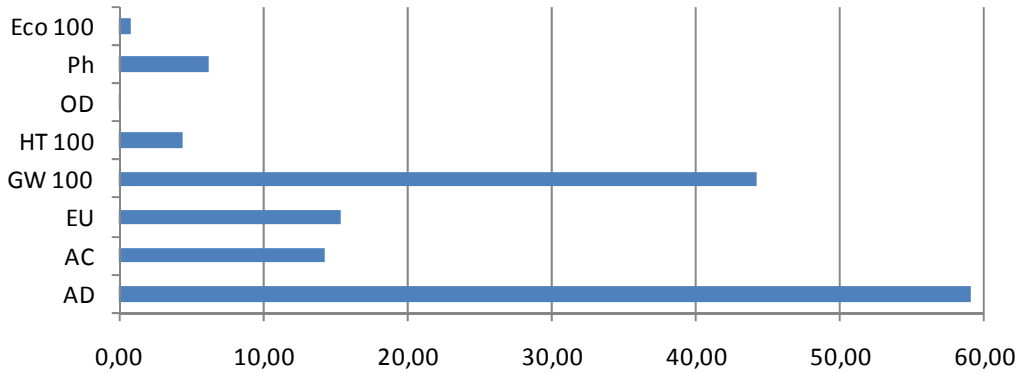


Figure 6.26. Final results of the deterministic LCEA

In the first probabilistic analysis (LCEA2), the results of the baseline impact categories in Table 6.49 were normalised using the normalisation values presented in Table 6.29 and weighted with the weighting factors indicated in Table 6.43. The results are summarised in Table 6.50.

The second probabilistic analysis (LCEA3) considered the uncertainty only in the impact assessment stage. Thus, based in the mean values of Table 6.49, the uncertainty in the results of impact assessment was considered by the uniform distributions indicated in Table 6.17 (Box 6.1), whereas the normalisation and weighting were performed as for LCEA1. The results are summarised in Table 6.50.

The third probabilistic analysis (LCEA4), considered the mean values of the baseline impact categories of Table 6.49, the normalisation distributions indicated in Table 6.32 and the weighting factors indicated in Table 6.43. The results are summarised in Table 6.50.

Table 6.50. Results of the probabilistic analysis

		LCEA1	LCEA2	LCEA3	LCEA4	LCEA5	LCEA6
Abiotic depletion	Mean	59.11	58.93	59.11	59.11	61.51	61.37
	SD	-	5.34	3.41	3.43	6.22	11.27
Acidification	Mean	14.22	14.11	8.07	24.56	12.53	12.24
	SD	-	1.88	3.49	17.56	1.40	12.47
Eutrophication	Mean	15.39	15.36	10.82	20.88	14.82	14.11
	SD	-	1.20	2.62	4.75	1.36	5.11
Global warming	Mean	44.21	44.02	45.18	41.69	45.07	43.45
	SD	-	3.22	1.13	6.07	6.66	9.88
Human Toxicity	Mean	4.34	4.33	5.23	4.34	4.52	5.51
	SD	-	0.77	0.53	0.25	0.46	1.35
Ozone layer depletion	Mean	0.13	0.13	0.12	0.06	0.13	0.06
	SD	-	0.05	0.01	0.02	0.02	0.03
Photochemical oxidation	Mean	6.17	6.18	6.80	6.48	5.95	6.96
	SD	-	0.89	0.36	0.19	0.82	1.46
Terrestrial ecotoxicity	Mean	0.78	0.78	3.96	0.55	0.86	3.00
	SD	-	0.23	2.18	0.12	0.09	2.13

The fourth probabilistic analysis (LCEA5), considered the mean values of the baseline impact categories of Table 6.49, the normalisation values presented in Table 6.29 and the weighting distributions indicated in Table 6.46. In this analysis the correlation between weighting factors was taken into account as indicated in Table 6.47. The results are summarised in Table 6.50.

Finally, the fifth probabilistic analysis (LCEA6) considered the uncertainty in input data and impact assessment simultaneously by defining uniform distributions, as indicated in Box 6.1, but considering the values of the uniform distributions given by the variables values obtained for each impact category. A probability distribution was fitted to each resulting impact category. Subsequently, the normalisation distributions indicated in Table 6.32 and the weighting distributions indicated in Table 6.46 were also applied. The results are summarised in Table 6.50. The results presented in the previous table show that the stage that contributes with greater variability for the overall analysis varies according to impact categories. While for the impact categories of “Human toxicity”, “Photochemical oxidation” and “Terrestrial ecotoxicity” the stage causing a greater variability in the result is the inventory stage, for the impact categories of “Acidification” and “Eutrophication” the major contributor is the normalization stage and for the impact categories of “Abiotic depletion” and “Global warming” the major contributor is the weighting stage. The results obtained for the different analysis are illustrated in Figure 6.27 for the impact category Global Warming.

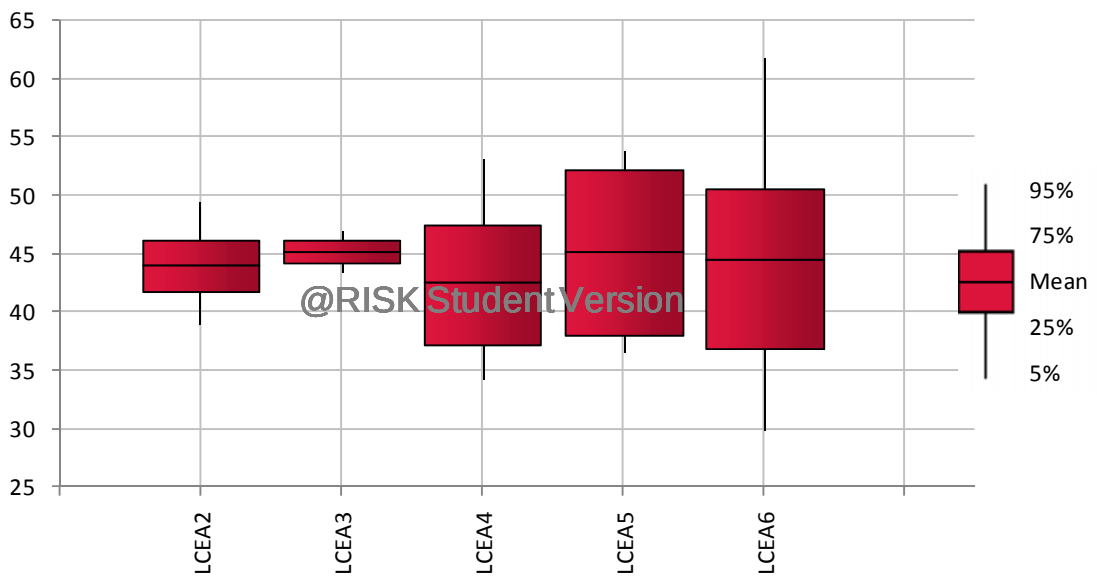


Figure 6.27. Probabilistic results for the impact category "Global warming"

Comparing the results of the deterministic analysis (1st column) and the full probabilistic analysis (last column) highlights the importance of the latter in relation to the relative importance of the impact categories. For instance, in the deterministic analysis the result of the impact category "Eutrophication" is slightly higher than the result of the impact category "Acidification". However, in the probabilistic analysis, although the mean values show the same trend, considering the respective standard deviations, then the difference between the results of both impact categories is no longer obvious.

The process illustrated in Box 6.3 considered the uncertainty in each stage of LCEA simultaneously. The results of the life cycle environmental analysis were not discussed in this sub-chapter as the aim was only to illustrate the procedure. However, this discussion will be made in the case studies.

6.5. SYNOPSIS OF LCEA

In this chapter the LCEA was further developed in the aims of the integral life cycle approach pursuit in this dissertation. In this chapter, the environmental indicators selected for the approach were described and the calculation methods for their calculation were discussed. In order to introduce the uncertainty inherent to this life cycle stage, an approach was introduced that enables to quantify, although not comprehensively, some of the uncertainties in the environmental indicators. The uncertainty in the indicator of waste was not considered in this chapter as it depends only of the inventory stage.

The normalisation and weighting steps of a LCEA are optional elements according to ISO standards. However, in this dissertation these two steps are recommended to be used in a LCEA in order to enable a better understanding of the environmental problem and to aid in decision making process.

A set of normalisation factors was proposed by using global normalisation values for global impact categories and Portuguese normalisation factors for local/regional categories. For a consistency between different scale levels, the normalisation factors are given per capita. The uncertainty in the normalisation values was addressed by a similar process as the previous stage.

In this chapter it was further proposed to weight the environmental categories according to two different perspectives: the geographical scale and the time scale. A methodology based in a pair-wise comparison was proposed to establish the weights for the impact categories. The uncertainty in the preference choices of the decision maker was considered by a probabilistic analysis.

Finally, the uncertainty propagation in the LCEA was evaluated by Monte Carlo simulations.

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CHAPTER 7. LIFE CYCLE COST ANALYSIS

7.1. INTRODUCTION

The life cycle cost analysis (LCCA) introduced in this chapter respects the boundary system of Figure 5.2 (chapter 5). The period of time of the analysis and the base date are also common to the environmental analysis (in Chapter 6) and social analysis (in Chapter 8).

As referred in chapter 5, the lifecycle cost calculations are based on data collected per unit process in the inventory stage (see Figure 5.1). Without violating these basic assumptions, there are differences in the level of aggregation of unit processes between the environmental analysis and the cost analysis (see discussion in Chapter 5, section 5.4.1). For instance, the market price of a material reflects the complete upstream processes of material production, i.e., the cradle-to-gate cost of a material [7.1]. Moreover, in the case of the life cycle of a bridge, the cost paid for the construction of the bridge includes the unit processes of material production and construction and all corresponding sub-unit processes.

Taking this into consideration, the costs to be considered in the life cycle analysis may be divided into three main groups: (i) the construction costs (CC), (ii) the operation costs (OC), and (iii) the end-of-life cost (EC), as expressed by:

$$LCCA = CC + OC + EC \tag{7.1}$$

where, *OC* includes the costs of maintenance and rehabilitation of the bridge over the service life; and *EC* includes the costs of demolition and disposal minus the residual value of the structure at the time of decommission. Each of these costs is described in the following sub-chapter.

7.2. INDICATORS OF ECONOMICAL PERFORMANCE

7.2.1. Construction costs

Construction costs are all the costs related to each process needed to build the bridge. In this dissertation, this indicator includes: (i) the cost of material acquisition and transportation, (ii) the cost of construction equipment, and (iii) the cost of man-power. Most of these costs are usually calculated based on the bill of materials and unit costs provided in the project.

These costs usually occur in the first or second years of the bridge life cycle. However, due to the long time-period of analysis, it may be assumed that they occur in the first year, as the base year, of the bridge life cycle.

7.2.2. Operation costs

Maintenance costs include all costs occurring since the bridge is open to traffic until the end of its life. This indicator includes: (i) costs due to periodic inspections, (ii) costs due to periodic

activities required to maintain the bridge's condition in the required level, and (iii) costs due to repair or replacement activities.

As discussed in Chapter 5, the estimation of these costs may be based on a sophisticated approach relying on mathematical deterioration models that calculate the expected bridge condition (or its components) as a function of time or/and other variables such as traffic-loading, climatic conditions, etc; or in a simplified approach based on scenarios and on best practices. This issue will be further developed in section 7.3.2.

7.2.3. End-of-life cost

7.2.3.1. Demolition and disposal costs

These costs refer to the end-of-life activities such as the total or partial demolition of the bridge and the removal of the demolition waste to its final destination. These costs may be estimated based on scenarios and best practices.

7.2.3.2. Residual value

The residual value of a system (or system components) is its remaining value at the end of the study-period, or at the time when it is replaced during the study-period [7.2]. Residual values can be based on value in place, resale value, salvage value or scrap value. In the case of a bridge being demolished at the end of its service life, then its residual value corresponds to the value of the demolition materials, in case they have any positive value. For instance, steel scrap has a positive value and can be sold. In this case, this figure is represented as a negative number in the model (expression 7.1), since it is a revenue and not a cost for the construction company.

For systems with expected service lives extending beyond the end of the study period, the residual value should be based on their value in place [7.2], not on their "salvage" value. As a "rule of thumb" the residual value of a system with remaining useful life in place can be calculated by linearly prorating its initial cost. For instance, two bridges with different expected service lives are intended to be compared: bridge A with an expected service life of 75 years and bridge B with an expected service life of 50 years. In order to compare the two bridges a common study period is needed. In this case, it may be assumed that the study-period coincides with lower expected service life, which is 50 years. The residual value of bridge B may be calculated by its salvage value; while the residual value of bridge A is 1/3 [=(75-50)/75] of its initial cost.

In the case of bridges, when the study period is long, the residual value of the system may be small and largely offset by disposal costs. Discounting further reduces its weight in the life cycle analysis, and so it is often less important to improve the estimate of a residual value than of other input values. However, for shorter study periods or in the case of the comparison example given in the previous paragraph, the estimate of the residual value may become a critical factor.

7.3. CALCULATION METHOD

7.3.1. Net present value

Different costs related to different operations occur over the life cycle of a bridge. To account for different operations taking place at different times, incremental costs can be converted to current costs using a discounted cash flow method [7.3]. This is particularly important when comparing alternative solutions that have different maintenance and replacement cycles.

In this approach, future costs occurring over the life cycle of the bridge are discounted to their present-value as of the base date by using expression (7.2) [7.2]:

$$PVLCCA = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} = CC + \sum_{t=1}^{N-1} \frac{OC}{(1+d)^t} + \frac{(DC - RC)}{(1+d)^N} \tag{7.2}$$

where, C_t is the sum of all relevant costs, less any positive cash flows, occurring in year t; N is the number of years in the study period; and d is the discount rate used to adjust cash flows to present value.

The present-value procedure reduces a series of cash flows, which occur at different times in the future, to a single value at one point in time, the present. The transformation of future costs to present values is called discounting.

7.3.1.1. Discounting

According to ISO 15786-5 [7.4] in LCCA real costs, based on real discount rates, should be used to ensure accuracy regardless of the point in time at which they are incurred. This is an advantage in estimating future costs as there´s no need to account for inflation or deflation, which otherwise would increase the level of uncertainty in the analysis.

Costs are expressed in currency of constant purchasing power, fixed on a reference date, usually the base year of the study. The real discount rate adjusts costs for the real earning opportunities of money over time [7.5].

However, there is no consensus regarding the selection of the most suitable discount rate. Government agencies tend to use real discount rates in their analysis. In the UK a discount rate of 8% is usually used, whilst in the USA the rate is 6%, in Germany 3% and in Switzerland 2% [7.6]. Public projects are typically mandated to use a specific rate, while private projects may specify their own discount rate [7.7].

Rebitezer [7.1] proposes to use a 5% discount rate and to employ a sensitivity analysis, varying the rate from 0 – 10%, in order to test the robustness of the results.

Discounting is relevant for long lasting products with substantial cost during the operation and end-of-life stage, such is the case of bridges. The variation of the present value with different discount rates is represented in Figure 7.1, where it is evidenced that the higher the discount rate the less important are the long-term costs.

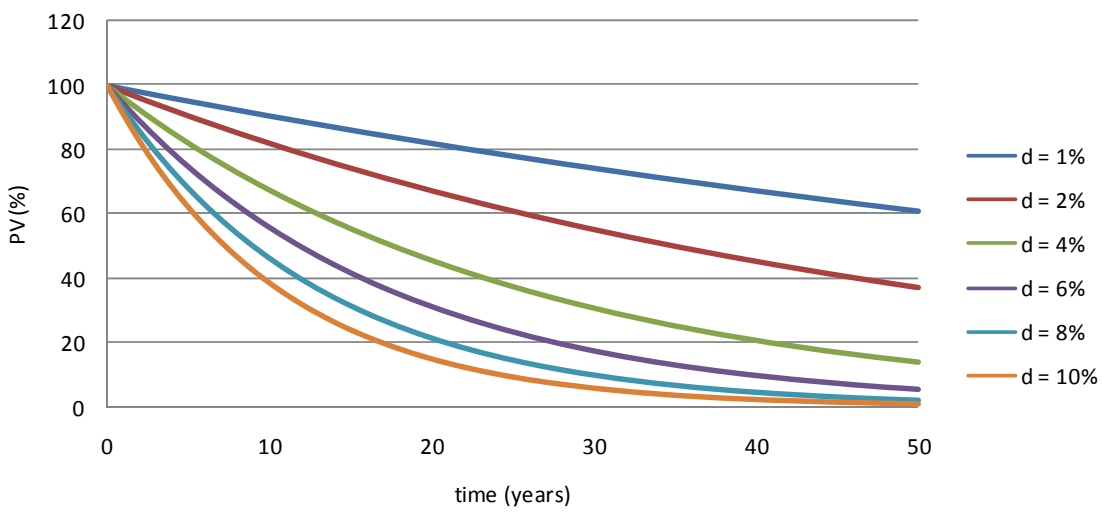

Figure 7.1. Variation of Present Value (PV) with time (adapted from [7.3])

The example presented in Box 7.1 illustrates the use of different discount rates in the life cycle analysis of bridges.

Box 7.1. Variation of present value of life cycle cost with discount rate

The life cycle costs of a bridge are indicated in Table 7.1 for a period of time of 100 years. It is assumed that the bridge is built at year 0 and is demolished at year 100. The costs of maintenance and rehabilitation of the bridge are also indicated in the table for years 25, 50 and 75.

Table 7.1. Life cycle costs of a bridge

Time	0	25	50	75	100
Cost	535 143 €	137 980 €	192 280 €	148 980 €	140 960 €

Using a discount rate of 0% the total life cycle cost of the bridge is about 1 155 343.00 €. Using discount rates of 2%, 4%, 6%, 8% and 10%, the present value of the total life cycle cost of the bridge, according to expression (7.2), is respectively 743 878.00 €, 624 612.00 €, 580 031.00 €, 559 918.00 € and 549 643.00 €. The use of the discount rates of 2%, 4%, 6%, 8% and 10% reduce the life cycle cost with d = 0% by about 35.6%, 45.9%, 49.8%, 51.5% and 52.4%, respectively.

It should also be noted that by the use of a discount rate of 4%, the total life cycle cost of the bridge represents an increase, in relation to the initial cost of the bridge, of approximately 16.7%; while with a discount rate of 8% the increase is only 4.6%.

The results obtained by the use of different discount rates are represented in Figure 7.2.

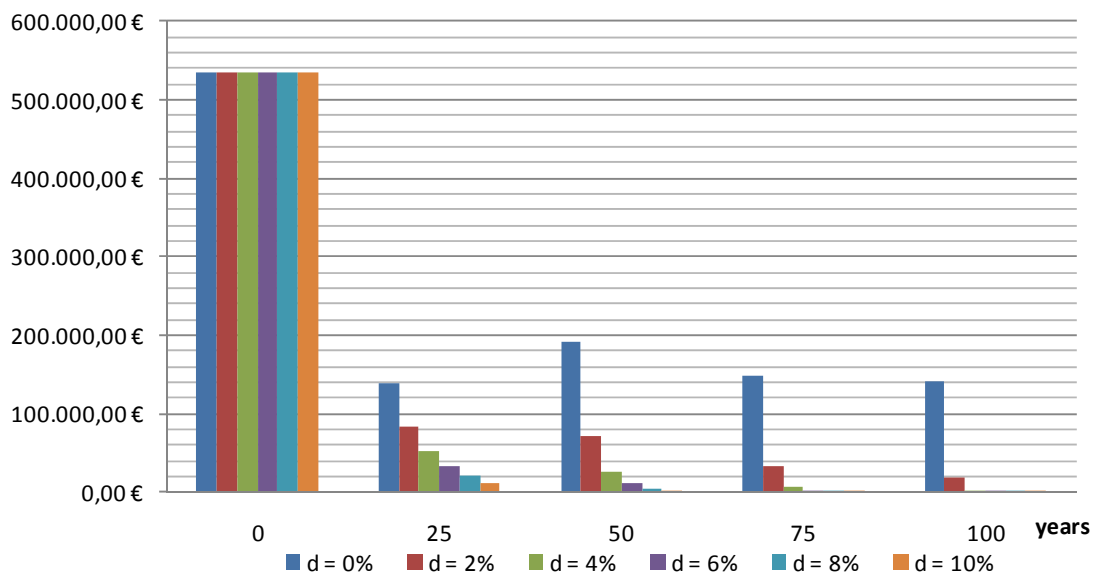

Figure 7.2. Present values of life cycle costs

It may be concluded from the example provided in the previous box that discount rates higher than 4% turn the costs occurring after the year 50 almost negligible. In the life cycle cost analysis of bridges, usually important costs take place over the entire life cycle. Thus, particularly when comparing different bridges with different maintenance/rehabilitation requirements, it is important to use a discount rate that allows a fair comparison of all the costs occurring over the time period considered.

Thus, for long time period of analysis, the discount rate should be less than 4%. However, a sensitivity analysis in relation to the discount rate is also advisable, considering the range of values 0% to 4%.

7.3.2. Estimation of future costs

In a LCCA with long periods of time, future costs, which in the case of bridges include costs of maintenance, rehabilitation and demolition, are likely to be estimates. Considering that this type of analysis is supposed to be performed in the early stage of development of a project or a decision making process; then, even detailed initial costs may not be available. Therefore, future costs are by nature uncertain.

However, even considering that future values are uncertain, it is still better to include them in the analysis rather than to base the conclusions on initial costs only [7.2]. Ignoring uncertain log-term costs implies that they are expected to be zero, which is a poor assumption to make.

Hence, future costs may be calculated based on two different methodologies: a scenario-based approach (deterministic) and a probabilistic-based approach. These two approaches are described in the following sub-sections.

7.3.2.1. Scenario-based approach

The scenario-based approach is based on maintenance/rehabilitation scenarios estimated for the bridge. These scenarios may be based on current practice and “best-guess” estimates.

In this case, the approach leads to a deterministic value, and the consistency of the outcome may be verified by a sensitivity analysis. Sensitivity analysis uses single-value inputs and measures the impact on the outcome of the analysis of changing one uncertain key value or a combination of values at a time. The result shows how the change in the input value(s) changes the outcome, while all other values are held constant.

It is noted that in Chapter 5 (section 5.2.2) a lifetime scenario-based approach was adopted for the definition of the maintenance and rehabilitation plan of the structure over its life cycle. Thus, in the LCCA described in this chapter the same approach is adopted.

7.3.2.2. Probabilistic-based costs

As in every life cycle analysis involving long periods of time, LCCA is also subjected to several sources of uncertainties and the uncertainty is usually higher the further downstream the life cycle chain.

In the case of a life cycle cost analysis, as costs are dependent on the time they occurred, there are two types of uncertainty events: (i) the uncertainty about the occurrence of a certain event, and (ii) in the case the event occurs, the time at which it occurs.

For the result of the LCCA to become widely accepted, the forecasting of the events mentioned in the previous paragraph should be addressed.

For instance, considering the life cycle of a bridge, it is expected that during a lifetime period of 100 years, the bridge would have to go through several interventions (maintenance and rehabilitation operations) over that period.

The occurrence of the intervention *i* at time t_i may be represented on a discrete time axis by introducing units such as years or months. Hence, the PDFs associated with different intervention cycles at the point time t_L* is represented in Figure 7.3.

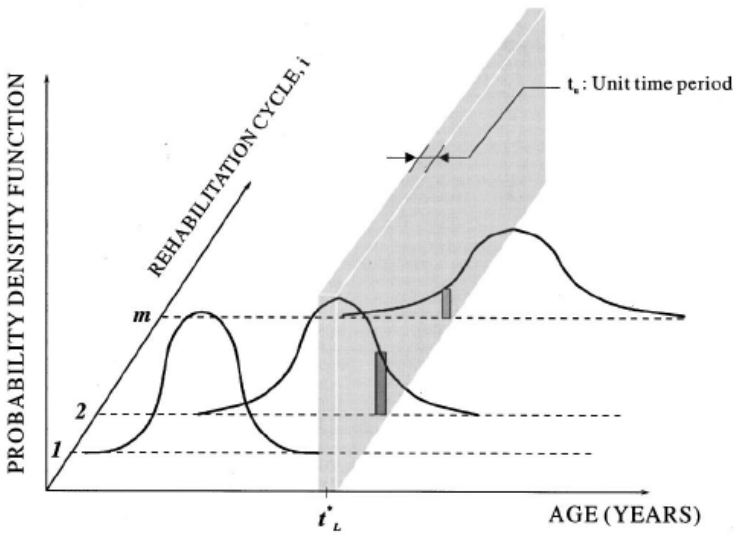

Figure 7.3. Probability density functions associated with different interventions [7.8]

The probability associated with each intervention cycle at t_L* can be easily computed by summing all probabilities associated with this point in time, representing the superposed probability of (any) intervention at time t_L*, as illustrated in Figure 7.4.

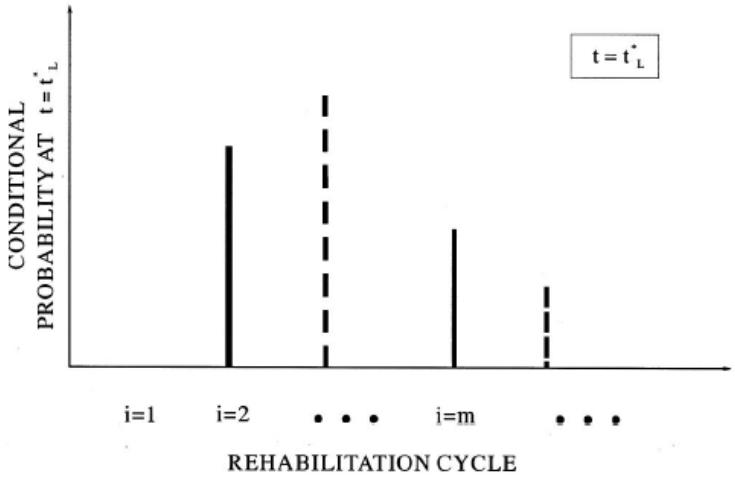

Figure 7.4. Superposed probability of an intervention cycle at $t = t_L$* [7.8]

Assuming the probability of occurrence of an intervention (P_T), the expected intervention cost at time t_L* is given by expression (7.3) [7.8]:

$$E\left[C_{r,n}^{T}\right] = P_{T,n}[t] \times C_{r,n}^{T}\left(t_L^*\right) = P_{T1,\ldots,Tn}[t_1,\ldots,t_n] \times C_{r,n}^{T}\left(t_1^*,\ldots,t_n^*\right) \tag{7.3}$$

with the constraint $t_1 + t_2 + \ldots + t_n = t_L^*$. This cost is associated with the scenario when interventions *1, 2,…, n* occur at times t_1*, t_2*,..., t_n*, respectively.

The total expected cost associated with all intervention cycles is given by expression (7.4) [7.8]:

$$E\left[C_r\left(t_L^*\right)\right] = \sum_{all_i} E\left[C_{r,i}^{T}\right] = \sum_{all_i} \left\{P_{T,i}[t] \times C_{r,i}^{T}\left(t_L^*\right)\right\} \tag{7.4}$$

and the total expected cumulative cost of rehabilitation during the time interval (0, t_n*) is

$$E\left[C_{r,cumul}\left(t \le t_L^*\right)\right] = \sum_{all_t \le t_L^*} \left[\sum_{all_i} \left\{P_{T,i}[t] \times C_{r,i}^{T}\left(t_L^*\right)\right\}\right] \tag{7.5}$$

This procedure enables the calculation of the sum of probabilities of annual interventions and the expected number of cumulative interventions, and it is illustrated by the example in Box 7.2.

Box 7.2. Expected life-cycle maintenance cost

A life cycle cost analysis of the maintenance of a steel structure is made assuming a lifetime period of 100 years. The only maintenance action considered in this analysis is the replacement of the coating system of the structure. The coating system of the steel structure is expected to have a service life of 25 years; thus, for the study period of the structure, three interventions are needed, at years 25, 50 and 75. The cost for replacing the coating of the steel structure is assumed to be 50 000 €.

Considering only the intervention referred above, the life cycle maintenance cost of the structure is given by expression (7.2):

$$PVLCCA = \sum_{t=0}^{100} \frac{50000}{(1+3.8\%)^t} = 30476.02\,€$$

However, considering that the service life of the steel coating is an uncertain variable and assuming, instead of the deterministic value, a normal distribution with mean value of 25 years and standard deviation of 7.5 years, then the expected life cycle maintenance cost of the structure is obtained by a probabilistic analysis, assuming that the first maintenance is performed in year 25 [N(25, 7.5)], the second maintenance is performed in year 50 [N(50, 7.5)] and the third maintenance is performed in year 75 [N(75, 7.5)]. In this case, a Monte Carlo simulation approach was used by running 10000 iterations. The present value of expected maintenance cost, per year, is represented in Figure 7.5.

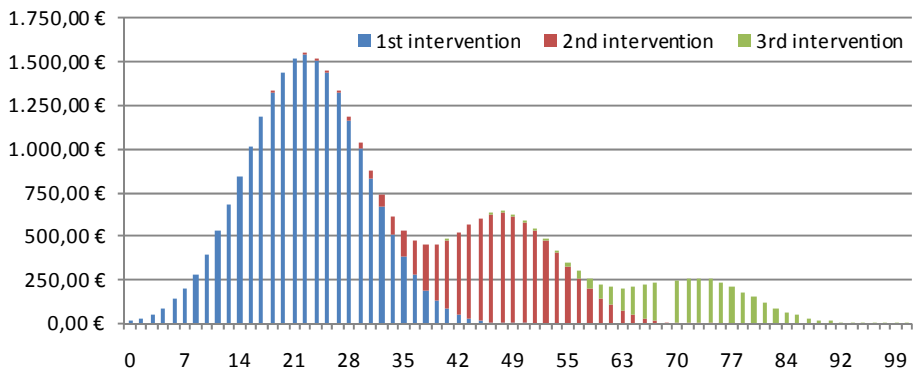

Figure 7.5. Present value of expected annual maintenance cost

In this example the different maintenance interventions overlap, as the initial probabilities of maintenance are distributed over a wide time range. If the probabilities are distributed in shorter time ranges than the number of overlapped annual maintenance costs will reduce.

The accumulation of the present value of expected maintenance costs over the study period (100 years) is represented in Figure 7.6.

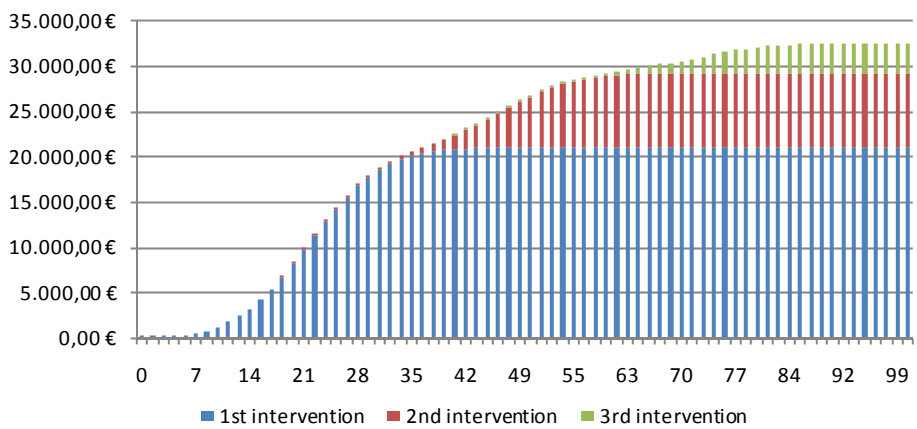

Figure 7.6. Present value of expected cumulative maintenance cost

Thus, the total life cycle maintenance cost of the structure is represented by the Probability Density Function (PDF) represented in Figure 7.7, with a mean value of 33 859.27 € and a standard deviation of 15 486.66 €. In the graph, the 90% confidence interval is also represented, with a minimum value of 16 300 € and a maximum value of 62 700 €.

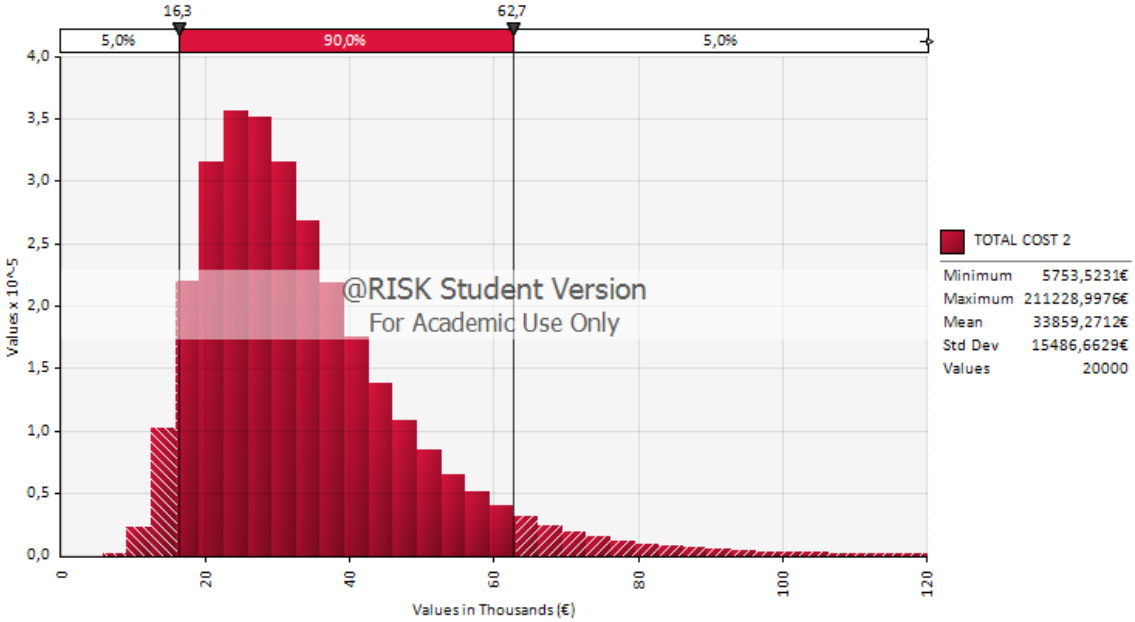

Figure 7.7. PDF of the total life cycle maintenance cost of the structure

The correlation between maintenance and rehabilitation interventions should be considered in the determination of the expected life cycle cost of a structure. The importance of considering the correlation between consecutive interventions is illustrated in the following example.

Box 7.3. Correlation between intervention cycles

The expected life cycle maintenance cost the steel structure referred in Box 7.2 is hereby determined assuming that the variables defining the three interventions are correlated and assuming no correlation. The results are respectively represented in Figure 7.8 and Figure 7.9.

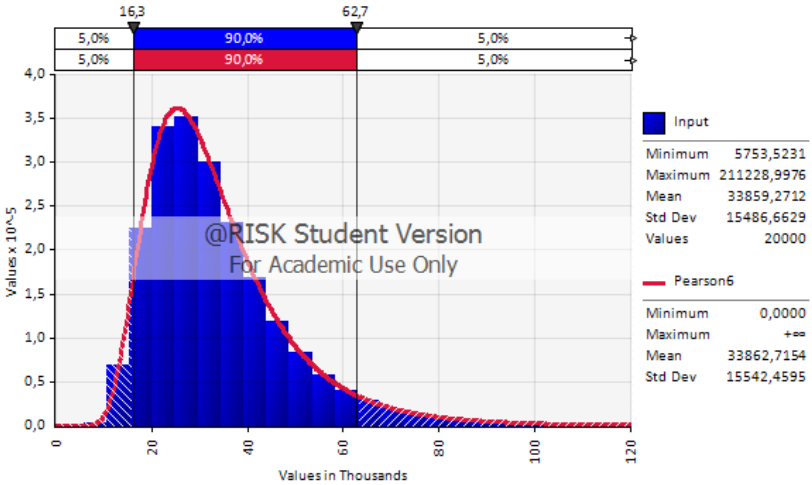

Figure 7.8. PDF of the total life cycle maintenance cost assuming correlation

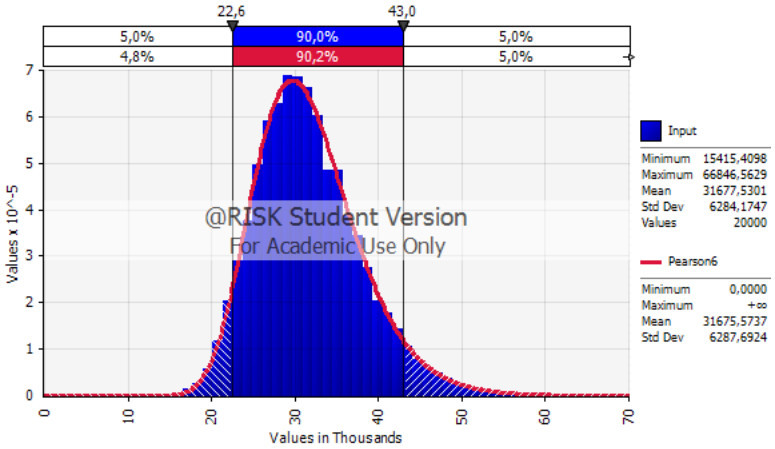

Figure 7.9. PDF of the total life cycle maintenance cost with no correlation

The type of correlation illustrated in the previous box is relatively easy to consider in the analysis. However, the correlation between different types of intervention is not that easy to consider, unless the time-dependent behaviour of the deteriorating system is known.

As referred in the second paragraph of this sub-section, there are two types of uncertainty events in LCCA: the uncertainty about the occurrence of an event and the uncertainty in relation to the time at which it occurs.

In the LCCA proposed in this chapter, the first type of uncertainty is addressed by a scenario-based approach (as discussed in Chapter 5), while the second type of uncertainty is addressed by a probabilistic-based approach. A probabilistic analysis is based on the assumption that no single figure can adequately represent the full range of possible outcomes. Therefore, for the most important parameters in the LCCA, instead of single values, a probabilistic distribution is adopted.

7.4. SYNOPSIS OF LCCA

In this chapter the LCCA was further developed in the aims of the integral life cycle approach pursuit in this dissertation. The first part of the chapter described the economical indicators selected for the approach. Three different types of costs were considered: construction costs, operation costs and end-of-life costs.

In the second part of the chapter, a calculation method for the quantification of the indicators was presented. The adopted approach reduces different costs, which occur at different times in the future, to a single value at one point in time, the present, by means of a discount rate. The discount rate is one of the most important parameters in LCCA, particularly in relation to long lasting product-systems with substantial costs occurring over the lifetime, which is the case of bridges.

In the adopted approach, discounting of future costs is based on real discount rates, in order to avoid the need to account for inflation or deflation, which otherwise would increase the level of uncertainty in the analysis.

Finally, two types of uncertainty events in LCCA were discussed: the uncertainty about the occurrence of an event and the uncertainty in relation to the time at which it occurs. Two different approaches were proposed to address both types of uncertainties. The first type of uncertainty is addressed by a scenario-based approach and the second type of uncertainty is addressed by a probabilistic-based approach, in which the most relevant parameters in the LCCA are represented by probabilistic distributions.

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CHAPTER 8. LIFE CYCLE SOCIAL ANALYSIS

8.1. INTRODUCTION

This chapter describes the quantification of the Life Cycle Social Analysis (LCSA) of a bridge. The evaluation of the social criteria fully respects the boundary system of the integral analysis (see Figure 5.2).

Social criteria enable to quantify the impacts of the bridge on its direct users and surrounding population. Users of the bridge are all people travelling through the roads beneath and above the bridge.

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

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

Two other indicators are also considered in the life cycle social analysis: noise and aesthetics. These two indicators are hereby considered as optional as they differ from the other indicators.

The first difference between these two impacts and the remaining is that, although they can be quantified over the life cycle of the bridge, there's no sense on adding their effects over that period of time.

The other difference is that the two optional indicators have a strong subjective nature and this should be taken into account in its quantification.

All this issues will be further discussed over the chapter. The first part of the chapter regards the mandatory indicators, while the optional indicators are further developed in the second part.

8.2. MANDATORY INDICATORS OF SOCIAL PERFORMANCE

The user costs referred in Chapter 4 are considered in this dissertation as social costs. The main reason for this is that user costs are not usually considered in current economic analysis. However, these costs represent a major share of costs in a life cycle analysis. Hence, in this framework those costs are included in the social dimension to enhance its importance.

Vehicles categories may vary from country to country. The differences concern mainly the number of weight classes and axle configurations considered, and the definition of weight

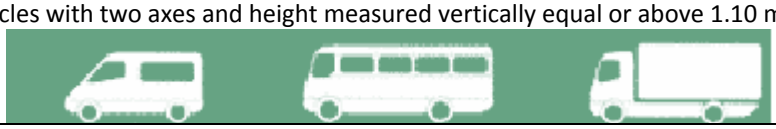
classes themselves. In this section, four different classes of vehicles are adopted according to *Instituto de Estradas de Portugal* (EP), which are representative of the total traffic flow in the national road-network.

Table 8.1. Classes of vehicles according to EP

Classes of vehicles		Description
Light-duty vehicles	Passenger car (VLP)	Cars, with or without trailers, and vehicles with a maximum of 9 seats
	Commercial vehicle (VCL)	Vehicles with a maximum load of 3.5 t
Heavy-duty vehicles	Trucks (VPM)	Vehicles with load over 3.5 t; tractors; truck-trailers
	Trolleybus (VPP)	Buses, trolleybuses and tourism buses

The classification of vehicles from EP is similar to the vehicle classes adopted in BRISA for the purposes of applying toll rates per kilometre of motorway travelled.

Table 8.2. Classes of vehicles according to BRISA

Class of vehicle	Description
1	Motorcycles and vehicles with height measured vertically as from first axis below 1.10 m, with or without trailer
2	Vehicles with two axes and height measured vertically equal or above 1.10 m 
3	Vehicles with three axes and height measured vertically equal or above 1.10 m
4	Vehicles with three or more axes and height measured vertically equal or above 1.10 m

8.2.1. Driver's delay cost

The cost of the time lost by a driver while travelling through a work zone is here denominated as Driver's Delay Cost (DDC). This cost is given by the difference between the cost of the time lost by a driver while travelling at normal speed and the time lost while travelling at a reduced speed due to construction works on the same length of the motorway [8.1], as given by expression (8.1),

$$DDC = \left(\frac{L}{S_a} - \frac{L}{S_n} \right) \times N \times ADT \times \sum_{i=1}^{4} \left(DTC_i \times p_i \right) \tag{8.1}$$

where, L is the length of affected motorway (in km), S_a is the traffic speed during work activity (km/h), S_n is the normal traffic speed (km/h), N is the number of days of road work, ADT is the average daily traffic (no.cars/day), N is the number of days of road work, DTC_i is the cost per hour of a driver's time of a class *i* vehicle and p_i is the percentage of class *i* vehicles in total traffic

flow. In expression (8.1) four classes of vehicles are considered, as indicated in the previous section.

The driver's time cost per hour (*DTC*) adopted in this dissertation is based on a model of user's costs developed for the Portuguese road-network [8.2]. This model was developed with the aim to quantify the costs of the users of national roads based on information provided by official entities and adapted to the Portuguese context, to be used in the general management of the national network of roads.

The referred model was developed in 2006 and for some parameters data was collected in the northern part of the country; thus, same adaptations were needed to apply those user costs to the present analysis, as explained over the next paragraphs.

8.2.1.1. Quantification of driver's time cost per hour and per vehicle-class (DTC_i)

The aim of the model [8.2] to quantify the driver's time cost is to define a cost for the travelling time of the user of a road. The model adopted is based on the assumption that the employer is willing to pay an amount of money equivalent to the value of the salary earned by the employee, for unit of time, in order to reduce the time of travelling, as long as the time was spent in a productive manner. Hence, this model is based on the average salaries of the driver and any other passenger(s), and on the purpose of the trip. Furthermore, two main purposes for travelling are considered in the model: working trip and non-working trip.

According to the model [8.2], the driver´s time cost per hour is based on the average salary of a person, per month, and on the class of the vehicle. The average salary per month, and per economic activity, is provided by the Statistical Report published yearly by the *Ministério do Trabalho e da Solidariedade Social* [8.3]. In case of vehicles of classes 1 and 2, the costs of driver's working time are given as an weighted average of the salaries of all economic activities in Portugal; while, for vehicle classes 3 and 4, costs are given by the salaries of the economic activity referring to transportation, storage and communications (economic activity I). The adopted values are indicated in Table 8.3 and they correspond to values of the year 2008.

As already referred, in the adopted model [8.2] the purpose of the trip is differentiate by working trip or non-working trip. The assumed rates of occupation per vehicle are also indicated in Table 8.3.

Table 8.3. Driver's time cost per hour and rate of occupation of vehicles

Classes of vehicles	1	2	3	4
Cost of driver's working time (€/month)	1064.00	1064.00	1597.00	1597.00
Cost of driver's working time (€/h) [(1)]	6.20	6.20	9.30	9.30
Rate of occupation (km)	2	1	24	1
Rate of occupation	1 person working + 1 person non-working	1 person working	1 person working + 23 non-working persons	1 person working

[(1)] Assuming a working time of 40 h/week and 4.3 weeks/month

The driver´s time cost, per hour and per class of vehicle, is given by the following expression:

$$DTC_i = \sum_m \left(TC_m \times OR_{i,m} \right) \tag{8.2}$$

where, TC_m is the time cost of per hour a person travelling with purpose *m* (in €/h/person); and $OR_{i,m}$ is rate of occupation inside vehicle-class *i* travelling with purpose *m* (no.persons/vehicle).

Considering a working trip (m = 1) and non-working trip (m = 2) and assuming that the cost of a person travelling in a non-working trip ($TC_{m=2}$) is ¼ of the cost per hour of a person travelling in a working trip ($TC_{m=1}$),

$$TC_{m=2} = 0.25 \times TC_{m=1} \tag{8.3}$$

Hence, based on the values of Table 8.3 and expressions (8.2) and (8.3), the drivers' time costs, per hour and per class of vehicle, are indicated in Table 8.4.

Table 8.4. DTC per hour and class of vehicle

	Class 1	Class 2	Class 3	Class 4
TC_1 (€/h)	6.20	6.20	9.30	9.30
$OR_{i,1}$	1	1	1	1
TC_2 (€/h)	1.55	1.55	2.33	2.33
$OR_{i,2}$	1	0	23	0
DTC_i (€/h)	7.75	6.20	62.90	9.30

Hence, the driver's delay cost (DDC) due to traffic congestion in a work zone depends of the traffic in the motorway, the characteristics of the work zone and the unit costs calculated in the previous paragraphs. Box 8.1 exemplifies the calculation of the DDC for a work zone in a motorway.

Box 8.1. Driver's delay cost (DDC) in a work zone

Due to maintenance activities in a motorway, a working zone is considered with a length of 1 km, for a period of 1 day. The traffic speed during work activity is 80 kw/h, while under normal traffic conditions the speed is 120 kw/h. The motorway has a ADT of 31522 vehicles/day in the considered segment, with the following distribution per vehicles: 80% of vehicles are class 1, 8% are class 2, 10% are class 3 and 2% are class 4.

The total driver's delay cost for this work zone is given by expression (8.1):

$$DDC = \left(\frac{1}{80} - \frac{1}{120} \right) \times 1 \times 31522 \times \left[(7.75 \times 0.80) + (6.20 \times 0.08) + (62.90 \times 0.10) + (9.30 \times 0.02) \right] \Leftrightarrow$$

$$\Leftrightarrow DDC = 1730.03\,€$$

Hence, the driver's delay cost in the work zone is about 1730 €, per day.

8.2.1.2. Uncertainties in the calculation of driver's time cost per hour

As referred in the previous sub-section, the costs of driver's working time were considered as a weighted average of the salaries of all economic activities in Portugal. However, the variability of the annual income for different economic activities is considerable high, as illustrated in Figure 8.1 [8.4]:

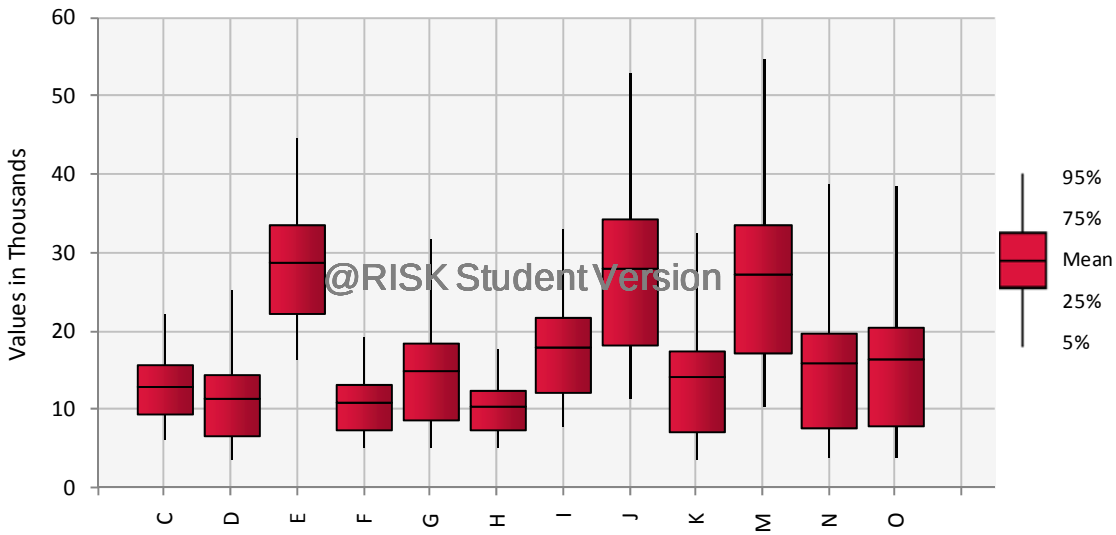


Figure 8.1. Variability of annual income per economic activity [8.4]

Although these values refer to the year 2006 (there is no more recent statistical data available), the graph shows that the mean value of the annual income differ considerably depending on the economic activity.

To take this variability into account, the same distribution, per economic activity was considered for the income of 2008. Thus, the variability of the cost of driver's working time for vehicle classes 1 and 2 and the variability of the cost of driver's working time for vehicle classes 3 and 4, are represented in Figure 8.2.

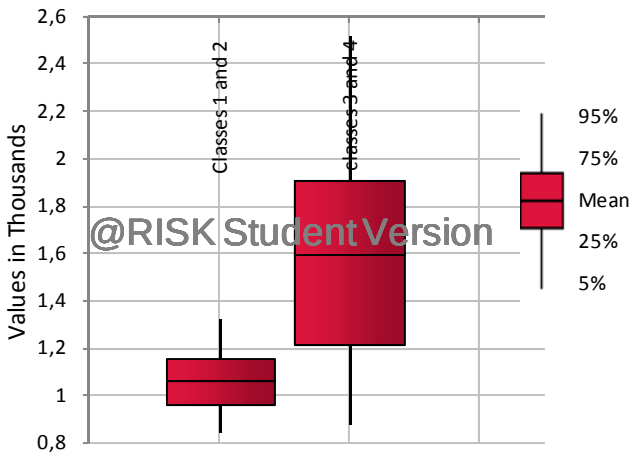


Figure 8.2. Variability of the cost of drivers' working time (per month)

Therefore, for the cost of driver's working time for vehicle classes 1 and 2 a lognormal distribution is considered with mean value of 1063.76 € and standard deviation of 146.86 €; while , for the cost of driver's working time for vehicle classes 3 and 4, a lognormal distribution is considered with mean value of 1599.50 € and standard deviation of 532.31 €.

8.2.1.3. Influence of work zone characteristics

The calculation of the DDC by expression (8.1) considers that the characteristics of the work zone are constant during the entire period of the work activity. It does not take into

consideration that the traffic speed in a work zone depends of the capacity of the motorway and consequently on the hourly traffic flow.

As discussed in chapter 5, the model QUEWZ98 allows considering the characteristics of the traffic behaviour in a work zone based on the capacity of the work zone. By using this model it is possible to consider the hourly variation of traffic in the work zone, the corresponding variation in the traffic speed and the length of the affected zone. Thus, taking this model into account in the calculation of DDC, expression (8.1) is adapted according to the following expression:

$$DDC = \sum_{j=1}^{24}\left[\sum_{k=1}^{5}\left(\frac{L_k}{S_{a_k}} - \frac{L_k}{S_n}\right) \times HT \times \sum_{i=1}^{4}\left(DTC_i \times p_i\right)\right] \times N \qquad (8.4)$$

where, HT is average hourly traffic and L_k is the length of the work zone with traffic speed S_{ak}. The total length of the affected zone is given by the sum of the length of deceleration zone (L_1), length of the queue zone (L_2), length of the acceleration zone 1 (L_3), length of the effective work zone (L_4) and length of the acceleration zone 2 (L_5). If there is no queue then $L_2 = 0$.

To illustrate the influence of the characteristics of the work zone in the calculation of DDC, the example of Box 8.1 is re-evaluated in Box 8.2.

Box 8.2. Driver's delay cost (DDC) in a work zone taking into account its characteristics

Due to maintenance activities in a motorway, a working zone is considered with an estimated length of 1 km, for a period of 1 day. The traffic speed in the work zone is 80 km/h, while under normal traffic conditions the speed is 120 km/h. The motorway has an ADT of 31522 vehicles/day in the considered segment, with the following distribution per vehicles: 80% of vehicles are class 1, 8% are class 2, 10% are class 3 and 2% are class 4. Moreover the hourly distribution of the traffic during the day is given in the following graph:

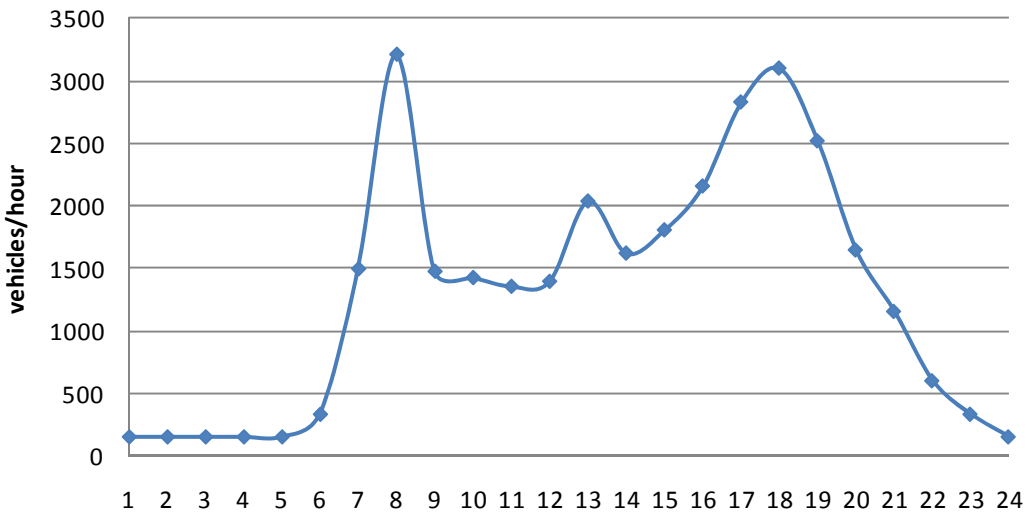


Figure 8.3. Average hourly traffic in the motorway

Moreover, it is assumed that the motorway under normal traffic conditions has two lanes of traffic in each direction. During the work activity all lanes are open although the total wide of

each carriageway is reduced and thus traffic speed is conditioned. Hence, the total driver's delay cost for this work zone, as given by expression (8.2), is given in the following table:

Table 8.5. DDC in work zone, per carriageway

Time	Hourly traffic	Length of affected zone (km)		Driver Delay Cost (DDC)	
		Classes 1 and 2	Classes 3 and 4	Classes 1 and 2	Classes 3 and 4
0-1	80	0.68	1.52	1,10 €	2,19 €
1-2	80	0.68	1.52	1,10 €	2,19 €
2-3	80	0.68	1.52	1,10 €	2,19 €
3-4	80	0.68	1.52	1,10 €	2,19 €
4-5	80	0.68	1.52	1,10 €	2,19 €
5-6	170	0.70	1.51	2,48 €	4,77 €
6-7	750	0.82	1.50	15,14 €	24,83 €
7-8	1605	1.01	1.50	44,49 €	62,53 €
8-9	740	0.82	1.50	14,87 €	24,44 €
9-10	715	0.82	1.50	14,20 €	23,48 €
10-11	680	0.81	1.50	13,29 €	22,14 €
11-12	700	0.81	1.50	13,81 €	22,90 €
12-13	1020	0.88	1.50	23,09 €	35,84 €
13-14	813	0.84	1.50	16,87 €	27,29 €
14-15	905	0.86	1.50	19,55 €	31,03 €
15-16	1080	0.90	1.50	25,02 €	38,41 €
16-17	1415	0.97	1.50	36,93 €	53,49 €
17-18	1550	1.00	1.50	42,25 €	59,88 €
18-19	1260	0.94	1.50	31,19 €	46,36 €
19-20	825	0.84	1.50	17,22 €	27,79 €
20-21	580	0.77	1.49	10,52 €	18,15 €
21-22	304	0.72	1.50	4,78 €	8,85 €
22-23	170	0.70	1.51	2,48 €	4,77 €
23-24	80	0.68	1.52	1,10 €	2,19 €
TOTAL				354.80 €	550.11 €

Hence, the driver's delay cost in the work zone, considering both carriageways, is about 1810.00 €, per day. When comparing this value with the value obtained in the example of Box 8.1, the difference is not significant (an increase of about 4.6%).

However, if the same cost is evaluated for the same work zone, under the same traffic, but considering that one lane of traffic is closed in each direction, then the following results would be obtained:

- if the lane is closed between the period of 22h – 6h (night period): DDT = 1816.24 €/day;
- if the lane is closed between the period of 6h – 22h (day period): DDT = 7969.06 €/day.

In both cases, it is considered that the traffic is conditioned for the 24 hours, although during the close of the lanes, the congestion increases.

In the first case, as the close of the lane is made during the night, the motorway capacity is enough for the traffic to flow without major disturbance. However, in the second case, the close of the lane is made during the day, when the demand of the traffic is higher. In this case there´s a queue formation during the periods of 7h-9h and 17h-19h, and the driver delay cost is increase about 4 times more.

8.2.2. Vehicle operation costs

A vehicle travelling through a work zone is subjected to delays. This construction related delays result in additional costs for the owner of the vehicle. These additional costs are hereby denominated Vehicle Operating Costs (VOC). This cost is given by the difference between the cost of the operation of the vehicle while travelling at normal speed and the operation of the vehicle while travelling at a reduced speed due to construction works on the same length of the motorway [8.1], as given by expression (8.6),

$$VOC = \left(L - \frac{S_a}{S_n} \times L \right) \times N \times ADT \times \sum_{i=1}^{4} \left(VOC_i \times p_i \right) \tag{8.5}$$

where, S_a is the traffic speed during work activity (km/h), S_n is the normal traffic speed (km/h), L is the length of affected motorway (km), N is the number of days of road work, ADT is the average daily traffic (no.cars/day), VOC_i is the operation cost of class i vehicle (€/km); and p_i is the percentage of class i vehicles in total traffic flow.

The operation cost of class i vehicle (VOC_i), per km, adopted in this dissertation is based on the model [8.2] referred in the last section, with few adaptations as explained over the next paragraphs.

8.2.2.1. Quantification of operation cost of class *i* vehicle (VOC_i)

The quantification of the cost of vehicle-class i operation (VOC_i) includes four components [8.2]: the cost due to fuel consumption (Cc_i), the cost of tires (Cp_i), the cost of maintenance (Cm_i) and the cost of depreciation of the vehicle (Cd_i), as given by (8.7), in €/km:

$$VOC_i = Cc_i + Cp_i + Cm_i + Cd_i \tag{8.6}$$

The cost of vehicle-class i due to fuel consumption (Cc_i) is expressed by the product between the fuel consumption (cc_i), in l/km, and its respective cost (Cmc_i), in €/l:

$$Cc_i = cc_i \times Cmc_i \tag{8.7}$$

In the previous expression, the cost of fuel is the commercial cost of fuels (gasoline and diesel) available from numerous sources. The fuel consumption of each class of vehicles was based in commercial information of typical vehicles in each class and on relevant information from national transport associations.

The cost of tires of vehicle-class i (Cp_i) is given by expression (8.9), where np_i is the number of tires of class i vehicles, Cmp_i is the market price of each tyre (in €) and pvp_i the correspondent lifetime (in km),

$$Cp_i = \frac{np_i \times Cmp_i}{pvp_i} \tag{8.8}$$

The lifetime of tires for each class of vehicles was estimated based on information collected from transport associations.

The cost of maintenance of vehicle-class *i* (Cm_i) is given by (8.10), where $Cmmt_i$ (in €) is the cost of preventive maintenance of class *i* vehicle during its entire lifetime (pvv_i), in years, and kma_i is the annual average distance travelled by class *i* vehicle (in km/yr),

$$Cm_i = \frac{Cmmt_i}{pvv_i \times kma_i} \tag{8.9}$$

The maintenance cost of a vehicle was estimated based on the number of preventive maintenance done per year by each vehicle (considering a typical vehicle per class) and on the respective lifetime. This data was obtained from specific surveys made in companies and other available data from relevant associations.

Finally, the cost of depreciation of vehicle-class *i* (Cd_i) is given by (8.11), where $Cmdt_i$ (in €) is the total depreciation value of class *i* vehicle over its lifetime,

$$Cd_i = \frac{Cmdt_i}{pvv_i \times kma_i} \tag{8.10}$$

The depreciation value of a vehicle of class i was considered as the difference between the commercial price of a new class-i vehicle and the commercial price of the same vehicle at the end of its life. Both prices were estimated based on information collected from relevant literature and transport associations.

A synthesis of the data adopted in this work is provided in Table 8.6. This data is based on data from [8.2] but updated by using an inflation rate of 2% for years 2006 and 2007.

Table 8.6. Summary of estimated data for calculation of vehicle operation costs [8.2]

Classes of vehicles		1		2	3	4
Fuel consumption per vehicle (l/100km)		gasoline	diesel	diesel	diesel	diesel
	(cc_i)	5.9	4.8	4.5	44.0	44.0
Cost of fuel (€)	(Cmc_i)	1.445	1.199	1.199	1.199	1.199
Lifetime of vehicles (years)	(pvv_i)	10		8	12	12
Average no. of km per year	(kma_i)	20000		30000	70000	85000
Lifetime of tires (km)	(pvp_i)	40000		40000	75000	200000
No. of tires	(np_i)	4		4	6	2[(1)];4[(2)];6[(3)]
Cost of tire (€)	(Cmp_i)	73.00		62.40	333.00	473.30[(1)]; 489.03[(2)]; 463.60[(3)]
Maintenance of vehicles (€)	($Cmmt_i$)	1575.30		1860.00	16316.00	28026.90
Depreciation of vehicles (€)	($Cmdt_i$)	17177.20		11562.80	216526.40	84451.13

[(1)] front tires; [(2)] rear tires; [(3)] semi-trailer

Hence, based on the values of Table 8.6 and expressions (8.8) to (8.11), the operation costs of class-i vehicle, per km, are indicated in Table 8.7.

Table 8.7. VOC per class of vehicle

	Class 1	Class 2	Class 3	Class 4
Cc_i (€/km)	0.0714	0.0540	0.5276	0.5276
Cp_i (€/km)	0.0073	0.0062	0.0266	0.0284
Cm_i (€/km)	0.0079	0.0078	0.0194	0.0275
Cd_i (€/km)	0.0859	0.0482	0.2578	0.0828
VOC_i (€/km)	0.1725	0.1161	0.8314	0.6663

According to (8.5) vehicle operation costs (VOC) due to traffic congestion in a work zone depends of the traffic in the motorway, the characteristics of the work zone and the unit costs calculated in the previous paragraphs, as exemplified in Box 8.3.

Box 8.3. Vehicle operation costs (VOC) in a work zone

Assuming the characteristics of the work zone and of the traffic as described in Box 8.1, the total costs due to vehicle operation in the work zone is given by expression (8.6):

$$VOC = \left(1 - \frac{80}{120} \times 1\right) \times 1 \times 31522 \times \begin{bmatrix} (0.1725 \times 0.80) + (0.1161 \times 0.08) + (0.8314 \times 0.10) \\ + (0.6663 \times 0.02) \end{bmatrix} \Leftrightarrow$$

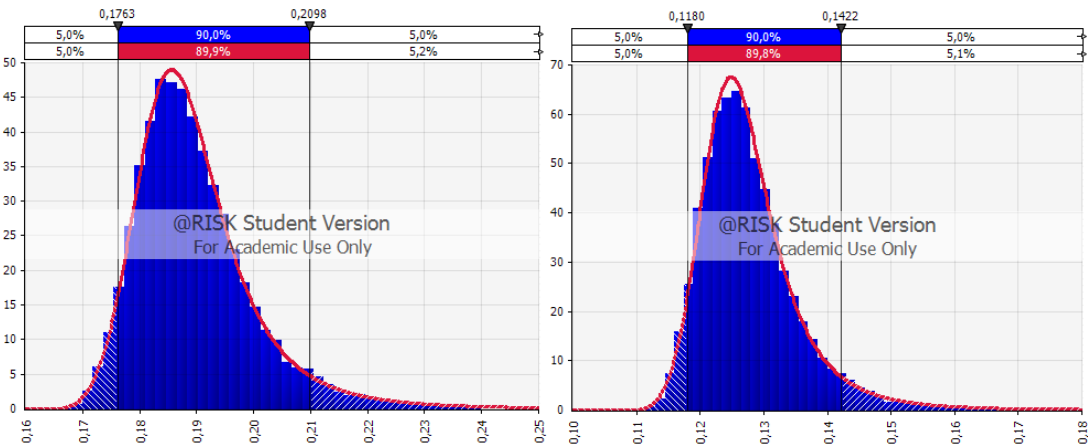
$$\Leftrightarrow VOC = 2560.92\,€$$

Hence, the vehicle operation costs in the work zone are about 2561 € per day.

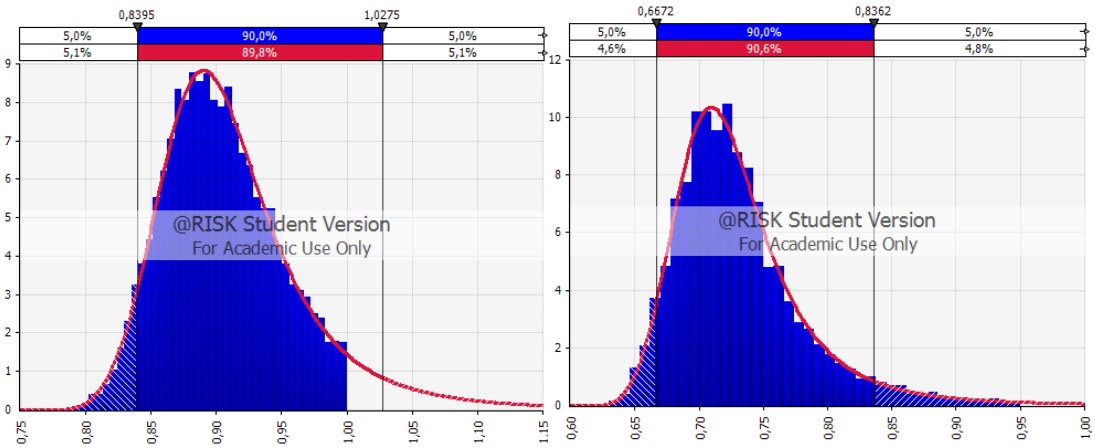
8.2.2.2. Uncertainties in the calculation of vehicle operation costs per km

The estimation of all the values needed for the calculation of VOC, as described in the previous sub-section, is subjected to a high degree of uncertainty and variability. Uncertainty due to simplifications considered in the quantification approaches and in data. The sources of variability include the several types of vehicles included in each class and the differences between them; also the regional variability in prices in the country.

To take his into account, probabilistic distributions were assigned to each value in Table 8.6. Therefore, lognormal distributions were assigned to each cost, with mean value given by the value in Table 8.6 and a standard deviation of 10% of the mean value. All the remaining parameters, except the number of tires, were assigned triangular distributions with mean value given by the value in Table 8.6 and minimum and maximum values of $\pm 10\%$.



(a) VOC_1 (b) VOC_2



(c) VOC_3 (d) VOC_4

Figure 8.4. Uncertainties values and distributions of VOC_i

The uncertainty propagation in the calculation of VOC_i was obtained by a Monte Carlo simulation (10000 iterations). The results obtained for each case are represented in Figure 8.4, together with the fitted distributions assumed for each case, which characteristics are indicated in Table 8.8.

Table 8.8. Uncertainties in VOC per class of vehicle

	VOC_1	VOC_2	VOC_3	VOC_4
Fitted distribution	Log-logistic	Log-logistic	Log-logistic	Log-logistic
Mean value	0.1900	0.1279	0.9152	0.7332
Standard deviation	0.0117	0.0084	0.0663	0.0599
Minimum value	0.1636	0.1085	0.7724	0.6191
Maximum value	+∞	+∞	+∞	+∞

8.2.2.3. Influence of work zone characteristics

Expression (8.6) considers that the characteristics of the work zone are constant during the entire period of the work activity. It does not take into consideration that the traffic speed in a work zone depends of the capacity of the motorway and consequently on the hourly traffic flow.

As discussed in the previous section using the model QUEWZ98 it is possible to consider the hourly variation of traffic in the work zone, the corresponding variation in the traffic speed and the length of the affected zone. Thus, taking this model into account in the calculation of VOC, expression (8.6) is adapted according to the following expression:

$$VOC = \sum_{j=1}^{24}\left[\sum_{k=1}^{5}\left(L_k - \frac{S_{a_k}}{S_n}\times L_k\right)\times HT \times \sum_{i=1}^{4}\left(VOC_i \times p_i\right)\right]\times N \qquad (8.11)$$

where, HT is average hourly traffic and L_k is the length of the work zone with traffic speed S_{ak}. The total length of the affected zone is given by the sum of the length of deceleration zone (L_1), length of the queue zone (L_2), length of the acceleration zone 1 (L_3), length of the effective work zone (L_4) and length of the acceleration zone 2 (L_5). If there is no queue then $L_2 = 0$.

The use of expression (8.11) is exemplified in Box 8.4.

Box 8.4. Vehicle operation cost (VOC) in a work zone taking into account its characteristics

Considering the hourly distribution of the traffic during the day as given in Box 8.2, and all the other characteristics of the traffic in the work zone, the vehicle operation costs for the work zone is given in the following table, according to (8.11):

Table 8.9. VOC in work zone, per carriageway

Time	Hourly traffic	Length of affected zone (km)		Vehicle Operation Cost (VOC)	
		Classes 1 and 2	Classes 3 and 4	Classes 1 and 2	Classes 3 and 4
0-1	80	0.68	1.52	2.07	2.83 €
1-2	80	0.68	1.52	2.07 €	2.83 €
2-3	80	0.68	1.52	2.07 €	2.83 €
3-4	80	0.68	1.52	2.07 €	2.83 €
4-5	80	0.68	1.52	2.07 €	2.83 €
5-6	170	0.70	1.51	4.62 €	6.15 €
6-7	750	0.82	1.50	27.36 €	30.92 €
7-8	1605	1.01	1.50	78.51 €	75.06 €
8-9	740	0.82	1.50	26.89 €	30.45 €
9-10	715	0.82	1.50	25.71 €	29.28 €
10-11	680	0.81	1.50	24.08 €	27.67 €
11-12	700	0.81	1.50	25.01 €	28.59 €
12-13	1020	0.88	1.50	41.33 €	44.04 €
13-14	813	0.84	1.50	30.41 €	33.87 €
14-15	905	0.86	1.50	35.13 €	38.34 €
15-16	1080	0.90	1.50	44.72 €	47.07 €
16-17	1415	0.97	1.50	65.43 €	64.65 €
17-18	1550	1.00	1.50	74.63 €	72.02 €
18-19	1260	0.94	1.50	55.47 €	56.38 €
19-20	825	0.84	1.50	31.03 €	34.47 €
20-21	580	0.77	1.49	19.17 €	22.82 €
21-22	304	0.72	1.50	8.84 €	11.31 €
22-23	170	0.70	1.51	4.62 €	6.15 €
23-24	80	0.68	1.52	2.07 €	2.83 €
TOTAL				635.35 €	676.23 €

Hence, the vehicle operation costs in the work zone, considering both carriageways, is about 2623.00 €, which represents an increase of about 2.4% in relation to Box 8.3.

Re-evaluating the same work zone, under the same traffic, but considering that one lane of traffic is closed in each direction, then the following results would be obtained:

- if the lane is closed between the period of 22h – 6h (night period): VOC = 2632.68 €/day;
- if the lane is closed between the period of 6h – 22h (day period): VOC = 5682.59 €/day.

Considering the night close of the lane there's no significant difference in the result obtained before. However, when the close of the lane is made during the day, then there´s a queue formation and the vehicle operation costs increase about twice more.

8.2.3. Accident costs

Accident costs represent the additional costs due to a work zone in a road or motorway; thus, they are calculated by the difference between the cost of accidents in a length of motorway with

no work activity and the cost of accidents in the same length when there is work activity [8.1], as given by the following expression,

$$AC = L \times ADT \times N \times (R_a - R_n) \times C_a \tag{8.12}$$

where, L is the length of affected roadway, ADT is the average daily traffic (no.cars/day), N is the number of days of road work, R_a and R_n are the during work activity and normal accident rates (per vehicle-kilometre) and C_a is the cost per accident.

8.2.3.1. Quantification of cost per accident

The model adopted for the quantification of the cost of accident [8.2] takes into account the severity of the accident, the type of road and the volume of traffic. The quantification of the total accident cost is given by the cost related to the victims plus the cost of the accident itself, which includes the cost of authorities' assistance and the cost of medical assistance.

For the purpose of costs quantification, three types of main accidents are considered (i) accidents with light injuries, (ii) accidents with severe injuries, and (iii) fatal accidents. Damage only accidents are not included as these are not generally recorded by authorities.

The cost of the assistance supplied by the authorities is quantified based on the cost of operation of the vehicles used by the personnel providing the assistance, on the cost per hour of each professional and on the severity of the accident. The values estimated in the model [8.2] were based on prices from 2006. The values adopted in this work, indicated in Table 8.12, are based on these values but an update was made for prices of year 2008, using an inflation rate of 2%/per year according to the consumer price index quantified by "*Instituto Nacional de Estatística*".

Table 8.10. Assumptions for the calculation of authorities assistance [8.2]

Type of accident	No. vehicles, duration of assistance and no. officers deployed	Unit Cost	Final cost
With light-injuries	1 vehicle(*)	0.40 €/km	55.68 €
	2 officers - 2 hours	10.9 €/h	
With severe-injuries	2 vehicle(*)	0.40 €/km	155.04 €
	4 officers - 3 hours	10.9 €/h	
With fatalities	1 vehicle(*)	0.40 €/km	242.40 €
	4 officers - 3 hours	10.9 €/h	
	1 special officer - 8 hours	10.9 €/h	

(*) assuming a travelled distance of 30 km

The same approach was used to quantify the costs due to medical assistance. In this case, the cost was based on the type of the emergency vehicle needed, which depend on the severity of

Table 8.11. Assumptions for the calculation of medical assistance [8.2]

Type of accident	No. vehicles deployed	Unit Cost	Final cost
With light-injuries	1 ambulances	17.44 €	17.44 €
With severe-injuries	2 ambulances	17.44 €	100.27 €
	1 emergency medical vehicle	65.39 €	
With fatalities	2 ambulances	17.44 €	100.27 €
	1 emergency medical vehicle	65.39 €	

the accident. The costs adopted in this work are indicated in Table 8.11. Hence, the total cost of assistance per type of accident (ca_j) is given by the sum of the values in the previous tables, as shown in Table 8.12.

Table 8.12. Cost of assistance per type of accident (ca_j)

Type of accident	j	Cost of authorities assistance	Cost of medical assistance	Total cost of assistance
With light-injuries	1	55.68 €	17.44 €	73.12 €
With severe-injuries	2	155.04 €	100.27 €	255.31 €
With fatalities	3	242.40 €	100.27 €	342.67 €

The costs per victim adopted in this work are indicated in Table 8.13. These costs are based on the values estimated in [8.2], which were based on literature and similar models. An inflation rate of 2%/per year was used to update the values in the original model.

Table 8.13. Cost related to the victims (cv_k)

Type of victim	k	Cost of victim
Light-injury	1	41 600 €
Severe-injury	2	93 600 €
Fatality	3	520 000 €

According to the model [8.2], the total cost per accident is given by,

$$C_a = \sum_{j=1}^{3}\left(RA_j \times ca_j\right) + \sum_{k=1}^{3}\left(RV_k \times cv_k\right) \tag{8.13}$$

However, as the goal is the difference between the cost of accident under normal traffic conditions and the cost of accident in work zones, expression (8.12) is adapted to the following expression:

$$C_a = \sum_{j=1}^{3}\left[\left(RAa_j - RAn_j\right)\times ca_j\right] + \sum_{k=1}^{3}\left[\left(RVa_k - RVn_k\right)\times cv_k\right] \tag{8.14}$$

where, RAa_j and RAn_j are the rate of accident type *j* in work zone and non-work zone, respectively; and RVa_k and RVn_k are the rate of victim type *k* in work zone and non-work zone, respectively.

Thus, from expression (8.12), total accident costs in a work zone are given by,

$$AC = L \times ADT \times N \times \left\{\sum_{j=1}^{3}\left[\left(RAa_j - RAn_j\right)\times ca_j\right] + \sum_{k=1}^{3}\left[\left(RVa_k - RVn_k\right)\times cv_k\right]\right\} \tag{8.15}$$

8.2.3.2. Quantification of accident rates

8.2.3.2.1. Accident rates under normal traffic flow

The rates of accident in A1 motorway, under normal traffic conditions are obtained from *APCAP* – Association of Portuguese Concession Companies of Toll Motorways or Bridges.

The rate of accidents with victims' type j (RAn_j) is given by the number of accidents with victims' type *j* and the volume of traffic of the motorway [8.5]:

$$RAn_j = \text{no. accidents with victims type } j/\text{Volume of traffic} \quad (8.16)$$

where, the volume of traffic is the number of vehicles times the number of travelled kilometres.

The rate of victim type *k* (RVn_k) is given by the number of victims' type *k* and the volume of traffic of the motorway [8.5]:

$$RVn_k = \text{no. of victims type } k/\text{Volume of traffic} \quad (8.17)$$

Both rates (per vehicle-km) are given in Table 8.14, relative to year 2008 [8.5].

Table 8.14. Rates under normal traffic conditions (RAn_j and RVn_k)[8.5]

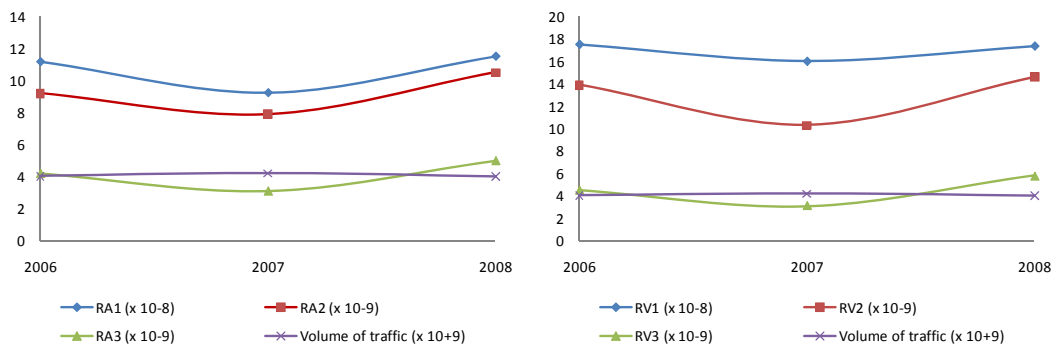
Type j = k	1	2	3
Rate of accident type j (x 10^{-8})	11.54	1.05	0.50
Rate of victims type k (x 10^{-8})	17.36	1.46	0.58

To compare the evaluation of the rates, data from 2006 [8.6] and 2007 [8.7] are also available from *APCAP*. The graph in Figure 8.5 presents the evolution of the rates of accidents and victims, and these lines are compared with the volume of traffic in the motorway.

Table 8.15. Rates under normal traffic conditions for 2006-2009 [8.5][8.6][8.7]

	2006	2007	2008
Rate of accidents with victim type j (RAn_j)			
With light-injuries (x 10^{-8})	11.20	9.25	11.54
With severe-injuries (x 10^{-8})	0.92	0.79	1.05
With fatalities (x 10^{-8})	0.42	0.31	0.50
Rate of victims type k (RVn_k)			
Light-injuries (x 10^{-8})	17.51	16.03	17.36
Severe-injuries (x 10^{-8})	1.39	1.03	1.46
Fatalities (x 10^{-8})	0.45	0.31	0.58
Volume of traffic (x 10^{8})	40.265	41.924	39.855

The trends of the rate of accidents and the rate of victims from 2006 to 2008 are represented in the graphs of Figure 8.5a and Figure 8.5b, respectively. Albeit the volume of traffic had been slightly reduce over the last years, the rate of accidents and the rate of victims had increased in 2008 in comparison with the same values from the previous year.



(a) (b)

Figure 8.5. (a) Rates of accidents per vehicle-km, and (b) Rates of victims per per vehicle-km

8.2.3.2.2. Accident rates in work zones

In order to evaluate the rate of accidents in work zones, three work zones in the motorway A1 were analysed. This motorway belongs to the concessionaire BRISA and connects the city of Lisbon to the city of Porto, with a length of 277 km.

The first work zone (WZ1) was located between km 46, near the location of Aveiras, and km 65, near the location of Santarém. The work over this length of the motorway took place between July 2002 and November 2004. The second work zone (WZ2) was situated between the locations of Santarém (at km 65) and Torres Novas (at km 94), and took place between June 2005 and December 2007. Finally, the third work zone (WZ3) analysed in motorway A1, took place between the locations of Condeixa (at km 181) and Coimbra-Sul (at km 189), from December 2007 to June 2009.

The three work zones relates to the widening of motorway A1 from 2 to 3 lanes of traffic in each direction. The correspondent work included the widening of the motorway platform, the demolition of existing cross-bridges and the construction of new cross-bridges to replace the ones that were demolished. The selection of these three work zones was due to the availability of data as explained over the next paragraphs.

Data for traffic accidents is published online, per year, from ANSR - *Autoridade Nacional Segurança Rodoviária* [8.8]. Data is available from 1999, however, data related to years 1999 to 2003 is limited and does not provide enough detail for the purpose of the present study. From 2004 onwards, detailed data is provided for each *Distrito* (main region) in terms of the number of accidents with severe injuries and/or fatalities. However, it should be noted that no data is available for accidents with light injuries and damage only accidents, as in the latter case no formal records of damage are recorded. This means that no accurate rates may be calculated from this data. Nevertheless, it is possible to evaluate the trend regarding the number of accidents and victims from 2004 to 2008, especially in the location of work zones. Data for 2009 is not complete at this stage and no detailed data is provided; therefore, year 2009 is not taken into consideration.

Taken into consideration the location of the work zones, Table 8.16 provides the number of accidents and the type of victims that occurred over the length of motorway indicated in the first column of the table. The period of time correspondent to the duration of each work zone is dashed for a better comprehension.

Table 8.16. Number of accidents with severe injuries and fatalities in work zones (based in [8.8])

	Location	Length		2004	2005	2006	2007	2008
WZ1	46 km << 65 km	19 km	No. of accidents	14[(1)]	8	4	1	6
			No. of severe injuries	13	8	3	0	9
			No. of fatalities	5	3	1	1	1
WZ2	65 km << 94 km	29 km	No. of accidents	7	2[(2)]	7	13	8
			No. of severe injuries	6	1	9	11	12
			No. of fatalities	4	1	2	5	2
WZ3	181 km << 189 km	8 km	No. of accidents	0	4	3	2	2
			No. of severe injuries	0	3	4	1	2
			No. of fatalities	0	2	0	1	1

[(1)] all accidents occurred until November 2004 (inclusive)
[(2)] all accidents occurred after June 2005

Although, the limitation of the work zones are the ones indicated in Table 8.16, a tolerance of 5 km was assumed in each limit of the work zone, in order to account for traffic disturbance over deceleration and acceleration lengths, respectively in the beginning and end of the work zone. In relation to WZ1, no data was provided before 2004, which makes the analysis very limited. However, a clear difference exists between the number of accidents in year 2004 and the following years with no work zone. This evidence is not that clear for the second work zone, which took place more than six months from the first intervention. Finally, in the third work zone there is no significant different in the number of accidents in the year correspondent to the intervention and the previous years, with no work zones. It should be noticed, however, that the length of this work zone is much smaller when compared with the two previous ones.

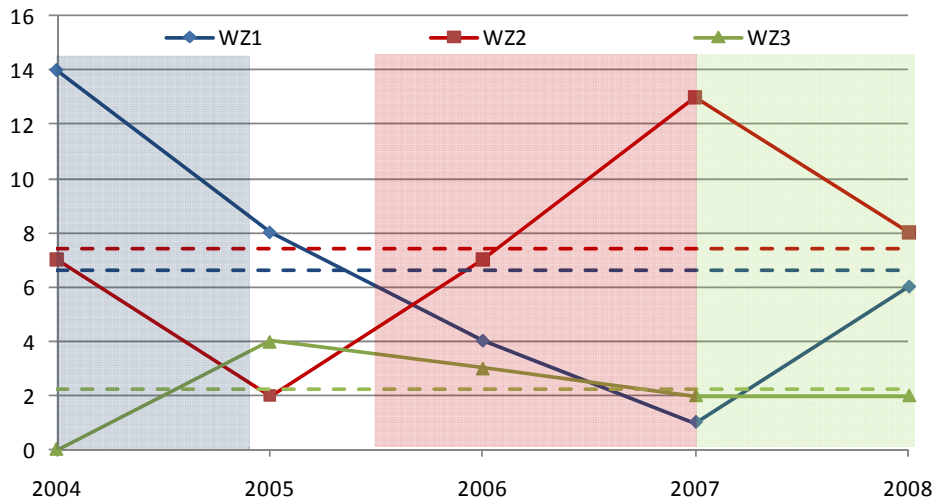


Figure 8.6. Number of accidents in work zones and mean values

The three interventions took place in consecutive time periods. The data available is not enough to conclude about accident rates in these work zones. It is however observed from Table 8.16 that the number of accidents in the three work zones seems to be decreasing from work zone 1 to work zone 3, the most recent intervention. This observation leads to the optimistic conclusion that the number of accidents in work zones has been decreasing over the last years. In spite of the rates of accidents under normal traffic conditions in A1, presented in Table 8.15, show an opposite trend. This reduction is justified due to safety measures introduced by BRISA over the last years as a consequence of the implementation of national policies to prevent road-accidents at the national level. These measures have been leading to a greater awareness and improved behaviour of drivers through work zones and thus a reduce number of accidents.

This conclusion is reinforced by the experience in other European countries, namely in the UK. A study carried out in the UK [8.9], in which 29 major motorways were monitored over the period of November 2001 to July 2003, showed that there was no significant difference in the rate of Personal Injury Accidents (PIA) when roadworks were present on the motorway. The rate in work zones was about 0.101 PIA per million vehicle kilometres and the equivalent rate in non-work zones was about 0.098, giving a ratio of 1.03. This fact is also justified by a large number of safety initiatives that have been taken place over the last decade by the Highways Agency in the UK.

As the data available was not enough for an accurate prediction of the rates of accidents and victims and, as discussed in the previous paragraphs, the rates in work zones are not significant different from non-working zones, a 5% increase in the rates under normal traffic conditions are assumed for the correspondent rates in work-zones. Therefore, the rate of accident type j (RAa_j) and the rate of victims type k (RVa_k) for work zones are represented in Table 8.17.

Table 8.17. Rates in work zone traffic conditions (RAa_j and RVa_k)

Type j = k	1	2	3
Rate of accident type j (x 10^{-8})	12.12	1.10	0.53
Rate of victims type k (x 10^{-8})	18.23	1.53	0.61

8.2.3.3. Quantification of accident costs

Accident costs in a work zone are calculated according to (8.15) considering that the characteristics of the work zone (in this case the length, L) are fix during the period of activity (N). The characteristics of the work zone in the calculation of user costs, as discussed in the previous sections, has a major influence in the quantification of the costs, particularly in the case when the traffic demand is higher than the work zone capacity. Considering the characteristics of the work zone in expression (8.15), leads to the following expression:

$$AC = \sum_{i=1}^{24}\left[\sum_{n=1}^{5} L_n \times HT \times \left\{\sum_{j=1}^{3}\left[\left(RAa_j - RAn_j\right)\times ca_j\right] + \sum_{k=1}^{3}\left[\left(RVa_k - RVn_k\right)\times cv_k\right]\right\}\right]\times N \qquad (8.18)$$

where, HT is average hourly traffic and L_n is the total length of the affected work zone given by the sum of the length of deceleration zone (L_1), length of the queue zone (L_2), length of the acceleration zone 1 (L_3), length of the effective work zone (L_4) and length of the acceleration zone 2 (L_5). If there is no queue then $L_2 = 0$.

The comparison of accident costs by using expressions (8.15) and (8.18) is illustrated in the example of Box 8.5.

Box 8.5. Accident costs in a work zone

Assuming the hourly distribution of traffic during the day and all the other characteristics of the traffic in the work zone given in Box 8.2, the accident costs for the work zone is given in the following table, according to (8.18):

Table 8.18. Accident costs in work zone, per carriageway

Time	Hourly traffic	Length of affected zone (km)		Accident Costs	
		Classes 1 and 2	Classes 3 and 4	Classes 1 and 2	Classes 3 and 4
0-1	80	0.68	1.52	0.03 €	0.01 €
1-2	80	0.6	.52	0.03 €	0.01 €
2-3	80	0.68	1.52	0.03 €	0.01 €
3-4	80	0.68	1.52	0.03 €	0.01 €
4-5	80	0.68	1.52	0.03 €	0.01 €
5-6	170	0.70	1.51	0.06 €	0.02 €
6-7	750	0.82	1.50	0.32 €	0.08 €
7-8	1605	1.01	1.50	0.83 €	0.17 €
8-9	740	0.82	1.50	0.31 €	0.08 €
9-1	71	0.82	1.50	0.30 €	0.07 €
10-11	680	0.81	1.50	0.28 €	0.07 €

Table 8.18. Accident costs in work zone, per carriageway (cont.)

11-12	700	0.81	1.50	0.29 €	0.07 €
12-13	1020	0.88	1.50	0.46 €	0.11 €
13-14	813	0.84	1.50	0.35 €	0.09 €
14-15	905	0.86	1.50	0.40 €	0.09 €
15-16	1080	0.90	1.50	0.49 €	0.11 €
16-17	1415	0. 7	1 50	0.70 €	0.15 €
17-18	1550	1.00	1.50	0.79 €	0.16 €
18-19	1260	0.94	1.50	0.60 €	0.13 €
19-20	825	0.84	1.50	0.35 €	0.09 €
20-21	580	0.77	1.49	0.23 €	0.06 €
21-22	304	0.72	1.50	0.11 €	0.03 €
22-23	170	0.70	1.51	0.06 €	0.02 €
23-24	80	0.68	1.52	0.03 €	0.01 €
TOTAL				7.11 €	1.65 €

Hence, the vehicle operation costs in the work zone, considering both carriageways, is about 17.52 €. If expression (8.15) was used instead, then the cost of accidents would be 18.31 €. In this case the value given by expression (8.18), which takes into account the characteristics of the work zone per hour, is about 95.7% of the value given by expression (8.15). This is explained by the fact that the former expression considers the length of affected work zone as a function of the hourly traffic and the capacity of the work zone, and in most cases (at least for class 1 and 2 vehicles) this value is lower than 1 km.

However, re-evaluating the same work zone, under the same traffic, but considering that one lane of traffic is closed in each direction, then the following results would be obtained:

- if the lane is closed between the period of 22h – 6h (night period): AC = 17.58 €/day;
- if the lane is closed between the period of 6h – 22h (day period): AC = 29.28 €/day.

In this case, considering the night close of the lane there's no significant difference in the result obtained before and the same explanation is valid. When the close of the lane is made during the day, then there´s a queue formation, which increases the length of affected motorway and consequently the accident costs.

The use of expression (8.18) has another advantage in relation to expression (8.15). As the computation is made per hour it is possible to differentiate the rates of accidents and victims during the day and during the night. The severity of road accidents during the darkening periods is usually higher than during the day light. This is demonstrated in Table 8.19 where the severity index represents the ratio between the number of fatalities and the number of accidents with victims [8.10].

Table 8.19. Road accidents and victims according to light conditions [8.10]

	Accidents with victims		Fatalities		Severe injuries		Light-injuries		Severity index	
	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
Day	23641	24811	424	419	1614	1581	28913	30596	1.8	1.7
Night	8909	9304	318	274	899	925	11120	11561	3.6	2.9
Dawn/twilight	1035	1158	34	44	91	117	1260	1384	3.3	3.8

Nevertheless, in the present methodology no differentiation is made between the accident rates for the day and night periods as the current data available are not enough for an accurate quantification.

8.2.3.4. Uncertainties in the calculation of accident costs

There are two major sources of uncertainty in the calculation of accidents costs. One source is the calculation of the accidents rates in normal conditions and in work zones; the other source is the calculation of the unit costs in Table 8.12 and Table 8.13.

In relation to the rates of accidents, as the aim in the methodology is the difference between the two rates, this difference can be translated into a percentage. Thus, a variation in this percentage is considered to account for the uncertainty in the calculation of the rates. In this approach a triangular distribution is assumed with mean value equal to 5% and minimum and maximum values of 3% and 7%, respectively.

In relation to the unit costs, small variation were considered in the parameters used for the calculation of the costs of authorities assistance (see Table 8.10) and the costs of medical assistance (see Table 8.11), as indicated in the next table.

Table 8.20. Assumed variation for main parameters in the quantification of ca_j and cv_k

		Mean values	Variation
Authorities assistance	Vehicle cost	0.40 €/km	+ 10%
	Travelled distance	30 km	± 10 km
	Cost of officer	10.9 €/h	+ 10%
Medical assistance	Cost of ambulance	17.44 €	+ 10%
	Cost of medical vehicle	100.27 €	+ 10%
	Light-injury	41 600 €	+ 10%
Victims	Severe-injury	93 600 €	+ 10%
	Fatality	520 000 €	+ 10%

The uncertainty in the unit costs is evaluated by Monte Carlo simulations. The characteristics of the fitted probabilistic distributions obtained in each case are indicated in the following table.

Table 8.21. Uncertainties in ca_i and cv_i

	ca_1	ca_2	ca_3	cv_1	cv_2	cv_3
Fitted distribution	Loglogistic	Loglogistic	Pearson5	Lognormal	Lognormal	Lognormal
Mean value	80.44 €	280.77 €	376.80 €	45 760 €	102 960 €	572 000 €
Standard deviation	5.35 €	16.36 €	22.25 €	4 160 €	9 360 €	52 000 €
Minimum value	69.83 €	250.83 €	332.68 €	41 600 €	93 600 €	520 000 €
Maximum value	+ ∞	+ ∞	+ ∞	+ ∞	+ ∞	+ ∞

8.3. OPTIONAL INDICATORS OF SOCIAL PERFORMANCE

Two indicators are here introduced as optional because its importance depends on the analyzed situation. The first indicator is noise, which may become important if the working place is located near a sensitive area and if the work is estimated to take place during night. The other indicator is aesthetics. This indicator may be important if the bridge is intended to have an aesthetic function besides its normal function. Although, the aesthetics of a bridge should also be considered part of its conceptual design problem. However, in particular cases such as special

types of bridges, bridges built in urban environments, etc., then the aesthetic value of the bridge may become an important criterion.

These two indicators have some characteristics in common. They are not usually assessed based on a life cycle approach and they are both subjective, which implies another approach for their quantification and interpretation.

8.3.1. Noise

8.3.1.1. Introduction

Noise can be defined as an undesirable sound thus implying that it has an adverse effect on human beings and their environment [8.11].

Noise affects a large number of people and it is usually perceived as one of the major environmental problems. It can affect people in both physiological and psychological ways, interfering with basic activities such as sleep, rest, study and communication. Noise is associated with many human activities, but it is road, rail and air traffic noise that has the highest impact. According to a study from the European Environmental Agency [8.12], in 1999, about 120 million people in the EU were exposed to road traffic noise levels above 55 Ldn dB and more than 50 million people were exposed to noise levels above 65 Ldn dB. Regarding rail traffic it was estimated that 10 % of the EU population were exposed to rail noise above 55 LAeq dB. Data on noise nuisance by aircraft was the most uncertain, however it was estimated that 10 % of the total EU population would be highly annoyed by air transport noise.

The evaluation of noise impacts is not simple as it is very closed related to human judgements and perception based (a given level of exposure is experienced differently by different individuals). Sound is the mechanical energy transmitted from a vibrating surface by a cycling series of compressions and rarefactions., also known as sound pressure wave [8.11]. Sound pressure does not provide practical units for sound or noise measurements as the range of sound pressure is too wide (from 0.0002 to 10000 µbar) and the human ear does not respond linearly to increases in sound pressure. In fact, the human response to sound pressure is essentially logarithmic. Hence, noise measurements are usually expressed by the Sound-Pressure Level (SPL), which is the logarithmic ratio of the sound pressure (P) to a reference pressure (P_0) and is given by expression (5.1) as a dimensionless unit of power, the decibel (dB). The reference level in equation (5.1) is 0.0002 µbar, which corresponds to the threshold of human hearing.

$$SPL = 20\log_{10}\left(\frac{P}{P_0}\right) \tag{8.19}$$

As referred in the previous paragraphs, the human ear does not respond uniformly to sounds of all frequencies, being less efficient in detecting sounds at low and high frequencies than at medium frequencies. To obtain a single number representing a sound level containing a wide range of frequencies and yet representative of the human response, a “A-weighted sound-level” is used, which weights the low and high frequencies with respect to average or “A” frequencies. Thus, the resultant SPL is “A-weighted” and the units are A-weighted decibels (dBA). The A-

weighted sound level is also called the “noise level”. The noise levels of some noise sources along with a subjective evaluation scale are represented in Table 8.22.

Construction noise can be a significant source of community noise. Several general factors are important in determining noise levels that will potentially impact populations. These factors are i) distance from the noise source, ii) natural and man-made barriers between the source and the impact population, and iii) weather conditions. In regard of construction, noise impacts can be of concern depending on the scale and intensity of the particular life cycle stage

Table 8.22. Common sounds in dBA [8.11]

Decibels (dBA)	Examples	Subjective evaluation
0	Threshold of audibility	Very faint
	Human breathing	
20		
		Faint
	Average residence	
40		
		Moderate
	Average office	
60		
	Near highway traffic	
		Loud
80		
	Noisy factory	Very loud
	Noisy urban street	
100		
		Deafening
120	Threshold of feeling – hard rock band	
	Threshold of pain	
140	Near jet engine	

Typical ranges of noise levels for different construction stages are indicated in Table 8.23, assuming that the equipment present at the site is the minimum required.

Table 8.23. Typical ranges of noise levels (in dBA) at construction sites (adapted from [8.11])

Phase of construction	Ground clearing	Excavation	Foundations	Erection	Finishing
Domestic housing	83	75	81	65	72
Office building, hotel, hospital, schools, etc	84	79	78	75	75
Industrial car parking, stores, service station, etc	83	71	77	72	74
Public works roads and highways, etc	84	78	88	78	84

8.3.1.2. Noise in Life Cycle Analysis

The impact category "noise" is not usually considered in current LCA methodologies. The reasons for this to happen is pointed out by some authors [8.13][8.14] as the difficulty of expressing noise measurements in a practical unit, the unavailability of appropriate methodology for noise assessment, and the fact that noise impact requires a highly site-dependent and time-dependent approach.

However, some attempts to introduce noise impact in LCA have been made over the last years. Heijungs et al. [8.15] proposed a "potential noise nuisance" impact by the aggregation of the sound production from the inventory analysis to yield an abstract sound level. However, no information about location was considered, thus ignoring the fact that some sound emissions could not cause any nuisance at all or vice-versa. Lafleche and Saccheto [8.13] introduced a "site-dependent approach" to assess noise impact on people and applied it to a case study: transport by car or truck along the Bologna-Milan highway. However, in their conclusions it was pointed out that noise impacts cannot be assessed regardless of the boundary conditions of the analysis. A methodology developed by Müller-Wenk [8.14] provides a quantitative assessment in LCA of noise impacts on human health originating from road vehicle noise. This approach models the full cause-effect chain from the noise emissions of a single vehicle up to the health damage and expresses the damage in DALY (Disability Adjusted Life Years) units. However, this method only applies to road traffic noise. A more recent approach, proposed by Benetto et al. [8.16], provides a method for noise impact assessment based on fuzzy sets. This method considers the quality assessment of the site studied prior to sound emissions generating the impact, and the impact assessment is calculated based on the quality of the site, the exposure of the targets and the nuisance of sound emissions. Although increasing the level of complexity in the calculations, the use of fuzzy variables is justifiable by the authors as the best way to interpret human judgements and perceptions.

8.3.1.3. Noise in relation to transport infrastructures

Bridges and viaducts are usually a small part of a major road infrastructure. Therefore, under normal conditions the major source of noise from a bridge would be the traffic over and under the bridge. However, in this study the impacts due to the normal use of the bridge are not covered and therefore, noise impact due to normal traffic conditions is not addressed as well.

Moreover, it is assumed that mitigation measures are considered in the design of the major infrastructure in order to reduce the noise impacts to nearby populations. These mitigation measures are usually designed in the overall project and not only for the bridge or viaduct included in the project.

8.3.1.4. Quantification of the potential noise impact due to construction activity

i) Background noise level

According to EU Directive 2002/49/EC [8.17] every European Member state is obliged to assess the exposure of the population to environmental noise through noise maps. Noise mapping represents data on an existing or predicted noise situation in terms of a noise indicator.

This obligation is mandatory for major road, rail and airport infrastructures and for agglomerations with more than 250 000 inhabitants.

Furthermore, it is mandatory that the information on environmental noise and its effects are made available to the public. In Portugal, the entity responsible for the approval and dissemination to the public of the noise maps is the *Instituto do Ambiente* [8.18].

Noise maps are based on two noise indicators, the day-evening-night noise indicator (L_{den}) and the night-time noise indicator (L_{night}), representing the noise indicator for overall annoyance and the noise indicator for sleep disturbance, respectively. Until the use of common methods for the determination of L_{den} and L_{night} is made obligatory by the EC, Member States can adapt existing national noise indicators and related data to the indicators mentioned above.

In Portugal the calculation of L_{den} and L_{night} is made according to the Regulation of Noise (RGR)[8.19]. Hence, the noise indicator associated with overall annoyance is given by expression (5.2)

$$L_{den} = 10\log\left[\frac{1}{24}\left(13\times10^{\frac{L_{day}}{10}} + 3\times10^{\frac{L_{evening}+5}{10}} + 8\times10^{\frac{L_{night}+10}{10}}\right)\right] \tag{5.20}$$

where, L_{day} $L_{evening}$ and L_{night} are the A-weighted long-term average sound level determined over all the day periods of a year, over all the evening periods of a year and over all the night periods of a year, respectively.

Based upon noise-mapping results, the noise Directive [8.17] obliges the adoption of action plans where necessary and in particular where exposure levels can induce harmful effects on human health and to preserve environmental noise quality where it is good. Action Plans are designed to manage noise issues and effects, including noise reduction if necessary. On this regard, the Portuguese Regulation of Noise (RGR) [8.19] set the limit values of L_{den} and L_{night}, above which appropriate mitigation measures have to be taken, according to the respective action plan. The limit values are different for different surroundings and different noise sensitiveness of the populations. The RGR [8.19] considers two different areas: sensitive areas and mixed areas. Sensitive areas are areas aimed for residential use, schools, hospitals or similar places, and recreation areas. Mixed areas aimed at other kinds of use than those of sensitive areas. The limit values for these two types of areas are given in Table 8.24 for the two indicators L_{den} and L_{night}. For places without classification, intermediate values are considering according to Table 8.24.

Table 8.24. Maximum admissible values of L_{den} and L_{night}

Classification	Indicator L_{den}	Indicator L_{night}
Sensitive areas	55 dBA	45 dBA
Mixed areas	65 dBA	55 dBA
Without classification	63 dBA	53 dBA

An example of a noise map for a motorway is illustrated in Figure 8.7.

Figure 8.7. Example of a noise map for a motorway (L_{den} in dBA) [8.18]

ii) Calculation of noise level due to construction activity

Noise from construction and demolition activities is different from noise from other major sources of noise as it is caused by many types of equipment and the resulting adverse effects are usually temporary due to relatively short-term duration of the activities.

For the determination of the sound level due to construction activity the indicator of equivalent sound level (L_{eq}) is used. This indicator expresses the energy equivalent sound level for any time period under consideration, that is, is the equivalent steady noise level that, in a stated period of time, would contain the same noise energy as the time-varying noise during the same time period [8.11].

The sound equivalent for the site for the entire operation is given by expression (5.21) [8.11]:

$$L_{eq} = 10\log\left[\frac{1}{T}\sum_{i=1}^{N} T_i (10)^{L_i/10}\right] \tag{5.21}$$

where, T is the total time of operation from the beginning of initial phase ($i = 1$) until final phase ($i = N$), T_i is the total time duration of phase i, L_i is the noise level of phase i and N the number of phases.

The noise level given by (5.21) may be correct for a distance x (in feet) from the site using expression (5.22). This expression allows drawing contours of noise levels around the site.

$$ADJ = -20\log(x + 250) + 48 \tag{5.22}$$

Two examples are provided in the following boxes to illustrate this. In the first example (Box 8.6), it is supposed to quantify the noise level for the entire construction stage.

Box 8.6. Example 1 – Noise level in the construction stage

Assuming the construction sequence and the time duration of each activity of the following table,

Table 8.25. Bill of equipment needed for the cast in situ of a concrete deck

Activity	Noise level L_i (in dBA)	Duration (in hours)
Excavation	78	96
Foundations	88	96
Erection of structure	78	744
Finishing	84	192

and considering the noise level for each activity given by Table 8.23, the noise level for the complete construction stage is given by equation (5.21):

$$L_{eq} = 10\log\left[\frac{1}{T}\sum_{i=1}^{N} T_i (10)^{L_i/10}\right] \Leftrightarrow$$

$$L_{eq} = 10\log\left[\frac{1}{1128}\left(96\times10^{78/10} + 96\times10^{88/10} + 744\times10^{78/10} + 192\times10^{84/10}\right)\right] \Leftrightarrow$$

$$L_{eq} = 79.53 \quad dBA$$

The second example, provided in Box 8.7, illustrates the quantification of the noise level during the cast in situ of a concrete deck of a bridge.

Box 8.7. Example 2 – Noise level for the construction of the deck

For the cast in situ of a concrete deck with a volume of concrete of 725 m3, the following equipment was necessary:

Table 8.26. Bill of equipment needed for the cast in situ of a concrete deck

Equipment	Noise emission ref. levels Li (in dBA)	Duration (in hours)
2 Concrete pumps	81	14
6 Vibrators	80	14
1 Compressor	78	14
2 Generators	81	14

and considering the noise level for each activity given by Table 8.23, the noise level for the construction of the deck is given by equation (5.3):

$$L_{eq} = 10\log\left[\frac{1}{T}\sum_{i=1}^{N} T_i (10)^{L_i/10}\right] \Leftrightarrow$$

$$L_{eq} = 10\log\left[\frac{1}{14}\left(2\times14\times10^{81/10} + 6\times14\times10^{80/10} + 14\times10^{78/10} + 2\times14\times10^{81/10}\right)\right] \Leftrightarrow$$

$$L_{eq} = 90.67 \quad dBA$$

8.3.1.5. Use of noise level in LCSA

The use of the equivalent sound level, as exemplified in the two previous boxes, may be a good indicator for bridge assessment. However, the major drawback of this approach is the lack of detailed data in relation to construction activities, which makes its use quite limited.

8.3.2. Aesthetics

8.3.2.1. Introduction

The evaluation of aesthetics is commonly understood as a highly subjected issue. The Oxford Dictionary [8.20] provides the following definitions of aesthetics (i) a set of principles concerned with the nature of beauty (especially in art), and (ii) the branch of philosophy which deals with questions of beauty and artistic taste.

Different persons have different perceptions of beauty, and what is pleasant and acceptable to one might be offensive and unacceptable to others. Naturally, this makes the evaluation of aesthetics a highly subjective and often controversial issue.

Due to the intrinsically subjective nature and philosophical domain of aesthetics, many references are found in the literature addressing different perspectives of aesthetics and, in particular, aesthetics of bridges. An intensive literature review on philosophical aspects of bridge aesthetics, aesthetics analysis of existing bridges, architectural aspects of bridge design and other aspects, is provided in Taly [8.21].

Methods of aesthetics design of bridges were discussed in Ohata et al. [8.22] and in Nakamura and Kubota [8.23]. A system based on genetic algorithm and computer graphics to evaluate alternative configurations for the aesthetic design of bridge structures was proposed by Furuta et al. [8.24]. Machwe et al. [8.25] presented an attempt to integrate aesthetic criteria, based on simplified qualitative rules, into an evolutionary computer-based system. The aim of the proposed system was to learn the basic characteristics relating to aesthetically pleasing designs from user-evaluation within an evolutionary search process and to proposed bridge-design solutions based on both aesthetics and structural criteria. More recently, a fuzzy-based methodology for bridge design, including aesthetic criteria, was proposed by Malekly et al. [8.26].

While for the design of long-span bridges, aesthetics aspects are usually considered to play an important role, the design of short and medium-span bridges seldom considers aesthetics. However, this type of bridges is larger in number and they form an integral part of urban and suburban locations. Moreover, considering the longevity of bridges (usually more than 100 years), bridges stand as legacies for several generations. Their appearance or aesthetics merits are very important aspects to consider not only for the present generation but also for future generations.

Therefore, it is the aim of this section to propose an indicator addressing bridge aesthetics and a calculation procedure to enable the comparison between alternative bridge designs. The scope of this indicator is short and medium span bridges.

It is not the aim of this section to discuss bridge aesthetics or to provide guidelines and recommendations for aesthetic design of bridges. The assessment of bridge aesthetics is based in a set of criteria that are commonly accepted for these types of bridges, as described in the following sub-section.

The introduction of this indicator is justified by the importance of aesthetics in the design of motorway bridges, as referred in the previous paragraphs, and by the belief that bridges with

aesthetic merit are not necessarily more expensive than bridges designed without any aesthetics concern. This belief is supported by other authors in the literature [8.27][8.28][8.29][8.30].

Nevertheless, in the framework of the integral approach developed in this dissertation, bridge aesthetics is balanced against all the other social indicators proposed in this chapter and with environmental and economical indicators defined in Chapters 6 and 7, respectively.

8.3.2.2. Evaluation of bridge aesthetics

The primary function of a bridge is undoubtedly to safety carry the load for which it was designed. The function of a bridge and its cost are usually considered as paramount features in bridge design. Moreover, most engineers feel that if the function of the bridge is properly defined, the correct form will follow and it will be aesthetically pleasing [8.31].

However, a bridge has also a strong visual impact on its users and on the surrounding population. Thus, apart from its primary function, a bridge should also be pleasant to our eyes. If for an engineer a bridge that fulfils its main function efficiently is beautiful, for common people, additional requirements may be necessary. Particularly, if bridges are intended to be built in urban areas, than aesthetics plays an important role.

Aesthetics is not an exact science [8.21] and there are no strict rules that can be used to judge what is beautiful and what is not. Moreover, aesthetics attributes are mainly qualitative and not quantitative. Nevertheless, there is a consensus among bridge designers in regard of a set of characteristics relevant to bridge aesthetics [8.32][8.28][8.27][8.21]. These will be briefly described in the following paragraphs.

i) Form and function

The form of the bridge is its three-dimensional array [8.30], which has a major influence on the visual experience of those going under or over the bridge.

In the context of bridges, form follows function, which can be interpreted as functional efficiency generates simplicity in form and aesthetic quality [8.32]. This assumption is supported by the overwhelming majority of texts written on bridge aesthetics over the last years [8.31]. Although there's an important relation between structural efficiency and aesthetic quality, that relation is far more complex than it seems [8.31]. The simple application of the premise "form follows function" is not usually enough if no additional consideration is taken for aesthetic values [8.31].

ii) Order and rhythm

Order is the arrangement of design elements so that each element has a clear place and function with no visual confusion [8.30]. Symmetry is a key element of order and the repetition of shapes provides a sense of order (rhythm) to the bridge. Order is considered by Raina [8.32] as a key aesthetic quality.

iii) Proportion

Proportion creates a sense of order by assigning appropriate relative sizes to the various elements of the bridge. Proportion between the various parts of a structure – height, width and depth; solids and voids; areas of sunlight and shadow, are important aspects to consider [8.32].

iv) Harmony

Harmony is achieved if bridge elements have visual similarity. The similarity in the shape of piers (for instance) provides harmony to the bridge, even in the case their size varies.

v) Scale

The scale of the bridge is defined by the absolute dimensions of the structure. The scale of the bridge relates to the size relationship between its constituent elements and between the bridge and its surroundings.

vi) Integration with environment

The integration of the bridge with the environment is considered by Raina [8.32] as one of the most important aesthetic features of bridges. The scale and proportions of the bridge should be chosen considering the surroundings of the bridge. In the case of bridges built in urban environments, special care should be taken because of their large impact on people.

vii) Contrast

Contrast may be achieved by playing with colour or light and shadow. Contrast allows relieving the monotony of simple harmony by complementing the characteristics of some design elements with their opposites. It enables to enhance structural elements in relation to the global structure.

viii) Surface treatment

Surface treatments include colours and texture. Colour can be applied to define, clarify, modify, accentuate or subdue the visual effects of structural elements. Warm colours (yellows and reds) tend to emphasize the presence and size of elements, whereas cool colours (blues and greens) diminish the visual importance of the elements to which they are applied [8.30]. Texture refers to patterned or unpatterned roughness on the surface of objects. It helps define form through surface variations and shadings. It can be used to soften or reduce imposing scale, add visual interest and introduce human scale to large objects such as piers, abutments and retaining walls [8.30].

As noted by Taly [8.21], to create aesthetically pleasing structures, the simple consideration of the topics described above is not enough. The imagination, intuition and sense of form and beauty are qualities that the bridge designer should possess, practice and improve.

Based on the aesthetics characteristics listed above, Puckett [8.28] proposed some practical guidelines for medium and short-span bridges. More recently, transportation agencies are also implementing guidelines for bridge design considering aesthetics aspects [8.29][8.30]. The purpose of these guidelines is to help design teams in the process of designing bridges of aesthetic value. According to these guidelines aesthetics concerns should be an integral part of bridge design from the beginning of the process, they cannot be added at the end to make the bridge more appeal. Moreover, an interaction between the design team and all the other involved parties (contractors, owner of the bridge, general public, etc) is advisable. A list of factors, in order of importance, can be drawn from a consensus among all the interested parties, which can be the basis for the design work.

Nevertheless, in those guidelines no methodologies are provided in order to simultaneously consider the combined effect of different objectives or to compare alternative bridge designs.

Hence, in the following sub-section, a methodology is proposed to evaluate the aesthetic of alternative bridge designs.

8.3.2.3. Assessment of bridge aesthetics

8.3.2.3.1. Introduction

Although the inherent subjectivity in assessing the aesthetics value of a bridge, some important steps have already been taken in order to make it more objective and feasible. Based in the recognized characteristics leading to bridge aesthetics, as discussed in the previous section, some attempts have been made in order to establish guidelines [8.29][8.30] and recommendations leading to the design of bridge with aesthetic value.

The methodology presented in this section is based on the approach described in the design guidelines developed by the Australian Road and Traffic Authority [8.29]. In these guidelines, design objectives and principles are provided for the design of appealing motorway bridges and suggestions are given in order to implement those principles. However, as already referred, no methodologies are provided in order to simultaneously consider the combined effect of different objectives nor to compare alternative bridge designs.

Therefore, in this section a methodology is proposed, aiming at the comparative assessment of alternative bridge designs in terms of its aesthetical value. The approach can be used as a standalone approach, although, in the global aim of the integral approach developed in this dissertation, the final outcome of the analysis is further balanced against other social, economic and environmental aspects.

The proposed approach comprehends four steps, as illustrated in Figure 8.8.

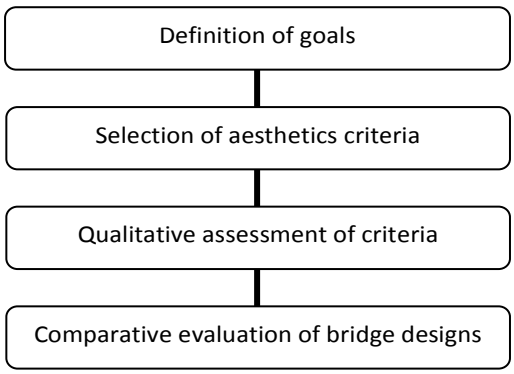


Figure 8.8. Methodology for aesthetics evaluation

In the first step the goal and scope of the analysis are established. The goal or goals of the analysis shall be clearly defined in order to decide about the main aspects contributing to those goals. For instance, the evaluation may consider the entire structure or only parts of it. Then, in the second step, aesthetics criteria or attributes are selected according to the goals of the analysis. The evaluation of the aesthetic value of the bridge is made in the 3rd step. In the last step, the comparison between bridge designs is made. In order for the comparison to take place, all the alternatives should fulfil the goal or goals of the analysis and should be evaluated against

the same set of selected criteria. The steps of the methodology are further detailed in the following paragraphs.

8.3.2.3.2. Selection of criteria

According to [8.29] the aesthetics evaluation takes into account three different perspectives of the bridge (see Figure 8.9): as a whole, its different parts and its details. In the first perspective, the bridge is evaluated taken into account the complete structure and its integration in the surrounding natural or urban environment. The second perspective considers the aesthetic evaluation of the different parts in which the structure is usually subdivided (superstructure and substructure) and and the interface between the bridge and its context.

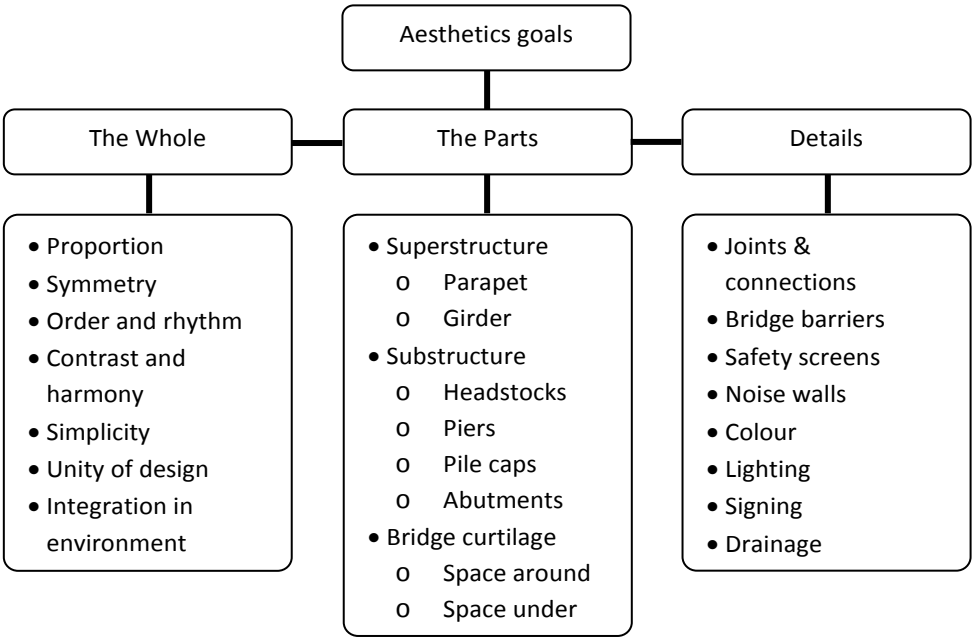


Figure 8.9. Aesthetic criteria for bridge design (based in [8.29])

The details of the different parts of the bridge are taken into consideration in the third perspective. For each perspective, different aspects and corresponding criteria may be selected.

The selection of the main aspects of the bridge and corresponding aesthetic criteria, from the list in Figure 8.9, depends of the type of bridge and of the goals of the analysis. For instance, usually the superstructure gets the most attention for aesthetics design and detailing. However, in the case of elevated structures, the appearance of elements of substructure has also a significant influence on the overall appearance of the whole structure; consequently they should also be given the required attention.

8.3.2.3.3. Assessment of criteria

Most of the criteria listed in Figure 8.9 can only be evaluated qualitatively, although in a few cases, some qualitative rules may be considered (for example, proportional ratios between bridge elements). Recommendations for each criterion are provided in [8.29] and [8.30], some examples are indicated in Table 8.27 for the whole structure.

Table 8.27. Aesthetics recommendations for bridge design (adopted from [8.29])

Proportion	The ratio between depth of superstructure and bridge spans (slenderness) can vary from 5 to 30; Avoid imbalanced proportions between structural elements; Repetition of similar proportional ratios leads to a more harmonious structure; The ratio of pier dimension to superstructure depth and the ratio of deck overhang relative to parapet should be carefully considered.
Symmetry	Symmetrical bridges are usually considered to be more aesthetically pleasing.
Order and rhythm	A bridge with structural elements in a consistent order is usually more pleasing.
Contrast	Natural elements can be used to create a contrast with the bridge structure.
Simplicity	The bridge structure should be simple and representing the load path acting upon the structure. The use of embellishments and ornamentation should be avoided.
Unity of design	Consider the design of the different parts of the structure individually and as how they contribute to the whole of a bridge. Good detailing of the structural elements and the way they relate with the whole structure are essential to the aesthetics of bridges.
Integration	A good integration of the bridge in the natural environment in which is located or in the urban environment is recommended. Consistency with existing bridges in the vicinity of the bridge is also advisable.

The aesthetic evaluation of the different aspects in Figure 8.9 is not simple as it depends on the individual preferences of the person performing the evaluation. However, for each criterion, a mark should be assigned, either in a numerical scale (e.g. from 1 to 10) or ordinal scale (e.g. from “poor” to “very good”).

8.3.2.3.4. Raking of alternatives based in a pair-wise comparison approach

The comparison of the design alternatives, taking into consideration the criteria described above is a decision-making problem. The method proposed hereby to address this problem is the Analytical Hierarchy Process (AHP), which has already been used in Chapter 6 to address the weighting of environmental criteria.

The choice of this method again in this section is due to ability of the method to reflect the way people think [8.33]. AHP can efficiently deal with objective as well as subjective attributes, particularly where the subjective judgements of different individuals constitute an important part of the decision process, such is the present case.

The main steps of the AHP have already been presented in Chapter 6. The first step is the establishment of the hierarchical structure with the goal at the top level, the attributes at the second level and the alternatives at the third level.

In this case, the hierarchical structure considered is represented in Figure 8.9 where the goal of the analysis is at the top and the main attributes are presented below at the second level. Each one of these main attributes is further divided into a number of other sub-attributes. Assuming that the sub-attributes are equally important in relation to the main attribute, the decision maker has to decide about the relative importance of the main attributes with respect to the goal. Thus, a pair-wise comparison matrix is formed using the fundamental scale of the AHP method [8.34], which is represented in Table 8.28.

Table 8.28. AHP scale [8.34]

Factor of preference	Importance
1	Equally preferred
2	Equally to moderately preferred
3	Moderately preferred
4	Moderately to strongly preferred
5	Strongly preferred
6	Strongly to very strongly preferred
7	Very strongly preferred
8	Very to extremely strongly preferred
9	Extremely preferred

In the present case, there are 3 main attributes, the pair-wise comparison of attribute i with attribute j yields a square matrix of 3 x 3. The relative normalized weight of each attribute (w_j) is determined by the ratio between the geometric mean of the i-th row and the sum of all geometric means of rows in the comparison matrix.

The third step is to compare the alternatives pair-wise with respect to how much better they are in satisfying each of the sub-attributes. Considering N alternatives and M sub-attributes, then there will be M number of N x N matrices of judgements. The judgements are entered using the fundamental scale represented in Table 8.28.

The Consistency Ratio (CR) of each pair-wise matrix has to be determined to check the consistency of the judgment.

The final step is to obtain the composite performance scores for the alternatives by multiplying the relative normalized weight (w_j) of each attribute with its corresponding normalized weight value for each alternative and summing over the attributes for each alternative.

Sensitivity analysis may be performed on the final outcome to check if it is stable to changes in the inputs whether judgments or priorities. Of special interest is to see if these changes change the order of the design alternatives.

To illustrate the proposed approach an example is provided in Box 8.8.

Box 8.8. Evaluation of bridge aesthetics

In this hypothetical example, three alternative bridge designs (A, B and C) are discussed and evaluated from the aesthetics perspective, according to the methodology presented in the previous paragraphs. Each design is evaluated considering the three different perspectives of the bridge: the bridge as a whole, the aesthetics of its parts and the corresponding details. Furthermore, in this example, it is considered that the importance of the bridge aesthetics as a whole is higher than the other two perspectives. It is also considered that the superstructure has a greater importance than the remaining parts of the structure and thus, only the superstructure is discussed. The other attributes, which are considered to be of high relevance for the aesthetics of the bridge design are indicated in Table 8.29.

These attributes are evaluated qualitatively by using an ordinal scale. In this stage each design was evaluated individually, and for each design aspect a mark between “Excellent” and “Poor” is assigned. The marks obtained for each bridge design are indicated in Table 8.29.

Table 8.29. Qualitative evaluation of bridge design alternatives

Attributes	Bridge design A	Bridge design B	Bridge design C
Proportion	Excellent	Very good	Very good
Symmetry	Excellent	Excellent	Good
Simplicity	Very good	Very good	Very good
Integration with environment	Very good	Fair	Good
Superstructure	Very good	Good	Very good
Colour & Lighting	Good	Good	Very good
Noise walls	Poor	Fair	Good

As referred in the first paragraph, it is considered that the aesthetics of the bridge as a whole is considered to be more important than the remaining aspects. Therefore, comparing the three perspectives, it is considered that the "the whole" is moderately preferred to "the parts" and "details", while these last two have the same importance. Hence, the weights of each perspective, reflecting their relative importance, are given by the matrix in Table 8.30.

Table 8.30. Pairwise comparison matrix for the main aspects of aesthetics

	The whole	The parts	Details	Relative weight
The whole	1	3	3	0.600
The parts	1/3	1	1	0.200
Details	1/3	1	1	0.200

The next step is to make a pairwise comparative analysis between the three alternatives for each attribute, taken into account the respective evaluation of each bridge design. In the following paragraphs, these comparisons are described.

The evaluation of the attribute proportion considers that Bridge Design A (BD_A) is very strong preferred to Bridge Design B (BD_B) and very strongly to extremely preferred to Bridge Design C (BD_C). Comparing DB_B and DB_C, BD_B is equally to moderately preferred to BD_C. These conclusions lead to the pairwise comparison matrix indicated in Table 8.31.

Table 8.31. Pairwise comparison matrix for Proportion

	Bridge design A	Bridge design B	Bridge design C	Relative weight
Bridge design A	1	7	8	0.784
Bridge design B	1/7	1	2	0.135
Bridge design C	1/8	½	1	0.081

Regarding the evaluation of the attribute symmetry, both DB_A and DB_B have an excellent mark; however, it is considered that comparing both designs, DB_B is equally to moderately preferred to DB_A and both designs are strongly preferred to DB_C. Thus, the pairwise comparison matrix indicated in Table 8.32 is obtained.

Table 8.32. Pairwise comparison matrix for Symmetry

	Bridge design A	Bridge design B	Bridge design C	Relative weight
Bridge design A	1	½	5	0.352
Bridge design B	2	1	5	0.559
Bridge design C	1/5	1/5	1	0.089

All bridge designs achieved a high mark in regard of the attribute simplicity. When comparing between the three alternative designs, it is considered that DB_A is equally preferred to DB_B and both designs are equally to moderately preferred to DB_C, leading to the pairwise comparison matrix represented in Table 8.33.

Table 8.33. Pairwise comparison matrix for Simplicity

	Bridge design A	Bridge design B	Bridge design C	Relative weight
Bridge design A	1	1	2	0.400
Bridge design B	1	1	2	0.400
Bridge design C	½	½	1	0.200

In the case of the integration of the bridges in the surrounding environment, the marks achieved by each bridge design are different. Thus, BD_A is very to extremely strongly preferred to BD_B and is strongly preferred to BD_C. BD_C is moderately preferred to BD_B. These conclusions lead to the pairwise comparison matrix in Table 8.34.

Table 8.34. Pairwise comparison matrix for Integration with environment

	Bridge design A	Bridge design B	Bridge design C	Relative weight
Bridge design A	1	8	5	0.742
Bridge design B	1/8	1	1/3	0.075
Bridge design C	1/5	3	1	0.183

The superstructure of BD_A is considered to be equally preferred to the superstructure of DB_C. Both superstructures are moderately preferred to the superstructure of DB_B, leading to the pairwise comparison matrix in Table 8.35.

Table 8.35. Pairwise comparison matrix for Superstructure

	Bridge design A	Bridge design B	Bridge design C	Relative weight
Bridge design A	1	3	1	0.429
Bridge design B	1/3	1	1/3	0.143
Bridge design C	1	3	1	0.429

The evaluation of colour and lighting granted the same mark to DB_A and DB_B, and they are considered to be equally preferred. However, DB_C is moderately to strongly preferred to the other designs. Therefore, the respective pairwise comparison matrix is represented in Table 8.36.

Table 8.36. Pairwise comparison matrix for Colour & Lighting

	Bridge design A	Bridge design B	Bridge design C	Relative weight
Bridge design A	1	1	¼	0.167
Bridge design B	1	1	¼	0.167
Bridge design C	4	4	1	0.667

The noise walls of DB_C is moderately to strongly preferred to DB_B and is very strongly to extremely preferred to DB_A. DB_B is moderately to strongly preferred to DB_A. These results lead to the pairwise comparison matrix in Table 8.37.

Table 8.37. Pairwise comparison matrix for Noise walls

	Bridge design A	Bridge design B	Bridge design C	Relative weight
Bridge design A	1	¼	1/8	0.070
Bridge design B	4	1	¼	0.223
Bridge design C	8	4	1	0.707

To check the consistency of each judgment, the Consistency Ratio (CR) for each matrix is calculated. The acceptable CR range varies according to the size of the matrix. For a matrix 3 x 3 if the CR is equal to, or less than 0.05 [8.34] than the evaluation within the matrix is acceptable, that is, there is a good level of consistency in the comparative judgments. If CR is above 0.05, than there is inconsistency of the judgments within the matrix and the evaluation process should be reviewed. The CRs obtained for each matrix are indicated in Table 8.38, showing a

good level of consistency in each case.

Table 8.38. Consistency Ratio (CR) of matrices

Matrix	Size of matrix	CI	RI	CR
Main perspectives	3 x 3	0.000	0.58	0.000
Proportion	3 x 3	0.017	0.58	0.030
Symmetry	3 x 3	0.027	0.58	0.046
Simplicity	3 x 3	0.000	0.58	0.000
Integration	3 x 3	0.022	0.58	0.038
Superstructure	3 x 3	0.000	0.58	0.000
Colour & lighting	3 x 3	0.000	0.58	0.000
Noise walls	3 x 3	0.027	0.58	0.046

Hence, the classification obtained for each bridge design is indicated in Table 8.39, where bridge design A achieved the highest mark and bridge design B the lowest.

Table 8.39. Final weight of bridge designs

	DB_A	DB_B	DB_C
Final weight	0.45	0.24	0.31

The results generated by using AHP show that DB_A has the highest ranking value among the remaining design alternatives, followed by DB_C and the least preferred being DB_B.

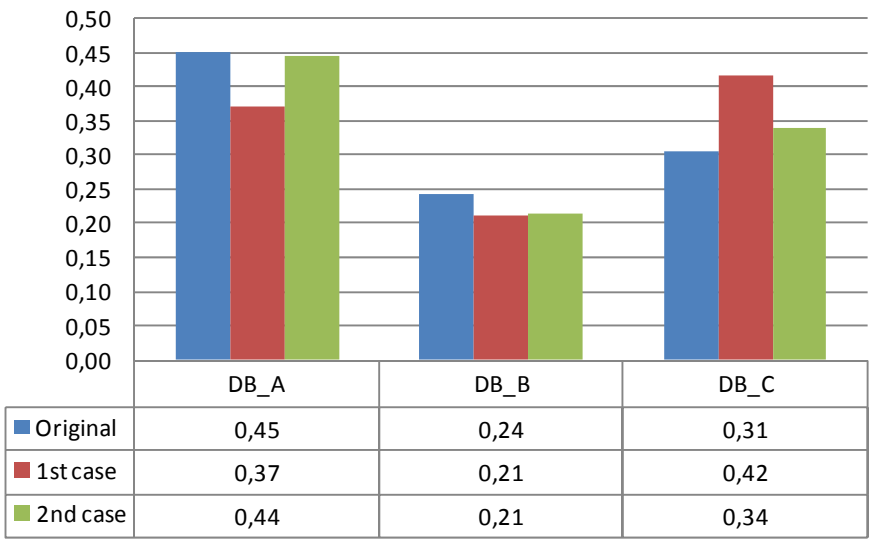


Figure 8.10. Sensitivity analysis of the final classification

For a better discussion of the results obtained and for the consistency of the decision, some sensitivity analysis could be performed. For instance, considering equal importance for the three main aspects of aesthetics (1st case), and considering that the importance of the whole is equally preferred to the importance of the parts, and their importance is considered to be moderately preferred to the importance of details (2nd case). The results obtained in each case, and the results obtained originally, are graphically represented in Figure 8.10.

From the sensitivity analysis, DB_A achieves the best classification in the original and second case. While DB_C achieves the best score in the first case and the second best score in the remaining cases. The classification of DB_B is always the lowest score no matter the set of weights.

8.3.2.4. Use of aesthetics in LCSA

The indicator of aesthetics may be used in any stage over the life cycle of the bridge. At any stage, the condition of the bridge may be assessed from the point of view of aesthetics. In this case, a similar approach, as described in the previous paragraphs, may be used for the quantification of aesthetics, eliminating or adding new criteria if necessary. Moreover, the proposed approach for the quantification of bridge aesthetics enables the comparison of alternative bridges and it is therefore, an useful tool in a decision making process.

8.4. SYNOPSIS OF LCSA

In this chapter the LCSA was further developed in the aims of the integral life cycle approach pursuit in this dissertation. Two types of indicators were proposed for the evaluation of the social component of bridges: mandatory and optional indicators.

Three indicators were proposed as mandatory: driver's delays cost, vehicle operation costs and safety costs. These indicators are quantified based in a life cycle based approach using the same scenarios as the two previous analyses (LCEA and LCCA).

These indicators represent the difference between the costs due to any work activity in the bridge and the respective costs due to no work activity. The quantification is based on the same traffic model as considered for LCEA (in Chapter 6).

Furthermore, some of the uncertainties in user's costs were identified in order to enable a probabilistic LCSA.

Finally, two indicators were proposed as optional: noise and aesthetics. These two indicators have some characteristics in common. They are not usually assessed based on a life cycle approach and they are both subjective. Therefore, two appropriate approaches were proposed to deal with their quantification and interpretation.

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CHAPTER 9. LIFE CYCLE ANALYSIS OF A COMPOSITE BRIDGE

9.1. INTRODUCTION

In this chapter, the methodology presented in the previous chapters is applied to a case study. This case study refers to a composite steel-concrete bridge that was built in 2007 over the dual carriageway A1 – *Auto-estrada do Norte*. A1 was the first motorway to be built in Portugal; it links the cities of Lisbon and Oporto and has an extension of 295 km. The Portuguese concessionaire BRISA operates this motorway.

Over the last years, major expansion works have been carried out in the network of motorways supported by BRISA. Widening works of a motorway is a legal obligation of BRISA under the Concession Agreement with the Portuguese State. These expansion works are fully supported by BRISA.

According to the Concession Agreement widening of the motorway is mandatory when average daily traffic reaches the following levels:

- 35 thousand vehicles: requires widening from 2 to 3 lanes;
- 60 thousand vehicles: requires widening from 3 to 4 lanes.

The current widening of the motorway from 2 to 3 lanes leads to the demolition of several bridges and overpasses along the corridor. The case study described in this chapter belongs to the set of new bridges replacing the existing ones. The bridge is an overpass denominated PS 398. The present analysis was performed after the completion of the project. The results obtained in the present analysis did not influence under no circumstances the design and construction of the bridge.

In the first part of this chapter, a description of the collected data is provided. The second part of this chapter provides detailed calculations and presents the outcome of the environmental, economical and social analysis. In the last part of the chapter, conclusions are drawn in relation to the application of the integral approach and in relation to the outcome of the analysis.

All project details of the bridge and some details of its construction were provided by BRISA. For the demolition of the bridge, data was obtained from a similar project of a bridge demolition, which was also supplied by BRISA. All the remaining data needed for the analysis was estimated based on direct interviews with different types of professionals and from a literature survey.

9.2. GOAL AND SCOPE OF THE CASE STUDY

9.2.1. Goal of the analysis

The goal of the analysis is to make a comprehensive account of the environmental, economical and social impacts of a motorway bridge over its service life. The service life is assumed to be 100 years and it is further assumed that at the end of this period the bridge is dismantled. Moreover, the aim of this life cycle analysis is to identify the processes with major impacts in the

life cycle of the bridge, enabling to set strategies and recommendations to minimize those impacts.

9.2.2. Functional unit

The functional unit of the life cycle analysis is a motorway bridge, with a required service life of 100 years, to overpass a dual carriageway with a capacity for four lanes in each direction. The functional unit is divided by the deck area of the bridge (in m^2).

9.2.3. System boundaries

All stages over the complete life cycle of the bridge; from raw material extraction until end-of-life procedures (see Chapter 5 - Figure 5.2), are included in the boundary system of the analysis.

9.3. DESCRIPTION OF THE CASE STUDY

9.3.1. Project details

Bridge PS 398 is an overpass built over the dual carriageway A1 – *Auto Estrada do Norte*, see Figure 9.1. After the widening works, each carriageway has a width of 16.30 m and it comprehends a main running surface with 11.25 m, a hard shoulder along the inner lane with a width of 4.05 m and a hard shoulder along the outer lane with 1.00 m. Each carriageway has a capacity for 3 lanes with a width of 3.75 m. The central reservation is 4.00 m wide.

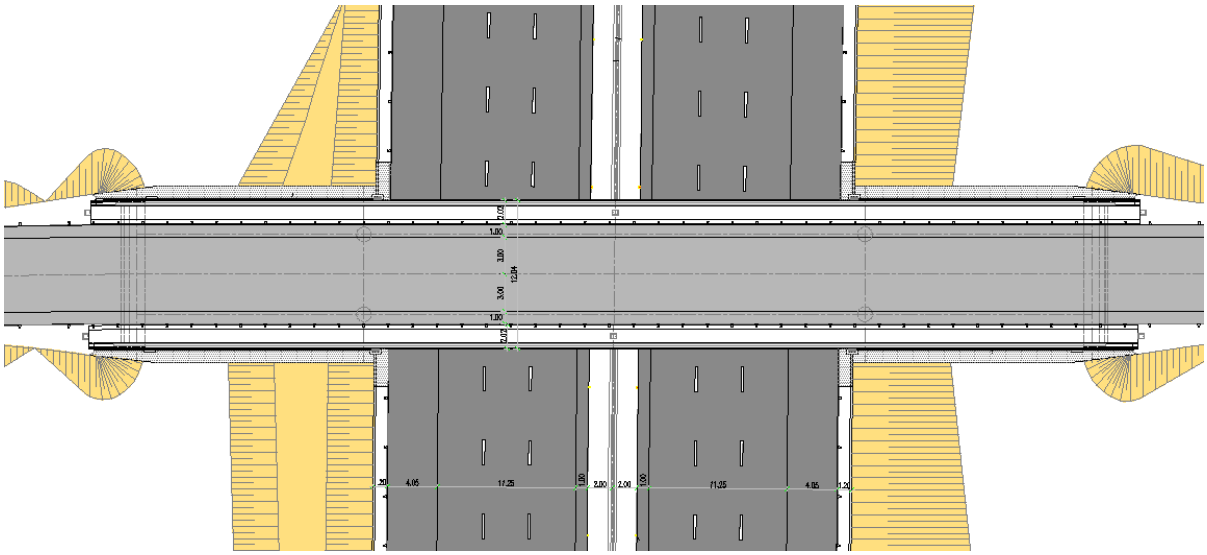

Figure 9.1. Plan view of the composite bridge PS 398

Bridge PS 398 has a composite steel-concrete structure with three spans of 18.50 m, 40.80 m and 18.50 m, as illustrated in Figure 9.2. The deck is fully restrained against displacements over the middle piers and simply supported in the abutments.

The cross-section of the bridge, which is represented in Figure 9.3, is made of two steel girders with a total height of 1.35 m and web thickness varying between 14 mm and 18 mm. The top flange is 700 mm wide and the flange thickness varies from 30 to 80 mm. The bottom flange is

800 mm wide and thickness varying from 40 to 80 mm. The girders are braced every 5.2 m in the main span, and every 5.0 m in the side spans by IPE 500 profiles.

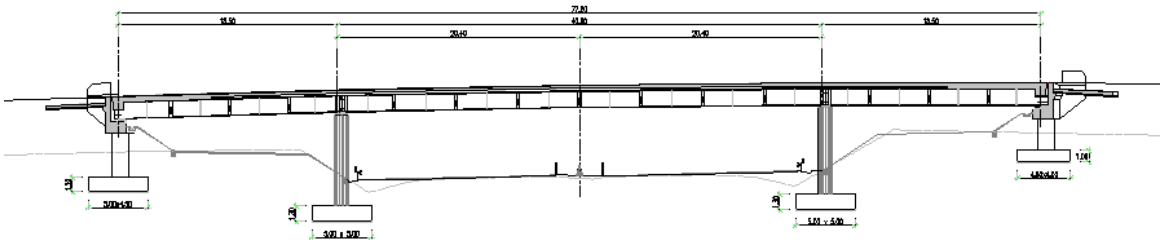

Figure 9.2. Elevation view of the composite bridge PS 398

At the middle piers and at the abutments the girders are equally braced by steel profiles with heights of 800 mm and 500 mm, respectively. Shear connectors are welded to the top flange of the girders. The shear connectors are projected through small holes in the slabs that are later filled with concrete. On top of the girders a precast concrete slab is placed with thicknesses of 0.44 m on top of the girders, 0.20 m at the end of the cantilevers and 0.25 m in the middle width span.

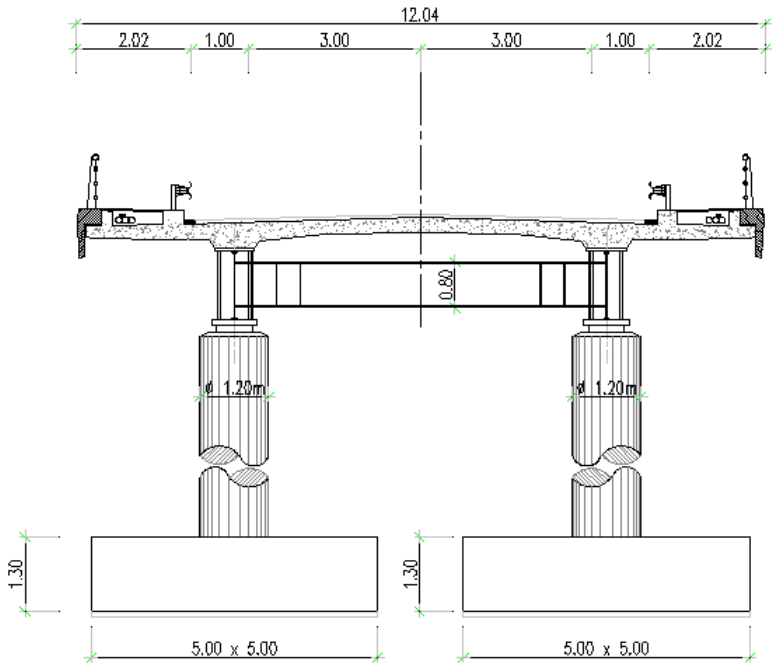

Figure 9.3. Cross-section of the composite bridge PS 398

The middle piers are made of cast “in situ” concrete, with a circular cross-section with diameter of 1.20 m.

The transversal profile of the deck comprehends two lanes of traffic, one in each direction, 3.00 m wide, two hard shoulders with 1.00 m and two side-walks for pedestrians with a width of 1.65 m. The effective width of the profile, measured by the clear distance between the parapets, is 11.30 m, while the total width is 12.04 m. The total area of the deck is 936.71 m^2.

The bill of the main materials of the bridge is represented in Table 9.1.

Table 9.1. Bill of main materials of PS 398

Main component	Elements	Material	Quantity	Unit
Foundations	Regularization	Concrete grade C16/20	29.00	m^3
	Bases	Concrete grade C25/30	223.00	m^3
Abutments	Elevation	Concrete grade C30/37	123.00	m^3
Piers	Elevation	Concrete grade C30/37	33.00	m^3
Deck	Precast slab	Concrete grade C35/45	161.00	m^3
		Reinforcement steel grade A500	58 313.00	kg
	Cast “in situ” slab	Concrete grade C35/45	116.00	m^3
		Concrete grade C35/45 (low shrinkage)	48.00	m^3
		Reinforcement steel grade A500	17 864.00	kg
	Girders	Steel grade S355	145 678.00	kg
	Shear studs	Steel grade F_{uk}=350 MPa	3 328.00	un
	Coating of steel	Paint	1 296.00	m^2
	Pavement	Asphalt layer 6 cm	622.40	m^2
Side-walks		Light-weight concrete	38.00	m^3
Global	All elements except deck	Reinforced steel grade A500	57 595.00	kg

The unit costs of the main materials and equipments of the bridge are indicated in Table 9.2.

Table 9.2. Unit costs of materials and equipment

Main component	Elements	Material	Unit cost	Unit
Foundations	Regularization	Concrete grade C16/20	49.32	€/m^3
	Bases	Concrete grade C25/30	58.31	€/m^3
Abutments	Elevation	Concrete grade C30/37	63.19	€/m^3
Piers	Elevation	Concrete grade C30/37	63.19	€/m^3
Deck	Precast slab	Concrete grade C35/45	58.04	€/m^3
		Reinforcement steel grade A500	0.65	€/kg
	Cast “in situ” slab	Concrete grade C35/45	70.81	€/m^3
		Concrete grade C35/45 (low shrinkage)	93.69	€/m^3
		Reinforcement steel grade A500	0.65	€/kg
	Girders	Steel grade S355	1.19	€/kg
	Shear studs	Steel grade F_{uk}=350 MPa	0.73	€/un
	Coating of steel	Paint	10.80	€/m^2
	Pavement	Asphalt layer 2 cm		€/m^2
		Asphalt layer 4 cm		€/m^2
	Protection of slab-deck	Painting of concrete slab (bottom side)	5 468.04	€
	Side-walks	Light-weight concrete	63.80	€/m^3
Global	All elements except deck	Reinforced steel grade A500	0.65	€/kg
Equipment	Expansion joints		13 380.00	€
	Bearings		8 867.36	€
	Parapet railing		9 845.20	€
	Slope protection		12 399.30	€
	Deflector rail		4 186.08	€
	Edge beams		10 158.40	€
Transport	Transport and erection of pre-cast slab		81 203.10	€

This analysis intends to consider, as far as possible, all materials and processes involved in the analysis. Therefore, for the initial cost of the structure all the costs of materials and equipments, were considered, no cut-off rule was used. However, for the environmental analysis some

materials and equipments were cut-off from the analysis due to lack of data (e.g. although data is available for the materials of expansion joints, no data is currently available for the processing of the joints).

9.3.2. Construction details

The construction of this bridge took a total of 87 days, from 3-08-07 to 28-10-07, according to the planning represented in Table 9.3, which was provided by BRISA. The detailed planning is presented in Annex B.

Table 9.3. Planning of the construction

Main Activity	Elements	Initial date	Final date
Excavation		03-08-07	22-10-07
Casting of abutments		09-08-07	28-10-07
Piers		09-08-07	25-08-07
	Foundation bases Piers	09-08-07 14-08-07	20-08-07 25-08-07
Installation of supports		26-08-07	01-09-07
Assembling of steel structure		30-08-07	13-09-07
	Pre-assembling of steel structure in the ground Erection of work form in middle span Erection of steel structure Welding middle span Coating middle span Removal of work form	30-08-07 01-09-07 05-09-07 07-09-07 09-09-07 12-09-07	04-09-07 04-09-07 06-09-07 08-09-07 11-09-07 13-09-07
Construction of concrete deck		14-09-07	10-10-07
	Erection of slab panels Settlement of steel structure Sealing of concrete panels Casting “in situ” of deck (near abutments) Casting of remaining parts of deck	14-09-07 18-09-07 19-09-07 23-09-07 05-10-07	17-09-07 18-09-07 22-09-07 04-10-07 10-10-07
Finishing		11-10-07	28-10-07

The abutments and piers are cast “in situ” to enable the installation of the steel structure. The steel structure is assembled in two half-parts, next to the motorway. Each part of the steel structure is then installed in its final position by the aid of cranes. After the installation of the two parts of the structure, the longitudinal girders are welded in the middle of the central span. Afterwards the full-deck-width precast concrete panels are installed. These precast concrete panels are connected to the steel girders by studs located in pockets in the panels, as shown in Figure 9.4. The panels are joined transversally by overlapping hoop bars that project from each edge of the panels. Individual bars are threaded within the loop bars to complete the connections, which are then encased in concrete. These joints are sealed with a low shrinkage concrete that is cast “in situ”.

The concrete slab near the abutments, in each side of the structure, is also cast “in situ”. Finally all the remaining deck equipment is installed in the bridge.

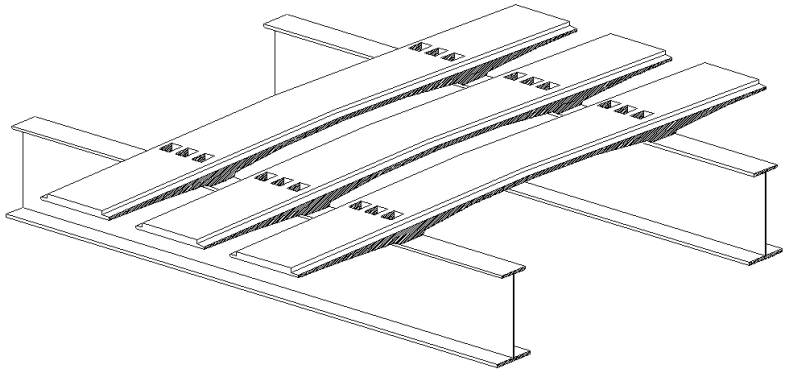

Figure 9.4. Installation of precast concrete panels

9.3.3. Traffic constraints during construction stage

During the construction of the bridge and according to information from the contractor, the motorway was always in service, although the traffic flow was subjected to various constraints. Being a new bridge, no traffic was considered above the bridge.

According to current national legislation, traffic conditions through work zones in major motorways are subjected to several restrictions. These restrictions are provided in Annex A. In this study it is assumed that during the construction of the bridge, as it is the common practice of BRISA, these restrictions were fully taken into account during the construction period.

Therefore, according to Table 9.3 and the detailed planning presented in Annex B, there were always two lanes of traffic in each direction of the motorway, except during the erection of the composite deck (six days). In this case, it is necessary to cancel the traffic in one carriageway and divert the traffic to the other one, resulting in one lane of traffic in each direction.

Moreover, during the entire period of construction (87 days) it is considered that the traffic speed in both carriageways was constrained to a maximum of 80 km/h.

9.4. SCENARIOS AND ASSUMPTIONS FOR LIFE CYCLE ANALYSIS

9.4.1. Traffic under and over the bridge

9.4.1.1. Traffic in the motorway

According to the traffic analysis provided by BRISA, the traffic evolution over the period of time 2008-2022, for the motorway segment in which this bridge is included, is represented in Table 9.4.

In the base year of the study (2008), there´s an Average Daily Traffic (ADT) of 31522 vehicles/day. In this study, it is considered that the percentages of lightweight vehicles and heavyweight vehicles are 88% and 12% of the ADT, respectively.

Table 9.4. Average Daily Traffic (ADT) over the years 2008-2022

	Year 2008	Year 2012	Year 2022
ADT (vehicles/day)	31522	35684	41512

Moreover, it is also considered that the traffic during the night period (22h – 7h) is about 10% for lightweight vehicles and 8% for heavyweight vehicles. The Average Hourly Traffic (AHT) is calculated assuming a uniform distribution of the ADT between the day and the night periods, respectively 15h and 9h. The predicted traffic is represented in Table 9.5.

Table 9.5. Traffic flow (AHT) over the years 2008-2022

	Year 2008				Year 2012				Year 2022			
	Light-veh.		Heavy-veh.		Light-veh.		Heavy-veh.		Light-veh.		Heavy-veh.	
AHT	day	night	day	night	day	night	day	night	day	night	day	night
(veh./h)	1662	308	235	34	1878	348	269	39	2182	404	316	46

Based on the two previous tables, a distribution of hourly traffic is assumed for the motorway. This distribution of hourly traffic, which is represented in Table 9.6, is used for the calculation of environmental, economic and social indicators. The traffic over the night period is highlighted in the table.

Table 9.6. Traffic flow per hour (vph) for year 2008

Time	Hourly traffic (vph)	Lightweight vehicles	Heavyweight vehicles
0-1	395	150	10
1-2	200	150	10
2-3	200	150	10
3-4	200	150	10
4-5	200	150	10
5-6	595	280	60
6-7	2450	1350	150
7-8	2980	2760	450
8-9	1425	1280	200
9-10	1125	1250	180
10-11	1325	1200	160
11-12	1390	1230	170
12-13	1990	1800	240
13-14	1622	1430	195
14-15	1755	1600	210
15-16	2150	1900	260
16-17	2715	2500	330
17-18	2850	2700	400
18-19	2320	2200	320
19-20	1225	1500	10
20-21	1150	1020	10
21-22	530	539	10
22-23	530	300	10
23-24	200	150	10

The traffic analysis provided by BRISA considered a period of 14 years. However, for the present case study a period of 100 years is considered. Therefore, it is necessary to estimate the traffic flow beyond the year 2022.

The estimation of the traffic growth over such a long period of time is not an easy task. In this analysis, it is assumed that the traffic growth follows a logarithmic trend; that is, after an initial period of time, the traffic growth will stabilize. This assumption may be justified by the fact that if traffic had a linear growth then the motorway would have to be continuously widened, which

would not probably be the most economic nor feasible solution. If this was the trend then maybe the solution would be to build a new motorway.

In fact, according to the current trend, the traffic in the global network of motorways of BRISA, and in particular in A1, has reduced over the last years. In 2008, the ADT in the network was reduced by 4.9%, while in relation to A1 the reduction was about 7%. In 2009, the reductions were about 1.9% and 4.2%, respectively for the entire network and for the A1. One of the main reasons for this trend was the construction of alternative motorways.

Hence, the traffic growth over the period of 100 years is obtained by a regression analysis of the traffic data using a logarithmic trend. The curve is illustrated in Figure 9.5.

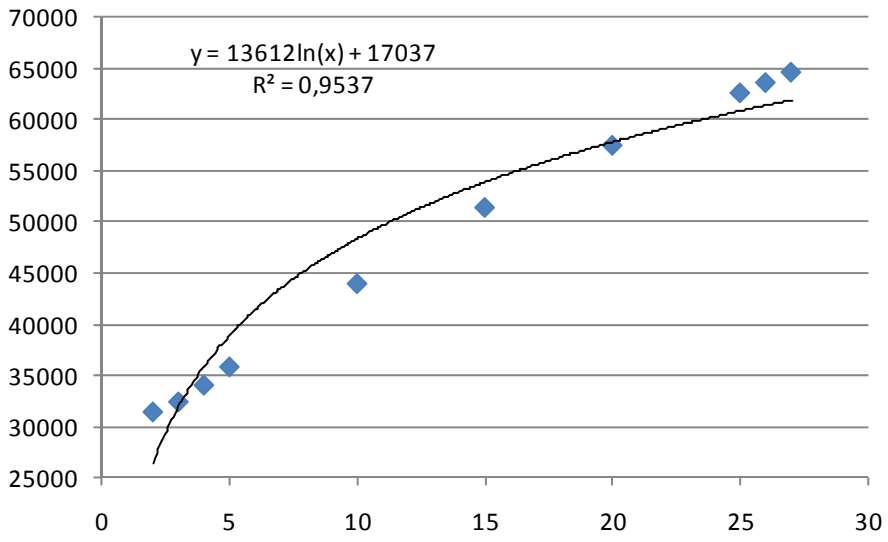

Figure 9.5. Logarithm growth of the traffic

Hence, according to the logarithmic trend the traffic prediction over the period of time 2008 – 2108 is indicated in Table 9.7:

Table 9.7. Estimated ADT over the years 2008-2108 for the motorway

	Year 2008	Year 2058	Year 2108
ADT (vehicles/day)	31522	70287	79723

According to this trend, approximately in year 2032, the traffic growth will reach 60000 vehicles/per day, which means that the motorway will have to be widened to four lanes of traffic in each carriageway.

9.4.1.2. Traffic over the bridge

Due to the lack of data, the traffic over the bridge is hereby estimated. This road is considered to be part of the national network of roads with a class I. Thus, for the base year of the study, 2008, an ADT of 5000 vehicles/day is considered. The estimated traffic growth over the period of time 2008-2108 is assumed to have a linear trend as indicated in Table 9.8.

Table 9.8. Estimated ADT over the years 2008-2108 for the road

	Year 2008	Year 2058	Year 2108
ADT (vehicles/day)	5000	7500	10000

Moreover, it is assumed that the distribution of hourly traffic over the bridge is similar to the distribution of hourly traffic in the motorway (see Table 9.6).

9.4.2. Operation stage – Maintenance and rehabilitation plan

According to traffic growth estimation (Table 9.7), between year 2008 and 2058, the number of average vehicles per day will increase over 60000 vehicles. Consequently, the motorway would have to be widened from three to four lanes in each carriageway over this period of time. However, since the bridge was initially designed considering this possibility, the middle span is long enough to overpass a motorway with four lanes in each direction, there is no need to carry any additional work in the bridge. Therefore, the new widening of the motorway will not affect the bridge and will not be taken into consideration in the analysis.

Moreover, it is hereby assumed that no severe damage or failure of the bridge will occur over the period of 100 years, taking into account the maintenance and rehabilitation plan discussed in the following paragraphs.

The maintenance and rehabilitation plan is based on the predicted service life of the individual equipments of the bridge and in the predicted service of the main structural components. As referred in Chapter 5, a steel-concrete composite bridge has a high probability of achieving a service life of 100 years considering preventive maintenance. For this bridge, two major types of maintenance actions are considered: (i) the maintenance of steel elements; and (ii) the maintenance of concrete elements.

The most critical factor affecting the service life of the steel structure is the protective coating system. Different values can be found in the literature for the service life or the time of the first maintenance of the coating system. Over the years, the durability of the protective coating system has progressively increased from 12 to 15 years to 20 to 25 years [9.1]. Furthermore, from the continued developments in coating technology and according to the requirements of current standards (e.g. EN ISO 12944 [9.2]), it is expected that the coating lifetime to first major maintenance occur over 30 years [9.1].Therefore, in relation to the steel structure, it is assumed to reach a service life of 100 years considering the replacement of the corrosion protection every 20 to 35 years.

In relation to structural concrete members, once they are exposed to sufficiently aggressive environmental conditions (e.g. cycles of freezing/thawing, cycles of wetting/drying, etc), they will eventually deteriorate and lose strength. Corrosion of reinforcement steel spalls the cover concrete, reduces the cross-sectional area of the reinforcement steel and consequently, its strength [9.3]. The time needed for concrete members to deteriorate depends on factors such as the severity of the exposure conditions and the characteristics of the structural concrete. Concrete deck slabs are constantly pounded by traffic and are directly exposed to weather. Consequently, they deteriorate faster than other parts of the bridge [9.4].

Several actions may be taken for the protection, repair and rehabilitation of bridge decks. Among the most common procedures are [9.5]: (i) mechanical concrete repair, (ii) patching, (iii) coating, (iv) realkalisation, (v) electrochemical chloride extraction, and (vi) cathodic protection. The choice of a specific treatment depends on the type and severity of the problem, on the time needed to proceed with the repair action and the estimated service life of the repair procedure

and respective cost. A cast “in situ” portland cement concrete deck can last for 50 years when an overlay is applied at 25 years of age [9.6]. The service lives of different treatments, based in literature reviews and surveys, are indicated in Table 9.9 [9.6]:

Table 9.9. Estimated service lives for different repair methods (from [9.6])

Concrete repair method	Service life
Polymer overlays	10-25 years
Sealers	5-10 years
Cement overlays	> 25 years

Hence, in this case study, structural concrete members are assumed to reach a service life of 100 years considering a new surface protection every 20 to 30 years.

The average service lives of bridge equipments are predicted based on specialized catalogues and other literature. Hence, the estimated intervals for maintenance and repair of the different components of the composite bridge are indicated in Table 9.10.

Table 9.10. Estimated service lives for bridge components

Bridge component	Service life
Surface protection of concrete elements	20-30 years
Corrosion protection of steel elements	20-35 years
Expansion joints	20-25 years
Bearings	20-25 years
Railings	20-25 years
Parapet	20-25 years
Edge beams	20-25 years
Asphalt surface	10-20 years

Thus, based on the predicted service lives of bridge components, a scenario-based maintenance and rehabilitation plan is established. This plan is indicated in Table 9.11. The respective unit costs are also indicated in the same table. In the definition of this plan, it was considered that maintenance actions with similar intervals of time would happen at the same year in order to reduce the number of times the bridge undergoes a work activity.

For the steel structure, a complete renewal of the coating system is assumed to occur every 25 years. Cost estimates for some coating systems may be found in the literature and other sources (see for instance [9.7]). However, in this case and based in information from contractors, a unit cost of 200€/m^2 is considered. This value includes the cost of material, preparation and cleaning costs and the application cost.

For the maintenance and rehabilitation of concrete structural elements, it is assumed that every 25 years a light repair takes place, except in year 50, where a major rehabilitation occurs. In the first case it is assumed that the depth of concrete deterioration is less than 20 mm and reinforcement steel is not exposed. Thus, the defective concrete is saw cut 10 mm deep and concrete is removed by hydrojetting. Afterwards a cementitious mortar is applied and cured. For the major rehabilitation, it is assumed that a deeper repair is needed. In this case, the deteriorated concrete is removed until reinforcement steel is exposed (about 50 mm deep). The bars are cleaned by sandblasting or hydrojetting and a new cover of concrete is placed and cured. The prices for both types of repair actions, which are indicated in Table 9.11, were obtained from contractors.

Likewise, the remaining unit costs indicated in Table 9.11 were obtained contractors.

Table 9.11. Scenario-based maintenance/rehabilitation plan

Activity	First intervention	Interval of time	Unit cost
Periodic inspections	2	2	2 €/m^2
Main inspection	5	5	5 €/m^2
Cleaning of expansion joints	1	1	10 €/m
Replacing of expansion joints	25	25	2 500 €/m
Surfacing (asphalt)	15	15	30 €/m^2
Replacing edge beam	25	25	70 €/m
Replacing railings	25	25	50 €/m
Re-painting parapets	25	25	40 €/m
Replacing bearings	25	25	3 500 €/un
Re-coating of steel beams	25	25	200 €/m^2
Repairing of concrete structure	25	25	50 €/m^2
Rehabilitation of concrete deck	50	-	100 €/m^2

The corresponding timetable of maintenance and rehabilitation activities over the service life of the bridge is illustrated in Table 9.12. For the sake of simplification, a time-interval of 5 years is considered, starting in year 15, when the first major activity takes place.

According to the time of intervention in the bridge for each activity, and in order to minimize the duration of work activity over and under the bridge, the activities happening in the same year are assumed to take place at the same time. This combination of activities leads to 5 combination of actions A to E (as indicated in the bottom line of Table 9.12). The periodic and main inspections are not represented in Table 9.12 as it is assumed that these activities do not interfere with traffic and consequently have no direct influence on the analysis.

Table 9.12. Timetable of maintenance/rehabilitation activities of PS398

years	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
Main structure																	
New surface deck			■										■				
Rehabilitation deck								■									
New surface columns			■										■				
Rehabilitation columns								■									
New surface abutments			■										■				
Rehabilitation abutm.								■									
Steel beams protection			■					■					■				
Equipment																	
Cleaning exp. joints	■	■		■	■	■	■		■	■	■	■		■	■	■	■
Replacing exp. joints			■					■					■				
Replacing bearings			■					■					■				
Replacing rails			■					■					■				
Replacing edge beams			■					■					■				
Re-painting parapet			■					■					■				
Others																	
Replacing asphalt layer	■			■			■			■			■			■	
Combined activities	A	E	B	A	E	E	A	C	E	A	E	E	D	E	E	A	E

Combined activity A is the combination of the replacement of the asphalt layer of the bridge, occurring every 15 years, with the cleaning of the expansion joints, which occurs every year. This

means that when the bridge will be subjected to the work activity due to the new pavement, then the expansion joints will also be cleaned.

Combined activity B represents the replacement of bridge equipment, together with the re-surfacing of concrete elements and re-painting of steel structure. This combined activity is similar to combined activity D, except that in the latter, there is also the replacement of the asphalt layer of the bridge.

Combined activity C combines the rehabilitation of the structure, in which all concrete elements will be subject to major intervention, to the painting of the steel structure and the replacement of major bridge equipment.

Combined activity E is in fact a standalone activity, corresponding to the cleaning of the joints, which occurs every year. Despite being an activity that takes place every year, for the sake of simplicity, this activity is represented in Table 9.12 only every 5 years.

The duration of each combined activity depends on the type of work to be done, in the ability of manpower and in the capacity rate of construction equipment. Thus, for each combined activity (indicated in Table 9.12) a planning of the respective work was made based on the estimated bill of materials and on the estimated capacity rate for each activity. Based in this information a period of time was estimated for each combined activity, which are indicated in Table 9.13. The detailed calculation and the time plan are provided in Annex B.

During the periods of time corresponding to maintenance and rehabilitation works, traffic over and/or under the bridge is affected. Table 9.13 indicates the total number of days estimated for each combined action and the corresponding traffic affectation.

Table 9.13. Total duration (in days) of maintenance/rehabilitation activities

Combined activity	Total duration (days)	Traffic affectation
A	16	Only affects traffic over the bridge
B	22	Affects traffic over and under the bridge
C	74	Affects traffic over and under the bridge
D	38	Affects traffic over and under the bridge
E	1	It was assumed that this activity does not affect traffic

Moreover, it is assumed that during the maintenance and rehabilitation of the bridge the traffic restrictions in work zones, according to current legislation (see Annex A) are always taken into account.

9.4.3. End-of-life of the bridge

The data presented in this section for the demolition of the structure is based on the demolition project of a real concrete bridge, provided by BRISA, and on direct information received from contractors.

The demolition of the bridge is made in three main stages: the first stage corresponds to the preparation of the terrain and erection of auxiliary structures to support the structure being demolished; the second stage corresponds to the demolition of the central span of the structure; and the third stage corresponds to the demolition “in situ” of the remaining structure. The detailed plan of demolition is provided in Annex B, the total number of days needed for each stage are indicated in Table 9.14.

During the demolition of the bridge, it is considered that the traffic over the bridge is diverted to an alternative road. Traffic under the bridge is conditioned by the demolition of the bridge; however, it is assumed that except for the 2nd stage there will always be at least two lanes of traffic in each direction. During the 2nd stage, traffic in the motorway will have to be diverted to only one carriageway as the carriageway below the part of the deck being dismantled has to be closed due to users' safety reasons.

Table 9.14. Total duration (in days) of bridge demolition

Demolition stages	Description	Duration (in days)
1st stage	Preparation of base supports for scaffolding; Preparation of terrain for deposit of concrete pieces; Erection of scaffolding; Transversal cuts in deck; Longitudinal cuts of deck (partially).	10
2nd stage	Dismantling of one part of composite deck and deposition of the resulting pieces in the side terrain; Dismantling of other part of composite deck and deposition of the resulting pieces in the side terrain.	6
3rd stage	Dismantling of scaffolding in central span; Demolition of the concrete pieces from the deck; Demolition "in situ" of piers and abutments; Removal and transportation of materials; Cleaning of the area.	7

After the demolition of the bridge, all the resulting demolition waste should be sent to a final destination. According to current European and National legislation (see Chapter 2), it is mandatory to sort the materials in the construction site or in a sorting plant (if sorting in the construction site is not possible). Thus, in this case and according to the European list of wastes, the materials are classified into three types of wastes:

i) 17 01 01 - Concrete;

ii) 17 03 – Asphalt, tar and tarred products;

iii) 17 04 05 – Iron and steel.

After sorting, the materials are sent to different places according to its characteristics and potential for recycling. Different scenarios are considered for the main materials involved in this case study: concrete and steel. Table 9.15 indicates the waste scenario for all the materials.

Table 9.15. End-of-life scenarios for main materials

Material	1st scenario	2nd scenario	3rd scenario	4th scenario
Concrete	Landfill	Landfill	Recycled	Recycled
Reinforcement steel	Recycled	Recycled	Recycled	Recycled
Structural steel	Recycled	Re-use	Recycled	Recycled
Asphalt	Recycled	Recycled	Recycled	Recycled

Scenario 4 is similar to scenario 3, except in the allocation procedures considered for the life cycle environmental analysis, as will be further described in section 9.5.4.

9.5. LIFE CYCLE ENVIRONMENTAL ANALYSIS

9.5.1. Stage of material production

This stage takes into consideration the production of all the materials needed to build the bridge, according to Figure 9.6. Data was collected from several sources as indicated in Table 9.16 (references are provided in Chapter 5).

Table 9.16. Sources of data for materials and transportation

Material/process	Source
Concrete (several grades)	Portland Cement Association (US)
Structural steel	Worldsteel organization
Reinforcement steel	Worldsteel organization
Painting	Ecoinvent
Asphalt	Ecoinvent
Transportation of steel plate	Ecoinvent

According to information from the Portuguese Association for Steel and Composite Construction (CMM), most of the steel used in Portugal for construction (steel profiles and plates) is imported from Europe (Luxemburg, Spain, France, Italy and Germany). Furthermore, due to its proximity to Portugal, Spain is the first source of steel to Portugal. Hence, an average distance of 700 km was considered.

The life cycle environmental analysis is performed using the environmental indicators discussed in Chapter 6. The calculation of potential environmental impacts was performed by the commercial programme SIMAPRO® [9.8].

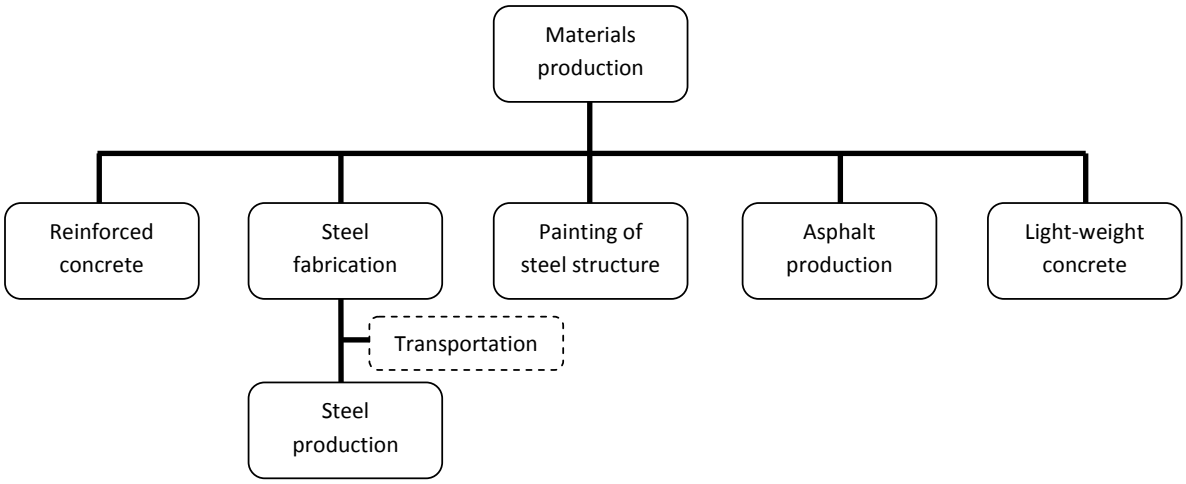

Figure 9.6. Material production stage

The results obtained for each baseline impact category (see Table 6.11, Chapter 6) are represented in Table 9.17. The burdens due to the transportation of steel plate were included in the process of steel production.

Table 9.17. Results of the material production stage per impact category

Impact category	Unit	Total	Reinforced concrete	Steel production	Painting of the bridge	Steel fabrication	Asphalt	Light-weight concrete
AD	kg Sb eq	3630.7	27.4%	60.3%	0.7%	4.0%	7.2%	0.3%
AC	kg SO_2 eq	2486.4	48.4%	42.2%	0.6%	6.2%	2.1%	0.4%
EU	kg NO_x eq	1870.6	55.9%	36.6%	0.5%	3.6%	2.8%	0.7%
GW	kg CO_2 eq	876470.0	47.4%	47.8%	0.2%	1.9%	2.1%	0.5%
OD	kg CFC-11 eq	0.012	0%	23.6%	3.8%	8.7%	62.4%	1.6%
HT	kg1,4-DB eq	97163.4	81.7%	5.1%	0.8%	9.2%	2.6%	0.6%
TT	kg 1,4-DB eq	141.1	64.5%	26.4%	1.2%	5.3%	2.1%	0.6%
Ph	kg C_2H_4	252.4	31.9%	64.2%	0.3%	2.2%	1.3%	0.1%

From Table 9.17 it is concluded that the production of reinforced concrete and structural steel are the main processes contributing to global impacts in the material production stage. The same results are plotted in Figure 9.7.

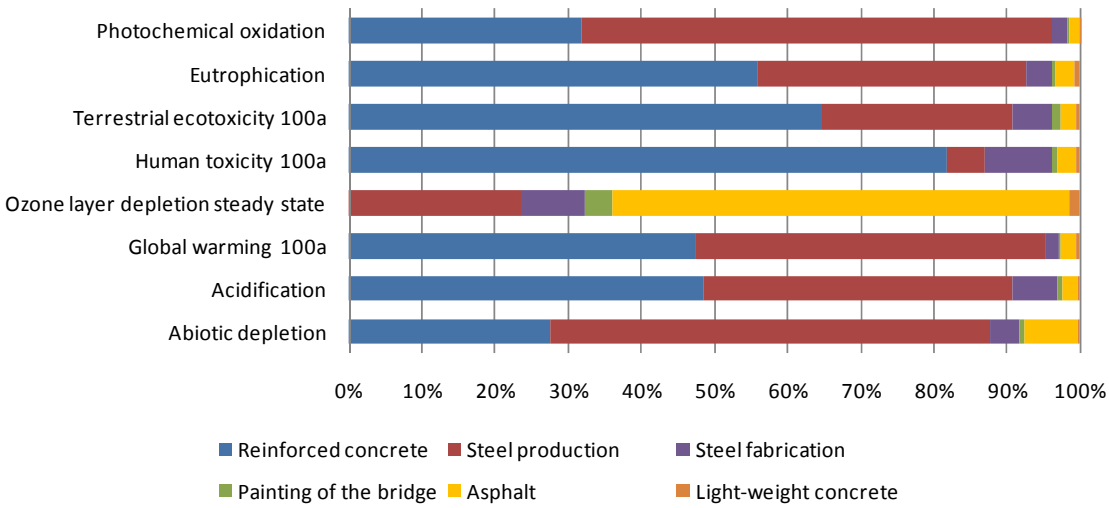

Figure 9.7. Contribution analysis of processes during the material production stage

9.5.2. Stage of construction

9.5.2.1. Transportation of materials and construction equipments

Construction materials and equipments have to be transported to the construction site. Some of the distances are calculated based on information from the constructor. However, most information is estimated due to lack of information. The travelling distances estimated for each case are indicated in Table 9.18.

The consumption of diesel is based on the travel distances displayed in Table 9.18 and in the number of trips needed for each case, as exemplified in the following paragraphs.

Dump trucks are used to haul excavated earth to the disposal site throughout the excavation stage. Assuming a dump truck with a hauling capacity of 25 tonnes per truck and considering

about 314 m^3 (approximately 635 tonnes) of soil to be sent to the disposal site, then during the excavation phase approximately 25 haul trips were considered.

Table 9.18. Transportation of materials and equipments for the construction stage

Activity	Distance (km)
Transportation of soil and debris	10
Transportation of steel beams	60
Transportation of precast slabs	60
Transportation of fresh concrete	40
Transportation of steel reinforcement	60

In the same way, for the casting of the concrete slab, 99 m^3 of fresh concrete class C35/45 are needed. Considering a concrete mixer truck with a capacity of 7 m^3 of fresh concrete, thus 14 round trips are needed.

The environmental data for fuel consumption of trucks and respective fuel production were taken from the ECOINVENT database.

9.5.2.2. Use of construction equipment

The construction of the bridge requires the use of heavy equipment such as crawler-excavators, loaders, bulldozers, water trucks, concrete mixers, cranes, etc, which are usually diesel powered.

The quantification of emissions due to the use of construction equipment is based in the plan of construction represented in Table 9.3, in the list of equipment provided by the constructor and the emission factors from the NONROAD2008 model described in Chapter 5.

The number of hours needed for each equipment were estimated from the time plan for construction and in the work capacity of each equipment (assumed that each equipment was used at full capacity).

Hence, the total emissions due to the use of diesel-fuelled construction equipment, for the period of time corresponding to the construction stage are indicated in Table 9.19.

Table 9.19. Total emissions (in tonnes) due to diesel-fuelled construction equipment in the construction stage

Activity	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
Excavation	0.005	0.018	0.034	0.004	0.004	0.001	3.145
Piers and abutments	0.008	0.039	0.116	0.006	0.006	0.002	9.741
Steel structure	0.005	0.028	0.056	0.005	0.005	0.001	6.535
Concrete deck	0.006	0.028	0.073	0.005	0.005	0.002	7.442
Finishing	0.004	0.020	0.061	0.004	0.004	0.001	6.864
TOTAL	0.029	0.134	0.340	0.024	0.023	0.007	33.727

The detailed calculation of non-mobile emissions is provided in Annex A.

9.5.2.3. Traffic over and under the bridge

In this sub-section, only the traffic congestion due to the construction activity is analysed. This bridge is a new bridge; therefore, during its construction, there is no traffic over the bridge and thus no emissions are considered in this stage.

During the time period of construction, according to Table 9.3, the traffic under the bridge is affected due to restrictions in the traffic speed and the narrowing of the carriageway. Traffic congestion due to work activity in the surrounding area of the bridge has two major types of

impacts: (i) the impacts due to direct emissions from vehicles, and (ii) the impacts due to the amount of fuel consumed. The impacts due to direct emissions from vehicles are quantified based on the QUEWZ98 model. The impacts due to the excess of fuel consumed, which include the upstream burdens due to the production of fuel, are quantified based on data from Ecoinvent. These impacts are described in the following paragraphs. In both cases, the quantification of the impacts is given by the difference between the impacts of the vehicles passing through the work zone and the impacts of the vehicles passing through the same zone but without any delays due to work activity.

9.5.2.3.1. Fuel consumption and vehicles' emissions per day

The characteristics of the traffic flow under the bridge are indicated in Table 9.6. It is assumed that the construction of the bridge is performed according to the safety rules imposed to the constructor by national legislation, for construction activities in national motorways (see Appendix A).

The quantification of emissions in the work zone caused by the bridge construction is based in the QUEWZ98 model as described in Chapter 6. The detailed calculation of the emissions in work zones is provided in Appendix A.

Table 9.20 indicates the emissions in the work zone per lane and per carriageway. The detailed calculation of emissions was provided in Box 5.3 (Chapter 5). Three different types of reference scenarios are analysed. In the three cases, it is assumed that during the 24 hours, there are always restrictions in the work zone implying a traffic flow under a reduced speed of 80 km/h. In the first scenario, the work activity happens during the day, from 6 – 20h, but there are always two lanes of traffic in each direction. In the second scenario, the work activity happens during the night period, from 22 – 6h, and during this period, there is only one lane of traffic in each direction. The last scenario is similar with scenario 2, although the lane closure happens during the day period, from 6 – 22h. The length of the work zone is assumed to be 1 km.

Table 9.20. Emissions (per day and per carriageway) in work zone during construction

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Max. queue (km)	CO (kg/day)	HC (kg/day)	NOx (kg/day)
1	2	2	0 - 24	6 - 20	0	33.20	0.33	0.29
2	2	1	0 - 24	22 - 6	0	33.20	0.34	0.30
3	2	1	0 - 24	6 - 22	0.5	80.68	4.75	1.22

In the second scenario, although there is one lane of traffic closure, as it happens during the night, it does not influence the emissions in the work zone. On the other hand, if the lane is closed during the day (third scenario), then there would be a major increase in the emissions and this is due to the queue formation in the work zone. The maximum queue in this case is about 0.5 km. These three scenarios highlight the importance of a careful planning of the work activity in the work zone in order to minimize the production of emissions.

Table 9.21 indicates the fuel consumption in the work zone for the three scenarios described above, the detailed calculation of fuel consumption was also provided in Box 5.3 (Chapter 5). The same conclusions can be drawn for this table. Naturally, the worst scenario is scenario 3, where there is a queue formation.

Table 9.21. Fuel consumption (per day and per carriageway) in work zone during construction

Scenario	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Fuel	
					Gasoline	Diesel
					(kg/day)	(kg/day)
1	2	2	0 - 24	6 - 20	167.92	308.35
2	2	1	0 - 24	22 - 6	168.68	309.20
3	2	1	0 - 24	6 - 22	388.16	625.89

9.5.2.3.2. Fuel consumption and vehicles' emissions during construction

For the calculation of the total emissions during the entire construction period, two global scenarios were considered, as indicated in Table 9.22. As already referred, the construction period lasted for 87 days. During this period there were always two lanes of traffic in each direction, although with reduced speed, except for six days. These six days correspond to the erection of the steel and concrete deck. The steel structure is built into two parts. During the erection of the two parts of the steel structure, the corresponding carriageway has to be closed to the traffic underneath. The complete erection of each half part of the structure takes about 8 hours. Also for placing the precast concrete panels on top of the steel structure there is also the need to close the traffic underneath the bridge. This also takes 8 hours for each part of the structure. During the closure of a carriageway, traffic has to be diverted to the other carriageway, resulting in one lane of traffic in each direction.

Hence, global scenario 1 considers that the closure of one carriageway occurs always during the night period, whereas global scenario 2 considers that the closure occurs during the day.

Table 9.22. Total emissions and fuel consumption in work zone during construction

	Emissions (kg)			Fuel (kg)	
	CO	HC	NOx	Gasoline	Diesel
Global scenario 1	5778.42	57.54	50.58	29227.20	53663.10
Global scenario 2	6348.18	110.46	61.62	31860.96	57463.38

As expected, the emissions and fuel consumption of global scenario 2 are higher than for global scenario 1. For the calculation of the total emissions in the construction stage, the best scenario, that is global scenario 1, was considered.

9.5.2.4. Synthesis of the construction stage

The construction stage takes into account all the processes needed for the construction of the bridge and affected by it. Hence, as represented in Figure 9.8, it includes the transportation of materials to the construction site (according to the distances indicated in Table 9.18), the transportation of equipment and the use of construction equipment.

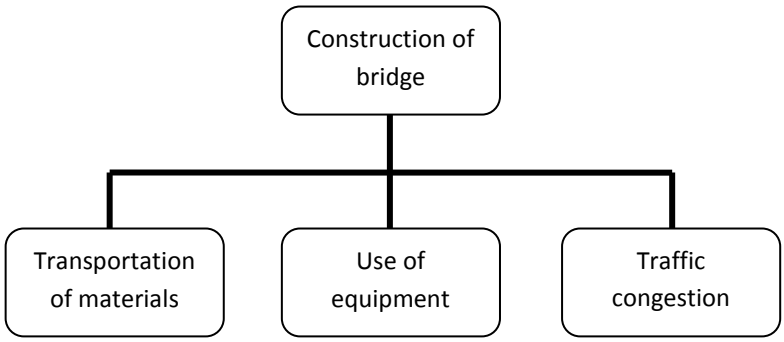

Figure 9.8. Construction stage

Moreover, it takes into account also the emissions due to the traffic congestion resulting from construction activity.

The results obtained for each baseline impact category (see Table 6.11, Chapter 6) are represented in Table 9.23 and Figure 9.9.

Table 9.23. Results of the construction stage per impact category

Impact category	Unit	TOTAL	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	2164.3	6.5 %	0 %	93.5 %
AC	kg SO_2 eq	830.3	7.1 %	21.5 %	71.4 %
EU	kg NO_x eq	743.1	11.0 %	54.9 %	34.1 %
GW	kg CO_2 eq	111361.6	17.5 %	30.5 %	52.1 %
OD	kg CFC-11 eq	0.042	7.4 %	0 %	92.6 %
HT	kg 1,4-DB eq	18488.9	15.1 %	2.3 %	82.6 %
TT	kg 1,4-DB eq	24.2	15.3 %	0 %	84.7 %
Ph	kg C_2H_4	194.6	1.2 %	2.0 %	96.7 %

In this stage the process that most contributes to major impact categories is clearly the “traffic congestion”. Its contribution is always above 80%, except for the impact categories of acidification, eutrophication and global warming, for which an important contribution is also provided by the “use of equipment”.

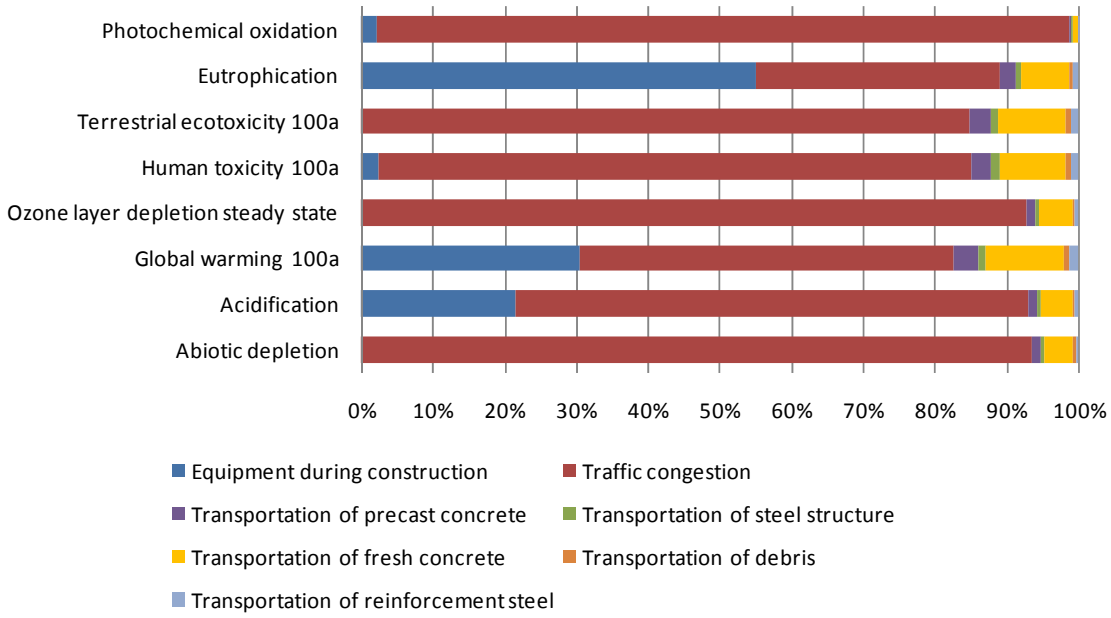

Figure 9.9. Contribution analysis of processes during the construction stage

9.5.3. Stage of operation

9.5.3.1. Transportation of materials and equipments

Each time the bridge undergoes an activity of maintenance or rehabilitation, materials and equipments have to be transported to the bridge site. The travelling distances considered in this stage are the same as in the construction stage, unless otherwise indicated.

9.5.3.2. Use of equipments

The quantification of emissions due to the use of equipment is based on the plan of maintenance provided in Annex B, in the estimated list of equipment and the emission factors from the NONROAD2008 model described in Chapter 5.

The number of hours needed for each equipment were estimated from the time plan for activity and in the work capacity of each equipment (assumed that each equipment was used at full capacity). Table 9.24 summarizes the total emissions due to the use of equipment in the operation stage.

Table 9.24. Total emissions (in tonnes) due to diesel-fuelled equipment in the operation stage

Activity	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
Combined act. 1	0.006	0.025	0.076	0.005	0.005	0.002	9.646
Combined act. 2	0.021	0.097	0.284	0.019	0.018	0.007	33.679
Combined act. 3	0.037	0.167	0.490	0.033	0.032	0.012	58.118
Combined act. 4	0.027	0.122	0.360	0.024	0.023	0.009	43.325

9.5.3.3. Traffic over and under the bridge

9.5.3.3.1. Fuel consumption and vehicles' emissions per day

Under the bridge, and according to Table 9.12, traffic is affected every 25 years. Thus, considering the base year of the study 2008, traffic will be affected in years 2033 (combined activity B), 2058 (combined activity C) and 2083 (combined activity D). For these three years, the respective ADT was estimated based on the logarithmic trend indicated in sub-section 9.4.1.1 and considering a similar distribution of traffic flow per hour as the one represented in Table 9.6.

Moreover, it was assumed that every time there's work activity on the bridge, the work is performed according to the safety rules imposed by national legislation for construction activities in national motorways (see Annex B).

The quantification of emissions in the work zone during the operation stage is based in the same model as described in the previous stage and considering a work zone length of 1 km. The detailed calculation of the emissions in work zones is provided in Annex B.

In the year 2033, there will be three lanes of traffic in each direction. In this case, four different scenarios were considered as indicated in Table 9.25. In all cases it is considered that there are always (for the 24 hours) restrictions in the work zone. Scenario 1 considers that work activity happens during the day, from 6h – 20h, but the three lanes of traffic are always open. Scenario 2 considers a lane closure for work activity during the night period (22h – 6h). Scenarios 3 and 4 consider a lane closure for work activity over the day period (6h – 22h), although scenario 4 considers a reduced day period (9h – 18h). The respective emissions are indicated in Table 9.25. The detailed calculations are provided in Annex B.

Table 9.25. Emissions (per day and per carriageway) in work zone during operation stage (year 2033)

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Max. queue (km)	CO (kg/day)	HC (kg/day)	NOx (kg/day)
1	3	3	0 - 24	6 - 20	0	53.30	0.69	0.49
2	3	2	0 - 24	22 - 6	0	53.30	0.70	0.49
3	3	2	0 - 24	6 - 22	0.6	135.05	7.74	1.95
4	3	2	0 - 24	9 - 18	0.4	84.08	3.28	1.00

As noted from the previous table, the closure of the lane during the day originates a queue, which creates a major increase of emissions.

The year 2058 corresponds to an ADT over 60000. Therefore, four lanes of traffic are considered in each direction. In this case, six different scenarios were considered assuming that there are always (for the 24 hours) restrictions in the work zone. Scenario 1 considers that work activity happens during the day, from 6h – 20h, but the four lanes of traffic are always open. Scenarios 2 and 3 consider the closure of one lane for work activity during the night period (22h – 6h) and day period (6h – 22h), respectively. Scenarios 4 to 6 consider the closure of two lanes of traffic. In scenario 4 the lane closure occurs over the night period (22h – 6h), in scenario 5 the lane closure occurs over the day period (6h – 22h), and in scenario 6 the lane closure occurs over the day but considering a reduced period (9h – 18h). The respective emissions are indicated in Table 9.26, the detailed calculations are provided in Annex B.

Table 9.26. Emissions (per day and per carriageway) in work zone during operation stage (year 2058)

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Max. queue (km)	CO (kg/day)	HC (kg/day)	NOx (kg/day)
1	4	4	0 - 24	6 - 20	0	68.56	0.76	0.61
2	4	3	0 - 24	22 - 6	0	68.56	0.77	0.62
3	4	3	0 - 24	6 - 22	0	68.56	1.26	0.73
4	4	2	0 - 24	22 - 6	0	68.53	0.78	0.62
5	4	2	0 - 24	6 - 22	2.3	478.89	39.47	9.07
6	4	2	0 - 24	9 - 18	1.6	225.51	15.71	3.85

It is noted from the previous table that reducing the day period of activity is enough to reduce by half the emissions.

The same scenarios as described for year 2058 were considered for year 2083, as indicated in Table 9.27. Because of the traffic growth over the period of 2058-2083, the amount of emissions increased in relation to the previous reference year.

Table 9.27. Emissions (per day and per carriageway) in work zone during operation stage (year 2083)

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Max. queue (km)	CO (kg/day)	HC (kg/day)	NOx (kg/day)
1	4	4	0 - 24	6 - 20	0	69.79	0.83	0.63
2	4	3	0 - 24	22 - 6	0	69.79	0.84	0.63
3	4	3	0 - 24	6 - 22	0	69.79	1.49	0.78
4	4	2	0 - 24	22 - 6	0	69.76	0.85	0.64
5	4	2	0 - 24	6 - 22	4.3	855.32	75.68	17.09
6	4	2	0 - 24	9 - 18	2.8	347.45	27.87	6.55

Over the bridge, and according to Table 9.12, traffic is affected over several years during the operation stage of the bridge. However, for simplification it was considered for every intervention on the bridge a constant ADT of 7500 per day (corresponding to the ADT in year 2058). Three different scenarios, as indicated in Table 9.28, were considered for a work zone length of 1 km. Also in all cases it is considered that there are always (for the 24 hours) restrictions in the work zone above the bridge. Scenario 1 considers that work activity happens during the day, from 6h – 20h, but all lanes of traffic are open. Scenario 2 considers a lane closure for work activity during the night period (22h – 6h) and scenario 3 considers a lane

closure for work activity over the day period (6h – 22h). The respective emissions are indicated in Table 9.28. Detailed calculations are provided in Annex B.

Table 9.28. Average emissions (per day) in work zone during operation stage (traffic over the bridge)

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Max. queue (km)	CO (kg/day)	HC (kg/day)	NOx (kg/day)
1	2	1	0 - 24	6 - 20	0	22.57	0.10	0.18
2	2	1	0 - 24	22 - 6	0	22.57	0.11	0.18
3	2	1	0 - 24	6 - 22	0	22.03	0.24	0.21

Fuel consumption in the work zones is estimated based in the same reference scenarios. Hence, fuel consumption, per day and per carriageway, is indicated in Table 9.29, Table 9.30 and Table 9.31 for years 2033, 2058 and 2083, respectively. The detailed calculations are provided in Annex B.

Table 9.29. Fuel consumption (per day and per carriageway) in work zone during operation (year 2033)

Scenario	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Fuel	
					Gasoline (kg/day)	Diesel (kg/day)
1	3	3	0 - 24	6 - 20	371.88	640.05
2	3	2	0 - 24	22 - 6	373.17	641.51
3	3	2	0 - 24	6 - 22	776.82	1230.44
4	3	2	0 - 24	9 - 18	578.16	947.86

Table 9.30. Fuel consumption (per day and per carriageway) in work zone during operation (year 2058)

Scenario	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Fuel	
					Gasoline (kg/day)	Diesel (kg/day)
1	4	4	0 - 24	6 - 20	390.07	699.35
2	4	3	0 - 24	22 - 6	391.09	700.51
3	4	3	0 - 24	6 - 22	485.91	808.29
4	4	2	0 - 24	22 - 6	391.90	701.42
5	4	2	0 - 24	6 - 22	1528.41	2195.24
6	4	2	0 - 24	9 - 18	963.57	1467.13

Table 9.31. Fuel consumption (per day and per carriageway) in work zone during operation (year 2083)

Scenario	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Fuel	
					Gasoline (kg/day)	Diesel (kg/day)
1	4	4	0 - 24	6 - 20	433.43	763.56
2	4	3	0 - 24	22 - 6	434.61	764.90
3	4	3	0 - 24	6 - 22	555.87	906.82
4	4	2	0 - 24	22 - 6	435.56	765.96
5	4	2	0 - 24	6 - 22	2368.63	3194.57
6	4	2	0 - 24	9 - 18	1337.79	1915.34

For the traffic over the bridge, the same scenarios were considered as indicated in Table 9.32.

Table 9.32. Fuel consumption (per day) in work zone during operation stage (traffic over the bridge)

Scenario	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Fuel	
					Gasoline (kg/day)	Diesel (kg/day)
1	2	2	0 - 24	6 - 20	64.11	133.50
2	2	1	0 - 24	22 - 6	64.28	133.69
3	2	1	0 - 24	6 - 22	85.17	157.27

9.5.3.3.2. Fuel consumption and vehicles' emissions during operation

Based in the scenarios presented in the previous clauses for the operation stage, for the calculation of total fuel consumption and respective emissions, several global scenarios were defined for each combined maintenance activity indicated in Table 9.12.

Combined activity A has a total duration of 16 days and only affects traffic over the bridge. During this period of time it is assumed that there will be always one lane of traffic closed. In global scenario 1 the closure is made over night, whereas in global scenario 2 the closure is made during the day. The corresponding emissions and fuel consumption, for the entire period of time, are indicated in Table 9.33.

Table 9.33. Total emissions and fuel consumption in work zone during operation stage (combined activities A)

	Emissions (kg)			Fuel (kg)	
	CO	HC	NOx	Gasoline	Diesel
Global scenario 1	361.12	1.76	2.88	1028.48	2139.04
Global scenario 2	352.48	3.84	3.36	1362.72	2516.32

Combined activity B occurs in year 2033 and has a total duration of 22 days. During this period, traffic is affected over and under the bridge. Six different global scenarios, as described in Table 9.34, were defined to combine each possible situation. Global scenario 1 corresponds to the best option while global scenario 6 corresponds to the combination of the worst possible situations.

Table 9.34. Total emissions and fuel consumption in work zone during operation stage (combined activities B)

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	night work motorway + night work over bridge	2308.74	26.11	20.62	14100.07	24750.43
Global scenario 2	night work motorway + day work over bridge	2302.80	27.54	20.95	14329.86	25009.81
Global scenario 3	day work motorway + night work over bridge	5088.24	265.47	70.26	27824.17	44774.05
Global scenario 4	day work motorway + day work over bridge	5082.30	266.90	70.59	28053.96	45033.43
Global scenario 5	reduce day work motorway + night work over bridge	3355.26	113.83	37.96	21069.73	35166.33
Global scenario 6	reduce day work motorway + day work over bridge	3360.32	115.26	38.29	21299.52	35425.71

In the case of combined activity C, it occurs in year 2058 and has a total duration of 74 days. Also during this period of time traffic is affected over and under the bridge. In this case, ten different global scenarios, as described in Table 9.35, were defined to combine each possible situation. In the same manner, global scenario 1 corresponds to the best option while global scenario 10 corresponds to the combination of the worst possible situations.

Finally, for combined activity D, occurring in year 2083 with a total duration of 38 days, traffic is also affected over and under the bridge. In this case, also ten different global scenarios, as described in Table 9.36, were defined to combine each possible situation.

Table 9.35. Total emissions and fuel consumption in work zone during operation stage (combined activities C)

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	night work motorway (3 lanes open)+ night work over bridge	8038.14	86.61	71.76	44391.39	79948.79
Global scenario 2	night work motorway (3 lanes open) + day work over bridge	8032.20	88.04	72.09	44621.18	80208.17
Global scenario 3	day work motorway (3 lanes open) + night work over bridge	8038.14	120.91	79.46	51028.79	87493.39
Global scenario 4	day work motorway (3 lanes open) + day work over bridge	8032.20	122.34	79.79	51258.58	87752.77
Global scenario 5	night work motorway (2 lanes open)+ night work over bridge	8036.04	87.31	71.76	44448.09	80012.49
Global scenario 6	night work motorway (2 lanes open) + day work over bridge	8030.10	88.74	72.09	44677.88	80271.87
Global scenario 7	day work motorway (2 lanes open) + night work over bridge	36761.24	2795.61	663.26	124003.79	184579.89
Global scenario 8	day work motorway (2 lanes open) + day work over bridge	36755.30	2797.04	663.59	124233.58	184839.27
Global scenario 9	reduce day work motorway (2 lanes open) + night work over	19024.64	1132.41	297.86	84464.99	133612.19
Global scenario 10	reduce day work motorway (2 lanes open)+ day work over	19018.70	1133.84	298.19	84694.78	133871.57

Table 9.36. Total emissions and fuel consumption in work zone during operation stage (combined combined activities D)

Scenario	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	night work motorway (3 lanes open)+ night work over bridge	3230.52	32.63	28.26	17217.51	31084.73
Global scenario 2	night work motorway (3 lanes open) + day work over bridge	3215.94	36.14	29.07	17781.54	31721.39
Global scenario 3	day work motorway (3 lanes open) + night work over bridge	3230.52	54.73	33.36	21340.35	35910.01
Global scenario 4	day work motorway (3 lanes open) + day work over bridge	3215.94	58.24	34.17	21904.38	36546.67
Global scenario 5	night work motorway (2 lanes open)+ night work over bridge	3229.50	32.97	28.60	17249.81	31120.77
Global scenario 6	night work motorway (2 lanes open) + day work over bridge	3214.92	36.48	29.41	17813.84	31757.43
Global scenario 7	day work motorway (2 lanes open) + night work over bridge	29938.54	2577.19	587.90	82974.19	113693.51
Global scenario 8	day work motorway (2 lanes open) + day work over bridge	29923.96	2580.70	588.71	83538.22	114330.17
Global scenario 9	reduce day work motorway (2 lanes open) + night work over	12670.96	951.65	229.54	47925.63	70199.69
Global scenario 10	reduce day work motorway (2 lanes open)+ day work over	12656.38	955.16	230.35	48489.66	70836.35

For the calculation of total emissions in the operation stage, as indicated in the following sub-section, the best scenarios corresponding to each combined maintenance activity were considered.

9.5.3.4. Synthesis of the operation stage

The operation stage of the bridge took into account the estimated maintenance and rehabilitation activities according to Table 9.12. These activities occur over different time periods over the service life of the structure, as described in the previous sub-sections. However, due to a repeated number of processes, the tree diagram of Figure 9.10 aggregates the processes with same characteristics occurring at different periods of time.

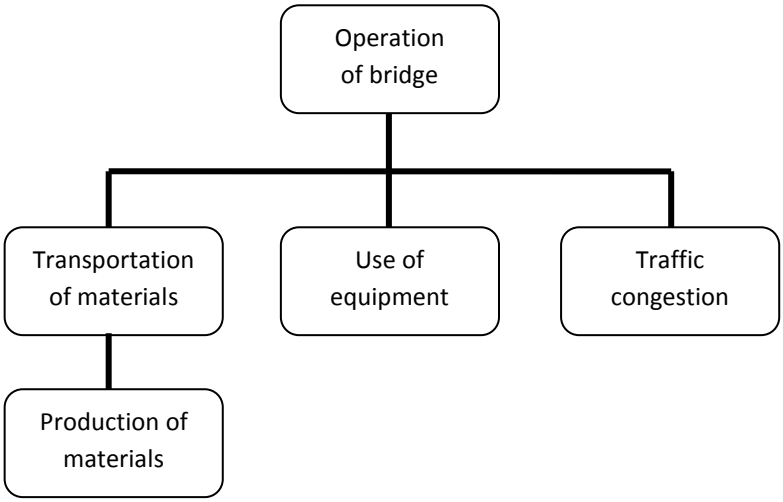

Figure 9.10. Processes included in the operation stage of the bridge

The outcome of each combined activity is indicated in Table 9.37, Table 9.38, Table 9.39 and Table 9.40, respectively for combined activities A to D. Each table indicates the total emissions per impact category and corresponding contribution of each process.

Table 9.37. Results of the operation stage per impact category (combined action A)

Impact category	Unit	TOTAL	Asphalt replacement	Use of equipment	Traffic congestion
AD	kg Sb eq	341.1	77.4 %	0 %	22.6 %
AC	kg SO_2 eq	117.1	45.9 %	34.5 %	19.6 %
EU	kg NO_x eq	154.8	34.1 %	58.9 %	7.0 %
GW	kg CO_2 eq	30999.3	61.0 %	31.2 %	7.8 %
OD	kg CFC-11 eq	0.009	83.2 %	0 %	16.8 %
HT	kg 1,4-DB eq	3222.9	79.0 %	3.0 %	18.0 %
TT	kg 1,4-DB eq	3.7	79.2 %	0 %	20.8 %
Ph	kg C_2H_4	15.0	21.9 %	5.1 %	73.0 %

From the previous table it is observed that the asphalt replacement contributes with a share of more than 50% for most impact categories, while traffic congestion represents a major contribution only for the impact category of photochemical oxidation. In should be noticed once more that this combined activity only affects traffic over the bridge.

In the case of combined activity B (see Table 9.38) the process that most contributes to major impact categories is clearly the “traffic congestion”. Its contribution is always above 80%, except for the impact categories of acidification, eutrophication and global warming, for which an important contribution is also provided by the “use of equipment”.

Table 9.38. Results of the operation stage per impact category (combined action B)

Impact category	Unit	TOTAL	Coating of steel	Concrete repair	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	975.7	1.9 %	0.7 %	0.2 %	0 %	97.3 %
AC	kg SO_2 eq	445.8	2.8 %	1.1 %	0.1 %	33.7 %	62.2 %
EU	kg NO_x eq	471.0	1.6 %	1.4 %	0.2 %	72.4 %	24.5 %
GW	kg CO_2 eq	65586.7	3.0 %	4.5 %	0.3 %	51.6 %	40.6 %
OD	kg CFC-11 eq	0.019	1.5 %	0.5 %	0.2 %	0 %	97.8 %
HT	kg 1,4-DB eq	8389.5	7.2 %	2.7 %	0.4 %	4.2 %	85.5 %
TT	kg 1,4-DB eq	11.5	11.5 %	4.1 %	0.4 %	0 %	84.1 %
Ph	kg C_2H_4	81.3	0.7 %	0.2 %	0 %	3.6 %	95.4 %

The same conclusions may be drawn for the case of combined activity C, where the process that most contributes to major impact categories is clearly the “traffic congestion”.

Table 9.39. Results of the operation stage per impact category (combined action C)

Impact category	Unit	TOTAL	Coating of steel	Concrete rehabilit.	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	3094.3	0.6 %	1.0 %	0.2 %	0 %	98.2 %
AC	kg SO_2 eq	1187.8	1.1 %	2.0 %	0.2 %	21.8 %	74.8 %
EU	kg NO_x eq	1007.9	0.7 %	3.3 %	0.4 %	58.3 %	37.3 %
GW	kg CO_2 eq	161992.4	1.2 %	9.1 %	0.5 %	36.0 %	53.2 %
OD	kg CFC-11 eq	0.059	0.5 %	0.8 %	0.2 %	0 %	98.5 %
HT	kg 1,4-DB eq	25415.9	2.4 %	4.5 %	0.5 %	2.4 %	90.2 %
TT	kg 1,4-DB eq	34.6	3.8 %	6.7 %	0.5 %	0 %	89.0 %
Ph	kg C_2H_4	272.1	0.2 %	0.3 %	0 %	1.9 %	97.5 %

Finally, in the case of combined activity D, the process of “traffic congestion” still has a major contribution to most impact categories, although the processes of “asphalt replacement” and “use of equipment” share the importance in some impact categories.

Table 9.40. Results of the operation stage per impact category (combined action D)

Impact category	Unit	TOTAL	Coating of steel	Concrete repair	Asphalt replacem.	Transp. of materials	Use of equipment	Traffic conges.
AD	kg Sb eq	1478.2	1.8 %	0.4 %	17.8 %	0.2 %	0 %	79.8 %
AC	kg SO_2 eq	610.8	2.5 %	0.8 %	8.7 %	0.2 %	31.2 %	56.6 %
EU	kg NO_x eq	647.9	1.4 %	1.0 %	8.0 %	0.4 %	66.7 %	22.6 %
GW	kg CO_2 eq	101198.7	2.0 %	2.9 %	18.5 %	0.4 %	43.0 %	33.2 %
OD	kg CFC-11 eq	0.030	1.4 %	0.3 %	24.0 %	0.2 %	0 %	74.1 %
HT	kg 1,4-DB eq	12908.8	5.8 %	1.8 %	19.5 %	0.4 %	3.5 %	69.0 %
TT	kg 1,4-DB eq	17.1	9.9 %	2.7 %	17.1 %	0.4 %	0 %	69.9 %
Ph	kg C_2H_4	114.0	0.7 %	0.2 %	2.9 %	0 %	3.3 %	93.0 %

The contribution of each combined activity to the aggregated result of the operation stage is illustrated in Figure 9.11, showing that combined activity C, which takes the longer period of time, has the major contribution in all impact categories.

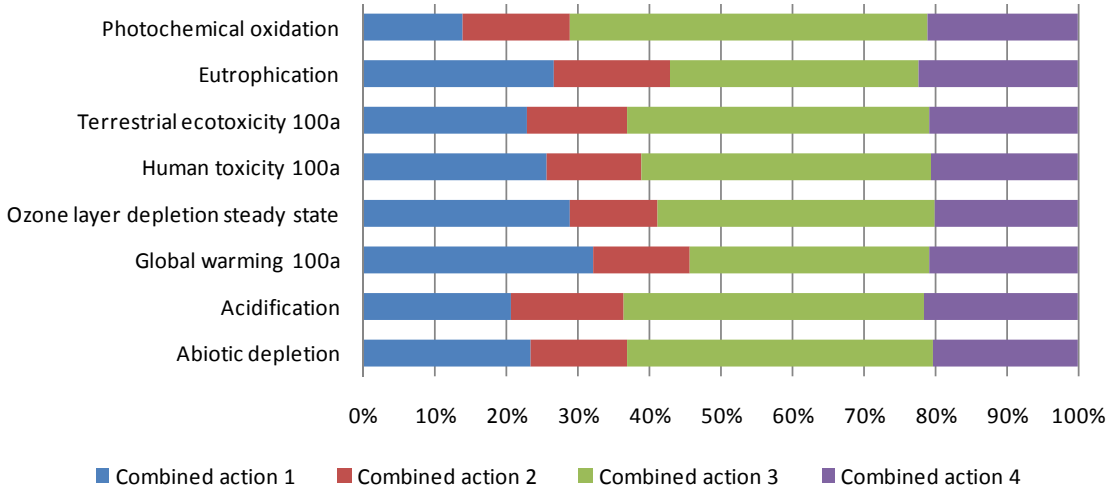

Figure 9.11. Contribution analysis of combined activities during the operation stage

9.5.4. End-of-life stage

9.5.4.1. Transportation of materials and equipments

In the end-of-life stage, it is assumed that the bridge is demolished and the resulting materials are sorted in the demolition place. After sorting, materials are sent for their final destination according to the respective end-of-life scenario. The estimated travelling distances between the sorting place and the final destination of the materials are indicated in Table 9.41. Furthermore, it is assumed that the transportation of materials is done by truck.

Table 9.41. Transportation of materials for the end-of-life stage

Activity	Distance (km)
Deposition of soil	10 km
Landfill of inert materials	50 km
Recycling plant of steel reinforcement	100 km
Recycling plant of structural steel	100 km
Recycling plant of concrete	60 km
Recycling plant of asphalt	20 km

9.5.4.2. Use of equipments

The quantification of emissions due to the use of demolition equipment is based in the plan of demolition represented in Table 9.14, in the estimated list of equipment and the emission factors from the NONROAD2008 model described in Chapter 5.

The number of hours needed for each equipment were estimated from the time plan for demolition and in the work capacity of each equipment (assumed that each equipment was used at full capacity). The total emissions are indicated in Table 9.42.

Table 9.42. Total emissions (in tonnes) due to diesel-fuelled equipment in the end-of-life stage

Activity	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
1st stage	0.005	0.024	0.060	0.005	0.004	0.001	6.900
2nd stage	0.008	0.042	0.101	0.007	0.007	0.002	10.993
3rd stage	0.018	0.067	0.156	0.014	0.013	0.004	17.764
TOTAL	0.031	0.134	0.317	0.025	0.025	0.008	35.657

9.5.4.3. Traffic over and under the bridge

During the demolition of the bridge, it is assumed that traffic over the bridge is diverted to an alternative road or is already being flowing by an alternative bridge. In any case, no emissions and fuel consumption were considered for this traffic. Therefore, in the following paragraphs fuel consumption and emissions are only accounted for traffic under the bridge, as it is assumed that the motorway is still on service by this time.

9.5.4.3.1. Fuel consumption and vehicles' emissions per day

The demolition of the bridge occurs at year 2108 and for this year the respective ADT is indicated in Table 9.7. Moreover, the distribution of traffic flow per hour was considered to be similar as the previous stages. Once again, it was assumed that the demolition work was performed according to the safety rules imposed by national legislation.

The quantification of emissions in the work zone during the operation stage is based in the same model as described in the previous stages and considering a work zone length of 1 km. The detailed calculation of the emissions in work zones is provided in Annex B.

In the year 2108, there will be four lanes of traffic in each direction. In this case, six different scenarios were considered as indicated in Table 9.43. Scenario 1 considers that work activity happens during the day, from 6h – 20h, but the four lanes of traffic are always open. Scenarios 2 and 3 consider the closure of one lane for work activity during the night period (22h – 6h) and day period (6h – 22h), respectively. Scenarios 4 to 6 consider the closure of two lanes of traffic. In scenario 4 the lane closure occurs over the night period (22h – 6h), in scenario 5 the lane closure occurs over the day period (6h – 22h), and in scenario 6 the lane closure occurs over the day but considering a reduced period (9h – 18h). The detailed calculations are provided in Annex B.

Table 9.43. Emissions (per day and per carriageway) in work zone during end-of-life stage

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Max. queue (km)	CO (kg/day)	HC (kg/day)	NOx (kg/day)
1	4	4	0 - 24	6 - 20	0	70.50	0.88	0.64
2	4	3	0 - 24	22 - 6	0	70.50	0.89	0.64
3	4	3	0 - 24	6 - 22	0	70.50	1.69	0.82
4	4	2	0 - 24	22 - 6	0	70.50	0.90	0.65
5	4	2	0 - 24	6 - 22	5.6	1193.23	107.92	24.22
6	4	2	0 - 24	9 - 18	3.6	443.72	37.46	8.68

Based in the same reference scenarios, fuel consumption is calculated and the values are indicated in Table 9.44.

Table 9.44. Fuel consumption (per day and per carriageway) in work zone during end-of-life stage

Scenario	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Fuel	
					Gasoline	Diesel
					(kg/day)	(kg/day)
1	4	4	0 - 24	6 - 20	465.23	809.70
2	4	3	0 - 24	22 - 6	466.54	811.18
3	4	3	0 - 24	6 - 22	611.17	983.78
4	4	2	0 - 24	22 - 6	467.58	812.36
5	4	2	0 - 24	6 - 22	3105.01	4073.80
6	4	2	0 - 24	9 - 18	1630.75	2264.26

9.5.4.3.2. Fuel consumption and vehicles' emissions during end-of-life

For the calculation of the total emissions during the entire demolition period, five global scenarios were considered, as indicated in Table 9.45. The demolition period is estimated to take 23 days (see Table 9.14). During this period, it is estimated there would be always four lanes of traffic in each direction, although with reduced speed, except for four working days (see demolition plan in Annex B). These four working days correspond to the demolition of the central span of the structure. The central span is divided into two parts. Each part needs 2 days (8 hours per day) to be demolished. During this period, the corresponding carriageway has to be closed to the traffic underneath. During the closure of a carriageway, traffic has to be diverted to the other carriageway, resulting in three or, in the worst case, two lanes of traffic in each direction. Table 9.45 indicates the global scenarios resulting from the above considerations.

Table 9.45. Total emissions and fuel consumption in work zone during end-of-life stage

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	Night work (3 lanes open)	3243.00	40.56	29.44	21411.06	37258.04
Global scenario 2	Day work (3 lanes open)	3243.00	46.96	30.88	22568.10	38638.84
Global scenario 3	Night work (2 lanes open)	3243.00	40.64	29.52	21419.38	37267.48
Global scenario 4	Day work (2 lanes open)	12224.84	896.80	218.08	42518.82	63359.00
Global scenario 5	Reduce day work (2 lanes open)	6228.76	333.12	93.76	30724.74	48882.68

For the calculation of the total emissions in the end-of-life stage, the best scenario, i.e. global scenario 1, was considered.

9.5.4.4. Synthesis of the end-of-life stage

In the end-of-life stage, four scenarios are considered, according to Table 9.15. In all scenarios, it is assumed that the bridge is demolished and the materials are sorted in the demolition place before being sent to their final destination; though, no transport is necessary between the demolition place and the sorting plant. This is usually the procedure according to current legislation as referred in Chapter 2.

The first scenario assumes that the steel structure is going to be recycled, assuming a recycling rate of 85%. As discussed in Chapter 5, a closed-loop is assumed. In second scenario, it is considered that 80% of the steel structure in reused, resulting in a pure closed-loop. The third scenario is similar to the first scenario but additionally it is considered that 80% of concrete is recycled using an open-loop approach. The economic allocation procedure discussed in Chapter 5 is used. Finally, the fourth scenario is similar to the previous one, except in the allocation approach considered. In this case, a cut-off rule was used for all the materials sent for recycling. For the recycling of asphalt a cut-off rule was used in all end-of-life scenarios due to the lack of data in relation to the respective recycling process. In relation to steel reinforcement, it was assumed that it was recycled in all scenarios using the same close-loop approach as for structural steel. Figure 9.12 represents the general unit processes included in this stage.

Before the evaluation of the environmental indicators used in the previous stages, another indicator is used in this sub-section: demolition waste. Taking into account end-of-life scenarios described in the previous paragraph, the gross amount of demolition waste produced in each

case is indicated in Table 9.46. It should be noted that the efficiency of recycling processes was not considered, which would increase the amount of waste produced in all scenarios.

Table 9.46. Demolition waste produced in end-of-life stage

	1st scenario	2nd scenario	3rd scenario	4th scenario
Volume of demolition waste (ton)	1662	1669	350	350

From Table 9.46, it is noticed the importance of recycling in the reduction of waste produced in this stage. The impacts due to the recycling share of materials and to the share of materials sent to a landfill of inert materials are considered in the set of indicators used in the following paragraphs. Therefore, to avoid double counting of impacts, this indicator will not be further used.

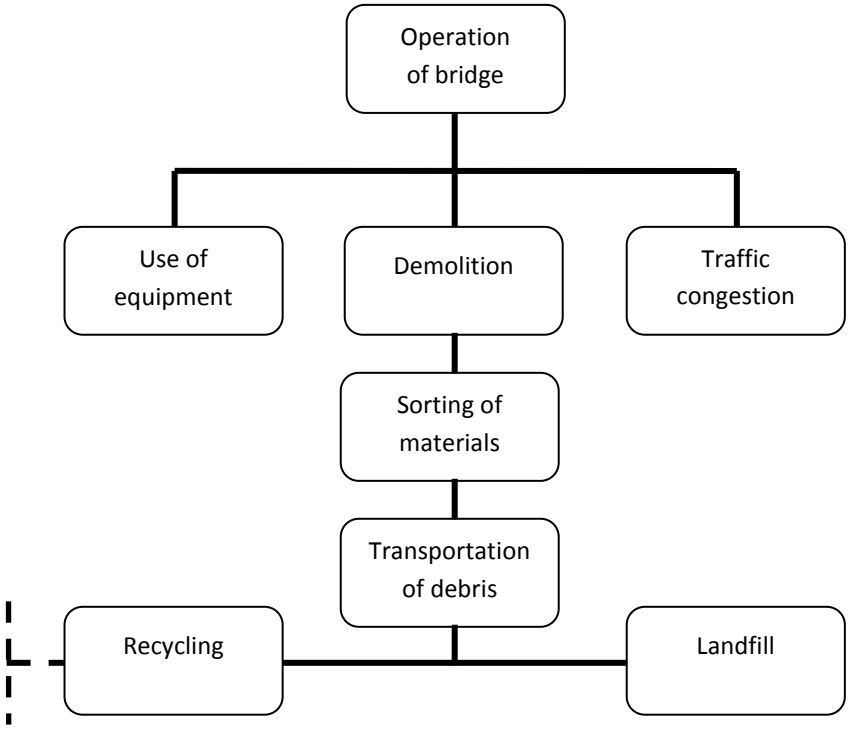

Figure 9.12. Processes included in the end-of-life stage

Hence, total emissions per impact category of this stage, considering the first end-of-life scenario, are indicated in Table 9.47. This table also indicates the contribution of each process per impact category.

Table 9.47. Results of the end-of-life stage per impact category

Impact category	Unit	TOTAL	Disassemble of structure	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	825.1	-32.6 %	6.9 %	0 %	60.5 %
AC	kg SO_2 eq	411.7	-27.1 %	7.6 %	18.7 %	46.6 %
EU	kg NO_x eq	631.6	-2.4 %	14.4 %	57.3 %	25.9 %
GW	kg CO_2 eq	-83212.3	-64.8 %	8.1 %	12.8 %	14.2 %
OD	kg CFC-11 eq	0.035	11.3 %	10.3 %	0 %	78.3 %
HT	kg 1,4-DB eq	19729.7	26.5 %	16.5 %	2.0 %	54.9 %
TT	kg 1,4-DB eq	27.5	31.4 %	15.7 %	0 %	52.9 %
Ph	kg C_2H_4	32.3	-42.0 %	1.4 %	2.0 %	54.6 %

The negative values in the previous table represent the credits given to the recycling processes. The contribution of each process per impact category is also illustrated in Figure 9.13, showing a major contribution from the "traffic congestion" as observed also for the previous stages.

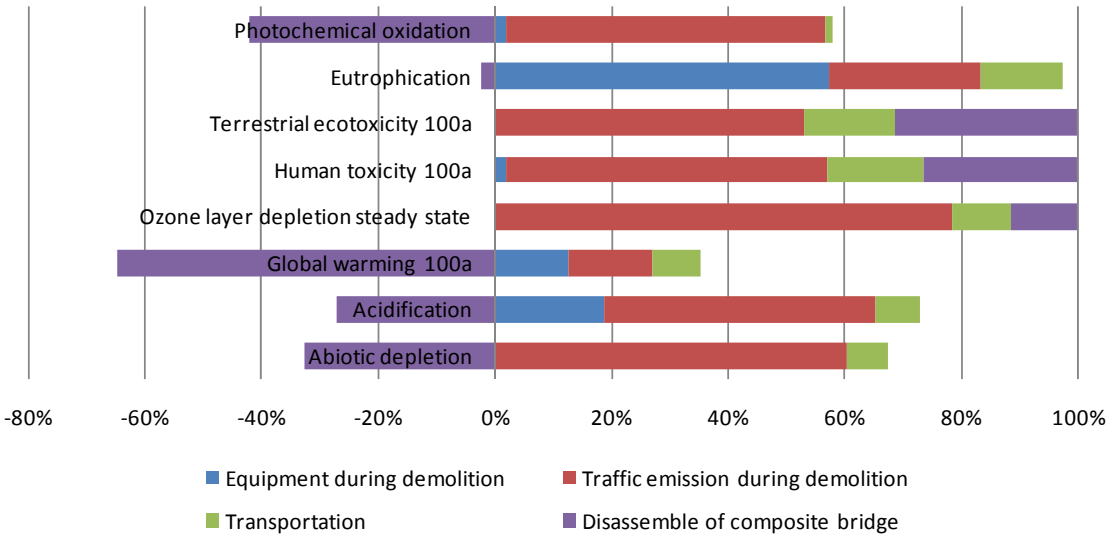

Figure 9.13. Contribution analysis of processes during the end-of-life stage

A comparison between end-of life scenarios for each impact category is provided in Figure 9.14.

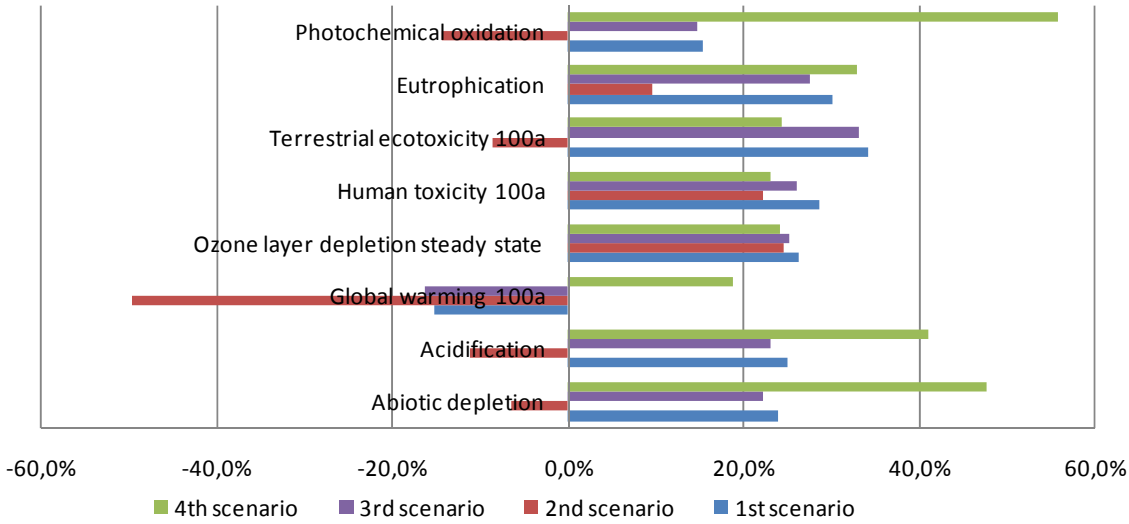

Figure 9.14. Comparison between end-of-life scenarios

9.5.5. Results of the environmental life-cycle analysis

9.5.5.1. Aggregate life-cycle results

In the previous sections, the partial results per stage have been presented. In this sub-section the results of the different stages are summed up in relation to each impact category and the aggregate results are presented in Table 9.48, considering the first end-of-life scenario.

To better understand the contribution of each stage to the aggregated result, these results are also represented in the contribution graph of Figure 9.15.

Table 9.48. Life-cycle results per life cycle stage (for 1st end-of-life scenario)

Impact category	Unit	Total	Materials	Construction	Operation	End-of-life
AD	kg Sb eq	13840.6	26.2 %	15.6 %	52.4 %	5.7 %
AC	kg SO_2 eq	6542.0	38.0 %	12.7 %	43.3 %	6.0 %
EU	kg NO_x eq	6146.2	30.4 %	12.1 %	47.2 %	10.3 %
GW	kg CO_2 eq	1385826.0	56.4 %	7.2 %	31.1 %	-5.4 %
OD	kg CFC-11 eq	0.24	4.9 %	17.4 %	63.4 %	14.2 %
HT	kg 1,4-DB eq	197283.7	49.3 %	9.4 %	31.8 %	9.5 %
TT	kg 1,4-DB eq	274.3	51.4 %	8.8 %	29.9 %	9.9 %
Ph	kg C_2H_4	1021.3	24.7 %	19.1 %	53.1 %	3.1 %

The material production stage is the stage that most contributes to impact categories Global warming (GWP), Human Toxicity (HT) and Terrestrial toxicity (TT), with percentages above 50% and close to 50%, respectively. On the other side, this stage has a minimum contribution to impact category Ozone Depletion (Ph), with a percentage less than 10%. The operation stage has a major contribution to most impact categories except GWP, HT and TT.

Stage of construction has a contribution less than 20% for all impact categories; while end-of-life stage has a global contribution of less than 10%.

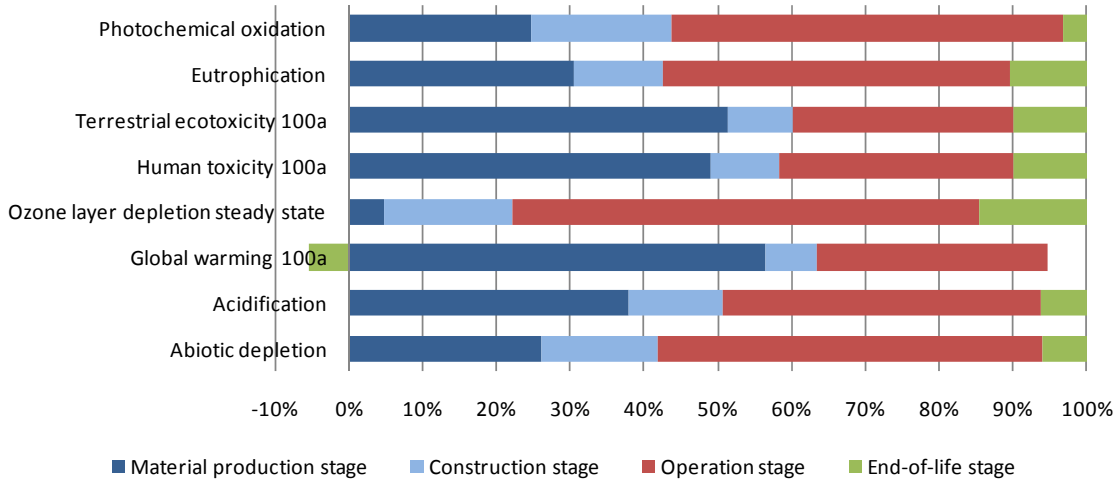

Figure 9.15. Contribution of each stage to impact category

The results presented in Figure 9.15 were rearranged according to the main process involved in the life-cycle analysis and the results are represented in Figure 9.16. Four main processes were identified: (i) production of material, (ii) transportation of materials and equipments, (iii) use of equipment, and (iv) traffic congestion. According to Figure 9.16, the processes of production of materials and traffic congestion are dominant for most impact categories. The production of materials has a contribution above 50% for the impact categories of “global warming”, “human toxicity” and “terrestrial toxicity”; while traffic congestion has a major contribution (above 50%) for the impact categories of “photochemical oxidation”, “ozone depletion” and “abiotic depletion”. The process of use of equipment has a significant contribution to the impact categories of “eutrophication”, “global warming” and “acidification”.

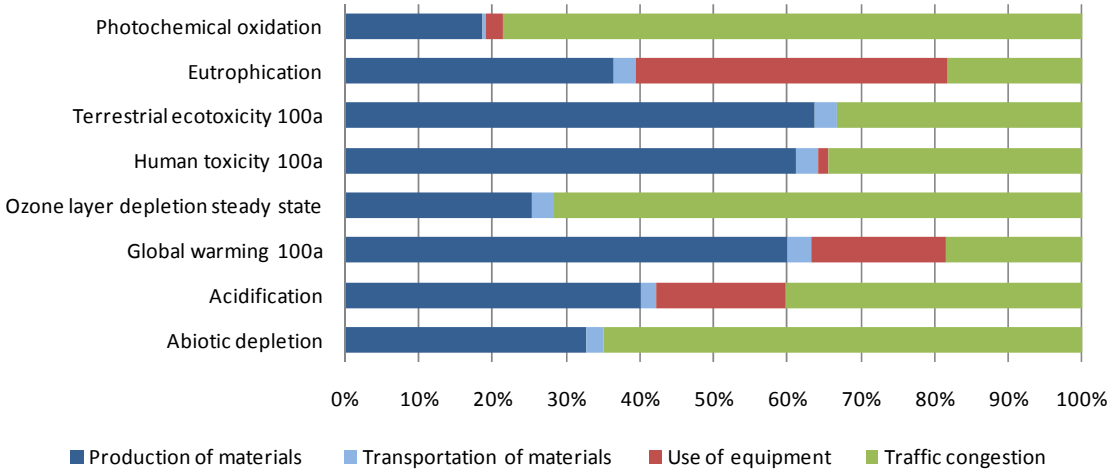

Figure 9.16. Contribution of each main process to impact category

9.5.5.2. Normalized results

Using the normalized set of values proposed in Chapter 6, the life cycle values obtained for each impact category are represented in Figure 9.17, considering the end-of-life scenarios described in Table 9.15.

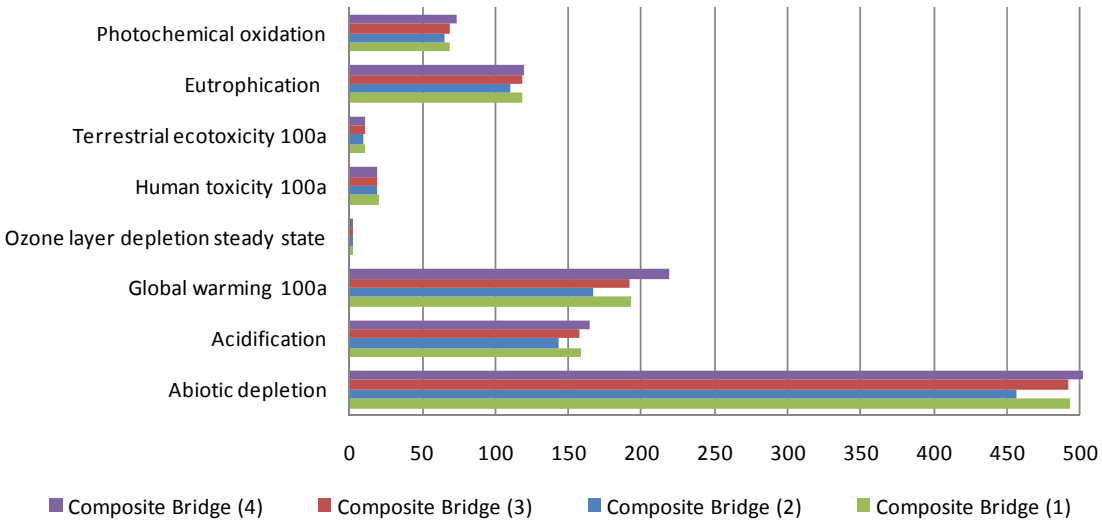

Figure 9.17. Normalized results for each impact category

From the previous graph it is observed that Abiotic Depletion and Global Warming are the most significant impact categories; Acidification and Eutrophication, although representing a significant value, are lower when compared with the previous ones.

9.5.5.3. Weighted results

Finally, using the set of weights defined in Chapter 6, the resulting life cycle results are presented in Figure 9.18.

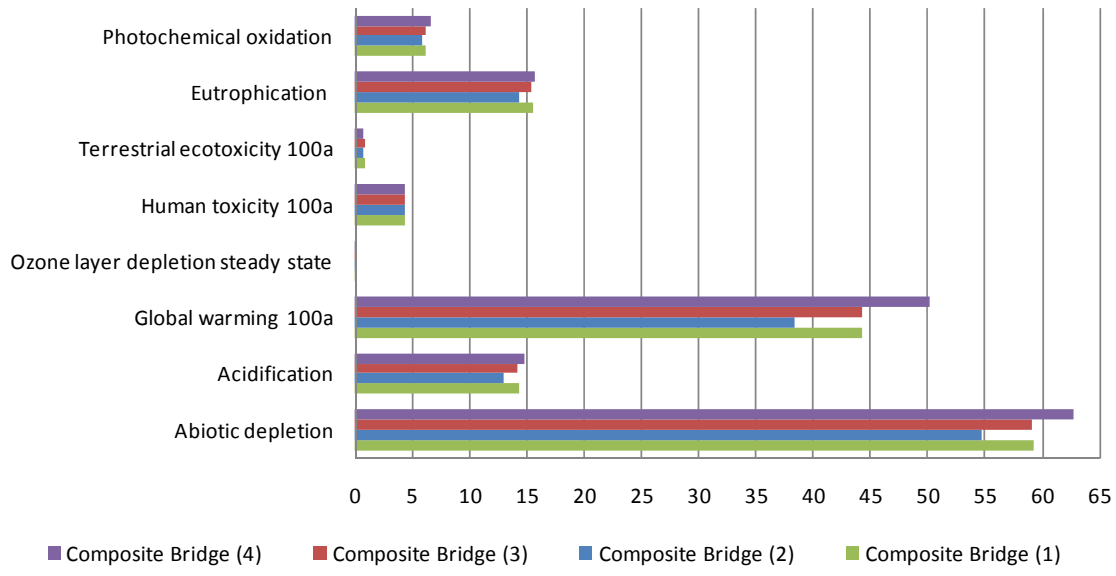

Figure 9.18. Weighted results for each impact category

Abiotic Depletion and Global Warming are still the most significant impact categories; Acidification and Eutrophication have also a significant value when compared with the remaining categories.

The same results divided by the area of the deck are indicated in Table 9.49. The first column refers to life-cycle results considering end-of-life scenario 1. This was considered the base scenario. The other columns refer to life-cycle results considering the remaining end-of-life scenarios of Table 9.15 and the respective variation in relation to the results presented in the first column (base scenario). The best results were obtained considering end-of-life scenario 2, in which the steel structure is re-used. However, taking into account that the period of analysis is 100 years, the reuse of 80% of the steel structure is a very optimistic scenario. The results indicated in the 3rd column, corresponding to end-of-life scenario 3, have a small variation in relation to the base scenario, showing that recycling of concrete has little influence in the final results (less than 1%). Finally, the last column referred to end-of-life scenario 4. In this case, the "cut-off" rule is conservative for some impact categories, mainly "Global Warming", while for the impact categories of "Ozone depletion", "Human toxicity" and "Terrestrial toxicity" the results decreased in relation to the base scenario.

Table 9.49. Life-cycle results of each impact category (per m^2)

Impact category	C. bridge (1)	Composite bridge (2)		Composite bridge (3)		Composite bridge (4)	
	Total	Total	Δ	Total	Δ	Total	Δ
AD	6.32E-02	5.84E-02	-7.5%	6.30E-02	-0.2%	6.69E-02	5.9%
AC	1.52E-02	1.38E-02	-9.1%	1.52E-02	-0.2%	1.58E-02	4.1%
EU	1.65E-02	1.53E-02	-7.0%	1.64E-02	-0.4%	1.67E-02	1.0%
GW	4.73E-02	4.09E-02	-13.5%	4.72E-02	-0.2%	5.36E-02	13.4%
OD	1.41E-04	1.39E-04	-0.9%	1.40E-04	-0.4%	1.39E-04	-1.2%
HT	4.65E-03	4.54E-03	-2.3%	4.62E-03	-0.5%	4.56E-03	-1.9%
TT	8.35E-04	7.30E-04	-12.6%	8.33E-04	-0.2%	8.10E-04	-2.9%
Ph	6.61E-03	6.23E-03	-5.7%	6.60E-03	-0.1%	7.10E-03	7.4%

The base scenario was selected taking account the current practice in the sector. However, considering that recycling has being increasingly promoted, it is predicted that in the near future recycling of concrete will be a standard practice. Therefore, life-cycle analysis, considering end-of-life scenario 3 will be used in the next section.

The results presented in Figure 9.19, which referred to end-of-life scenario 3, highlight the importance of the stages of material production and operation to the life cycle environmental analysis.

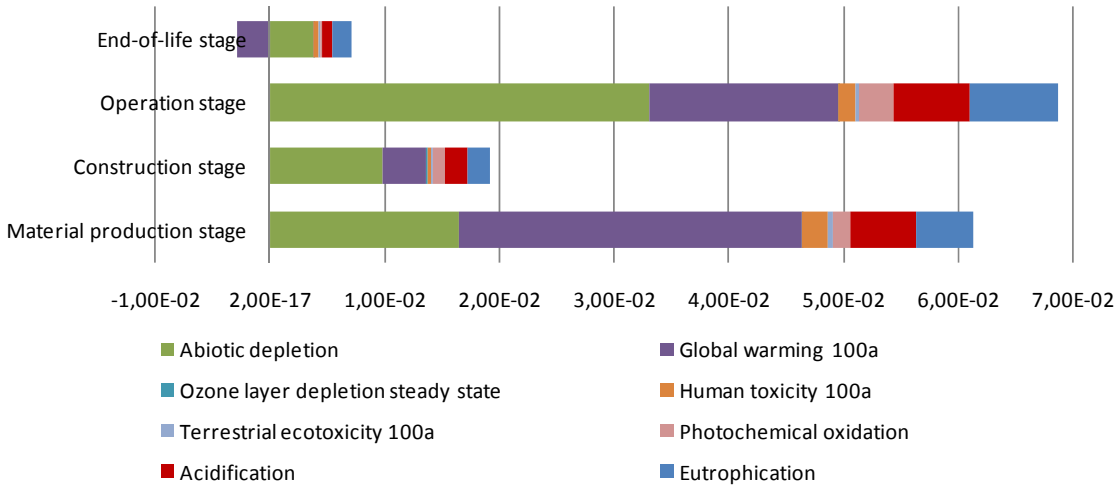

Figure 9.19. Weighted results per stage (considering end-of-life scenario 3)

9.5.6. Uncertainty analysis

In this section, the LCEA described in the previous sections was performed once again considering three types of uncertainties: parameter uncertainty, uncertainties due to choices and model uncertainties.

Parameter uncertainty was considered in the input data of the inventory stage. The approach used to quantify this type of uncertainty was described in Chapter 5. Thus, instead of fix values, input data was considered by the respective probability functions.

In the impact assessment stage, two types of uncertainty were considered: scenario uncertainty due to the choice of different time horizon for impact categories of global warming, ozone layer depletion, human toxicity and terrestrial ecotoxicity; and model uncertainty due to the lack of spatial differentiation for the impact categories of acidification and eutrophication. Uncertainty was also considered for the impact categories of photochemical oxidation and abiotic depletion considering a simplified approach. This procedure was described in Chapter 6, section 6.2.4. The outcome of the life cycle impact assessment, considering end-life scenario no. 3, was presented in Box 6.3 – Table 6.49.

Uncertainty is the normalization and weighting steps was also taken into account in the analysis presented in this section. The calculation of uncertainties considered in each case was detailed in Chapter 6, clauses 6.3.2.4 and 6.3.3.3.5, respectively.

The uncertainty analysis was performed by Monte Carlo simulation, considering 1000 iterations. The probabilistic analysis was performed by Microsoft Excel @Risk [9.9] add-in software package.

The life cycle environmental results of the simulation for the impact categories of Abiotic depletion, Acidification, Eutrophication and Global warming are represented in Figure 9.20 by the respective 90% confidence interval of the mean value. These results were obtained considering end-of-life scenario 3.

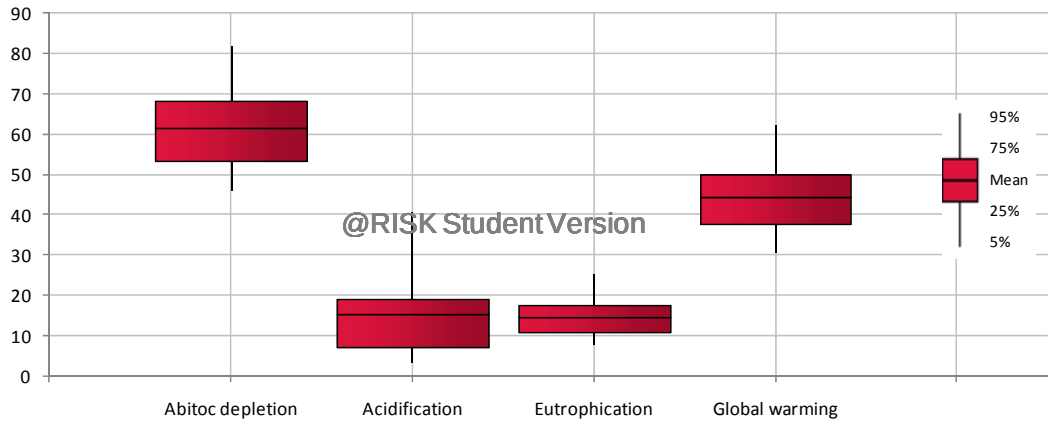

Figure 9.20. Results of the simulations for Abiotic depletion, Acidification, Eutrophication and Global warming

A distribution was fitted to the results of these simulations and the validity of the assumed distributions was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov*. The best-fit distributions for the impact categories represented in Figure 9.20 are indicated in Table 9.50.

Table 9.50. Best-fit distributions for the simulation results

	Abiotic depletion	Acidification	Eutrophication	Global warming
Distribution	lognormal	lognormal	lognormal	lognormal
Mean	61.62	15.58	14.77	44.35
SD	11.23	13.03	5.24	9.87

Likewise, the results for the remaining impact categories are represented in Figure 9.21 by the respective 90% confidence interval of the mean value.

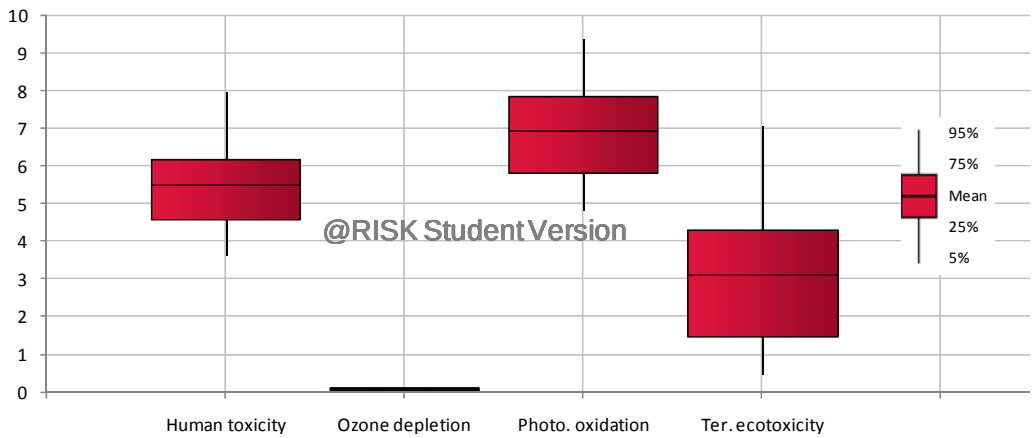

Figure 9.21. Results of the simulations for Human toxicity, Ozone layer depletion, Photochemical oxidation and Terrestrial ecotoxicity

Likewise, a distribution was fitted to the results of these simulations and the validity of the assumed distributions was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov*.

Table 9.51. Best-fit distributions for the simulation results

	Human toxicity	Ozone layer depl.	Photo. oxidation	Terres. ecotoxicity
Distribution	lognormal	lognormal	lognormal	lognormal
Mean	5.52	0.06	6.97	3.13
SD	1.35	0.03	1.48	2.21

Considering the results of the LCEA with the other end-of-life scenarios, similar distributions were obtained. For instance, for the impact category Global warming, the results obtained for the different analysis are represented in Figure 9.22, where GW_i represents the cumulative probability distribution of the LCEA result taking into account end-of-life scenario *i* (see Table 9.15).

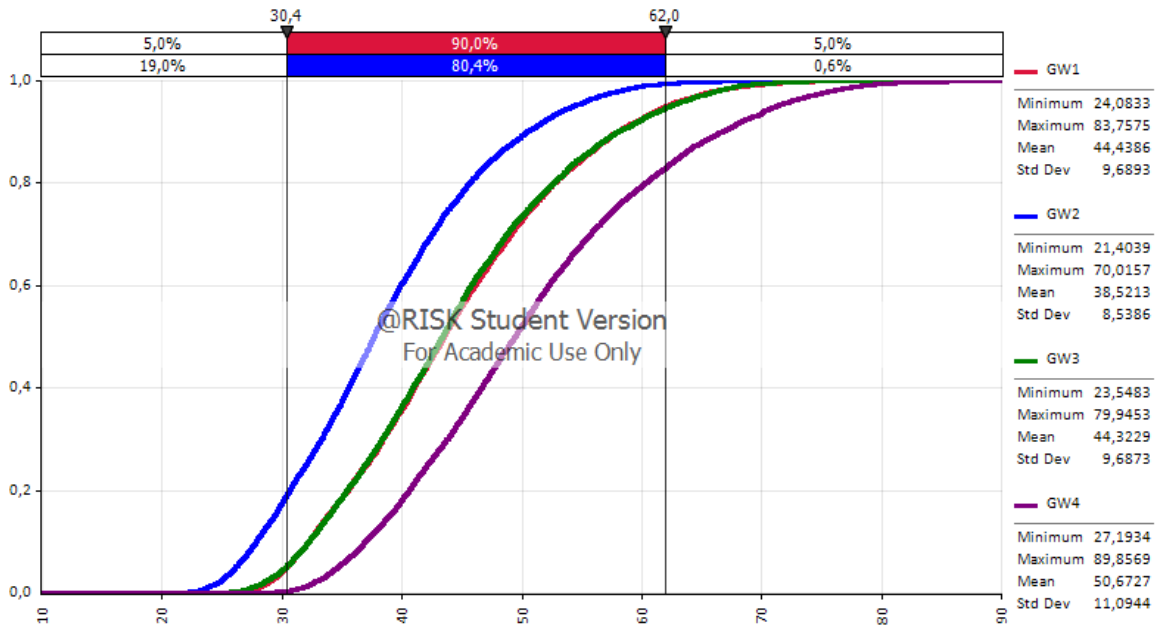

Figure 9.22. Cumulative probability distributions of life cycle analysis with different end-of-life scenarios

The figure illustrates the probability of each analysis obtaining a total value less than or equal to any variable value, for example, there is a 50% probability that the result of the LCEA considering the first end-of-life scenario will achieve a total value of less than or equal to 43.51. For the same probability, the results of the LCEA taken into account the second, third and fourth scenarios are 37.66, 43.37 and 49.44, respectively.

9.6. LIFE CYCLE COST ANALYSIS

9.6.1. Initial construction cost

The initial cost of the structure is 535 142.88 €, about 571.30 €/m^2, and it was calculated based on the bill of materials indicated in Table 9.1 and the unit costs in Table 9.2.

9.6.2. Operation costs

Over the period of 100 years, the bridge is assumed to be maintained and rehabilitated according to the plan indicated in Table 9.12.

The costs per year are based on the unit costs and frequencies indicated in Table 9.11. These costs are illustrated in Figure 9.23. Present values of accumulated costs are also represented in the same figure, considering a discount rate of 3.5%.

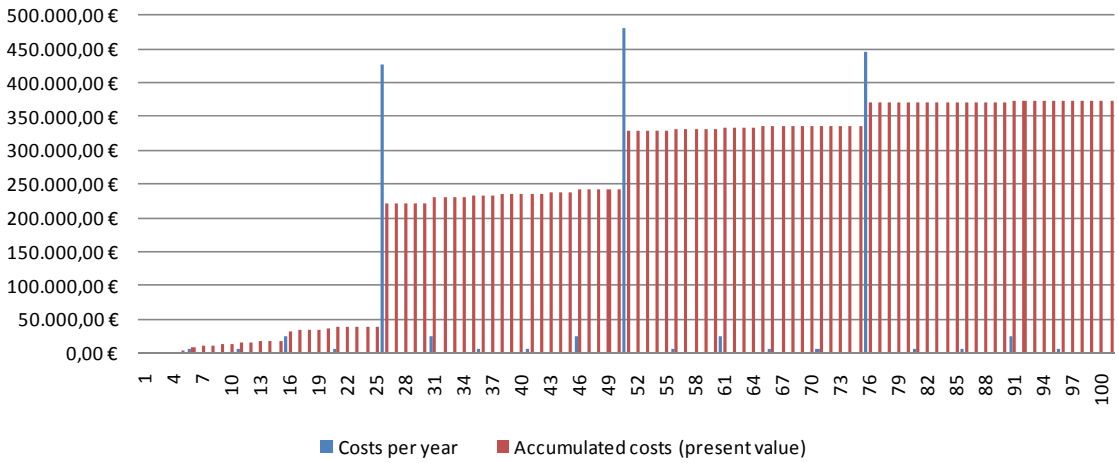

Figure 9.23. Operation costs of the bridge over its service life

The present value of the total cost for maintenance and rehabilitation for the period of 100 years is thus 373 227.61 €, which represents a cost of 398.44 €/m^2.

9.6.3. End-of-life cost

End-of-life costs encompass the cost of labour work, cost of equipments, cost of road warning signage, cost of transportation and cost for deposition of materials and/or revenue due to recycling of materials.

From information provided by a construction company the cost for demolition of a similar bridge is about 100€/m^2. This cost includes the cost of labour, the cost of equipment and fuel, the cost of ancillary material, the cost of sorting the materials, the cost of all the necessary measures to ensure the safety of the work zone and the cost for cleaning the zone.

This stage includes also the transportation of materials to the disposal/recycling site and the cost or revenue due to landfill or recycling, respectively. As indicated in section 9.4.3, demolition waste is classified into the following categories:

i) 17 01 01 - Concrete;

ii) 17 03 - Bituminous mixtures, coal tar and tarred products;

iii) 17 04 05 - Iron and steel.

These wastes are sent for recycling or deposit in a landfill. The cost of transportation requires the estimation of the distances from the demolition place to the disposal/recycling place, the

efficiency of the trucks and the price of the fuel. The cost for transportation is given in Table 9.52 assuming trucks with an average load of 25 tonnes.

Table 9.52. Cost for transportation of demolition waste materials

	Mass (tonnes)	No. of trucks	Distance to disposal/recycling site (km)	Fuel efficiency (l/km)	Cost of fuel (€/l)	Transportation fuel cost (€)
Concrete	1619.2	65	60	0.29(*)	1.065	2 409.03
Bituminous	89.6	4	20	0.29(*)	1.065	49.42
Iron and steel	199.2	8	100	0.29(*)	1.065	49.42
						2 952.66

(*) Considering the density of diesel 0.84 kg/l

In the case of the waste sent for a disposal site, the facility operator charges a fee to assume possession of the demolition waste. The cost to dispose Construction and Demolition Waste (C&DW) varies according to the type of material and the degree of contamination of the C&DW. For instance, according to the information received from an operator in Portugal, the cost for disposal of inert material varies from 4.0€- 80.0€ per tonne, depending on the percentage of non-inert materials included. Considering that the materials were sorted in the demolition place and assuming the fees indicated in Table 9.53, the cost for disposal of demolition waste is about 20 672.00€.

Table 9.53. Cost of fees for disposal

	Mass (tonnes)	Fee for disposal (€/tonne)	Cost for disposal (€)
Concrete	1619.2	10	16 192.00
Bituminous	89.6	50	4 480.00
			20 672.00

In the case of steel, it is assumed that the dealer pays the contractor 100€/tonne (this price is usually depending on the price of steel, according to the information from the U.S. recycling institute a price of $120/ton of steel may be considered). This figure has a negative sign since it is a revenue and not a cost for the contractor. Hence, the money earned from steel scrap is given in Table 9.54.

Table 9.54. Revenue due to scrap

	Mass (tonnes)	Price of scrap (€/tonne)	Scrap revenue (€)
Iron and steel	199.2	100	19 920.00

Hence, the total end-of-life cost is given by the sum of the previous components, leading to a total of 97 375.81 €. This cost is supposed to take place in year 100, and considering a discount rate of 3.5%, the net present value is 3 121.88 €.

Considering the end-of-life scenarios indicated in Table 9.15, and considering the same revenue for the recycling and the reuse of the steel structure, the end-of-life cost indicated in the previous paragraph corresponds to the cost of the first and second end-of-life scenarios. For the third scenario, the fee for the disposal of concrete material is not considered. However, no value is available for the revenue of the inert material and hence this value was neglected. Finally, for the fourth scenario a cut-off rule is used. In this case, the burdens and credits due to recycling materials are not considered. Therefore, to be consistent with this rule, the scrap revenue is cut-off from the final accounting. The end-of-life costs for each scenario are summarized in Table 9.55.

Table 9.55. End-of-life costs for each scenario

	1st scenario	2nd scenario	3rd scenario	4th scenario
Total cost (€)	97 375.81	97 375.81	81 183.81	117 295.81
PV total cost (€)	3 121.88	3 121.88	2 602.76	3 760.52
PV Total cost (€/m^2)	3.33	3.33	2.78	4.01

9.6.4. Life cycle cost

The compilation of the costs calculated in the previous sections lead to the total life-cycle net present cost (PVLCC) of 911 492.37 €, using a discount rate of 3.5% and the first end-of-life scenario. This represents a total cost of about 973.08 €/m^2. The costs per year and the accumulated present value of the bridge are illustrated in Figure 9.24.

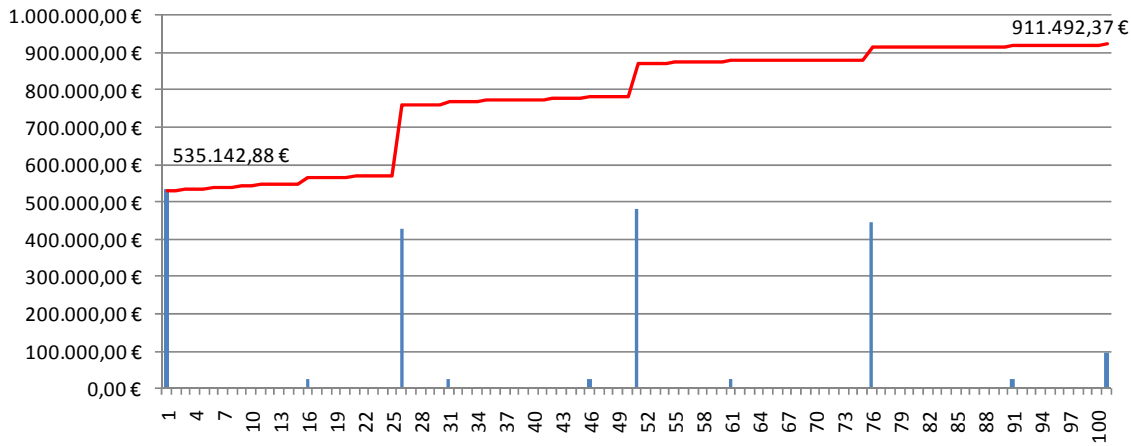

Figure 9.24. Life cycle costs of the composite bridge and accumulated present value (line in red)

Considering the four end-of-life scenarios, the respective life cycle net present costs (PVLCC) are summarized in Table 9.56.

Table 9.56. PVLCC considering different end-of-life scenarios

	1st scenario	2nd scenario	3rd scenario	4th scenario
PV LCC (€)	911 492.37	911 492.37	910 973.25	912 131.01
PV LCC (€/m^2)	973.08	973.08	972.52	973.76

9.6.5. Sensitivity analysis

To identify which are the most important variables affecting the life cycle cost of the bridge, a sensitivity analysis is performed as described in the following paragraph.

The sensitivity analysis is performed using the Microsoft Excel TopRank [9.10] add-in software package. The input variables tested in this analysis were: (i) the initial cost of construction; (ii) the unit costs in Table 9.11; (iii) the end-of-life cost; and (iv) the discount rate (d). All the input variables were assigned a variation of -20% and 20%.

A tornado graph (represented in Figure 9.25) was obtained comparing the effects of the most important input variables on the total life cycle cost of the structure. For each variable a bar is drawn between the extreme values of the final cost, calculated using the lower and upper input values. The importance of the variables is recognized from this graph, with the most important

variable plotted on the top of the graph and the variables with decreasing importance plotted down the vertical axis.

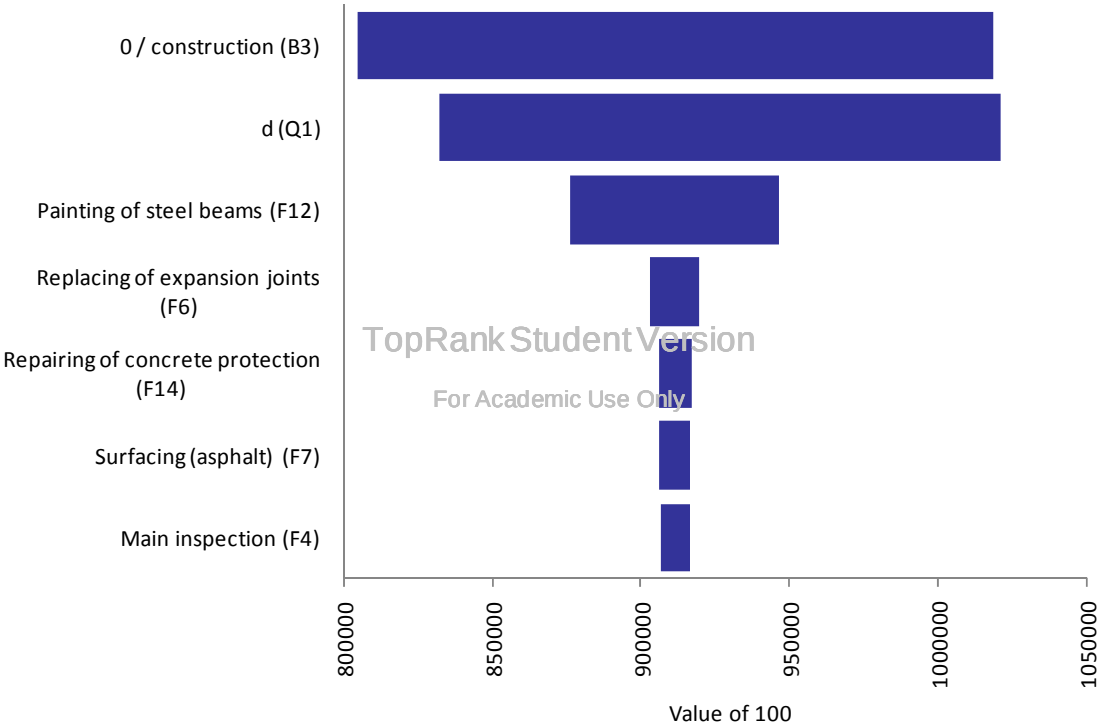

Figure 9.25. Tornado graph of the life cycle present value of the bridge

Hence, the most important variable is the construction cost of the bridge. This cost occurs at the base year of the study and thus, no discount is made. The second most important variable is the discount rate (d). This was already discussed in Chapter 7. The unit cost for re-coating of the steel structure (in €/m^2) has also a significant importance. Costs for replacing expansion joints (in €/m), for repairing the concrete structure (€/m^2) and for new surface replacement (€/m^2) come next in terms of importance.

The same conclusions can be drawn from the spider diagram represented in Figure 9.26. In this diagram, the slope of each line depicts the relative change in the final cost of the bridge per unit change in the input variable. Hence, the three most important variables are the discount rate, the construction cost and the cost for re-coating of the steel structure.

In the case of the discount rate (d), the relationship between the input and the output (final cost) is nonlinear and therefore this relationship is represented by a curve. For all the remaining variables, there's a linear relationship between the input and the output.

As observed from the diagram a small increase of 10% of the initial cost increases the final cost of the structure in 5%; whereas a small increase in the discount rate of 10% reduces the final cost of the structure in 5%.

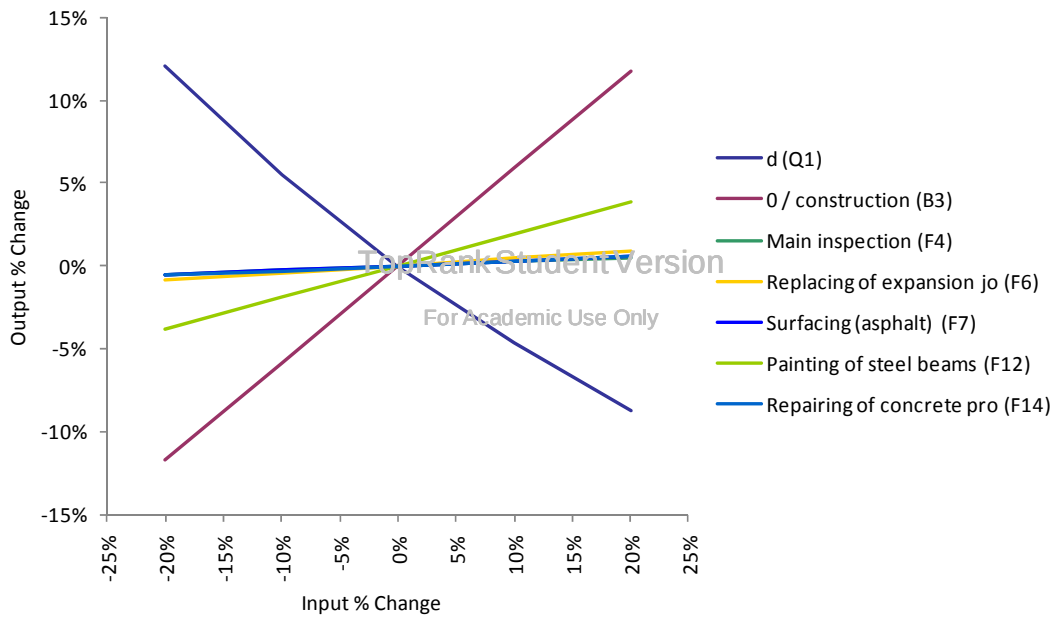

Figure 9.26. Spider diagram of the life cycle present value of the bridge

This sensitivity analysis allowed to identify which are the most important parameters in the life cycle cost analysis. The discount rate is naturally one of the most important parameters. However, the sensitivity analysis takes into account neither the simultaneous variation of different parameters, nor the relation between variables. Therefore, a more accurate analysis is performed in the following section by means of a probabilistic analysis.

9.6.6. Uncertainty analysis

9.6.6.1. Construction cost

The construction cost of the structure was calculated based on the bill of quantities provided by BRISA. These quantities are usually estimated based on the project. Therefore, in order to take into consideration some variations, both in terms of quantities and costs, a lognormal distribution was assigned to each value (quantities and respective cost), with mean values equal to the values indicated in Table 9.1 and Table 9.2, and a standard deviation of 10% and 25% of the mean value, for the quantities and the costs, respectively.

Hence, by running a Monte Carlo simulation with 10000 iterations, a mean value of 535 134.47€ and a standard deviation of 29 602.58€ were obtained. The probabilistic analysis was performed by Microsoft Excel @Risk [9.9] add-in software package. A distribution was fitted to the results of this simulation and the validity of the assumed distribution was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov*.

In both tests, the best distribution to fit the simulation was a lognormal distribution, as represented in Figure 9.27. Thus, for the initial cost of the structure lognormal distribution is considered with mean value 535 134.20 € and standard deviation of 29 600.10 €.

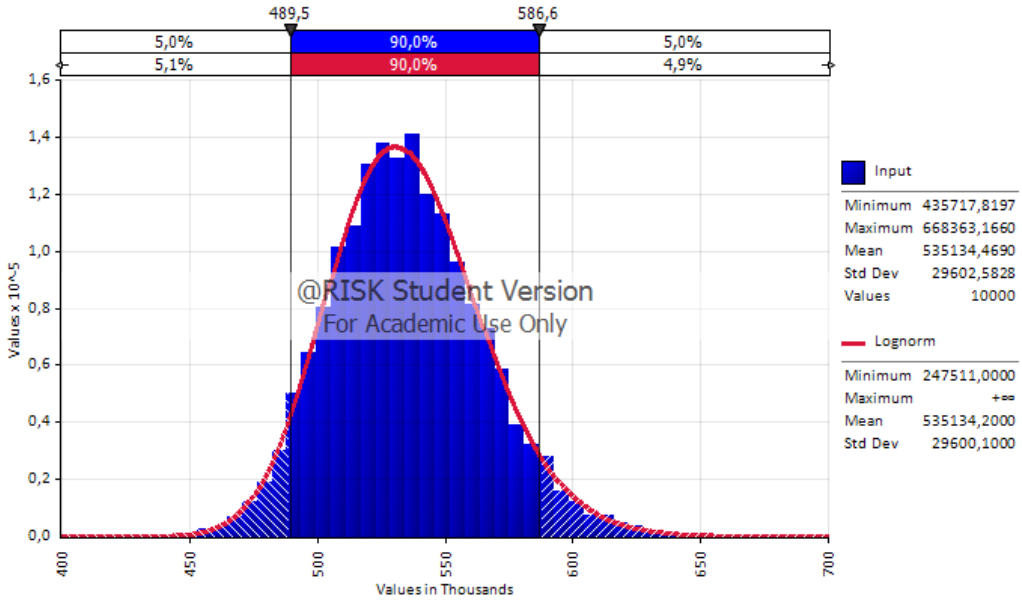

Figure 9.27. Best-fit distribution (red-line) according to *chi-square* test and *Kolmogorov-Smirnov* test

9.6.6.2. Discount rate and time of intervention

The importance of the discount rate was already discussed in Chapter 7. The higher the discount rate the less important are the costs occurring over the life cycle of the bridge, particularly those occurring in the medium to the long term. In this case study, a triangular distribution with mean value of 3.5% and minimum and maximum values of 2.5% and 4.5%, respectively, is considered.

Under the same discount rate, the time at which a cost occurs is also a very important issue, as the present value of the cost decreases as the time increases.

As observed in section 9.6.5, the unit cost for re-coating of the steel structure, the cost for repairing and the cost for rehabilitation of the concrete deck are also important parameters in the life cycle analysis. Therefore, the time at which the costs occur should also be an important parameter. The time considered for each activity was indicated in Table 9.11. In this case study a triangular distribution is defined for these three variables, considering the mean value as indicated in Table 9.11 and minimum and maximum values of 20 and 30 years, respectively. The assumed distribution covers the range of values indicated for the service life, according to Table 9.10.

The time between each activity is also taken into account, by correlating the time of the first intervention with the time of the subsequent interventions.

9.6.6.3. Probabilistic-based life cycle cost analysis of the bridge

The probabilistic life cycle cost analysis of the bridge was performed taking into account the above considerations and the uncertainty in the unit costs for the maintenance of the structure. Thus, a probability distribution was assigned to each unit cost of Table 9.11. For all variables, except for the unit cost of the re-coating of the steel structure, the cost for replacement of expansion joints and the unit cost of maintenance and rehabilitation of the concrete structure, a lognormal distribution was assigned with mean value equal to the value given in the table and a standard deviation of 10% of the mean value.

Given the importance of the remaining unit costs, a higher uncertainty was considered for those variables. Hence, for the other variables in Table 9.11, a lognormal distribution was assigned with mean value equal to the value given in the table and a standard deviation of 30% of the mean value.

The total life cycle cost of the bridge was obtained by running a Monte Carlo simulation with 10000 iterations, leading to a mean value of 918 202.84 € and a 90% confidence interval of the mean value between 791 000.00€ and 1 079 000.00€. Likewise, the probabilistic analysis was performed by Microsoft Excel @Risk [9.9] add-in software package.

The best distribution to fit the simulation is a lognormal distribution with a mean value of 918 206.80 € and a standard deviation of 87 906.50 €. The result of the simulation and the best-fit distribution (red line) are both represented in Figure 9.28.

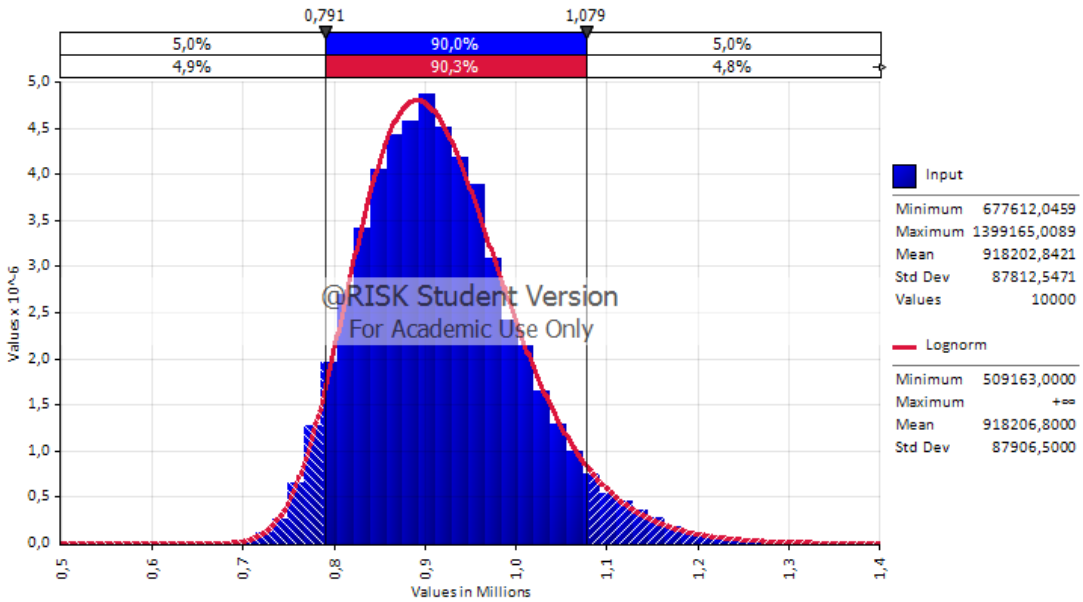

Figure 9.28. PVLCC of the bridge: best-fit distribution according to *chi-square* test and *Kolmogorov-Smirnov* test

The accumulated mean cost over the bridge life cycle is represented in Figure 9.29, together with the 90% confidence interval of the mean value.

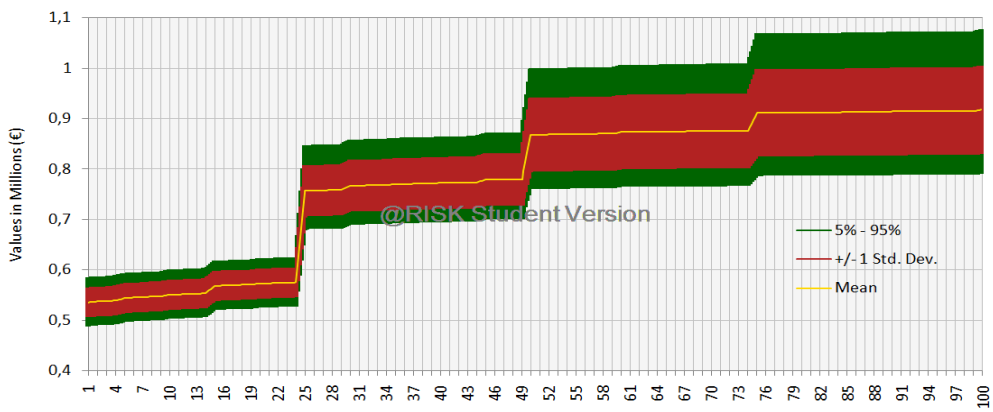

Figure 9.29. Accumulated present value cost (90% confidence interval of the mean value)

These results are relative to the life cycle analysis considering the 1st end-of-life scenario, for the other scenarios similar simulations were performed. In all cases, a lognormal distribution was fitted to the results of the simulations. The mean value and standard deviation of each distribution are indicated in Table 9.57.

Table 9.57. Probability distributions of the PVLCC considering different end-of-life scenarios

	1st and 2nd scenarios	3rd scenario	4th scenario
PV LCC (€)	LN(918206.80; 87906.50)	LN(917852.10; 88156.90)	LN(918794.30; 87774.20)

9.7. LIFE CYCLE SOCIAL ANALYSIS

9.7.1. Introduction

The impacts on the users of the motorway are quantified based on the methodology discussed in Chapter 8. However, in this case study only the mandatory indicators are used, as no comprehensive data is currently available for the assessment of the optional indicators discussed in Chapter 8. Hence, three types of costs are hereby considered for all stages: the cost of vehicle operation (VOC), the cost of driver delay (DDC) and the cost of safety.

9.7.2. Social impacts due to construction

The construction of the bridge took 87 days as illustrated in the construction plan provided in Annex B. Over this period of time traffic restrictions are imposed according to the requirements of Portuguese legislation regarding traffic conditions and safety of users through work zones (see Annex A).

As already referred the bridge is new, therefore no traffic was considered over the bridge during the construction stage. Thus, the construction of the bridge only affects the traffic in the motorway.

The calculation of users' costs during the construction stage is based on the same scenarios considered for the life cycle environmental analysis. Therefore, no further description is provided in this section in relation to scenarios.

Hence, user costs, per day and per carriageway, are summarized in Table 9.58. The detail calculation of each cost is provided in Annex B.

Table 9.58. User costs (per day and per carriageway) in work zone during construction

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	DDC (€/day)	VOC (€/day)	Safety (€/day)
1	2	2	0 - 24	6 - 20	904.91	1311.58	8.76
2	2	1	0 - 24	22 - 6	908.12	1316.34	8.79
3	2	1	0 - 24	6 - 22	3984.53	2841.30	14.64

Likewise, total user costs for the construction stage where evaluated based on the same global scenarios described for the life cycle environmental analysis (see section 9.5.2). Hence, total costs are summarized in Table 9.59.

Table 9.59. Total user costs during construction stage

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	Night work (1 lane open)	157492.86	228272.04	1524.60
Global scenario 2	Day work (1 lane open)	194409.78	246571.56	1594.80

9.7.3. Social impacts during the operation of the bridge

Likewise, the calculation of users' costs during the operation stage is based on the same scenarios considered for the life cycle environmental analysis (see section 9.5.3). Therefore no further description is provided in this section.

Therefore, user costs relative to traffic over the motorway, per day, are summarized in Table 9.60; whereas user costs relative to traffic under the motorway, per day and per carriageway, are summarized in Table 9.61, Table 9.62 and Table 9.63, for years 2033, 2058 and 2083, respectively. Detail calculations of costs are provided in Annex B.

Table 9.60. User costs (per day and per road) in work zone during operation stage

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	DDC (€/day)	VOC (€/day)	Safety (€/day)
1	2	2	0 - 24	6 - 20	364.45	535.33	2.76
2	2	1	0 - 24	22 - 6	365.18	536.41	2.76
3	2	1	0 - 24	6 - 22	453.37	667.16	3.46

Table 9.61. User costs (per day and per carriageway) in work zone during operation stage (2033)

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	DDC (€/day)	VOC (€/day)	Safety (€/day)
1	3	3	0 - 24	6 - 20	1949.64	2810.74	13.75
2	3	2	0 - 24	22 - 6	1955.1	2818.83	13.79
3	3	2	0 - 24	6 - 22	7161.82	5637.66	21.12
4	3	2	0 - 24	9 - 18	4095.65	4266.27	17.84

Table 9.62. User costs (per day and per carriageway) in work zone during operation stage (2058)

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	DDC (€/day)	VOC (€/day)	Safety (€/day)
1	4	4	0 - 24	6 - 20	2080.92	3009.63	14.81
2	4	3	0 - 24	22 - 6	2085.24	3016.02	14.84
3	4	3	0 - 24	6 - 22	2490.76	3611.16	17.93
4	4	2	0 - 24	22 - 6	2088.65	3021.09	14.87
5	4	2	0 - 24	6 - 22	25924.97	10597.27	32.27
6	4	2	0 - 24	9 - 18	11683.81	6863.34	24.36

Table 9.63. User costs (per day and per carriageway) in work zone during operation stage (year 2083)

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	DDC (€/day)	VOC (€/day)	Safety (€/day)
1	4	4	0 - 24	6 - 20	2295.03	3314.46	16.26
2	4	3	0 - 24	22 - 6	2300.05	3321.91	16.3
3	4	3	0 - 24	6 - 22	2851.21	4091.93	19.95
4	4	2	0 - 24	22 - 6	2304.02	3327.8	16.33
5	4	2	0 - 24	6 - 22	47034.47	15967.96	43.49
6	4	2	0 - 24	9 - 18	19025.96	9262.19	30.13

Total user costs for the operation stage where evaluated based on the same global scenarios described for the life cycle environmental analysis. These costs are summarized in Table 9.64, Table 9.65, Table 9.66 and 0, for combined actions A, B, C and D, respectively.

Table 9.64. Total user costs for Combined Action A

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	Night work (1 lane open)	5842.88	8582.56	44.16
Global scenario 2	Day work (1 lane open)	7253.92	10674.56	55.36

Table 9.65. Total user costs for Combined Action B

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway + night work crossover	74499.33	107629.36	529.58
Global scenario 2	night work motorway + day work crossover	75469.42	109067.61	537.28
Global scenario 3	day work motorway + night work crossover	251527.81	203469.58	778.80
Global scenario 4	day work motorway + day work crossover	252497.90	204907.83	786.50
Global scenario 5	reduce day work motorway + night work crossover	147278.03	156842.32	667.28
Global scenario 6	reduce day work motorway + day work crossover	148248.12	158280.57	674.98

Table 9.66. Total user costs for Combined Action C

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway (3 lanes open)+ night work crossover	237229.53	343295.74	1691.92
Global scenario 2	night work motorway (3 lanes open) + day work crossover	238199.62	344733.99	1699.62
Global scenario 3	day work motorway (3 lanes open) + night work crossover	265615.93	384955.54	1908.22
Global scenario 4	day work motorway (3 lanes open) + day work crossover	266586.02	386393.79	1915.92
Global scenario 5	night work motorway (2 lanes open)+ night work crossover	237468.23	343650.64	1694.02
Global scenario 6	night work motorway (2 lanes open) + day work crossover	238438.32	345088.89	1701.72
Global scenario 7	day work motorway (2 lanes open) + night work crossover	1906010.63	873983.24	2912.02
Global scenario 8	day work motorway (2 lanes open) + day work crossover	1906980.72	875421.49	2919.72
Global scenario 9	reduce day work motorway (2 lanes open) + night work crossover	909129.43	612608.14	2358.32
Global scenario 10	reduce day work motorway (2 lanes open)+ day work crossover	910099.52	614046.39	2366.02

Table 9.67. Total user costs for Combined Action D

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway (3 lanes open) + night work crossover	92070.51	133316.64	659.08
Global scenario 2	night work motorway (3 lanes open) + day work crossover	94451.64	136846.89	677.98
Global scenario 3	day work motorway (3 lanes open) + night work crossover	110809.95	159497.32	783.18
Global scenario 4	day work motorway (3 lanes open) + day work crossover	113191.08	163027.57	802.08
Global scenario 5	night work motorway (2 lanes open)+ night work crossover	92205.49	133516.90	660.10
Global scenario 6	night work motorway (2 lanes open) + day work crossover	94586.62	137047.15	679.00
Global scenario 7	day work motorway (2 lanes open) + night work crossover	1613040.79	563282.34	1583.54
Global scenario 8	day work motorway (2 lanes open) + day work crossover	1615421.92	566812.59	1602.44
Global scenario 9	reduce day work motorway (2 lanes open) + night work crossover	660751.45	335286.16	1129.30
Global scenario 10	reduce day work motorway (2 lanes open)+ day work crossover	663132.58	338816.41	1148.20

The summary of user costs, per combined activity, is represented in Figure 9.32, considering the best scenario in each case. Naturally, the longer the duration of the activity, the higher are the respective user costs.

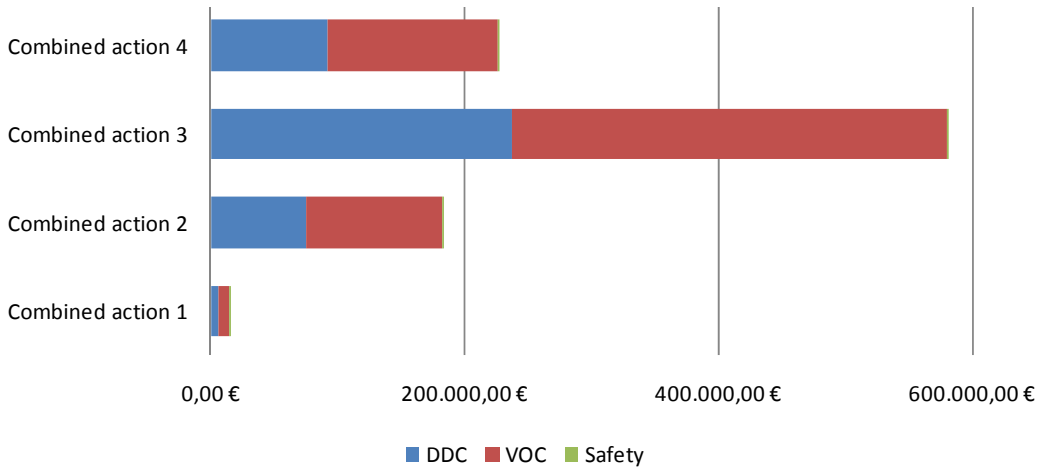

Figure 9.30. User costs per combined maintenance action

The user costs per year and the present value of the accumulated user costs are represented in Figure 9.31, considering a discount rate of 3.5%. These costs are also related to global scenario 1 in each combined activity.

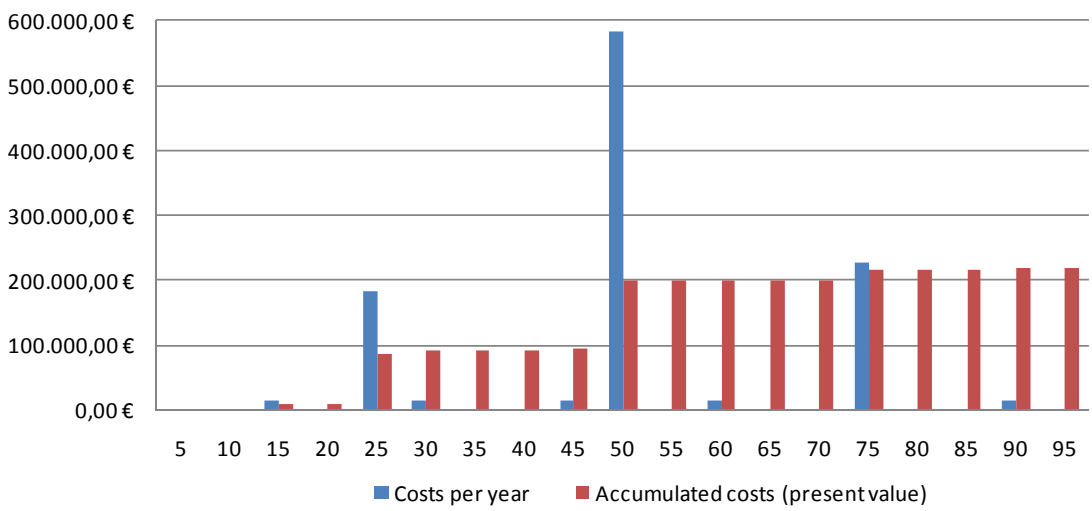

Figure 9.31. User costs of the bridge over its service life

9.7.4. Social impacts due to the demolition of the bridge

Like in the previous stages, the calculation of users' costs during the end-of-life stage is based on the same scenarios considered for the life cycle environmental analysis (see section 9.5.4). Therefore, no further description is provided in this section. Also, during this stage it is assumed that the traffic over the bridge is detoured to an alternative road and thus no user costs are taken into consideration in this traffic analysis.

Therefore, user costs, per day and per carriageway, are summarized in Table 9.58. Detail calculations of costs are provided in Annex B.

Table 9.68. User costs (per day and per carriageway) in work zone during end-of-life stage

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	DDC (€/day)	VOC (€/day)	Safety (€/day)
1	4	4	0 - 24	6 - 20	2450.72	3535.99	17.32
2	4	3	0 - 24	22 - 6	2456.27	3544.22	17.36
3	4	3	0 - 24	6 - 22	3145.25	4469.94	21.45
4	4	2	0 - 24	22 - 6	2460.66	3350.73	17.39
5	4	2	0 - 24	6 - 22	65809.68	20682.36	53.14
6	4	2	0 - 24	9 - 18	24827.79	11135.86	34.57

Hence, total user costs for the end-of-life stage where evaluated based on the same global scenarios described for the life cycle environmental analysis, which are summarized in Table 9.69.

Table 9.69. Total user costs during the demolition stage

Scenario	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway (3 lanes open)	112777.52	162721.38	797.04
Global scenario 2	day work motorway (3 lanes open)	118289.36	170127.14	829.76
Global scenario 3	night work motorway (2 lanes open)	112812.64	162773.46	797.28
Global scenario 4	day work motorway (2 lanes open)	619604.80	299826.50	1083.28
Global scenario 5	reduce day work motorway (2 lanes open)	291749.68	223454.50	934.72

9.7.5. Life cycle social impact

The compilation of the costs calculated in the previous sections lead to the total present value life cycle social cost of 614 174.00 €, which represents a cost of about 656.00 €/m^2. The costs per year and the accumulated present value cost of the bridge are illustrated in Figure 9.32. In this analysis a discount rate of 3.5% was considered.

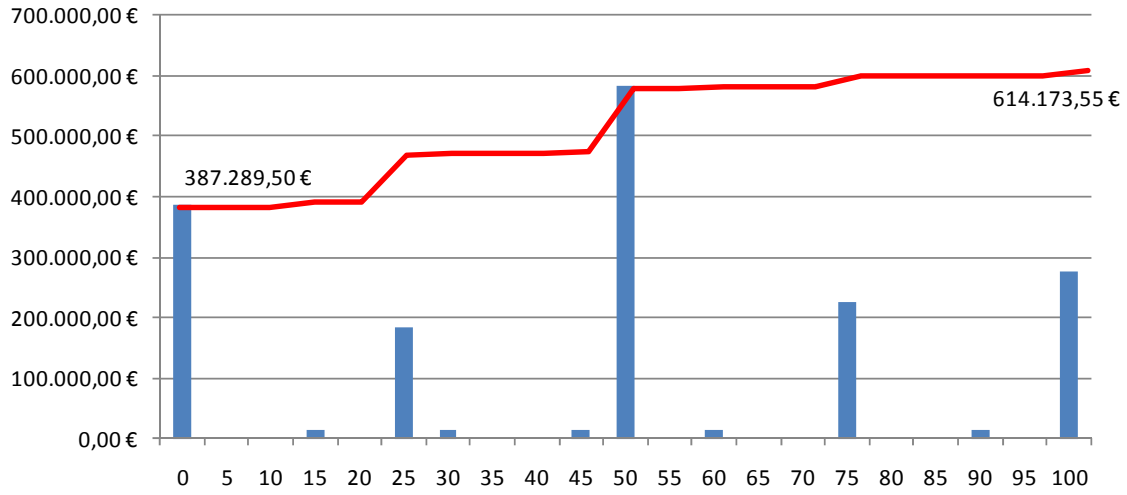

Figure 9.32. Life cycle social costs of the composite bridge and accumulated present value (line in red)

Considering the different stages over the life cycle of the bridge, the present value of the social cost per stage is indicated in Table 9.70.

Table 9.70. Social costs of the bridge per stage (present value)

Construction	Operation	End-of-life
387 289.50 €	218 025.97 €	8 858.08 €
413.46 €/m^2	232.76 €/m^2	9.46 €/m^2

The final value of the three indicators considered in the LCSA (the cost of vehicle operation (VOC), the cost of driver delay (DDC) and the cost of safety, are indicated in Table 9.71.

Table 9.71. Life cycle social costs of the bridge (present value)

DDC	VOC	Safety
249 902.93 €	362 084.41 €	2 186.21 €
266. 79 €/m^2	386.55 €/m^2	2.33 €/m^2

Life cycle social costs of the bridge were evaluated based on the best scenarios defined for each stage. As observed over the previous sections, the consideration of bad options in relation to traffic management may drastically increase social costs. The accumulated life cycle user costs considering the “best scenarios” and the “worst scenarios” for each bridge intervention are indicated in Figure 9.33.

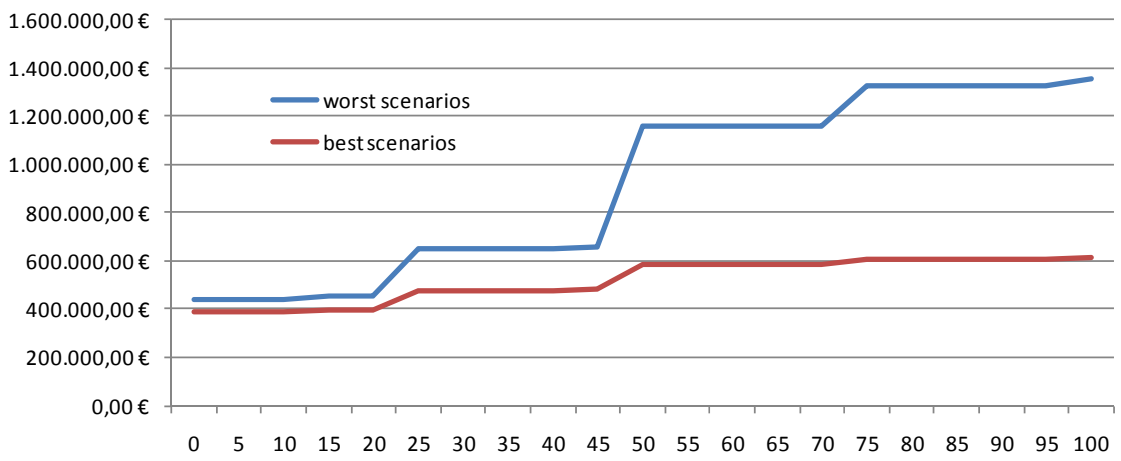

Figure 9.33. Accumulated life cycle user costs considering "best scenarios" and "worst scenarios"

As observed from the previous figure, a bad management of the construction work in the motorway can double life cycle user costs.

9.7.6. Uncertainty analysis

The uncertainties in the calculation of DDC, VOC and safety costs were discussed in Chapter 8. In the probabilistic analysis presented in this section, those uncertainties were taken into account. The probability distributions of the discount rate and time of intervention indicated in section 9.6.6 were also considered.

The total life cycle social cost of the bridge was obtained by running a Monte Carlo simulation with 10000 iterations, leading to a mean value of 618 371.95 € and a 90% interval of confidence of the mean value between 517 100.00 € and 732 100.00 €. The probabilistic analysis was performed by Microsoft Excel @Risk [9.9] add-in software package.

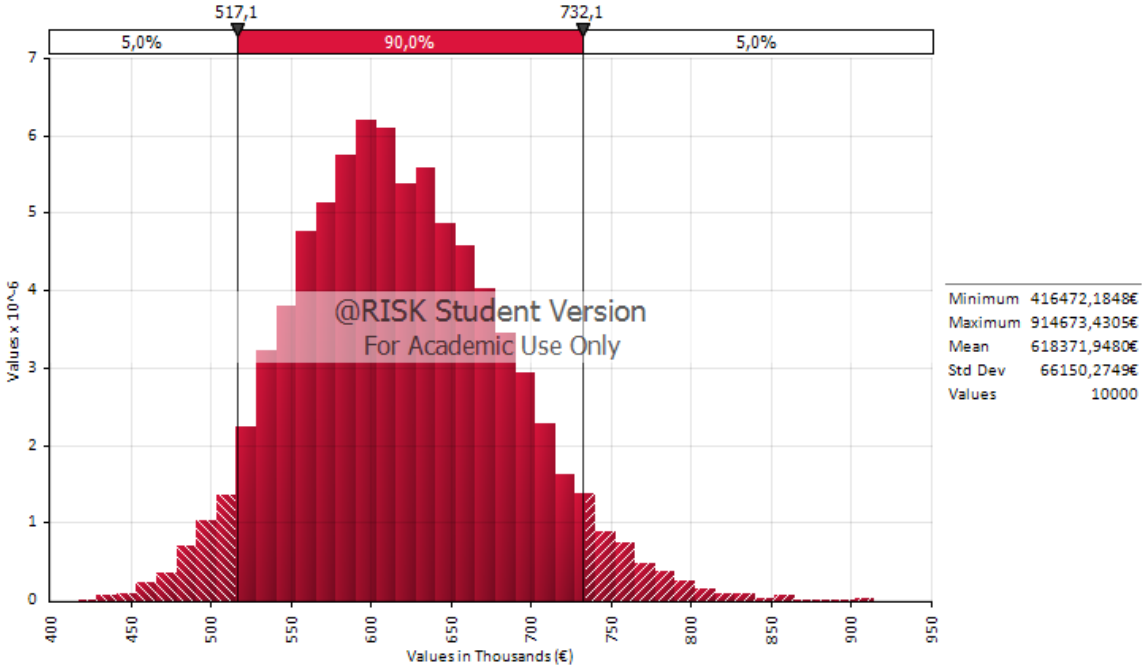

Figure 9.34. PVLCC of the bridge:

The accumulated mean cost over the bridge life cycle is represented in Figure 9.29, together with the 90% confidence interval of the mean value.

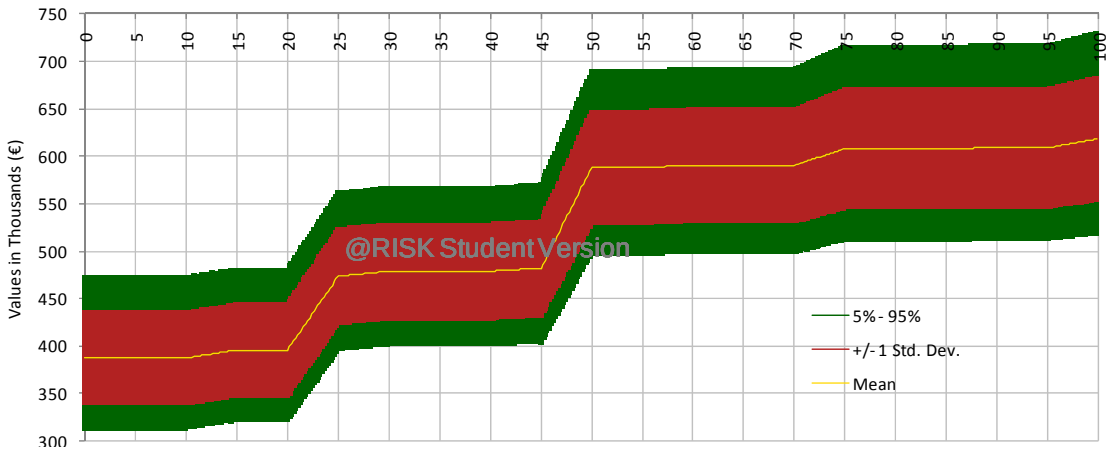

Figure 9.35. Accumulated present value cost (90% confidence interval)

Considering total life cycle social cost divided by DDC, VOC and safety cost, the results obtained from the simulations are indicated in Table 9.72, together with the best-fit distributions in each case. The validity of the fitted distributions was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov.*

Table 9.72. Simulation results and best-fit distributions of life cycle social costs

		D.D.C.	V.O.C.	Safety
Simulation results	Mean	251 568.18 €	364 504.21 €	2 198.22 €
	SD	33 041.46 €	40 592.68 €	243.34 €
Best-fit distribution: lognormal	Mean	251 568.50 €	364 503.70 €	2198.23 €
	SD	33 057.60 €	40 600.70 €	243.43 €

9.8. CONCLUDING REMARKS

This chapter described the application of the integral life cycle approach described in the previous chapters to a composite bridge, considering the environmental, economic and social criteria.

The aim of the life cycle approach was to assess the life cycle performance of the bridge, enabling the identification of the process(es) with major potential impacts and its causes. This was accomplished by a comprehensive data collection and impact evaluation in terms of the three main aspects.

Data collection is undoubtedly the most time-consuming task in life cycle analysis and it is currently a major barrier to the implementation of such analysis. Moreover, lack of data, particularly environmental data, was a problem often encountered along the study. In this case and whenever possible, data was replaced by the most similar data available.

In the environmental analysis, it was concluded that the stages of material production and operation are the ones with major impacts (see Figure 9.19). In these stages, “global warming” and “abiotic depletion” are the most important impact categories, followed by “acidification”

and “eutrophication”. The main causes are the consumption of primary materials and other resources (e.g. fuel).

In terms of processes involved in the analysis, production of materials and traffic congestion are the most important processes, with major contribution to all impact categories (see Figure 9.16). From this analysis, it may be concluded that the use of construction materials with lesser environmental impacts and a well-planned management of construction work throughout the life cycle of the bridge are important factors to consider in the pursuit of an improved life cycle environmental performance.

The normalization step of the environmental analysis allowed a more effective identification of the most important environmental categories. When comparing the results of Table 9.48 with normalized values of Figure 9.17, it is clear that judgements based on non-normalized values may lead to biased conclusions. Therefore, it is recommended to use normalization values of impact categories for a more accurate identification of major potential environmental impacts.

Weighted values of environmental categories confirmed the results obtained by normalization. However, in this case, the impact category of “global warming” was given higher importance reflecting current concerns about this important environmental problem.

In the life cycle cost analysis two major variables were identified as having major influence in the outcome of the analysis: the construction cost and the discount rate. Maintenance costs are also important factors, particularly the maintenance costs of major structural components. This highlights the importance of the durability of the materials.

The use of a high discount rate disregards the importance of maintenance and rehabilitation costs and provides a high importance to initial costs. When the aim of the analysis is to minimize impacts over the bridge life cycle, then the use of a low discount rate is recommended.

The results of the life cycle social analysis allow to conclude about the importance of minimizing maintenance and rehabilitation activities over the service life of the structure. According to established scenarios, total life cycle social cost is about 67% of the total life cycle cost of the bridge. Furthermore, this result is based on the use of best scenarios in each situation. If bad options are taken, then the results may worsen dramatically. This shows the importance of including social criteria in the life cycle design of bridges.

In addition, a probabilistic analysis was performed for the evaluation of environmental, economic and social criteria. The aim of this analysis was to consider the simultaneous variation of different parameters and scenarios in order to address the uncertainty in the involved variables and in the choices that are needed throughout the life cycle analysis. The probabilistic analysis provides an estimated range of values that is likely to include an unknown population parameter (e.g. the mean value). Therefore, the results of probabilistic analysis enable to verify the robustness of the solution and to draw conclusions that are more reliable. The advantages of the probabilistic analysis will be further discussed in Chapter 12.

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CHAPTER 10. LIFE CYCLE ANALYSIS OF A PRECAST CONCRETE BRIDGE

10.1. INTRODUCTION

This chapter describes the application of the integral life cycle methodology to the second case study. This case study refers to a pre-stressed concrete bridge that was built in 2006 in a new segment of the dual carriageway A17. This motorway links the cities of *Marinha Grande* and *Aveiro*, with an extension of 32 km, and it is also operated by BRISA.

The case study described in this chapter is a new bridge crossing the motorway, denominated PS 13. The present analysis was performed after the completion of the project. The results obtained in the present analysis did not influence under no circumstances the design and construction of the bridge.

In the first part of this chapter, a description of the collected data is provided. The second part of this chapter provides detailed calculations and presents the outcome of the environmental, economical and social analysis. In the last part of the chapter, conclusions are drawn in relation to the outcome of the analysis.

All project details of the bridge and some details for its construction were provided by BRISA. For the demolition of the bridge, data was obtained from a similar project of a bridge demolition, which was also supplied by BRISA. All the remaining data needed for the analysis was estimated based on direct interviews with different types of professionals and from a literature survey.

10.2. GOAL AND SCOPE OF THE CASE STUDY

10.2.1. Goal of the analysis

The goal of the analysis is to make a comprehensive account of the environmental, economical and social impacts of a motorway bridge over its service life. The service life is assumed to be 100 years and it is also assumed that at the end of this period the bridge is dismantled. Moreover, the aim of this life cycle analysis is to highlight the processes that most contribute to total account of impacts, enabling to set strategies and recommendations to minimize those impacts.

10.2.2. Functional unit

The functional unit of the life cycle analysis is a motorway bridge, with a required service life of 100 years, to overpass a dual carriageway with a capacity for four lanes in each direction. The functional unit is divided by the deck area of the bridge (in m^2).

10.2.3. System boundaries

All stages over the complete life cycle of the bridges; from raw material extraction until end-of-life procedures (see Chapter 5 – Figure 5.2), are included in the boundary system of the analysis.

10.3. DESCRIPTION OF CASE STUDY

10.3.1. Project details

Bridge PS 13 was built over the dual carriageway A17 – *Auto Estrada Marinha Grande/Mira* and it is represented in Figure 10.1. Each carriageway has a wide of 14.25 m and it comprehends a main running surface with 10.50 m, a hard shoulder along the inner lane with a width of 3.00 m and a soft shoulder along the outer lane with 0.75 m. Each carriageway has a capacity for 3 lanes of traffic with a width of 3.50 m. The central reservation is 6.00 m wide.

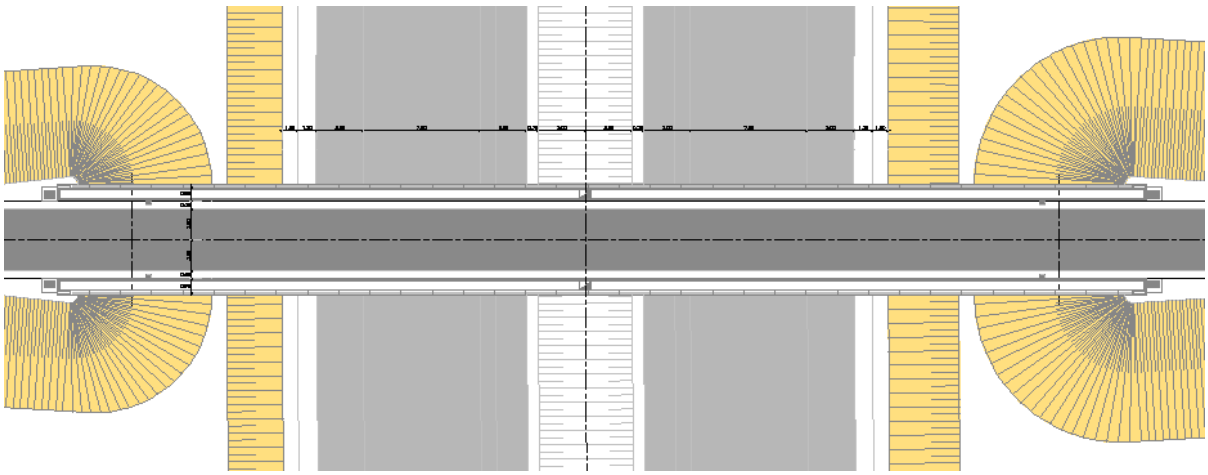

Figure 10.1. Plan view of the concrete bridge PS 13

The bridge has two spans of 28.78 m and 30.76 m and a cross-section of 7.14 m wide (Figure 10.2). The total area of the deck is 425.12 m^2. The elevation view is represented in Figure 10.2. The deck is fully supported over the middle pier and it has integral abutments.

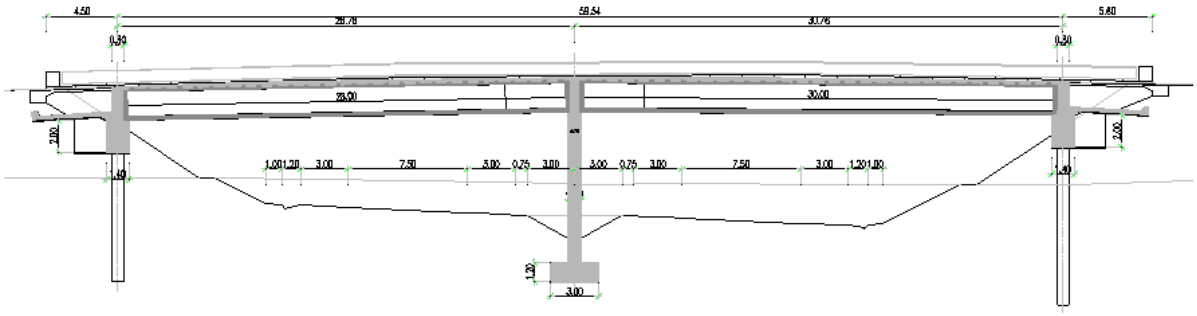

Figure 10.2. Elevation view of the concrete bridge PS 13

The middle pier has a rectangular cross-section with a width of 0.80 m and a length of 1.70 m. To obtain the monolithic connection over the middle pier, the top of the pier and the segment of slab over the pier are cast in a later stage. The continuity is enable by the reinforced steel and pre-stressed steel (cables and bars) introduced overt the pier. The connection over the abutments is obtained by a similar procedure.

The cross-section of the deck, which is illustrated in Figure 10.3, is made of one longitudinal precast concrete girder with a “U” shape, 1.80 m of height, and a cast “in situ” concrete slab

with variable thickness from 300 mm to 160 mm at the end of the cantilevers. The concrete slab is cast on top of precast concrete forms that act as composite with the slab.

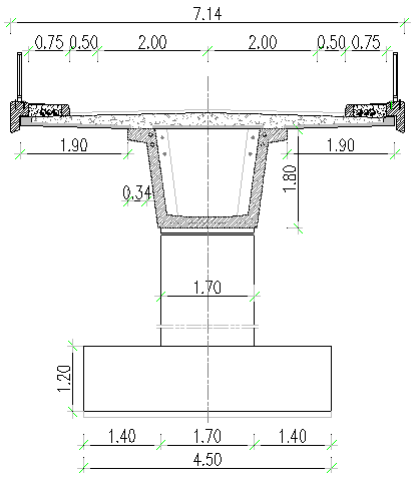

Figure 10.3. Cross-section of the concrete bridge PS 13

This cross-section encompasses two lanes of traffic, one in each direction, 2.00 m wide, two hard shoulders with 0.50 m and two side-walks for pedestrians with a width of 0.75 m.

The bill of main materials for this bridge is represented in Table 10.1.

Table 10.1. Bill of main materials of PS13

Main component	Elements	Material	Quantity	Unit
Foundations	Regularization	Concrete grade C16/20	8.34	m^3
	Piles	Concrete grade C30/37	36.10	m
	Pile caps and bases	Concrete grade C30/37	55.23	m^3
Abutments	Elevation	Concrete grade C30/37	41.36	m^3
Piers	Elevation	Concrete grade C30/37	12.97	m^3
Deck	Slab	Concrete grade C30/37	157.88	m^3
		Pre-stressed steel grade A950/1050 in bars	209.00	kg
	Precast beams	Concrete grade C45/55	74.26	m^3
		Pre-stressed steel grade A1670/1860 in cables	2 524.00	kg
		Pre-stressed steel grade A1670/1860 in tendons	1 542.00	kg
	Precast forms	Concrete grade C45/55	33.12	m^3
	Side-walks	Light-weight concrete	14.09	m^3
	Pavement	Asphalt layer 6 cm	297.70	m^2
Global	All elements	Reinforced steel grade A500	33 471.00	kg

The unit costs of the main materials and equipment of the bridge are indicated in Table 10.2.

This analysis intends to consider, as far as possible, all materials and processes involved in the analysis. Therefore, for the initial cost of the structure all the costs of materials and equipments were considered, no cut-off rule was used. However, for the environmental analysis some materials and equipments were cut-off from the analysis due to lack of data.

Table 10.2. Unit costs of materials and equipment

Main component	Elements	Material	Unit cost	Unit
Foundations	Regularization	Concrete grade C16/20	49.32	€/m^3
	Piles	Concrete grade C30/37	63.19	€/m
	Pile caps and bases	Concrete grade C30/37	63.19	€/m^3
Abutments	Elevation	Concrete grade C30/37	63.19	€/m^3
Piers	Elevation	Concrete grade C30/37	63.19	€/m^3
Deck	Slab	Concrete grade C30/37	63.19	€/m^3
		Pre-stressed steel grade A950/1050 in bars	1.99	€/kg
	Precast beams	Concrete grade C45/55	105.00	€/m^3
		Pre-stressed steel grade A1670/1860 in cables	1.99	€/kg
		Pre-stressed steel grade A1670/1860 in tendons	1.99	€/kg
	Precast forms	Concrete grade C45/55	105.00	€/m^3
	Side-walks	Light-weight concrete	44.00	€/m^3
	Pavement	Asphalt layer 6 cm	17.50	€/m^2
Global	All elements	Reinforced steel grade A500	0.65	€/kg
Equipment	Parapet railing		18 346.00	€
	Edge beams		8 844.16	€
	Slope protection		5 440.00	€

10.3.2. Construction details

The construction of this bridge took a total of 133 days, from 1-03-06 to 11-07-06, according to the planning represented in Table 10.3, which was provided by BRISA. The detailed planning is presented in Annex C.

Table 10.3. Planning of the construction

Main Activity	Elements	Initial date	Final date	Total (days)
Excavation		01-03-06	28-03-06	28
Casting of piles		29-03-06	04-04-06	7
Casting of main structure		05-04-06	16-05-06	
	Abutments Foundation bases Piers	05-04-06 05-04-06 26-04-06	16-05-06 25-04-06 16-05-06	42 21 21
Installing of precast structure		17-05-06	27-06-06	
(+ casting of slab)	Pre-stress beams Precast slab panels	17-05-06 31-05-06	30-05-06 27-06-06	14 28
Finishings		14-06-06	11-07-06	29

The first parts of the concrete structure to be built were the middle pier and the abutments to enable the installation of the precast girders. These elements were cast “in situ”. Then the two precast longitudinal girders were lifted to its final position, by the use of temporary supports near the middle pier.

Then the pre-stressed cables along the complete length of the structure and the pre-stressed bars over the middle pier were installed. In addition, the remaining parts of the pier and abutments were cast “in situ”.

After the tensioning of the cables, the temporary supports were removed. The precast forms were installed on top of the girders to enable cast “in situ” of the deck slab. The final stage of construction comprehended the installation of the remaining equipment.

10.3.3. Traffic constraints during construction stage

During the construction of the bridge the motorway was not in service. Therefore for the real construction of the bridge no traffic constraints were necessary to consider. However, to make this case study comparable with the others, it was assumed that the motorway was already in service during its construction. Moreover, it was considered that the traffic under the bridge had exactly the same characteristics as for motorway A1. Nevertheless, during this stage, there was no traffic above the bridge.

According to current national legislation, traffic conditions through work zones in major motorways are subjected to several restrictions. These restrictions are provided in Annex A. In this study it is assumed that during the construction of the bridge, and as it is the common practice of BRISA, these restrictions were fully taken into account during the construction period.

Therefore, according to Table 10.3 and the detailed planning presented in Annex C, there were always two lanes of traffic in each direction of the motorway, except during the casting of the middle pier and the installation of the precast structural elements: longitudinal girders and precast concrete panels of the slab. In this case, it was necessary to cancel the traffic in one carriageway and divert the traffic to the other one, resulting in one lane of traffic in each direction. The installation of precast elements took 30 work days (according to the timetable), but it was assumed that traffic was diverted only for 20 days.

Moreover, during the entire period of construction (133 days) it is considered that traffic speed in both carriageways was constrained to a maximum of 80 km/h.

10.4. SCENARIOS AND ASSUMPTIONS FOR LIFE CYCLE ANALYSIS

10.4.1. Traffic under and over the bridge

The volume of traffic in motorway A17 is much smaller than in A1. In 2008 the TMDA was 4.528 vehicles/day. However, as referred in the previous sub-chapter, in order to make this case study comparable with the other case studies, the same traffic characteristics (over and under the bridge) are considered for this bridge, over the entire time horizon of analysis.

Traffic characteristics are described in Chapter 9 – section 9.4.1.

10.4.2. Operation stage – Maintenance and rehabilitation plan

In this case study, all the assumptions considered for the maintenance and rehabilitation of the bridge described in the previous case study are also considered for the present case study.

Therefore, according to the time of intervention in the bridge for each activity (see Chapter 9, Table 9.11), and in order to minimize the duration of work activity over and under the bridge, the activities happening in the same year are assumed to take place at the same time. This combination of activities leads to 4 combination of actions A to D (as indicated in the bottom line of Table 10.4). The periodic and main inspections are not represented in Table 10.4 as it is assumed that these activities have no direct influence on the analysis.

Table 10.4. Time-table of maintenance/rehabilitation activities of PS13

years	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
Main structure																	
New surface deck																	
Rehabilitation deck																	
New surface columns																	
Rehabilitation columns																	
New surface abutments																	
Rehabilitation abutm.																	
Equipment																	
Replacing rails																	
Replacing edge beams																	
Re-painting parapet																	
Others																	
Replacing asphalt layer																	
Combined activities	A		B	A			A	C		A			D			A	

Combined activity A refers simply to the replacement of the asphalt layer of the bridge.

Combined activity B represents the replacement of bridge equipment, together with the re-surfacing of concrete elements. This combined activity is similar to combined activity D, except that in the latter, there's also the replacement of the asphalt layer of the bridge.

Combined activity C combines the rehabilitation of the structure, in which all concrete elements will be subject to major intervention and the replacement of bridge equipment.

The duration of each combined activity depends on the type of work to be done, in the ability of manpower and in the capacity rate of construction equipment. Thus, for each combined activity (indicated in Table 10.4) a planning of the respective work was made based on the estimated bill of materials and on the estimated capacity rate for each activity. Based in this information a period of time was estimated for each combined activity, which are indicated in Table 10.5. The detailed calculation and the time plan are provided in Annex C.

During the periods of time corresponding to maintenance and rehabilitation works, traffic over and/or under the bridge is affected. Table 10.5 indicates the total number of days estimated for each combined action and the corresponding traffic affectation.

Table 10.5. Total duration (in days) of maintenance/rehabilitation activities

Combined activity	Total duration (days)	Traffic affectation
A	8	Only affects traffic over the bridge
B	18	Affects traffic over and under the bridge
C	43	Affects traffic over and under the bridge
D	26	Affects traffic over and under the bridge

Likewise, it is assumed that during the maintenance and rehabilitation of the bridge traffic restrictions in work zones, according to current legislation (see Annex A) are always taken into account.

10.4.3. End-of-life of the bridge

Based in a demolition project of a similar concrete bridge, provided by BRISA, the demolition of the bridge is assumed to be made in three main stages: the first stage corresponds to the preparation of the terrain and erection of auxiliary structures to support the structure being demolished; the second stage corresponds to the demolition of the central span of the structure; and the third stage corresponds to the demolition “in situ” of the remaining structure. The detailed plan of demolition is provided in Annex C, the total number of days needed for each stage are indicated in Table 10.6.

Table 10.6. Total duration (in days) of bridge demolition

Demolition stages	Description	Duration (in days)
1st stage	Preparation of base supports for scaffolding; Preparation of terrain for deposit of concrete pieces; Erection of scaffolding; Transversal cuts in deck; Longitudinal cuts of deck (partially).	4
2nd stage	Dismantling of one part of composite deck and deposition of the resulting pieces in the side terrain; Dismantling of other part of composite deck and deposition of the resulting pieces in the side terrain.	5
3rd stage	Dismantling of scaffolding in central span; Demolition of the concrete pieces from the deck; Demolition "in situ" of piers and abutments; Removal and transportation of materials; Cleaning of the area.	3

During the demolition of the bridge, it is considered that the traffic over the bridge is diverted to an alternative road. Traffic under the bridge is conditioned by the demolition of the bridge; however, it is assumed that except for the 2nd stage there will always be at least two lanes of traffic in each direction. During the 2nd stage, traffic in the motorway will have to be diverted to only one carriageway as the carriageway below the part of the deck being dismantled has to be closed due to users’ safety reasons.

After the demolition of the bridge and sorting of materials in the demolition site, the materials are sent to different places according to its characteristics and potential for recycling. In this case study, three end-of-life scenarios are going to be considered, as indicated in Table 10.7.

Table 10.7. End-of-life scenarios for main materials

Material	1st scenario	2nd scenario	3rd scenario
Concrete	Landfill	Recycled	Recycled
Reinforcement steel	Recycled	Recycled	Recycled
All the other materials	Landfill	Landfill	Landfill

Scenario 3 is similar to scenario 2, except in the allocation procedures considered for the life cycle environmental analysis, as will be further described in section 10.5.4.

10.5. LIFE CYCLE ENVIRONMENTAL ANALYSIS

10.5.1. Stage of material production

This stage takes into consideration the production of all the materials needed to build the bridge, as indicated in Figure 10.4. Data was collected from the same sources as indicated in Chapter 9. The life cycle environmental analysis is performed using the environmental indicators discussed in Chapter 6. The calculation of the potential environmental impacts was performed by the commercial programme SIMAPRO® [10.1].

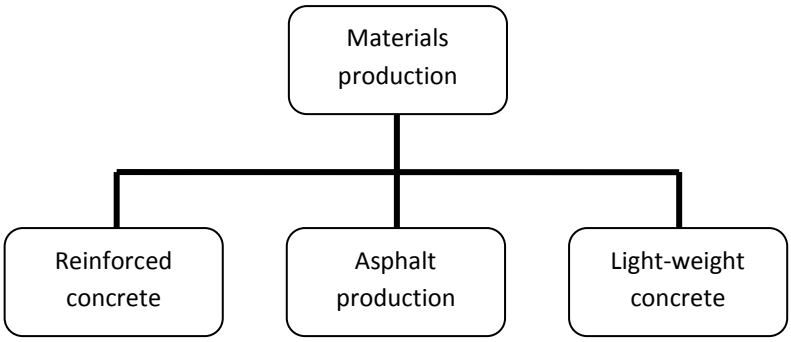

Figure 10.4. Material production stage

The results obtained for each baseline impact category (see Table 6.11, Chapter 6) are represented in Table 10.8.

Table 10.8. Results of the material production stage per impact category

Impact category	Unit	Total	Reinforced concrete	Asphalt	Light-weight concrete
AD	kg Sb eq	430.4	69.4%	29.6%	1.0%
AC	kg SO_2 eq	592.2	95.1%	4.3%	0.6%
EU	kg NO_x eq	556.0	94.6%	4.5%	0.9%
GW	kg CO_2 eq	202428.6	94.6%	4.5%	0.9%
OD	kg CFC-11 eq	0.004	0%	98.1%	1.9%
HT	kg1,4-DB eq	46200.6	96.9%	2.6%	0.4%
TT	kg 1,4-DB eq	42.6	95.9%	3.3%	0.7%
Ph	kg C_2H_4	31.8	94.6%	5.0%	0.4%

From Table 10.8 it is concluded that the production of reinforced concrete is the main process contributing to global impacts in the material production stage, except for the environmental category Ozone layer depletion. The same results are plotted in Figure 10.5.

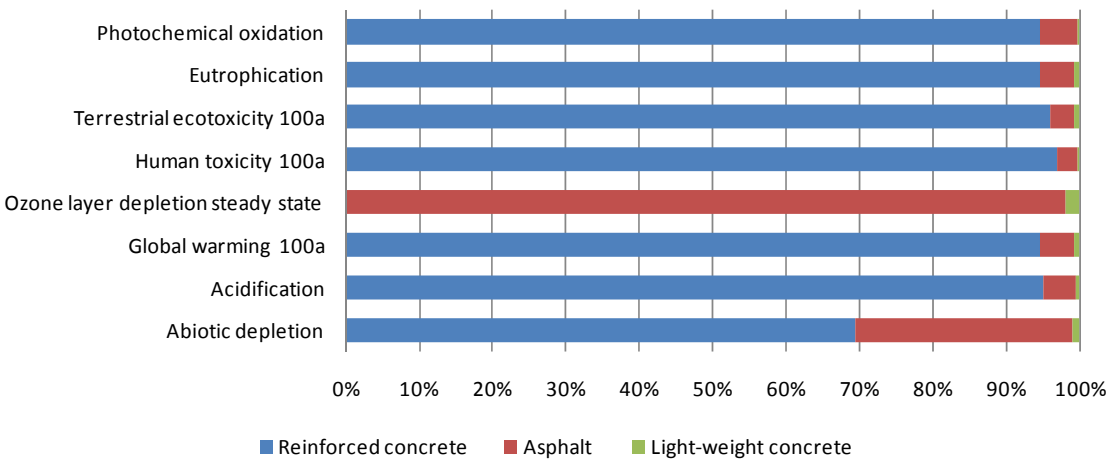

Figure 10.5. Contribution analysis of processes during the material production stage

10.5.2. Stage of construction

10.5.2.1. Transportation of materials and construction equipments

For the transportation of the precast girders and the precast concrete panels, a distance of 60 km was considered from the concrete plant to the construction site. For all other materials and equipments, the distances considered in this case study are the ones considered for the previous case study (see Table 9.18 in Chapter 9).

10.5.2.2. Use of construction equipment

The quantification of emissions due to the use of construction equipment is based in the plan of construction represented in Table 10.3, in the list of equipment provided by the constructor and emission factors from NONROAD2008 model described in Chapter 5.

The number of hours needed for each equipment were estimated from the plan for construction and in the work capacity of each equipment (assumed that each equipment was used at full capacity).

Hence, total emissions due to the use of diesel-fuelled construction equipment, for the period of time corresponding to the construction stage are indicated in Table 10.9.

Table 10.9. Total emissions (in tonnes) due to diesel-fuelled construction equipment in the construction stage

Activity	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
Excavation and piles	0.002	0.009	0.020	0.002	0.002	0.000	1.733
Abutments and bases	0.002	0.007	0.021	0.001	0.001	0.000	1.797
Abutments and piers	0.000	0.002	0.007	0.000	0.000	0.000	0.563
Concrete deck	0.007	0.027	0.098	0.006	0.005	0.002	10.202
Finishings	0.008	0.029	0.059	0.006	0.006	0.001	6.057
TOTAL	0.019	0.075	0.206	0.015	0.014	0.004	20.353

The detailed calculation of non-mobile emissions is provided in Annex C.

10.5.2.3. Traffic over and under the bridge

In this sub-section only the traffic congestion due to the construction activity is analysed.

During the time period of construction, according to Table 10.3, the traffic under the bridge is affected due to restrictions in the traffic speed and the narrowing of the carriageway. This bridge is a new bridge; therefore, during its construction there is no traffic over the bridge.

The following paragraphs describe the quantification of fuel consumption and emissions due to traffic congestion. Only the difference between between traffic conditions in a work zone and traffic conditions in the same zone but without work activity is hereby considered.

10.5.2.3.1. Fuel consumption and vehicles' emissions

The characteristics of the traffic flow under the bridge were indicated in Chapter 9, section 9.4.1.

For the calculation of total emissions during the entire construction period, two global scenarios were considered, as indicated in Table 10.10. These global scenarios are based on the reference scenarios described in Chapter 9, section 9.5.2.

As, already referred, the construction period took 133 days. During this period there were always two lanes of traffic in each direction, although with reduce speed, except for twenty days. These twenty days correspond to the assembling of the concrete girders and precast concrete panels of the slab. In this case, it was necessary to cancel the traffic in one carriageway and diverted the traffic to the other one, resulting in one lane of traffic in each direction.

Hence, global scenario 1 considers that the closure of one carriageway occurs always during the night period, whereas global scenario 2 considers that the closure occurs during the day.

Table 10.10. Total emissions in work zone during construction

	Emissions (kg)			Fuel (kg)	
	CO	HC	NOx	Gasoline	Diesel
Global scenario 1	8833.46	88.18	77.54	44697.12	82055.10
Global scenario 2	10732.66	264.58	114.34	53476.32	94722.70

10.5.2.4. Synthesis of the construction stage

The construction stage takes into account all the processes needed for the construction of the bridge and affected by it. Hence, as represented in Figure 10.6, it includes the transportation of materials to the construction site, the transportation of equipment, the use of construction equipment and the emissions due to the traffic congestion resulting from construction activity.

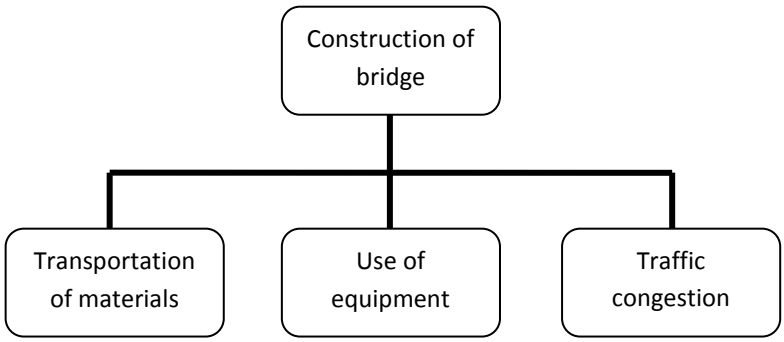

Figure 10.6. Construction stage

The results obtained for each baseline impact category (see Chapter 6, Table 6.11) are represented in Table 10.11 and Figure 10.7.

Table 10.11. Results of the construction stage per impact category

Impact category	Unit	TOTAL	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	3234.3	1.8 %	0 %	98.2 %
AC	kg SO_2 eq	1064.9	2.3 %	10.4 %	87.4 %
EU	kg NO_x eq	667.9	4.9 %	37.0 %	58.1 %
GW	kg CO_2 eq	119412.7	6.7 %	17.5 %	75.8 %
OD	kg CFC-11 eq	0.062	2.0 %	0 %	98.0 %
HT	kg 1,4-DB eq	25370.5	4.5 %	1.0 %	94.4 %
TT	kg 1,4-DB eq	33.7	4.5 %	0 %	95.5 %
Ph	kg C_2H_4	299.5	0.3 %	0.8 %	98.9 %

In this stage the process that most contributes to all impact categories is clearly "traffic congestion". Its contribution is always above 90%, except for the impact categories of acidification, eutrophication and global warming, for which an important contribution is also provided by the "use of equipment".

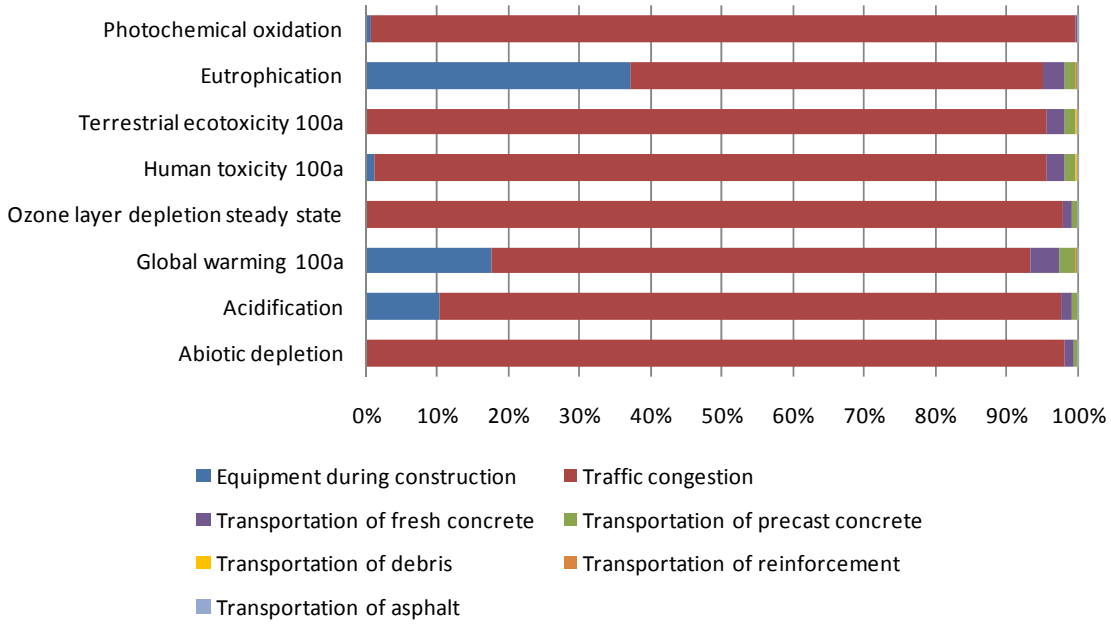

Figure 10.7. Contribution analysis of processes during the construction stage

10.5.3. Stage of operation

10.5.3.1. Transportation of materials and equipments

The distances considered in this case study for the transportation of materials and equipments are the ones considered for the previous case study (see Chapter 9, Table 9.18).

10.5.3.2. Use of equipments

The quantification of emissions due to the use of equipment is based in the plan of maintenance provided in Annex C, in the list of equipment provided by the constructor and emission factors from NONROAD2008 model described in Chapter 5. The number of hours needed for each equipment were estimated from the plan of maintenance and in the work capacity of each equipment (assumed that each equipment was used at full capacity).

Table 10.12 summarizes the total emissions due to the use of equipment in the operation stage.

Table 10.12. Total emissions (in tonnes) due to diesel-fuelled equipment in the operation stage

Activity	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
Combined act. 1	0.003	0.012	0.038	0.003	0.002	0.001	4.823
Combined act. 2	0.008	0.037	0.109	0.007	0.007	0.003	12.910
Combined act. 3	0.017	0.078	0.229	0.015	0.015	0.006	27.184
Combined act. 4	0.011	0.050	0.147	0.010	0.010	0.004	17.733

10.5.3.3. Traffic over and under the bridge

10.5.3.3.1. Fuel consumption and vehicles' emissions

The characteristics of the traffic flow over and under the bridge for the operation stage were indicated in Chapter 9, section 9.4.1.

For the calculation of fuel consumption and emissions during the entire operation stage, several global scenarios were considered for each combined maintenance activity indicated in Table 10.4. These global scenarios are based on the reference scenarios described in Chapter 9, section 9.5.3.

Combined activity A has a total duration of 8 days and only affects traffic over the bridge. During this period of time it is assumed that there will be always one lane of traffic closed. In global scenario 1 the closure is made over night, whereas in global scenario 2 the closure is made during the day. The corresponding emissions and fuel consumption, for the entire period of time, are indicated in Table 10.13.

Table 10.13. Total emissions in work zone during operation stage (combined activities A)

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	Night work over bridge	180.56	0.88	1.44	514.24	1069.52
Global scenario 2	Day work over bridge	176.24	1.92	1.68	681.36	1258.16

Combined activity B occurs in year 2033 and has a total duration of 18 days. During this time traffic is affected over and under the bridge. Six different global scenarios, as described in Table 10.14, were defined to combine each possible situation. Global scenario 1 corresponds to the best traffic-management option while the other global scenarios combine other possible situations as described in Table 10.14.

Table 10.14. Total emissions in work zone during operation stage (combined activities B)

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	Night work motorway + night work over bridge	1365.66	14.40	12.06	7871.04	13950.18
Global scenario 2	Night work motor. + day work over bridge	1365.66	14.40	12.06	7871.04	13950.18
Global scenario 3	Day work motorway + night work over bridge	2837.16	141.12	38.34	15136.74	24550.92
Global scenario 4	Day work motorway + day work over bridge	2837.16	141.12	38.34	15136.74	24550.92
Global scenario 5	Reduce day work motorway + night work over bridge	1919.70	60.84	21.24	11560.86	19464.48
Global scenario 6	Reduce day work motorway + day work over bridge	1919.70	60.84	21.24	11560.86	19464.48

Combined activity C occurs in year 2058 and has a total duration of 43 days. In addition, during this period of time, traffic is affected over and under the bridge. In this case, ten different global scenarios, as described in 0, were defined to combine each possible situation.

Table 10.15. Total emissions in work zone during operation stage (combined activities C)

Scenario	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	night work motorway (3 lanes open)+ night work over bridge	4794.10	50.84	42.68	26159.26	47207.80
Global scenario 2	night work motorway (3 lanes open) + day work over bridge	4794.10	50.84	42.68	26159.26	47207.80
Global scenario 3	day work motorway (3 lanes open) + night work over bridge	4794.10	70.44	47.08	29952.06	51519.00
Global scenario 4	day work motorway (3 lanes open) + day work over bridge	4794.10	70.44	47.08	29952.06	51519.00
Global scenario 5	night work motorway (2 lanes open)+ night work over bridge	4792.90	51.24	42.68	26191.66	47244.20
Global scenario 6	night work motorway (2 lanes open) + day work over bridge	4792.90	51.24	42.68	26191.66	47244.20
Global scenario 7	day work motorway (2 lanes open) + night work over bridge	21207.30	1598.84	380.68	71652.06	106997.00
Global scenario 8	day work motorway (2 lanes open) + day work over bridge	21207.30	1598.84	380.68	71652.06	106997.00
Global scenario 9	reduce day work motorway (2 lanes open) + night work over	11072.10	648.44	171.88	49058.46	77872.60
Global scenario 10	reduce day work motorway (2 lanes open)+ day work over	11072.10	648.44	171.88	49058.46	77872.60

Finally, for combined activity D, occurring in year 2083 with a total duration of 26 days, traffic is also affected over and under the bridge. Likewise, ten different global scenarios, as described in Table 10.16, were defined to combine each possible situation.

Table 10.16. Total emissions in work zone during operation stage (combined activities D)

Scenario	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	night work motorway (3 lanes open)+ night work over bridge	1843.04	17.80	16.02	9491.20	17240.72
Global scenario 2	night work motorway (3 lanes open) + day work over bridge	1838.72	18.84	16.26	9658.32	17429.36
Global scenario 3	day work motorway (3 lanes open) + night work over bridge	1843.04	29.50	18.72	11673.88	19795.28
Global scenario 4	day work motorway (3 lanes open) + day work over bridge	1838.72	30.54	18.96	11841.00	19983.92
Global scenario 5	night work motorway (2 lanes open)+ night work over bridge	1842.50	17.98	16.20	9508.30	17259.80
Global scenario 6	night work motorway (2 lanes open) + day work over bridge	1838.18	19.02	16.44	9675.42	17448.44
Global scenario 7	day work motorway (2 lanes open) + night work over bridge	15982.58	1364.92	312.30	44303.56	60974.78
Global scenario 8	day work motorway (2 lanes open) + day work over bridge	15978.26	1365.96	312.54	44470.68	61163.42
Global scenario 9	reduce day work motorway (2 lanes open) + night work over	6840.92	504.34	122.58	25748.44	37948.64
Global scenario 10	reduce day work motorway (2 lanes open)+ day work over	6836.60	505.38	122.82	25915.56	38137.28

For the calculation of total emissions in the operation stage, as indicated in the following sub-section, the best scenarios corresponding to each combined maintenance activity were considered.

10.5.3.4. Synthesis of the operation stage

The operation stage of the bridge took into account the estimated maintenance and rehabilitation activities according to Table 10.4. These activities occur over different time periods over the service life of the structure, as described in the previous sub-sections. However, due to a repeated number of processes, the tree diagram of Table 10.8 aggregates the processes with same characteristics occurring at different time periods.

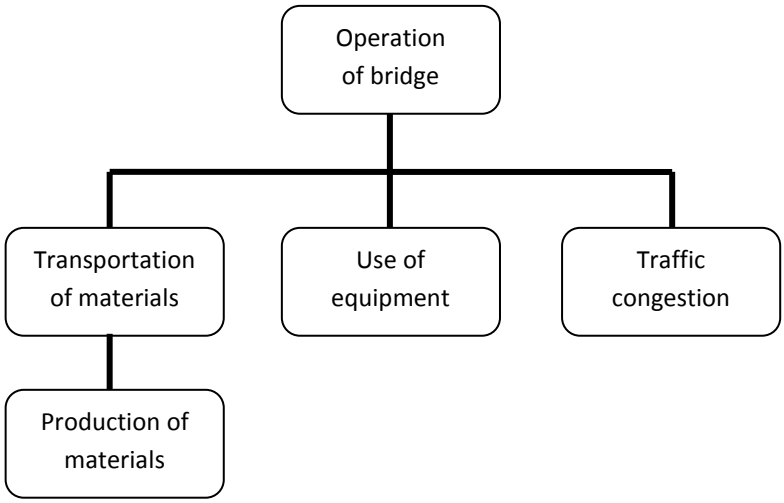

Figure 10.8. Operation stage of the bridge

The outcome of each combined activity is indicated in Table 10.17, Table 10.18, Table 10.19 and Table 10.20, respectively for combined activities A to D. Each table indicates total emissions per impact category and corresponding contribution of each process.

From Table 10.17 it is observed that the asphalt replacement contributes with a share of more than 50% for most impact categories, while traffic congestion represents a major contribution only for the impact category of photochemical oxidation. Once more, it is noticed that this combined activity only affects traffic over the bridge.

Table 10.17. Results of the operation stage per impact category (combined activities A)

Impact category	Unit	TOTAL	Asphalt replacement	Use of equipment	Traffic congestion
AD	kg Sb eq	166.5	76.8 %	0 %	23.2 %
AC	kg SO_2 eq	57.7	45.1 %	35.0 %	19.9 %
EU	kg NO_x eq	76.5	33.4 %	59.6 %	7.1 %
GW	kg CO_2 eq	15201.2	60.2 %	31.8 %	7.9 %
OD	kg CFC-11 eq	0.004	82.8 %	0 %	17.2 %
HT	kg 1,4-DB eq	1570.9	78.5 %	3.0 %	18.5 %
TT	kg 1,4-DB eq	1.8	78.6 %	0 %	21.4 %
Ph	kg C_2H_4	7.4	21.4 %	5.0 %	73.6 %

In the case of combined activity B, Table 10.18, the process that most contributes to major impact categories is clearly “traffic congestion”. Its contribution is always above 80%, except for the impact categories of acidification, eutrophication and global warming, for which an important contribution is also provided by the “use of equipment”.

Table 10.18. Results of the operation stage per impact category (combined activities B)

Impact category	Unit	TOTAL	Concrete repair	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	537.7	0.7 %	0.1 %	0 %	99.2 %
AC	kg SO_2 eq	217.1	1.3 %	0.2 %	26.8 %	71.8 %
EU	kg NO_x eq	200.4	1.9 %	0.2 %	65.3 %	32.6 %
GW	kg CO_2 eq	29827.0	5.7 %	0.4 %	43.5 %	50.5 %
OD	kg CFC-11 eq	0.010	0.5 %	0.2 %	0 %	99.3 %
HT	kg 1,4-DB eq	4310.9	3.1 %	0.4 %	3.2 %	93.4 %
TT	kg 1,4-DB eq	5.7	4.7 %	0.4 %	0 %	94.9 %
Ph	kg C_2H_4	46.6	0.2 %	0 %	2.5 %	97.3 %

The same conclusions may be drawn for the case of combined activity C, where the process that most contributes to major impact categories is again “traffic congestion”, as indicated in Table 10.19.

Table 10.19. Results of the operation stage per impact category (combined activities C)

Impact category	Unit	TOTAL	Concrete rehabilitation	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	1814.7	1.0 %	0.2 %	0 %	98.8 %
AC	kg SO_2 eq	661.9	2.1 %	0.3 %	18.4 %	79.3 %
EU	kg NO_x eq	518.3	3.7 %	0.4 %	53.0 %	42.8 %
GW	ton CO_2 eq	87191.9	9.7 %	0.6 %	31.3 %	58.4 %
OD	kg CFC-11 eq	0.035	0.8 %	0.3 %	0 %	99.0 %
HT	ton1,4-DB eq	14554.6	4.6 %	0.5 %	2.0 %	92.9 %
TT	kg 1,4-DB eq	19.6	6.8 %	0.5 %	0 %	92.6 %
Ph	kg C_2H_4	161.0	0.3 %	0 %	1.5 %	98.1 %

Finally, in the case of combined activity D, the process of “traffic congestion” still has a major contribution to most impact categories, although the processes of “asphalt replacement” and “use of equipment” share the importance in some impact categories.

Table 10.20. Results of the operation stage per impact category (combined activities D)

Impact category	Unit	TOTAL	Concrete repair	Asphalt replacem.	Transp. of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	785.3	0.5 %	16.2 %	0.2 %	0 %	83.1 %
AC	kg SO_2 eq	298.8	0.9 %	8.6 %	0.2 %	26.2 %	64.0 %
EU	kg NO_x eq	287.9	1.3 %	8.7 %	0.4 %	61.3 %	28.3 %
GW	kg CO_2 eq	47440.8	3.6 %	19.2 %	0.4 %	37.5 %	39.4 %
OD	kg CFC-11 eq	0.016	0.3 %	22.0 %	0.2 %	0 %	77.5 %
HT	kg 1,4-DB eq	6493.4	2.0 %	18.8 %	0.4 %	2.8 %	75.9 %
TT	kg 1,4-DB eq	8.3	3.2 %	17.0 %	0.4 %	0 %	79.4 %
Ph	kg C_2H_4	63.4	0.2 %	2.5 %	0 %	2.4 %	94.9 %

The contribution of each combined activity to the aggregated result of the operation stage is illustrated in Figure 10.9, showing that combined activity C, which takes the longer period of time, has the major contribution in all impact categories.

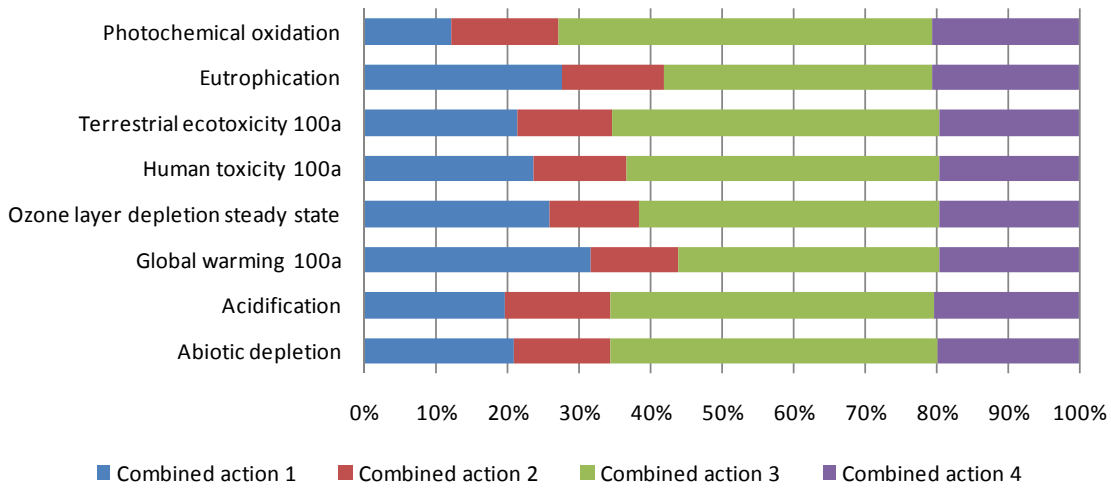

Figure 10.9. Contribution analysis of processes during the operation stage

10.5.4. End-of-life stage

10.5.4.1. Transportation of materials and equipments

Likewise, the distances considered in this case study for the transportation of materials and equipments, during the end-of-life stage, are the ones considered for the previous case study (see Chapter 9, Table 9.18).

10.5.4.2. Use of equipments

The quantification of emissions due to the use of construction equipment is based in the plan of demolition represented in Annex C, in the list of equipment provided by the constructor and emission factors from NONROAD2008 model described in Chapter 5.

The number of hours needed for each equipment were estimated from the plan of demolition and in the work capacity of each equipment (assumed that each equipment was used at full capacity). Total emissions are indicated in Table 10.21.

Table 10.21. Total emissions (in tonnes) due to diesel-fuelled equipment in the end-of-life stage

Activity	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
1st stage	0.003	0.014	0.032	0.003	0.003	0.001	3.668
2nd stage	0.003	0.016	0.037	0.003	0.002	0.001	3.956
3rd stage	0.010	0.038	0.087	0.008	0.008	0.002	9.759
TOTAL	0.016	0.068	0.157	0.014	0.013	0.004	17.383

10.5.4.3. Traffic over and under the bridge

10.5.4.3.1. Fuel consumption and vehicles' emissions

The characteristics of the traffic flow over and under the bridge for the end-of-life stage were indicated in Chapter 9, section 9.4.1.

For the calculation of fuel consumption and emissions during the end-of-life stage, five global scenarios were considered as described in Table 10.22. These global scenarios are based on the reference scenarios described in Chapter 9, section 9.5.4.

The demolition period is estimated to take 12 days (see Table 10.6). During this period it is estimated there would be always four lanes of traffic in each direction, although with reduced speed, except for three working days (see demolition plan in Annex C), corresponding to the demolition of the central span. During this period, a carriageway has to be closed to the traffic underneath and traffic has to be diverted to the other carriageway, resulting in three or, in the worst case, two lanes of traffic in each direction. Table 10.22 indicates the global scenarios resulting from the above considerations.

Table 10.22. Total emissions in work zone during end-of-life stage

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	Night work (3 lanes open)	1692.00	21.18	15.36	11173.38	19441.68
Global scenario 2	Day work (3 lanes open)	1692.00	25.98	16.44	12041.16	20477.28
Global scenario 3	Night work (3 lanes open)	1692.00	21.24	15.42	11179.62	19448.76
Global scenario 4	Day work (2 lanes open)	8428.38	663.36	156.84	27004.20	39017.40
Global scenario 5	Deduce day work (2 lanes open)	3931.32	240.60	63.60	18158.64	28160.16

For the calculation of total emissions in the end-of-life stage, the best scenario, i.e. global scenario 1, was considered.

10.5.4.4. Synthesis of the end-of-life stage

In this stage three scenarios are considered, according to Table 10.7. In all scenarios, it is assumed that the bridge is demolished and the materials are sorted in the same place before being sent to their final destination. Therefore, no transportation is needed between the demolition place and the sorting plant. This is usually the procedure according to current legislation, as referred in Chapter 2.

The first scenario assumes that the concrete is sent to a landfill of inert materials. The second scenario considers that 80% of concrete is recycled using an open-loop approach. The economic allocation procedure discussed in Chapter 5 was considered. Finally, the third scenario is similar to the previous one, except in the allocation approach considered. In this case, a cut-off rule was used for all the materials sent for recycling. For the recycling of asphalt a cut-off rule was used in all end-of-life scenarios due to the lack of data in relation to the respective recycling process. In relation to steel reinforcement, it was assumed that it was recycled in all scenarios using the close-loop approach described in Chapter 5 for steel. Figure 10.10 represents the general unit processes included in this stage.

Taking into account end-of-life scenarios described in the previous paragraph, the gross amount of demolition waste produced in each case is indicated in Table 10.23. The efficiency of recycling processes was not considered, which would increase the amount of waste produced in all scenarios.

Table 10.23. Demolition waste produced in end-of-life stage

	1st scenario	2nd scenario	3rd scenario
Volume of demolition waste (ton)	1027	205	205

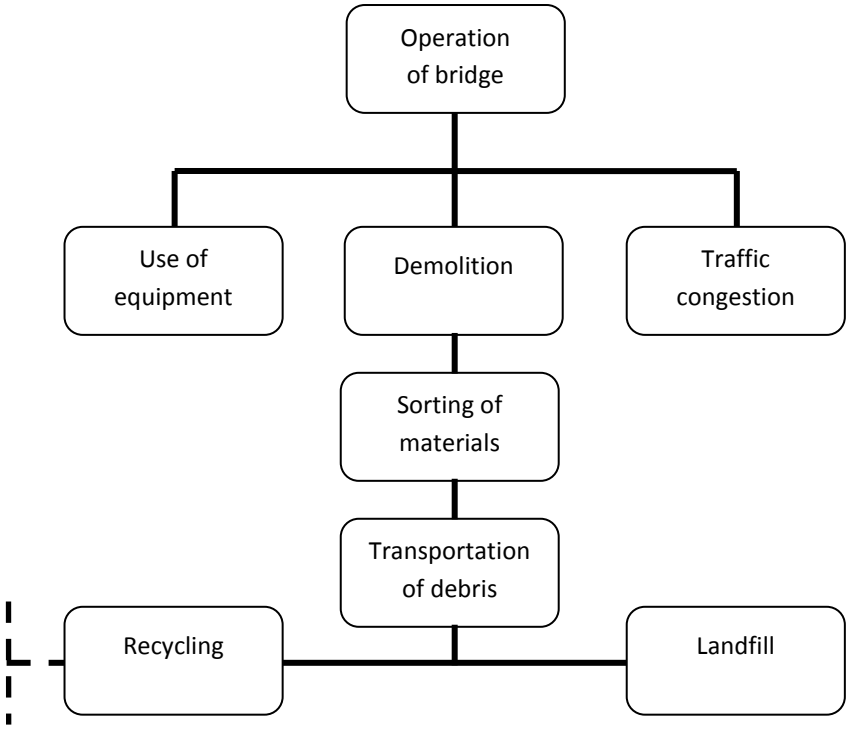

Figure 10.10. End-of-life stage

Naturally, the importance of recycling in the reduction of waste produced is noted from Table 10.23. As referred in the previous chapter, to avoid double counting of impacts, this indicator will not be further used.

Therefore, total emissions per impact category of this stage, considering the first end-of-life scenario, are indicated in Table 10.24. This table also indicates the contribution of each process per impact category.

Table 10.24. Results of the end-of-life stage per impact category

Impact category	Unit	TOTAL	Disassemble of structure	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	931.2	9.0 %	10.7 %	0 %	80.3 %
AC	kg SO_2 eq	385.1	10.9 %	10.8 %	21.6 %	56.7 %
EU	kg NO_x eq	410.3	18.1 %	14.1 %	45.9 %	21.9 %
GW	kg CO_2 eq	59067.1	11.7 %	23.4 %	29.6 %	35.2 %
OD	kg CFC-11 eq	0.019	11.2 %	11.8 %	0 %	77.0 %
HT	kg 1,4-DB eq	10237.5	23.5 %	19.4 %	1.9 %	55.2 %
TT	kg 1,4-DB eq	11.5	10.7 %	23.0 %	0 %	66.3 %
Ph	kg C_2H_4	62.9	2.4 %	2.7 %	3.2 %	91.7 %

The contribution of each process per impact category is also illustrated in Figure 10.11, showing a major contribution from “traffic congestion”, as observed also for the previous stages.

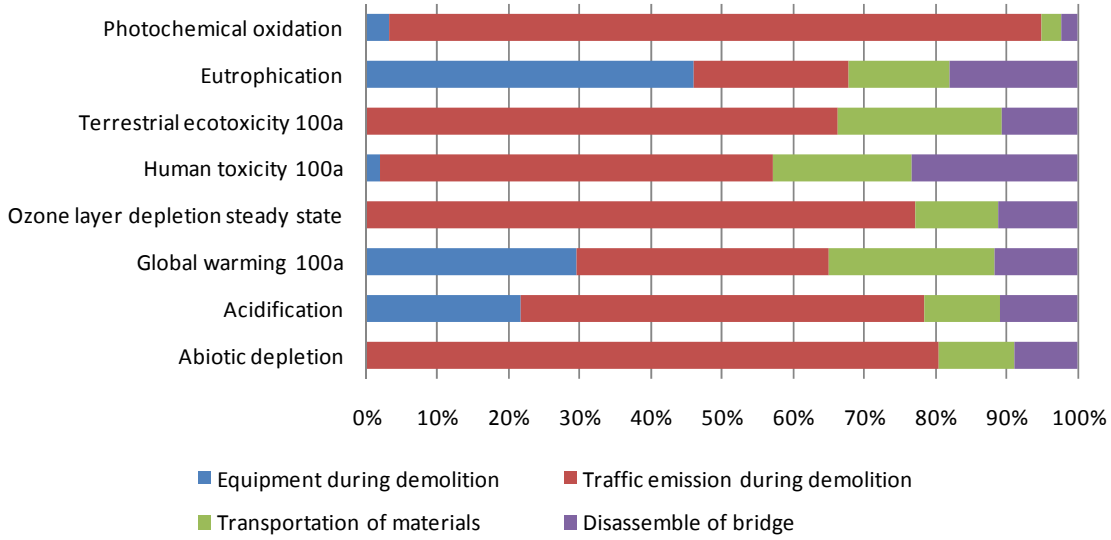

Figure 10.11. Contribution analysis of processes during the end-of-life stage

A comparison between end-of-life scenarios, for each impact category, is provided in Table 10.25.

Table 10.25. Comparison between end-of-life scenarios

Impact category	Unit	1st end-of-life scenario	2nd end-of-life scenario	3rd end-of-life scenario
AD	kg Sb eq	931.21	912.88	868.50
AC	kg SO_2 eq	385.09	376.30	354.15
EU	kg NO_x eq	410.33	395.23	355.67
GW	kg CO_2 eq	59067.11	57644.40	53943.84
OD	kg CFC-11 eq	0.02	0.02	0.02
HT	kg 1,4-DB eq	10237.47	9725.61	8464.42
TT	kg 1,4-DB eq	11.47	11.19	10.55
Ph	kg C_2H_4	62.87	62.54	61.77

10.5.5. Results of the environmental life-cycle analysis

10.5.5.1. Aggregate life-cycle results

In the previous sections, partial results per stage have been presented. In this sub-section the results of the different stages are summed up in relation to each impact category. In this case the tree diagram is not presented due to the enormous amount of processes included, which would make the diagram unreadable. The results are represented Table 10.26, considering the first end-of-life scenario.

In order to better understand the contribution of each stage to the aggregated result, the results are illustrated in a contribution graph represented in Figure 10.12.

Table 10.26. Life-cycle results per life cycle stage (for 1st end-of-life scenario)

Impact category	Unit	Total	Materials	Construction	Operation	End-of-life
AD	kg Sb eq	8483.3	5.1 %	37.2 %	46.8 %	11.0 %
AC	kg SO_2 eq	3482.0	17.0 %	29.8 %	42.1 %	11.1 %
EU	kg NO_x eq	3023.4	18.4 %	22.1 %	45.9 %	13.6 %
GW	ton CO_2 eq	618875.2	32.7 %	18.9 %	38.9 %	9.5 %
OD	kg CFC-11 eq	0.165	2.2 %	36.6 %	49.9 %	11.3 %
HT	ton1,4-DB eq	114379.5	40.4 %	21.6 %	29.0 %	9.0 %
TT	kg 1,4-DB eq	129.8	32.9 %	25.3 %	33.0 %	8.8 %
Ph	kg C_2H_4	702.5	4.6 %	41.9 %	44.4 %	9.1 %

From the observation of the contribution analysis, several conclusions may be taken. The operation stage is the stage with higher contribution to most impact categories, although less than 50%. The stage of material production has a significant contribution to the impact categories of Global Warming, Human Toxicity and Terrestrial Ecotoxicity. Stage of construction has a contribution between 20% and 40%. The end-of-life stage has a smaller contribution, of about 10% (average) to the life cycle analysis.

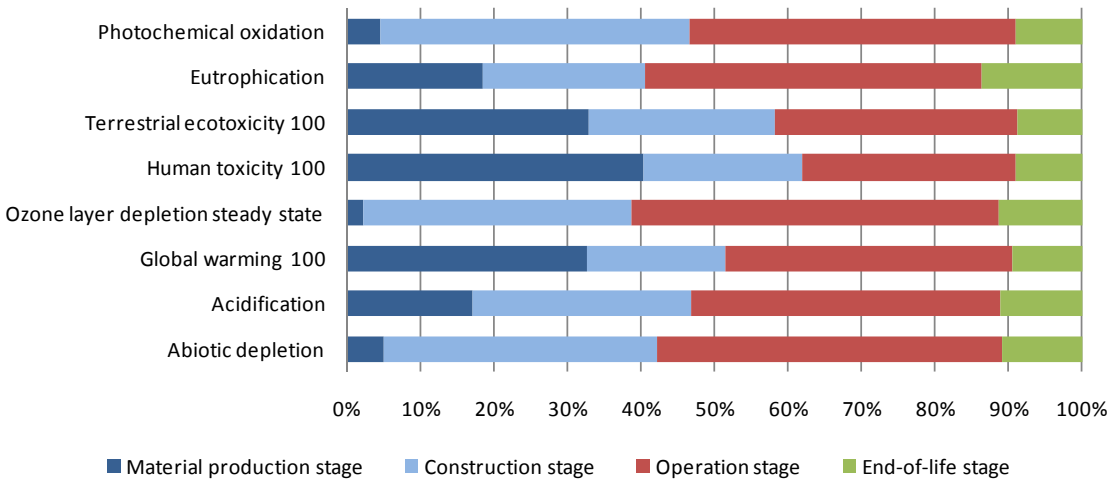

Figure 10.12. Contribution of each stage to impact category

Another important observation from the outcome of the LCEA is provided in terms of the aggregate contribution of main processes to the life cycle results. Thus, Figure 10.13 illustrates the contribution of the processes of material production, transportation, use of equipment and traffic congestion. Each of this main process aggregates the results obtained in each stage. For instance, the result of transportation includes the environmental impacts due to the transportation of materials and equipment obtained in the stages of material production, construction, operation and end-of-life.

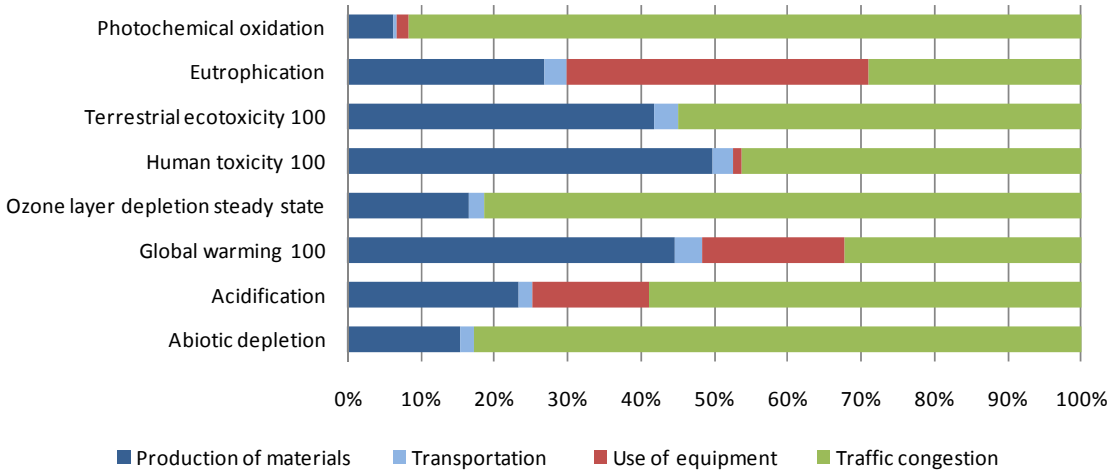

Figure 10.13. Contribution of each main process to impact category

Traffic congestion resulting from work zones is the most important contributing process, as noted from the previous graph. This process is responsible for more than 50% in most impact categories, except Global Warming, Eutrophication and Human Toxicity. The second most important process is the production of materials, which has almost 50% of contribution for Human Toxicity and Global Warming. The transportation of materials has a small contribution to all impact categories, while the use of equipment has a significant contribution to the impact categories of Global Warming, Eutrophication and Acidification.

No conclusions may be taken from these results in relation to the impact categories leading to higher and lower potential impacts. To enable such conclusions, normalization and weighting are performed, as described in the following sub-sections.

10.5.5.2. Normalized results

Using the normalized set of values proposed in Chapter 6, the values obtained for each impact categories are represented in the graph of Figure 10.14, considering the end-of-life scenarios described in Table 10.7.

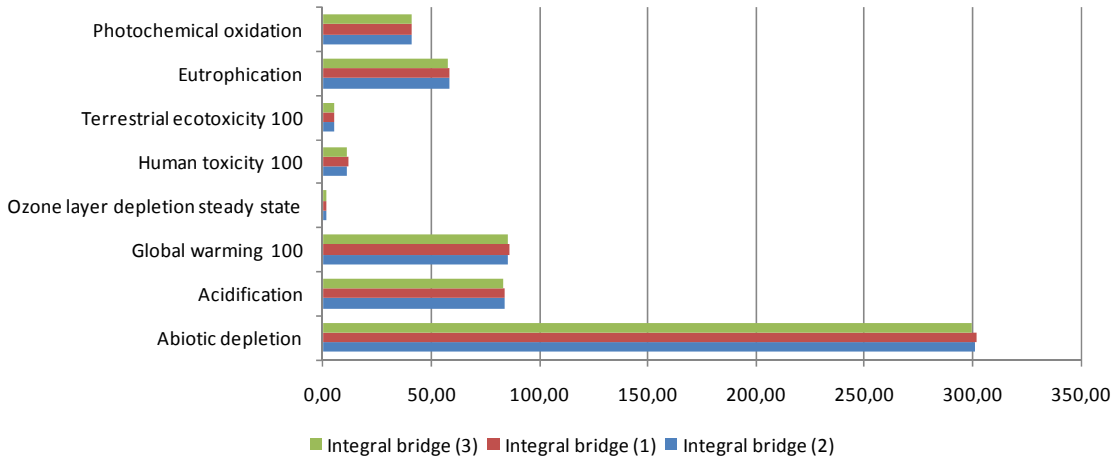

Figure 10.14. Normalized results for each impact category

From the previous graph it is observed that Abiotic depletion, Global warming, Acidification and Eutrophication are the most important environmental categories.

10.5.5.3. Weighted results

Finally, using the set of weights defined in Chapter 6, the resulting life cycle results are presented in Figure 10.15.

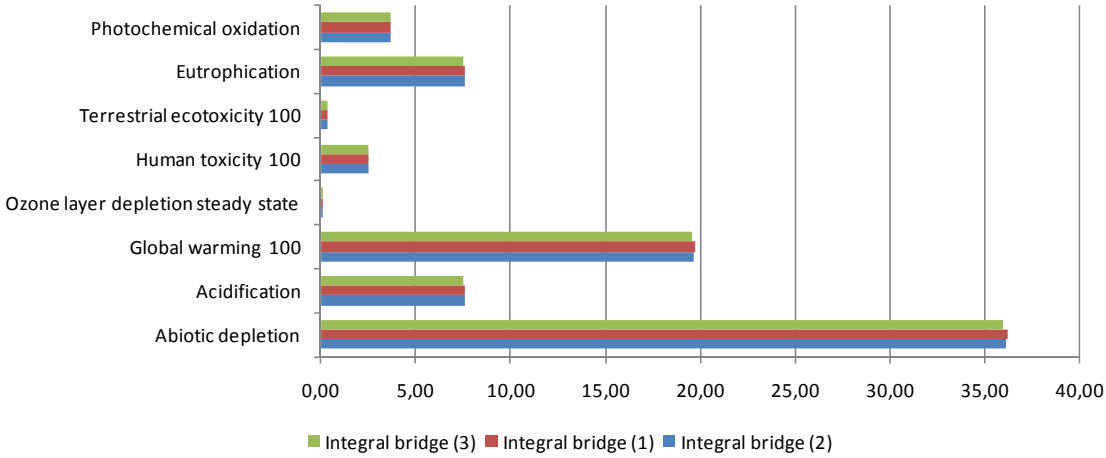

Figure 10.15. Weighted results for each impact category

Abiotic depletion and Global warming are still the most significant impact categories. Acidification and Eutrophication have also a significant value when compared with the remaining categories.

The same results divided by the area of the deck are indicated in Table 10.27. The first column refers to life-cycle results considering end-of-life scenario 1. This was considered the base scenario. The other columns refer to life-cycle results considering the remaining end-of-life scenarios of Table 10.7 and the respective variation in relation to the results presented in the first column (base scenario). The results indicated in the 2nd column, corresponding to end-of-life scenario 2, have a small variation in relation to the base scenario, showing that recycling of concrete has little influence in the final results (less than 1%). Finally, the last column referred to end-of-life scenario 3, in which the "cut-off" rule was used. This rule is often considered as conservative (see discussion in Chapter 5). However, in this case, the results are lower than in the case of scenarios 1 and 2. Thus, in this case the "cut-off" rule despises potential impacts due to final disposition of demolition waste and recycling of materials.

Table 10.27. Life-cycle results of each impact category (per m^2)

Impact category	Integral bridge (1)	Integral bridge (2)		Integral bridge (3)	
	Total	Total	Δ	Total	Δ
AD	8.52E-02	8.50E-02	-0.22%	8.46E-02	-0.74%
AC	1.78E-02	1.78E-02	-0.25%	1.76E-02	-0.89%
EU	1.79E-02	1.78E-02	-0.50%	1.76E-02	-1.81%
GW	4.64E-02	4.63E-02	-0.23%	4.61E-02	-0.83%
OD	2.13E-04	2.12E-04	-0.28%	2.11E-04	-0.95%
HT	5.92E-03	5.89E-03	-0.45%	5.83E-03	-1.55%
TT	8.69E-04	8.67E-04	-0.21%	8.63E-04	-0.71%
Ph	8.69E-03	8.69E-03	-0.05%	8.68E-03	-0.16%

The base scenario was selected taking account the current practice in the sector. However, considering that recycling has being increasingly promoted, it is predicted that in the near future recycling of concrete will be a standard practice. Therefore, life-cycle analysis, considering end-of-life scenario 2 will be used in the next section.

In this case study, the two most important stages are the construction stage and the operation stage, as illustrated in Figure 10.16. These results are referred to end-of-life scenario 2.

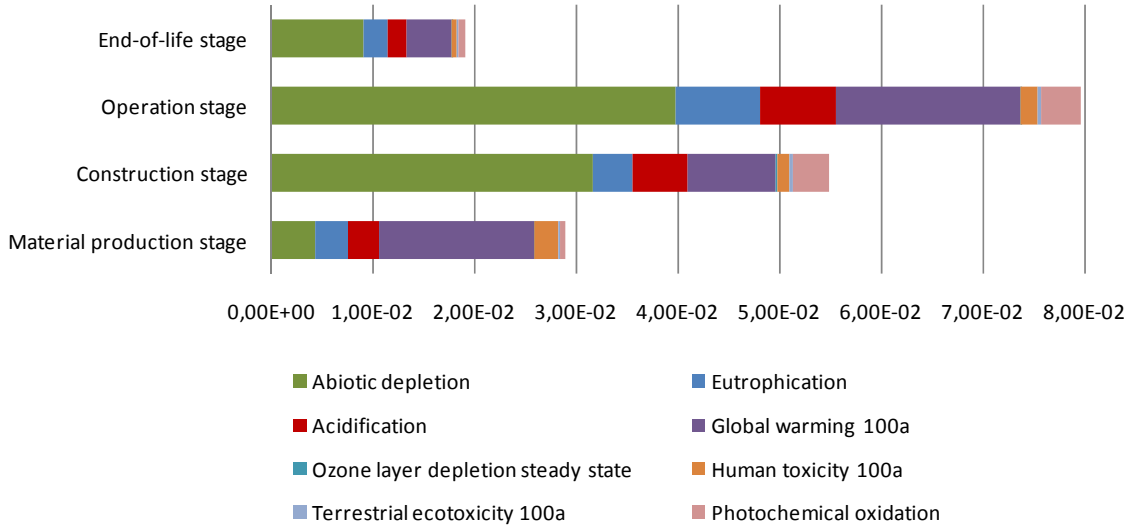

Figure 10.16. Weighted results per stage (considering end-of-life scenario 2)

10.5.6. Uncertainty analysis

The uncertainty analysis is performed using the same approach as the previous case study (Chapter 9). Therefore, three types of uncertainties are hereby considered: parameter uncertainty, uncertainties due to choices and model uncertainties

The uncertainty analysis was performed by Monte Carlo simulations, considering 1000 iterations. The probabilistic analysis was performed by Microsoft Excel @Risk [10.2] add-in software package.

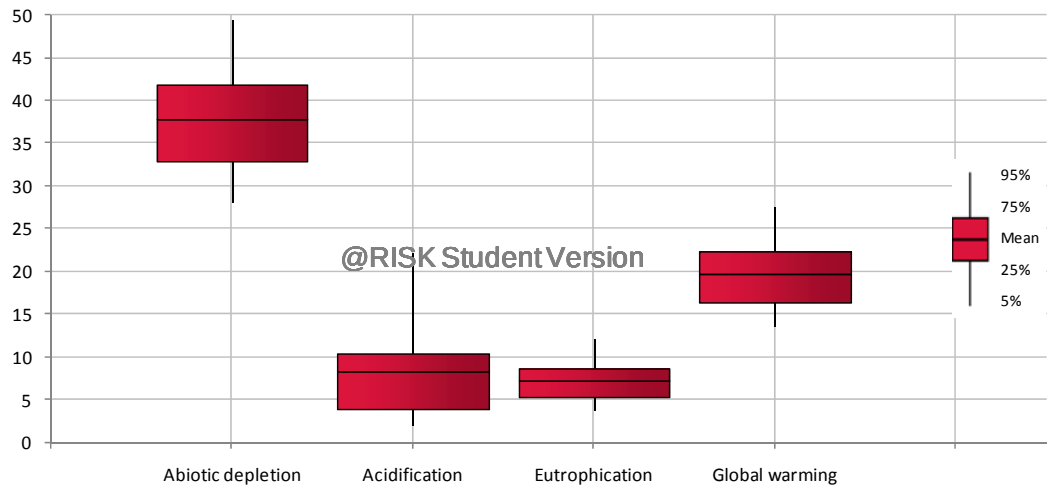

Figure 10.17. Results of the simulations for Abiotic depletion, Acidification, Eutrophication and Global warming

The life cycle environmental results of the simulation for the impact categories of Abiotic depletion, Acidification, Eutrophication and Global warming are represented in Figure 10.17 by the respective 90% confidence interval for the mean value. These results were obtained considering end-of-life scenario 2 (see Table 10.7).

A distribution was fitted to the results of these simulations and the validity of the assumed distributions was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov*. The best-fit distributions for the impact categories represented in Figure 10.17 are indicated in Table 10.28.

Table 10.28. Best-fit distributions for the simulation results

	Abiotic depletion	Acidification	Eutrophication	Global warming
Distribution	lognormal	lognormal	lognormal	lognormal
Mean	37.72	8.44	7.28	19.67
SD	6.60	7.25	2.61	4.37

Likewise, the results for the remaining impact categories are represented in Figure 10.18 by the respective 90% confidence interval for the mean value.

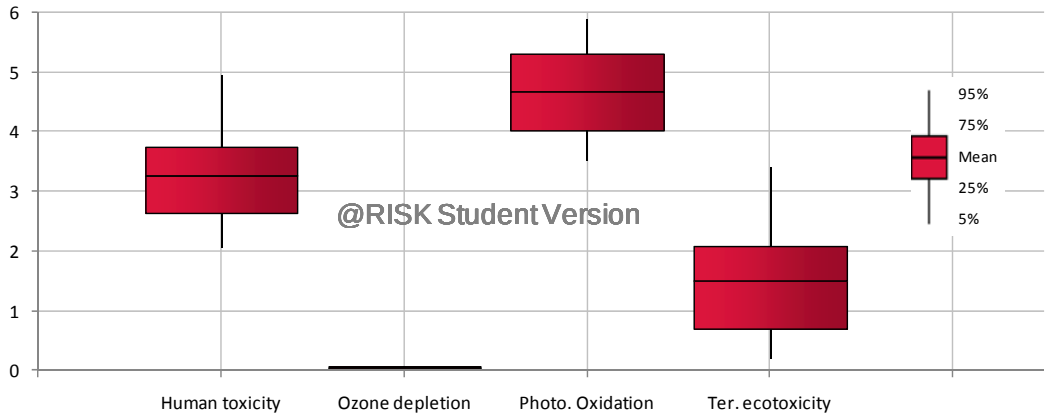

Figure 10.18. Results of the simulations for Human toxicity, Ozone layer depletion, Photochemical oxidation and Terrestrial ecotoxicity

Also in this case, a distribution was fitted to the results of these simulations and the validity of the assumed distributions was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov*. The best-fit distributions for these impact categories are indicated in Table 10.29.

Table 10.29. Best-fit distributions for the simulation results

	Human toxicity	Ozone layer depl.	Photo. oxidation	Terres. ecotoxicity
Distribution	lognormal	lognormal	betageneral	betageneral
Min/Max	-	-	2.79/7.03	0.04/8.58
Mean	3.27	0.04	4.69	1.49
SD	0.88	0.02	0.75	1.05

10.6. LIFE CYCLE COST ANALYSIS

10.6.1. Initial construction cost

The initial cost of the structure is 191 649.00 €, about 451.00 €/m^2, and it was calculated based on the bill of materials indicated in Table 10.1 and the unit costs in Table 10.2.

10.6.2. Operation costs

Over the 100 years, the bridge is maintained and rehabilitated according to the scenario preview in Table 10.4. It is assumed that in the year 50, a major rehabilitation of the structure takes place.

The costs per year are based on the unit costs and frequencies indicated in Chapter 9, Table 9.11. These costs are illustrated in Figure 10.19. The accumulated costs are also represented in the same figure, considering a discount rate of 3.5%.

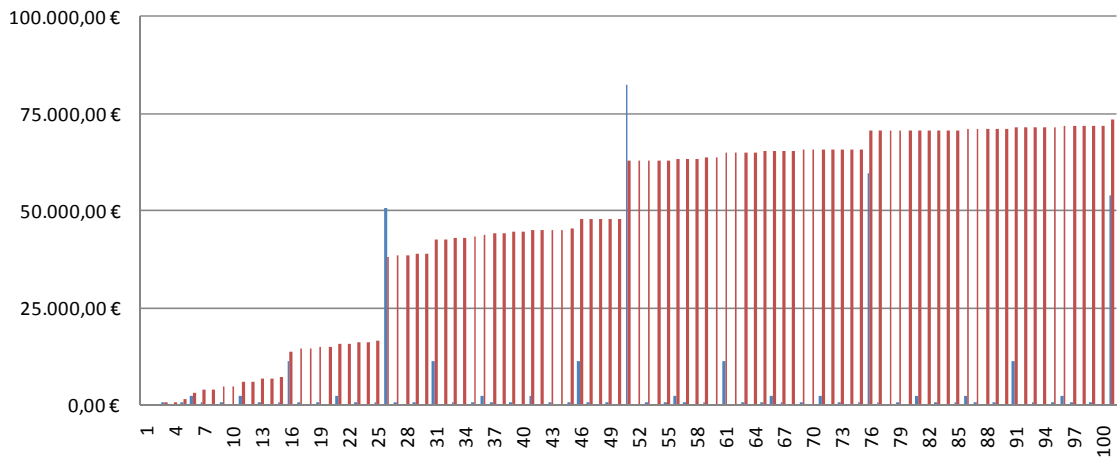

Figure 10.19. Operation costs of the bridge over its service life

The present value of the total cost for maintenance and rehabilitation for the period of 100 years is thus 71 743.17 €, which represents a cost of 168.76 €/m^2.

10.6.3. End-of-life cost

End-of-life costs encompasses the cost of labour work, cost of equipments, cost of road warning signage, cost of transportation and cost for deposition of materials and/or revenue due to recycling of materials.

From information provided by a construction company the cost for demolition of a similar bridge is about 100€/m^2. This cost includes the cost of labour, the cost of equipment and fuel, the cost of ancillary material, the cost of sorting the materials, the cost of all the necessary measures to ensure the safety of the work zone and the cost for cleaning the zone.

This stage includes also the transportation of materials to the disposal/recycling site and the cost or revenue due to landfill or recycling, respectively. According to current European legislation (list of waste), the demolition waste is classified into the following categories:

- (17 01 01) - Concrete;
- (17 03) - Bituminous mixtures, coal tar and tarred products;
- (17 04 05) - Iron and steel.

These wastes are sent for recycling or deposit in a landfill. The cost of transportation requires the estimation of the distances from the demolition place to the disposal/recycling place, the efficiency of the trucks and the price of the fuel. The cost for transportation is given in Table 10.30 assuming trucks with an average load of 25 tonnes.

Table 10.30. Cost for transportation of demolition waste materials

	Mass (tonnes)	No. of trucks	Distance to disposal/recycling site (km)	Fuel efficiency (l/km)	Cost of fuel (€/l)	Transportation fuel cost (€)
Concrete	1 002.9	40	60	0.29(*)	1.065	1 482.48
Bituminous	42.9	2	20	0.29(*)	1.065	24.71
Iron and steel	24.5	1	100	0.29(*)	1.065	61.77
						1 568.96

(*) Considering the density of diesel 0.84 kg/l

The total cost for disposal is indicated in Table 10.31, assuming the disposal fees indicated in the same table.

Table 10.31. Cost of fees for disposal

	Mass (tonnes)	Fee for disposal (€/tonne)	Cost for disposal (€)
Concrete	1 002.9	10	10 029.00
Bituminous	42.9	50	2 145.00
			12 174.00

It is assumed that only 65% of the steel reinforcement is recovered. Thus, the money earned with the steel scrap is given in Table 10.32.

Table 10.32. Revenue due to scrap

	Mass (tonnes)	Price of scrap (€/tonne)	Scrap revenue (€)
Iron and steel	24.5	100	2 450.00

The total end-of-life cost is given by the sum of the previous components, leading to a total of 53 804.52 €. This cost is supposed to take place in year 100, and considering a discount rate of 3.5%, the present value is 1 724.98 €.

Considering the end-of-life scenarios indicated in Table 10.7, the end-of-life cost indicated in the previous paragraph relates to the first end-of-life scenario. For the second scenario, the fee for the disposal of concrete material is not considered. However, no value is available for the revenue of the inert material and hence this value was neglected. For the third scenario a cut-off rule is used and thus the scrap revenue is cut-off from the final accounting. The end-of-life costs for each scenario are summarized in Table 10.33.

Table 10.33. End-of-life costs for each scenario

	1st scenario	2nd scenario	3rd scenario
Total cost (€)	53 804.52	43 775.52	56 254.52
PV total cost (€)	1 724.98	1 403.45	1 803.53
PV Total cost (€/m^2)	4.06	3.30	4.24

10.6.4. Life cycle cost

The compilation of the costs calculated in the previous sections lead to the total life cycle present cost (PVLCC) of 265 116.80 €, using a discount rate of 3.5%. This represents a total cost of 623.63 €/m^2. The costs per year and the accumulated present value of the bridge are illustrated in Figure 10.20.

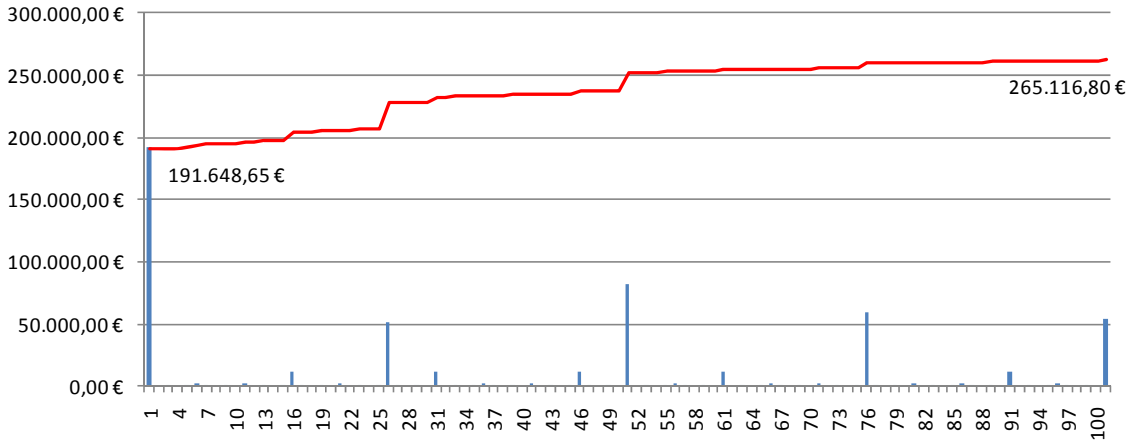

Figure 10.20. Life cycle costs of the composite bridge and accumulated present value (line in red)

Considering the three end-of-life scenarios, the respective life cycle net present costs (PVLCC) are summarized in Table 10.34.

Table 10.34. PVLCC considering different end-of-life scenarios

	1st scenario	2nd scenario	3rd scenario
PV LCC (€)	265 116.80	264 795.27	265 195.35
PV LCC (€/m^2)	623.63	622.88	623.82

10.6.5. Uncertainty analysis

10.6.5.1. Construction cost

The construction cost of the structure was calculated based on the bill of quantities provided by BRISA. Likewise, in order to take into consideration some variations, both in terms of quantities and in terms of costs, a lognormal distribution was assigned to each value (quantities and respective cost), with mean values equal to the values indicated in Table 10.1 and Table 10.2, and a standard deviation of 10% and 25% of the mean values, for the quantities and the costs, respectively.

Hence, by running a Monte Carlo simulation with 10000 iterations, a mean value of 220 641.75 € and a standard deviation of 6 380.60 € were obtained. The probabilistic analysis was performed by Microsoft Excel @Risk [10.2] add-in software package. A distribution was fitted to the results of this simulation and the validity of the assumed distribution was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov*.

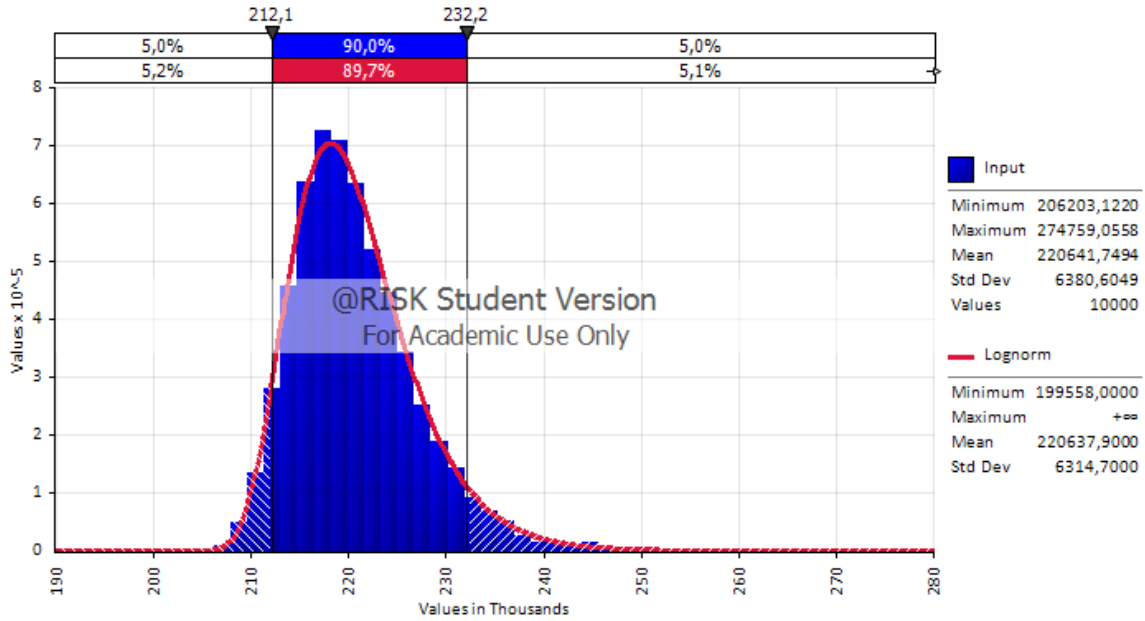

Figure 10.21. Best-fit distribution (in red) according to *chi-square* test and *Kolmogorov-Smirnov* test

In both tests the best distribution to fit the simulation was a lognormal distribution, as represented in Figure 10.21. Thus, for the initial cost of the structure lognormal distribution is considered with mean value 220 637.90 € and standard deviation of 6 314.70€.

10.6.5.2. Discount rate and time of intervention

Following the same approach of previous case study (Chapter 9), a triangular distribution with mean value of 3.5% and minimum and maximum values of 2.5% and 4.5%, respectively, is considered for the discount rate.

A triangular distribution was considered for the interval of time correspondent to the maintenance of concrete deck with a mean value of 25 years and minimum and maximum values of 20 and 30 years, respectively. In addition, a triangular distribution was considered for the interval of time correspondent to the replacement of the deck's surface, with a mean value of 15 years and minimum and maximum values of 12 and 18 years, respectively.

10.6.5.3. Probabilistic-based life cycle cost analysis of the bridge

For the probabilistic life cycle cost analysis, a probability distribution was also assigned to each unit cost of Table 9.11 (see Chapter 9). In all variables, except for the unit cost of maintenance and rehabilitation of the concrete structure, a lognormal distribution was assigned with mean value equal to the value given in the table and a standard deviation of 10% of the mean. For the other two variables, a lognormal distribution was assigned with mean value equal to the value given in the table and a standard deviation of 30%

The total life cycle cost of the bridge was obtained by running a Monte Carlo simulation with 10000 iterations, leading to a mean value of 300 027.99 € and a 90% confidence interval of the mean value between 277 600.00 € and 325 800.00€. The probabilistic analysis was performed by Microsoft Excel @Risk [10.2] add-in software package.

The best distribution to fit the simulation is a lognormal distribution with a mean value of 300 028.20 € and a standard deviation of 14 797.60 €. The result of the simulation and the best-fitted distribution (line in red) are both represented in Figure 10.22.

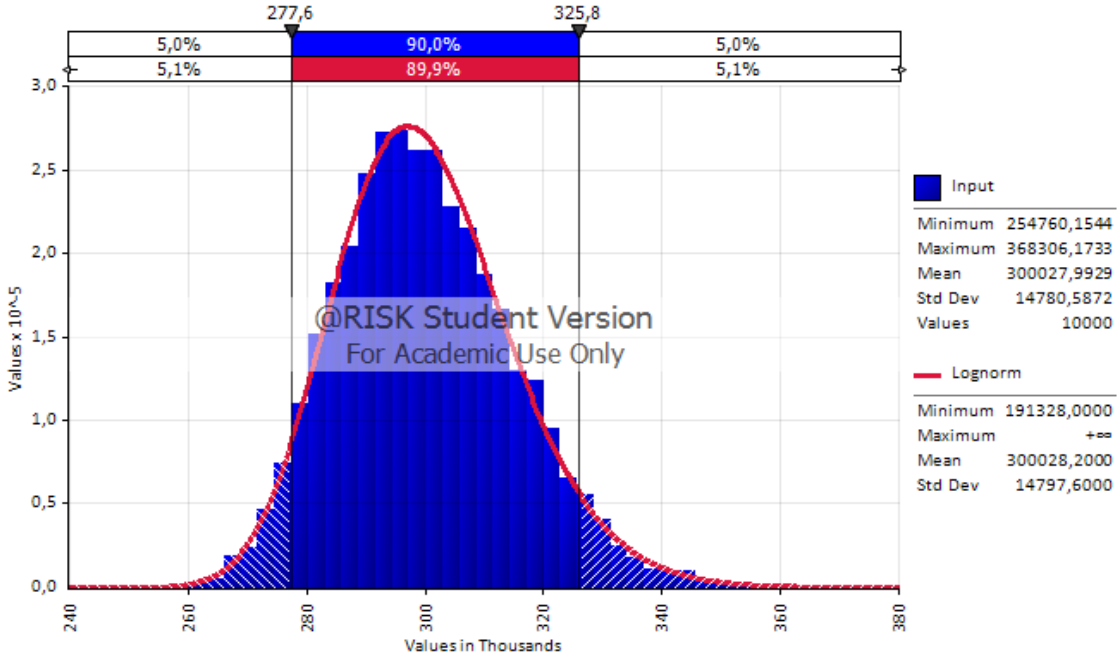

Figure 10.22. PVLCC of the bridge: best-fit distribution according to *chi-square* test and *Kolmogorov-Smirnov* test

The accumulated mean cost over the bridge life cycle is represented in the graph of Figure 10.23, together with the 90% confidence interval of the mean value.

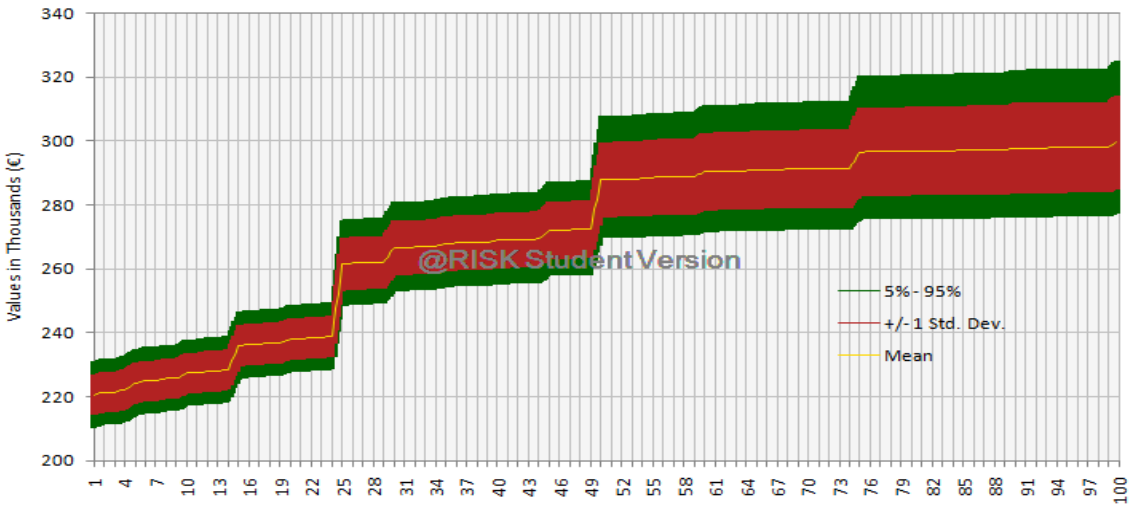

Figure 10.23. Accumulated present value cost (90% confidence interval)

These results are relative to the life cycle analysis considering the 1st end-of-life scenario. For the other scenarios, similar simulations were performed. In all cases, a lognormal distribution was fitted to the results of the simulations. The mean value and standard deviation of each distribution are indicated in Table 10.35.

Table 10.35. Probability distributions of the PVLCC considering different end-of-life scenarios

	1st scenario	2nd scenario	3rd scenario
PV LCC (€)	LN(300028.20; 14797.60)	LN(299584.30; 14764.50)	LN(300045.55; 14920.50)

Finally, to evaluate the input parameters that have the most impact on the life cycle cost of the bridge, a sensitivity analysis was performed. The results of the Spearman rank correlation analysis are illustrated in Figure 10.24, showing that the most important variables are the discount rate, the initial cost of the structure, the cost for the maintenance/rehabilitation of the concrete structure and the respective interval of time.

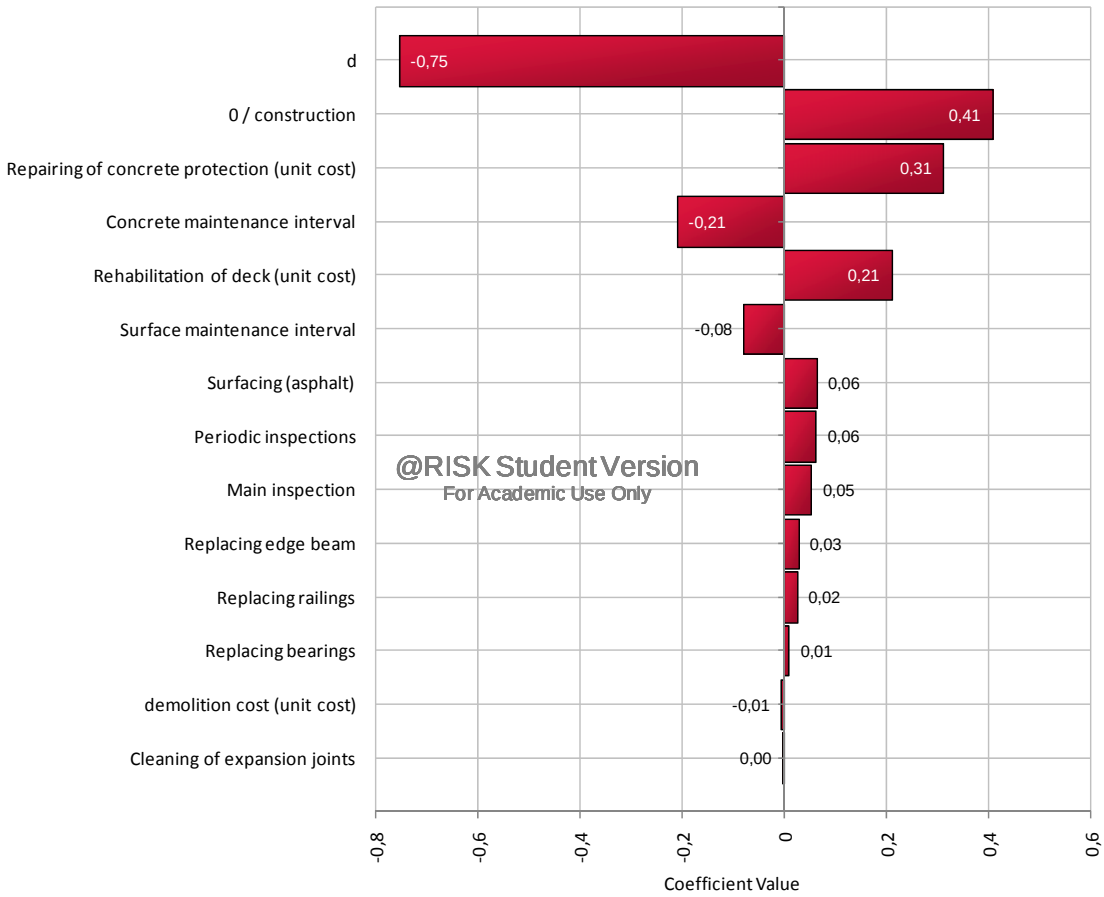

Figure 10.24. Sensitivity analysis of the PVLCC – Spearman rank

10.7. LIFE CYCLE SOCIAL ANALYSIS

10.7.1. Introduction

The impacts on the users of the motorway are quantified based on the methodology discussed in Chapter 8. Likewise, in this case study only the mandatory indicators are used, as no comprehensive data is currently available for the assessment of the optional indicators discussed in Chapter 8. Hence, three types of costs are hereby considered for all stages: the cost of vehicle operation (VOC), the cost of driver delay (DDC) and the cost of safety.

10.7.2. Social impacts due to construction

The construction of the bridge took 133 days as indicated in Table 10.3. Over this period of time traffic restrictions are imposed according to the requirements by the Portuguese Government regarding traffic conditions and safety of users through work zones (see Appendix A).

As already referred, the bridge is new; therefore, no traffic was considered over the bridge in this stage. Thus, the construction of the bridge only affects the traffic in the motorway.

The calculation of users' costs during the construction stage is based on the same reference scenarios considered for the previous case study, which were described in Chapter 9, and on the same global scenarios described for the life cycle environmental analysis (see section 10.5.2). Hence, total costs are summarized in Table 10.36.

Table 10.36. Total user costs during construction stage

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	Night work (1 lane open)	240834.46	349070.68	2331.36
Global scenario 2	Day work (1 lane open)	363890.86	410069.08	2565.36

10.7.3. Social impacts during the operation of the bridge

The calculation of users' costs during the operation stage is based on the same reference scenarios considered for the previous case study, which were described in Chapter 9, and on the same global scenarios described for the life cycle environmental analysis (see section 10.5.3). These costs are summarized in Table 10.37, Table 10.38, Table 10.39 and Table 10.40, for combined actions A, B, C and D, respectively.

Table 10.37. Total user costs for Combined Action A

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	Night work (1 lane open)	2921.44	4291.28	22.08
Global scenario 2	Day work (1 lane open)	3626.96	5337.28	27.68

Table 10.38. Total user costs for Combined Action B

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway + night work crossover	41751.90	60374.88	297.90
Global scenario 2	night work motorway + day work crossover	41751.90	60374.88	297.90
Global scenario 3	day work motorway + night work crossover	135472.86	111113.82	429.84
Global scenario 4	day work motorway + day work crossover	135472.86	111113.82	429.84
Global scenario 5	reduce day work motorway + night work crossover	80281.80	86428.80	370.80
Global scenario 6	reduce day work motorway + day work crossover	80281.80	86428.80	370.80

Table 10.39. Total user costs for Combined Action C

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway (3 lanes open)+ night work crossover	139911.78	202507.86	998.72
Global scenario 2	night work motorway (3 lanes open) + day work crossover	139911.78	202507.86	998.72
Global scenario 3	day work motorway (3 lanes open) + night work crossover	156132.58	226313.46	1122.32
Global scenario 4	day work motorway (3 lanes open) + day work crossover	156132.58	226313.46	1122.32
Global scenario 5	night work motorway (2 lanes open)+ night work crossover	140048.18	202710.66	999.92
Global scenario 6	night work motorway (2 lanes open) + day work crossover	140048.18	202710.66	999.92
Global scenario 7	day work motorway (2 lanes open) + night work crossover	1093500.98	505757.86	1695.92
Global scenario 8	day work motorway (2 lanes open) + day work crossover	1093500.98	505757.86	1695.92
Global scenario 9	reduce day work motorway (2 lanes open) + night work crossover	523854.58	356400.66	1379.52
Global scenario 10	reduce day work motorway (2 lanes open)+ day work crossover	523854.58	356400.66	1379.52

Table 10.40. Total user costs for Combined Action D

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway (3 lanes open)+ night work crossover	50882.44	73721.60	365.16
Global scenario 2	night work motorway (3 lanes open) + day work crossover	51587.96	74767.60	370.76
Global scenario 3	day work motorway (3 lanes open) + night work crossover	60803.32	87581.96	430.86
Global scenario 4	day work motorway (3 lanes open) + day work crossover	61508.84	88627.96	436.46
Global scenario 5	night work motorway (2 lanes open)+ night work crossover	50953.90	73827.62	365.70
Global scenario 6	night work motorway (2 lanes open) + day work crossover	51659.42	74873.62	371.30
Global scenario 7	day work motorway (2 lanes open) + night work crossover	856102.00	301350.50	854.58
Global scenario 8	day work motorway (2 lanes open) + day work crossover	856807.52	302396.50	860.18
Global scenario 9	reduce day work motorway (2 lanes open) + night work crossover	351948.82	180646.64	614.10
Global scenario 10	reduce day work motorway (2 lanes open)+ day work crossover	352654.34	181692.64	619.70

The summary of user costs, per combined activity, is represented in Figure 10.25, considering the best scenario in each case.

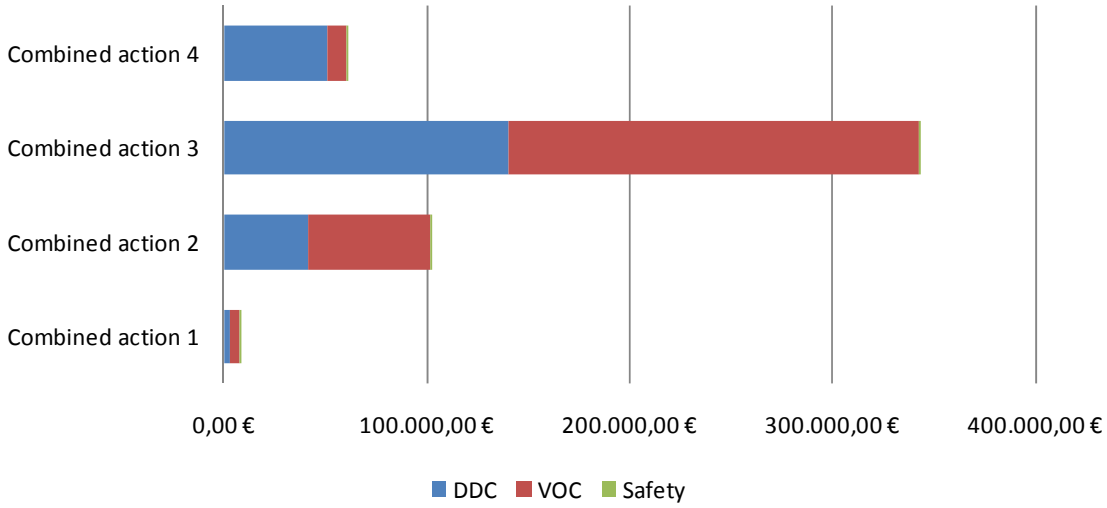

Figure 10.25. User costs per combined maintenance action

The user costs per year and the present value of the accumulated user costs are represented in Figure 10.26, considering a discount rate of 3.5%. These costs are also related to global scenario 1 in each combined activity.

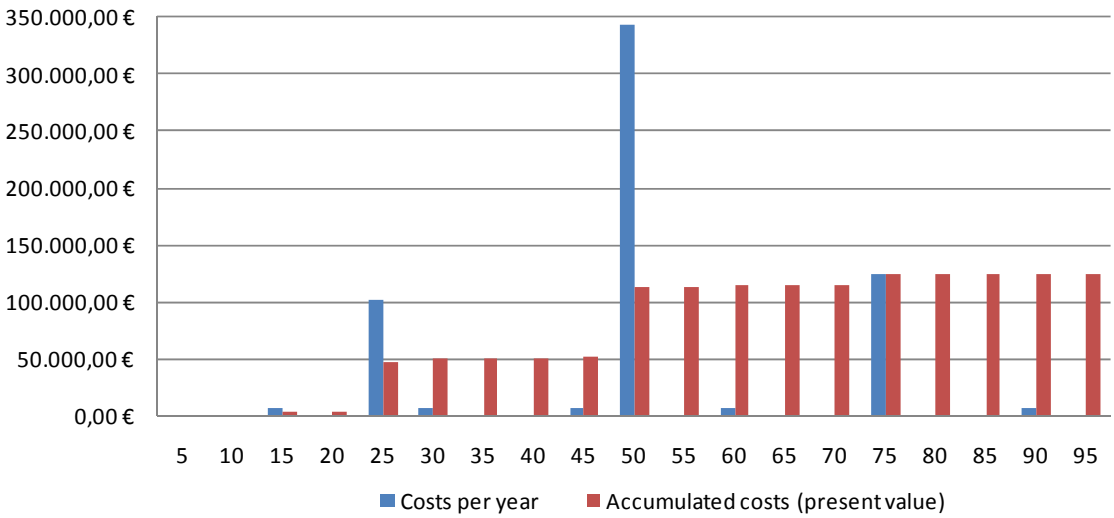

Figure 10.26. User costs of the bridge over its service life

10.7.4. Social impacts due to the demolition of the bridge

Like in the previous stages, the calculation of users' costs during the end-of-life stage is based on the same reference scenarios considered for the previous case study, which were described in Chapter 9, and on the same global scenarios considered for the life cycle environmental analysis (see section 10.5.4). Therefore, no further description is provided in this section.

In addition, during this stage it is assumed that the traffic over the bridge is detoured to an alternative road and thus, no user costs are taken into consideration in this traffic analysis.

Therefore, total user costs for the end-of-life stage are indicated in Table 10.41.

Table 10.41. Total user costs during the demolition stage

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway (3 lanes open)	58850.58	84913.14	415.92
Global scenario 2	day work motorway (3 lanes open)	62984.46	90467.46	440.46
Global scenario 3	night work motorway (2 lanes open)	58876.92	84952.20	416.10
Global scenario 4	day work motorway (2 lanes open)	438971.04	187741.98	630.60
Global scenario 5	reduce day work motorway (2 lanes open)	193079.70	130462.98	519.18

10.7.5. Life cycle social impact

The compilation of the costs calculated in the previous sections lead to the total present value life cycle social cost of 720 838.29 €, which represents a cost of about 1696.00 €/m^2. The costs per year and the accumulated present value cost of the bridge (in red) are illustrated in Figure 10.27. In this analysis, a discount rate of 3.5% was considered.

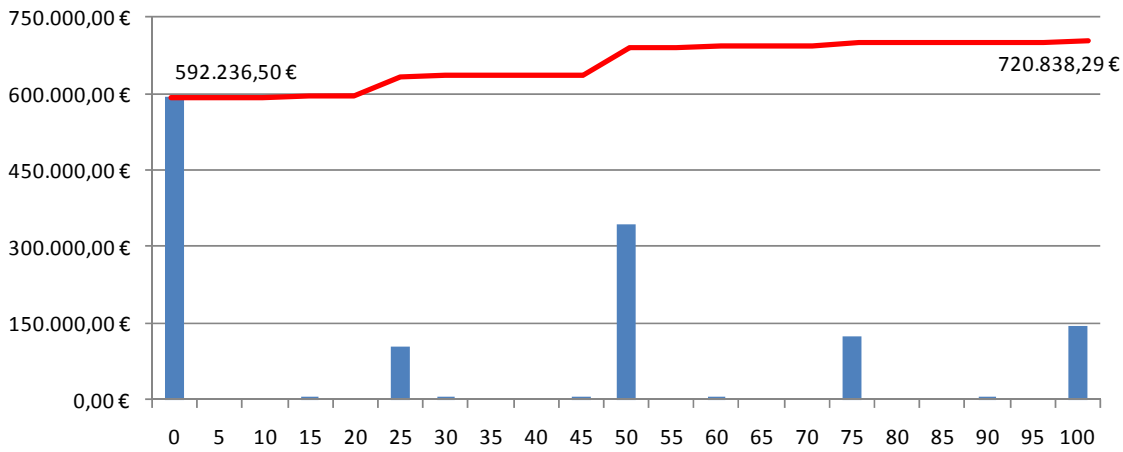

Figure 10.27. Life cycle social costs of the bridge and accumulated present value (in red)

Considering the different stages over the life cycle of the bridge, the present value of the social cost per stage is indicated in Table 10.42.

Table 10.42. Social costs of the bridge per stage (present value)

Construction	Operation	End-of-life
592 236.50 €	123 979.38 €	4 622.42 €
1 393.12 €/m^2	291.64 €/m^2	10.87 €/m^2

The final value of the three indicators considered in the LCSA (the cost of vehicle operation (VOC), the cost of driver delay (DDC) and the cost of safety are indicated in Table 10.43.

Table 10.43. Life cycle social costs of the bridge (present value)

DDC	VOC	Safety
293 204.08 €	424 927.43 €	2 706.78 €
689.70 €/m^2	999.56 €/m^2	6.37 €/m^2

Life cycle social costs of the bridge were evaluated based on the best scenarios defined for each stage. As observed over the previous sections, the consideration of bad options in relation to traffic management may drastically increase social costs. The accumulated life cycle user costs

considering “best scenarios” and “worst scenarios” for each bridge intervention are indicated in Figure 10.28.

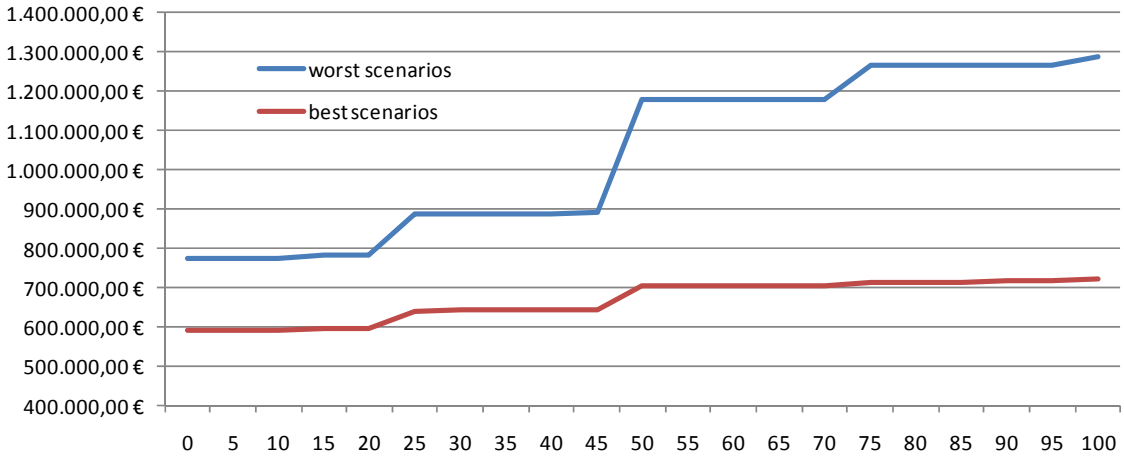

Figure 10.28. Accumulated life cycle user costs considering “best scenarios” and “worst scenarios”

In this case-study, a bad management of the construction work in the motorway increases life cycle social costs of the bridge to almost twice the value corresponding to a good management.

10.7.6. Uncertainty analysis

The uncertainty analysis of life cycle social costs presented in this section took into account the uncertainties in the calculation of DDC, VOC and safety costs, which were discussed in Chapter 8, and the probability distributions of the discount rate and time of intervention indicated in section 10.6.5.

The total life cycle social cost of the bridge was obtained by running a Monte Carlo simulation with 10000 iterations, leading to a mean value of 741 594.90 € and a 90% interval of confidence of the mean value between 667 700.00 € and 821 300.00 €. The probabilistic analysis was performed by Microsoft Excel @Risk [10.2] add-in software package.

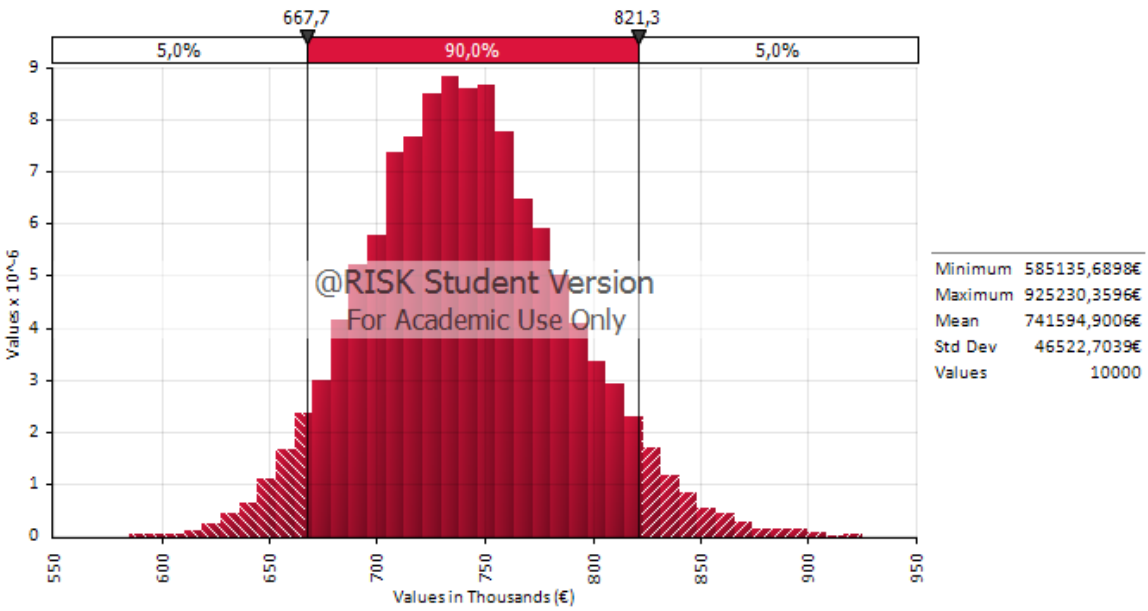

Figure 10.29. PVLCC of the bridge:

The accumulated mean cost over the bridge life cycle is represented in Figure 10.30 together with the 90% confidence interval of the mean value.

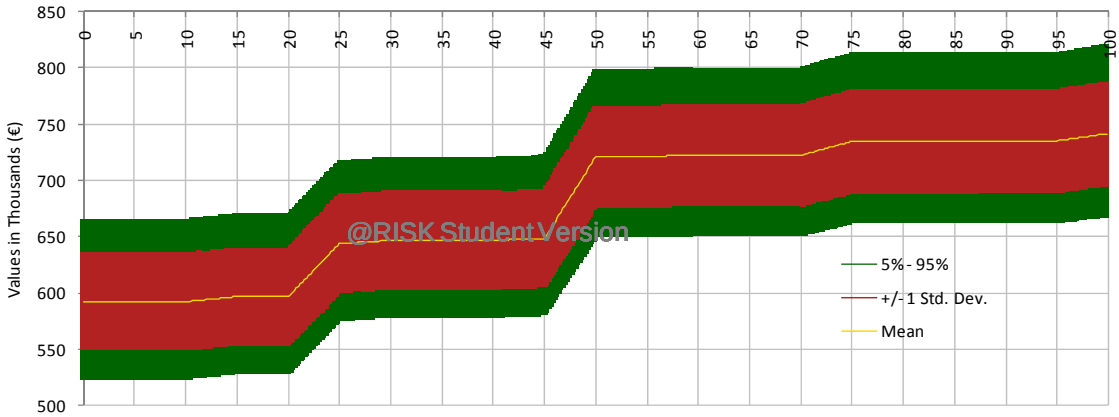

Figure 10.30. Accumulated present value cost (90% confidence interval)

Considering the total life cycle social cost divided by DDC, VOC and safety, the results obtained from the simulations are indicated in Table 10.44 together with the best-fit distributions in each case. The validity of the fitted distributions was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov.*

Table 10.44. Simulation results and best-fit distributions of life cycle social costs

		D.D.C.	V.O.C.	Safety
Simulation results	Mean	301 657.75 €	437 163.38 €	2 767.32 €
	SD	32 244.68 €	31 887.48 €	207.20 €
Best-fit distribution: lognormal	Mean	301 657.40 €	437 162.90 €	2 767.34 €
	SD	32 246.20 €	31 882.30 €	207.16 €

10.8. CONCLUDING REMARKS

This chapter described the application of the integral life cycle approach to a pre-stressed bridge with integral abutments, taking into account environmental, economical and social criteria.

The aim of the life cycle approach was to assess the life cycle performance of the bridge, enabling the identification of the process(es) with major potential impacts and its causes.

Most of the comments, in relation to the application of the integral life cycle approach, provided in the end of Chapter 9 are also applicable to this case study. However, they will not be referred in here to avoid repetition. Therefore, concluding remarks provided in this section focus only on the results of the case study.

In this case study, from the environmental analysis, it was concluded that the stages of construction and operation are the ones with major impacts (see Figure 10.16). In these stages, “global warming” and “abiotic depletion” are the most important impact categories, followed by “acidification” and “eutrophication”. In this case, the main cause in both stages is traffic congestion due to work activity in work zones and consequently fuel consumption.

Bridges with integral abutments avoid the use of expansion joints and bearings, which are equipments that usually required frequent maintenance and replacement over the bridge life

cycle. Consequently, this type of bridge reduces maintenance requirements and corresponding impacts and costs.

In this case, the total life cycle cost of the bridge (present value) represents more 38% of the initial cost of the structure. This is almost half the value obtained in the previous case study.

Likewise, in the life cycle social analysis, total life cycle social cost (present value) represents more 22% of the initial social cost of the structure. Again, this is half the value obtained in the previous case study.

In this case study, the environmental impacts and social costs due to the construction of the bridge are much higher than in the previous case study. As explained in the beginning of this chapter, this bridge was in fact built in a new motorway. Therefore, fewer concerns were taken in relation to the construction system and the time plan for construction of the bridge. However, to compare this case study with the others, it was assumed that the motorway was in service by the time of construction and subjected to the same traffic flow. Naturally, this assumption led to an increase of the environmental and social impacts in the construction stage in comparison with the previous case study.

REFERENCES OF CHAPTER 10

[10.1] Pré Consultants. 2010. SimaPro LCA software (PhD version).

[10.2] Palisade. 2009. @Risk - Risk Analysis and Simulation Add-In for Microsoft Excel 5.5 (student version).

CHAPTER 11. LIFE CYCLE ANALYSIS OF A CONCRETE BRIDGE

11.1. INTRODUCTION

This chapter describes the application of the integral life cycle methodology to the third case study. This case study refers to a concrete bridge that was built in 2007 in the dual carriageway A1, operated by BRISA.

As already referred in Chapter 9, the widening of the motorway lead to the demolition of several bridges and overpasses along the network. The case study described in this chapter belongs to the set of new bridges replacing the existing ones. The bridge is an overpass denominated PS 390. The present analysis was performed after the completion of the project. As with the previous case studies, the results obtained in the present analysis did not influence under no circumstances the design and construction of the bridge.

In the first part of this chapter, a description of the collected data is provided. The second part of this chapter provides detailed calculations and presents the outcome of the environmental, economical and social analysis. In the last part of the chapter, conclusions are drawn in relation to the outcome of the analysis.

All project details of the bridge and some details for its construction were provided by BRISA. For the demolition of the bridge, data was obtained from a similar project of a bridge demolition, which was also supplied by BRISA. All the remaining data needed for the analysis was estimated based on direct interviews with different types of professionals and from a literature survey.

11.2. GOAL AND SCOPE OF THE CASE STUDY

11.2.1. Goal of the analysis

The goal of the analysis is to make a comprehensive account of the environmental, economical and social impacts of a motorway bridge over its service life. The service life is assumed to be 100 years and it is also assumed that at the end of this period the bridge is dismantled. Moreover, the aim of this life cycle analysis is to highlight the processes that contribute most to total account of impacts, enabling to set strategies and recommendations to minimize those impacts.

11.2.2. Functional unit

The functional unit of the life cycle analysis is a motorway bridge, with a required service life of 100 years, to overpass a dual carriageway with a capacity for four lanes in each direction. The functional unit is divided by the deck area of the bridge (in m^2).

11.2.3. System boundaries

All stages over the complete life cycle of the bridges; from raw material extraction until end-of-life procedures (see Chapter 5 – Figure 5.2), are included in the boundary system of the analysis.

11.3. DESCRIPTION OF CASE STUDY

11.3.1. Project details

Bridge PS 390 was built over the dual carriageway A1 – *Auto Estrada do Norte* and it is represented in Figure 11.1. Each carriageway has a wide of 16.30 m and it comprehends a main running surface with 11.25 m, a hard shoulder along the inner lane with a width of 4.05 m and a hard shoulder along the outer lane with 1.00 m. Each carriageway has a capacity for 3 lanes of traffic with a width of 3.75 m. The central reservation is 4.00 m wide.

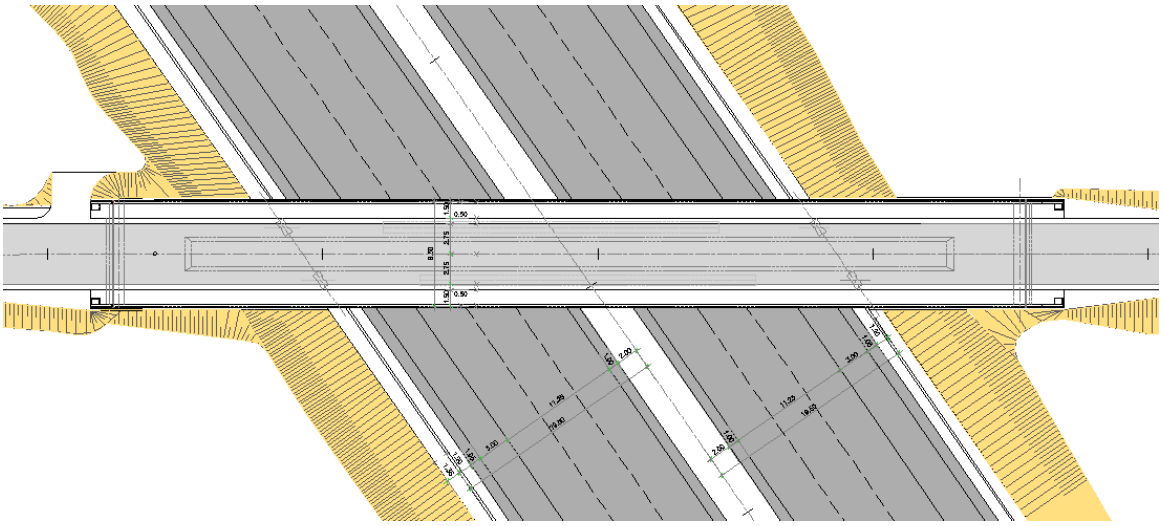

Figure 11.1. Plan view of the concrete bridge PS 390

The bridge has three spans of 16.665 m, 48.50 m and 16.665 m, and it is represented in Figure 11.2. The deck is fully supported over the middle piers and simply supported at the abutments.

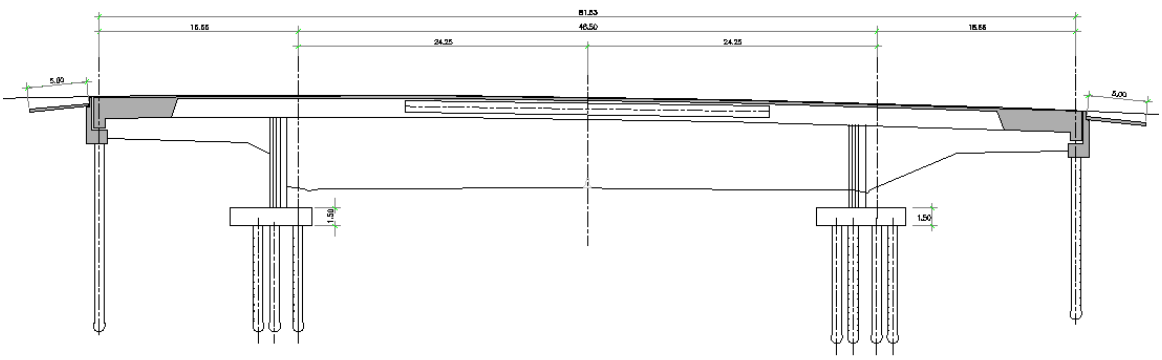

Figure 11.2. Elevation view of the concrete bridge PS 390

The deck is composed of two longitudinal concrete girders, 1.80 m of height, and a concrete slab with variable thickness from 250 mm to 150 mm, in the end of cantilevers. The cross-section is represented in Figure 11.3. The concrete girders and the concrete slab are cast “in situ”. These girders are pre-stressed. The beams in the middle span are hollowed in order to reduce the self-weight of the structure. The piers have a rectangular cross-section with a width of 0.70 m and a length of 1.50 m.

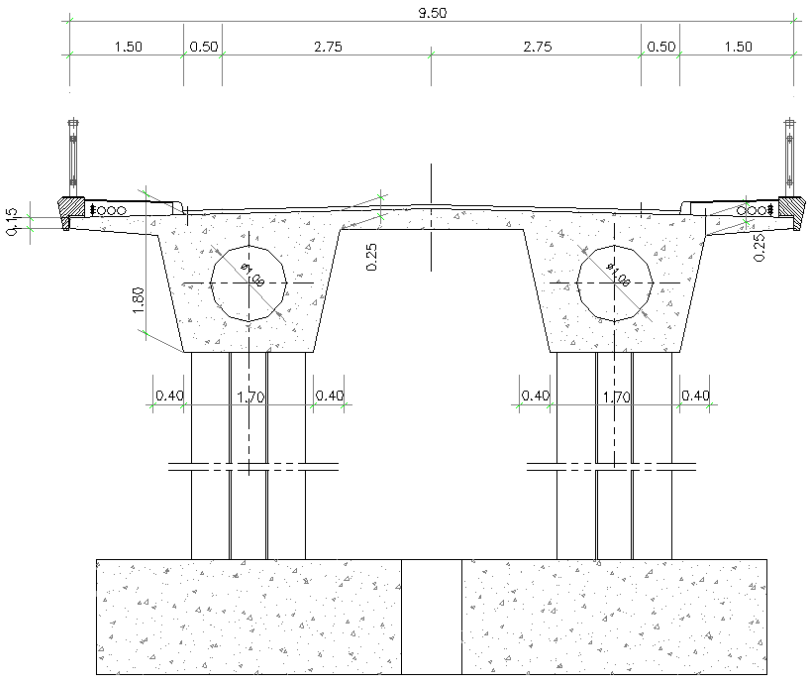

Figure 11.3. Cross-section of the concrete bridge PS 390

The cross-section of the deck comprehends two lanes of traffic, one in each direction, 2.75 m wide, two hard shoulders with 0.50 m and two side-walks for pedestrians with a width of 1.50 m. The total area of the deck is 777.39 m^2.

The bill of main materials for this bridge is represented in Table 11.1.

Table 11.1. Bill of main materials of PS 390

Main component	Elements	Material	Quantity	Unit
Foundations	Regularization	Concrete grade C16/20	19.00	m^3
	Piles (ϕ 0.60 m)	Concrete grade C25/30	256.00	m
	Pile caps and bases	Concrete grade C25/30	127.00	m^3
Abutments	Elevation	Concrete grade C25/30	96.00	m^3
Piers	Elevation	Concrete grade C30/37	29.00	m^3
Deck	Girders and slab	Concrete grade C30/37	779.00	m^3
	Girders	Pre-stressed steel grade A950/1050 in tendons	21 666.00	kg
	Side-walks	Light-weight concrete	44.00	m^3
	Pavement	Asphalt layer 2 cm	745.00	m^2
		Asphalt layer 4 cm	745.00	m^2
Global	All elements	Reinforced steel grade A500	82 414.00	kg

The unit cost of the materials and of the equipment of the bridge are indicated in Table 11.2.

This analysis intends to consider, as far as possible, all materials and processes involved in the analysis. Therefore, for the initial cost of the structure all the costs of materials and equipments were considered, no cut-off rule was used. However, for the environmental analysis some materials and equipments were cut-off from the analysis due to lack of data.

Table 11.2. Unit costs of materials and equipment

Main component	Elements	Material	Unit cost	Unit
Foundations	Regularization	Concrete grade C16/20	49.33	€/m^3
	Piles (ϕ 0.60 m)	Concrete grade C25/30	154.70	€/m
	Pile caps and bases	Concrete grade C25/30	58.31	€/m^3
Abutments	Elevation	Concrete grade C25/30	58.31	€/m^3
Piers	Elevation	Concrete grade C30/37	63.19	€/m^3
Deck	Girders and slab	Concrete grade C30/37	63.19	€/m^3
	Girders	Pre-stressed steel grade A950/1050 in tendons	1.99	€/kg
	Side-walks	Light-weight concrete	63.80	€/m^3
	Pavement	Asphalt layer 2 cm	4.00	€/m^2
		Asphalt layer 4 cm	13.50	€/m^2
Global	All elements	Reinforced steel grade A500	0.65	€/kg
Equipment	Expansion joints		8 092.00	€
	Bearings		1 992.00	€
	Parapet railing		10 389.00	€
	Slope protection		8 701.00	€
	Edge beams		10 984.00	€

11.3.2. Construction details

The construction of this bridge took a total of 93 days, from 6-09-07 to 7-12-07, according to the planning represented in Table 11.3, which was provided by BRISA. The detailed planning is presented in Annex D.

Table 11.3. Construction plan

Main Activity	Elements	Initial date	Final date	Total (days)
Excavation		06-09-07	22-11-07	78
Casting of piles		12-09-07	23-09-07	12
Casting of abutments		24-09-07	28-11-07	66
Piers		24-09-07	10-10-07	17
	Foundation bases Piers	24-09-07 29-09-07	05-10-07 10-10-07	12 12
Casting of deck		12-10-07	13-11-07	33
	Formwork Reinforcement steel Concrete Prestress steel	12-10-07 17-10-07 04-11-07 12-11-07	23-10-07 03-11-07 04-11-07 13-11-07	12 18 1 2
Finishings		14-11-07	07-12-07	24

This viaduct was completely cast “in situ”. The steps for the erection of the viaduct are described in the following paragraphs.

Naturally, the first part of the concrete structure to be built was the piers and the abutments. These elements were cast “in situ”. Then the deck formwork was erected to enable the construction of the deck.

Afterwards, the reinforcement and pre-stressed cables were installed along the complete length of the structure and the deck was cast “in situ”. After the tensioning of the cables, the deck formwork was removed. The final stage of construction comprehended the installation of the remaining equipment.

11.3.3. Traffic constraints during construction stage

During the construction of this bridge, traffic characteristics (under and above the motorway) were assumed to be the same as for the two previous case studies.

Likewise, in this study it is assumed that during the construction of the bridge, traffic restrictions imposed by current legislation (see Annex A) were fully taken into account.

Therefore, according to Table 11.3 and the detailed planning presented in Annex D, there were always two lanes of traffic in each direction of the motorway, except for 6 work days corresponding to the erection of the deck formwork above the motorway. In this case, it was necessary to cancel the traffic in one carriageway and divert the traffic to the other one, resulting in one lane of traffic in each direction.

Moreover, during the entire period of construction (93 days) it was considered that the traffic speed in both carriageways was constrained to a maximum of 80 km/h, except during the period corresponding to the cast “in situ” of the deck above the motorway (15 hours), for which a maximum speed of 50 km/h was considered.

11.4. SCENARIOS AND ASSUMPTIONS FOR LIFE CYCLE ANALYSIS

11.4.1. Traffic under and over the bridge

The same traffic conditions considered for the two previous case studies are considered in this case study. Hence, traffic characteristics are described in Chapter 9, section 9.4.1.

11.4.2. Operation stage – Maintenance and rehabilitation plan

All the assumptions considered for the maintenance and rehabilitation of the two previous case studies are also assumed for the present case study.

Therefore, according to the time of intervention in the bridge for each activity (see Chapter 9, Table 9.11), and in order to minimize the duration of work activity over and under the bridge, the activities happening in the same year are assumed to take place at the same time. This combination of activities leads to 4 combination of actions A to D (as indicated in the bottom line of Table 11.4). The periodic and main inspections are not represented in Table 11.4 as it is assumed that these activities have no direct influence on the analysis.

Combined activity A is the combination of the replacement of the asphalt layer of the bridge with the cleaning of the expansion joints, which occurs every year. This means that when the bridge will be subjected to the work activity due to pavement, then the expansion joints will also be cleaned

Combined activity B represents the replacement of bridge equipment, together with the re-surfacing of concrete elements. This combined activity is similar to combined activity D, except that in the latter, there's also the replacement of the asphalt layer of the bridge.

Combined activity C combines the rehabilitation of the structure, in which all concrete elements will be subject to major intervention and the replacement of major bridge equipment.

Table 11.4. Time-table of maintenance/rehabilitation activities of PS390

years	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
Main structure																	
New surface deck			■										■				
Rehabilitation deck								■									
New surface columns			■										■				
Rehabilitation columns								■									
New surface abutments			■										■				
Rehabilitation abutm.								■									
Equipment																	
Cleaning exp. joints	■	■		■	■	■	■		■	■	■	■		■	■	■	■
Replacing exp. joints			■					■					■				
Replacing bearings			■					■					■				
Replacing rails			■					■					■				
Replacing edge beams			■					■					■				
Re-painting parapet			■					■					■				
Others																	
Replacing asphalt layer	■			■			■			■			■			■	
Combined activities	A	E	B	A	E	E	A	C	E	A	E	E	D	E	E	A	E

Combined activity E is in fact a standalone activity, corresponding to the cleaning of the joints, which occurs every year. Despite being an activity that takes place every year, for the sake of simplicity, this activity is represented in Table 11.4 only every 5 years.

The duration of each combined activity depends on the type of work to be done, in the ability of manpower and in the capacity rate of construction equipment. Thus, for each combined activity (as indicated in Table 11.4) a planning of the respective work was made based on the estimated bill of materials and on the estimated capacity rate for each activity. Based in this information a period of time was estimated for each combined activity, which are indicated in Table 11.5. The detailed calculation and the time plan are provided in Annex D.

During the periods of time corresponding to maintenance and rehabilitation works, traffic over and/or under the bridge is affected. Table 11.5 indicates the total number of days estimated for each combined action and the corresponding traffic affectation.

Table 11.5. Total duration (in days) of maintenance/rehabilitation activities

Combined activity	Total duration (days)	Traffic affectation
A	15	Only affects traffic over the bridge
B	23	Affects traffic over and under the bridge
C	93	Affects traffic over and under the bridge
D	38	Affects traffic over and under the bridge
E	1	It was assumed that this activity does not affect traffic

Moreover, it is assumed that during the maintenance and rehabilitation of the bridge traffic restrictions in work zones, according to current legislation (see Annex A) are always taken into account.

11.4.3. End-of-life of the bridge

Likewise, the demolition of the bridge is assumed to be made in three main stages: the first stage corresponds to the preparation of the terrain and erection of auxiliary structures to support the structure being demolished; the second stage corresponds to the demolition of the central span of the structure; and the third stage corresponds to the demolition “in situ” of the remaining structure. The detailed plan of demolition is provided in Annex D, the total number of days needed for each stage are indicated in Table 11.6.

Table 11.6. Total duration (in days) of bridge demolition

Demolition stages	Description	Duration (in days)
1st stage	Preparation of base supports for scaffolding; Preparation of terrain for deposit of concrete pieces; Erection of scaffolding; Transversal cuts in deck; Longitudinal cuts of deck (partially).	10
2nd stage	Dismantling of one part of composite deck and deposition of the resulting pieces in the side terrain; Dismantling of other part of composite deck and deposition of the resulting pieces in the side terrain.	4
3rd stage	Dismantling of scaffolding in central span; Demolition of the concrete pieces from the deck; Demolition "in situ" of piers and abutments; Removal and transportation of materials; Cleaning of the area.	5

During the demolition of the bridge, it is considered that the traffic over the bridge is diverted to an alternative road. Traffic under the bridge is conditioned by the demolition of the bridge; however, it is assumed that except for the 2nd stage there will always be at least two lanes of traffic in each direction. During the 2nd stage, traffic in the motorway will have to be diverted to only one carriageway as the carriageway below the part of the deck being dismantled has to be closed due to users’ safety reasons.

After the demolition of the bridge and sorting of materials in the demolition site, the materials are sent to different places according to its characteristics and potential for recycling. In this case study, three end-of-life scenarios are going to be considered, as indicated in Table 11.7.

Table 11.7. End-of-life scenarios for main materials

Material	1st scenario	2nd scenario	3rd scenario
Concrete	Landfill	Recycled	Recycled
Reinforcement steel	Recycled	Recycled	Recycled
All the other materials	Landfill	Landfill	Landfill

Scenario 3 is similar to scenario 2, except in the allocation procedures considered for the life cycle environmental analysis, as will be further described in section 11.5.4.

11.5. LIFE CYCLE ENVIRONMENTAL ANALYSIS

11.5.1. Stage of material production

This stage takes into consideration the production of all the materials needed to build the bridge, as indicated in Figure 11.4. Data was collected from the same sources as indicated in Chapter 9. The life cycle environmental analysis is performed using the environmental indicators discussed in Chapter 6. The calculation of the potential environmental impacts was performed by the commercial programme SIMAPRO® [11.1].

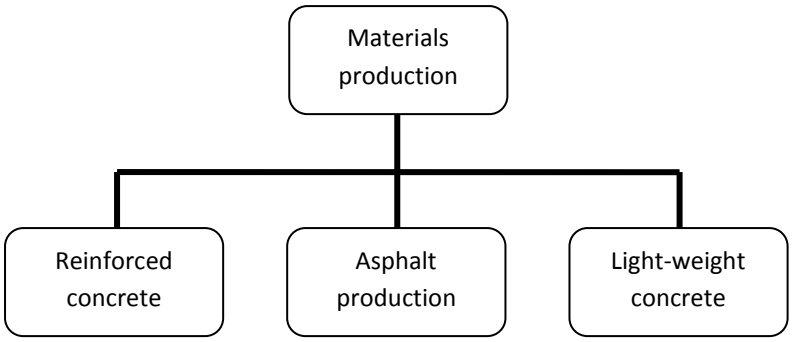

Figure 11.4. Material production stage

The results obtained for each baseline impact category (see Table 6.11, Chapter 6) are represented in Table 11.8.

Table 11.8. Results of the material production stage per impact category

Impact category	Unit	Total	Reinforced concrete	Asphalt	Light-weight concrete
AD	kg Sb eq	1008.6	76.4 %	22.3 %	1.4 %
AC	kg SO_2 eq	1444.6	96.1 %	3.1 %	0.7 %
EU	kg NO_x eq	1342.4	95.6 %	3.3 %	1.1 %
GW	kg CO_2 eq	489811.9	95.6 %	3.3 %	1.1 %
OD	kg CFC-11 eq	0.006	0 %	96.7 %	3.3 %
HT	kg1,4-DB eq	109669.6	97.5 %	2.0 %	0.6 %
TT	kg 1,4-DB eq	104.9	96.7 %	2.4 %	0.9 %
Ph	kg C_2H_4	80.3	96.0 %	3.5 %	0.5 %

From Table 11.8 it is concluded that the production of reinforced concrete is the main process contributing to global impacts in the material production stage, except for the environmental category Ozone layer depletion. The same results are plotted in Figure 11.5.

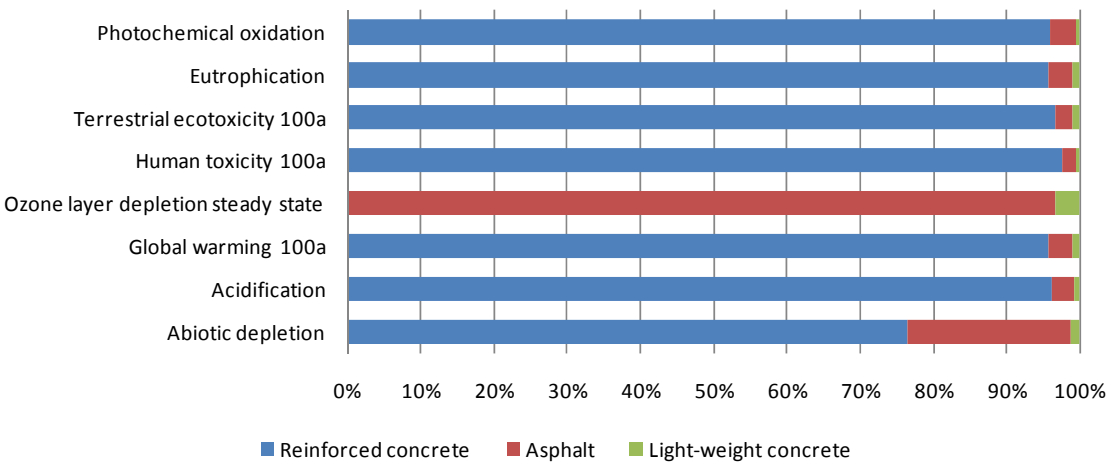

Figure 11.5. Contribution analysis of processes during the material production stage

11.5.2. Stage of construction

11.5.2.1. Transportation of materials and construction equipments

For the transportation of materials and equipments the distances considered in this case study are the ones considered for the first case study (see Table 9.18 in Chapter 9).

11.5.2.2. Use of construction equipment

The quantification of emissions due to the use of construction equipment is based in the plan of construction represented in Table 11.3, in the list of equipment provided by the constructor and emission factors from NONROAD2008 model described in Chapter 5.

The number of hours needed for each equipment were estimated from the plan for construction and in the work capacity of each equipment (assumed that each equipment was used at full capacity).

Hence, total emissions due to the use of diesel-fuelled construction equipment, for the period of time corresponding to the construction stage are indicated in Table 11.9.

Table 11.9. Total emissions (in tonnes) due to diesel-fuelled construction equipment in the construction stage

Activity	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
Excavation and piles	0.022	0.081	0.155	0.017	0.016	0.003	13.892
Piers and abutments	0.004	0.019	0.055	0.003	0.003	0.001	4.668
Concrete deck	0.022	0.094	0.295	0.017	0.016	0.006	28.407
Finishings	0.007	0.029	0.068	0.006	0.006	0.002	7.262
TOTAL	0.055	0.222	0.573	0.042	0.041	0.012	54.228

The detailed calculation of non-mobile emissions is provided in Annex D.

11.5.2.3. Traffic over and under the bridge

In this sub-section only the traffic congestion due to the construction activity is analysed.

During the time period of construction, according to Table 11.3, the traffic under the bridge is affected, due to restrictions in the traffic speed and the narrowing of the carriageway. This bridge is a new bridge; therefore, during its construction there is no traffic over the bridge.

The following paragraphs describe the quantification of fuel consumption and emissions due to traffic congestion. Only the difference between between traffic conditions in a work zone and traffic conditions in the same zone but without work activity is hereby considered.

11.5.2.3.1. Fuel consumption and vehicles' emissions

The characteristics of the traffic flow under the bridge were indicated in Chapter 9, section 9.4.1.

For the calculation of the fuel consumption and emissions during the entire construction period, two global scenarios were considered, as indicated in Table 11.12. These global scenarios are base on the reference scenarios described in Chapter 9, section 9.5.2. However, two additional reference scenarios were considered, as described in the following paragraph.

As already referred, the construction period lasted for 93 days. During this period of time it was considered that the traffic speed in both carriageways was constrained to a maximum of 80 km/h, except during the period corresponding to the cast "in situ" of the deck above the motorway (15 hours), for which a maximum speed of 50 km/h was considered. Hence, two reference scenarios were defined: scenario 1A, considering the 15 hours period from 19 h – 10 h, and scenario 1B, considering the 15 hours period from 6 h – 21 h. The respective emissions are indicated in Table 11.10.

Table 11.10. Emissions (per day and per carriageway) in work zone during construction

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Max. queue (km)	CO (kg/day)	HC (kg/day)	NOx (kg/day)
1A	2	2	0 - 24	19 - 10	0	32.86	0.48	0.33
1B	2	2	0 - 24	6 - 21	0	32.07	0.86	0.41

Table 11.11 indicates the fuel consumption in the work zone for the two additional scenarios described in the previous paragraph.

Table 11.11. Fuel consumption (per day and per carriageway) in work zone during construction

Scenario	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	Fuel	
					Gasoline	Diesel
					(kg/day)	(kg/day)
1A	2	2	0 - 24	19 - 10	192.25	337.18
1B	2	2	0 - 24	6 - 21	254.69	411.69

Hence, global scenario 1 considers that traffic restrictions occur during the night period, whereas global scenario 2 considers that restrictions occur during the day.

Table 11.12. Total emissions and fuel consumption in work zone during construction

	Emissions (kg)			Fuel (kg)	
	CO	HC	NOx	Gasoline	Diesel
Global scenario 1	6176.24	61.80	54.14	31290.90	57420.96
Global scenario 2	6744.42	115.48	65.34	34049.54	61370.26

11.5.2.4. Synthesis of the construction stage

The construction stage takes into account all the processes needed for the construction of the bridge and affected by it. Hence, as represented in Figure 11.6, it includes the transportation of materials to the construction site, the transportation of equipment, the use of construction equipment and the emissions due to the traffic congestion resulting from construction activity.

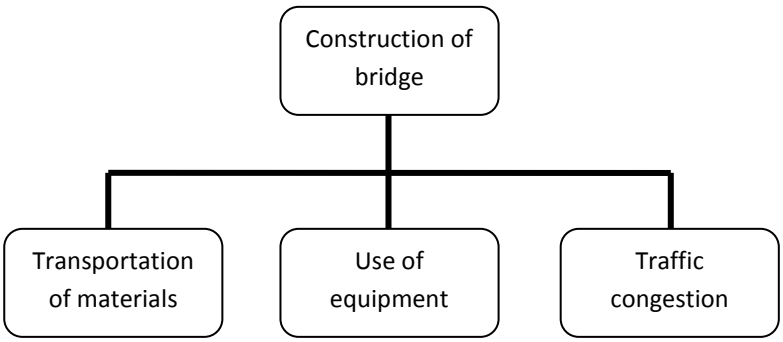

Figure 11.6. Construction stage

The results obtained for each baseline impact category (see Chapter 6, Table 6.11) are represented in Table 11.13 and Figure 11.7.

Table 11.13. Results of the construction stage per impact category

Impact category	Unit	TOTAL	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	2319.71	6.6 %	0 %	93.4 %
AC	kg SO_2 eq	1000.01	6.4 %	30.1 %	63.5 %
EU	kg NO_x eq	1048.3	8.5 %	65.6 %	25.9 %
GW	kg CO_2 eq	137893.0	15.4 %	39.6 %	45.0 %
OD	kg CFC-11 eq	0.045	7.5 %	0 %	92.5 %
HT	kg 1,4-DB eq	20118.8	15.2 %	3.6 %	81.2 %
TT	kg 1,4-DB eq	26.0	15.6 %	0 %	84.4 %
Ph	kg C_2H_4	210.5	1.3 %	3.1 %	95.6 %

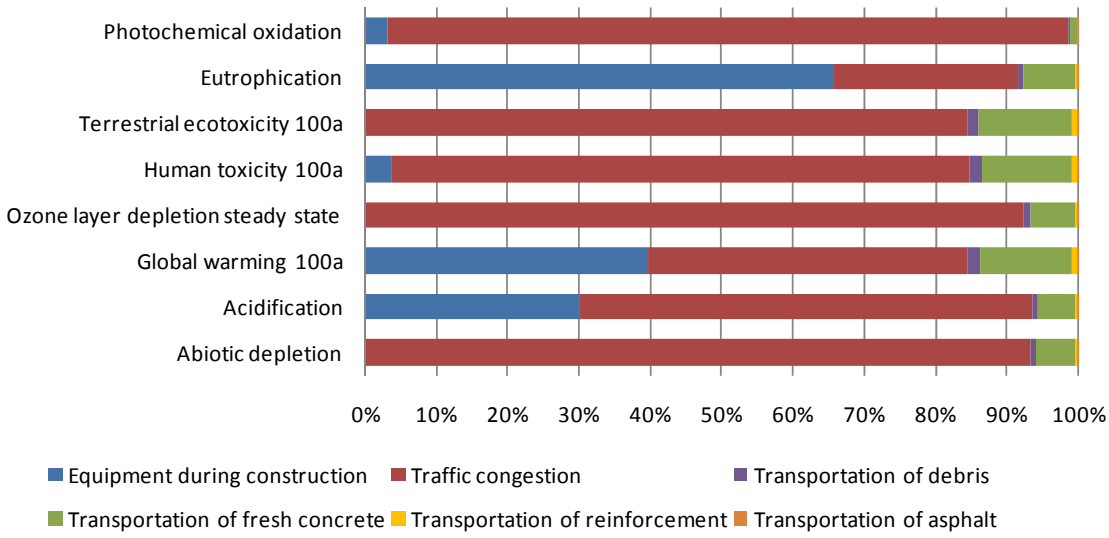

Figure 11.7. Contribution analysis of processes during the construction stage

In this stage the process that most contributes to all impact categories is clearly "traffic congestion". Its contribution is always above 80%, except for the impact categories of acidification, eutrophication and global warming, for which an important contribution is also provided by the "use of equipment".

11.5.3. Stage of operation

11.5.3.1. Transportation of materials and equipments

The distances considered in this case study for the transportation of materials and equipments are the ones considered for the first case study (see Chapter 9).

11.5.3.2. Use of equipments

The quantification of emissions due to the use of equipment is based in the plan of maintenance provided in Annex D, in the list of equipment provided by the constructor and emission factors from NONROAD2008 model described in Chapter 5.

The number of hours needed for each equipment were estimated from the plan of maintenance and in the work capacity of each equipment (assumed that each equipment was used at full capacity). Hence, total emissions for the operation stage are indicated in Table 11.14.

Table 11.14. Total emissions (in tonnes) due to diesel-fuelled equipment in the operation stage

Activity	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
Combined act. 1	0.005	0.023	0.070	0.005	0.005	0.002	8.842
Combined act. 2	0.018	0.079	0.233	0.016	0.015	0.006	27.712
Combined act. 3	0.037	0.165	0.486	0.033	0.032	0.012	57.643
Combined act. 4	0.023	0.102	0.303	0.020	0.020	0.008	36.554

11.5.3.3. Traffic over and under the bridge

11.5.3.3.1. Fuel consumption and vehicles' emissions

The characteristics of the traffic flow over and under the bridge for the operation stage were indicated in Chapter 9, section 9.4.1.

For the calculation of fuel consumption and emissions during the entire operation stage, several global scenarios were considered for each combined maintenance activity indicated in Table 11.4. These global scenarios are base on the reference scenarios described in Chapter 9, section 9.5.3.

Combined activity A has a total duration of 15 days and only affects traffic over the bridge. During this period of time it is assumed that there will be always one lane of traffic closed. In global scenario 1 the closure is made over night, whereas in global scenario 2 the closure is made during the day. The corresponding emissions and fuel consumption, for the entire period of time, are indicated in Table 11.15.

Table 11.15. Total emissions in work zone during operation stage (combined activity A)

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	Night work over bridge	338.55	1.65	2.70	964.20	2005.35
Global scenario 2	Day work over bridge	330.45	3.60	3.15	1277.55	2359.05

Combined activity B occurs in year 2033 and has a total duration of 23 days. During this time traffic is affected over and under the bridge. Six different global scenarios, as described in Table 11.16, were defined to combined each possible situation. Global scenario 1 corresponds to the best traffic-management option while the other global scenarios combine other possible situations as described in Table 11.16.

Table 11.16. Total emissions in work zone during operation stage (combined activity B)

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	Night work motorway + night work over bridge	2437.91	27.58	21.78	14910.01	26166.38
Global scenario 2	Night work motorway + day work over bridge	2433.59	28.62	22.02	15077.13	26355.02
Global scenario 3	Day work motorway + night work over bridge	5380.91	281.02	74.34	29441.41	47367.86
Global scenario 4	Day work motorway + day work over bridge	5376.59	282.06	74.58	29608.53	47556.50
Global scenario 5	Reduce day work motorway + night work over bridge	3545.99	120.46	40.14	22289.65	37194.98
Global scenario 6	Reduce day work motorway + day work over bridge	3541.67	121.50	40.38	22456.77	37383.62

Combined activity C occurs in year 2058 and has a total duration of 93 days. Likewise, during this period of time, traffic is affected over and under the bridge. Hence, ten different global scenarios, as described in Table 11.17, were defined to combine each possible situation. The description of each scenario is provided in the table; in the same manner, global scenario 1 corresponds to the best traffic-management option.

Table 11.17. Total emissions in work zone during operation stage (combined activity C)

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	night work motorway (3 lanes open)+ night work over bridge	9980.39	108.16	89.22	55397.35	99686.72
Global scenario 2	night work motorway (3 lanes open) + day work over bridge	9976.07	109.20	89.46	55564.47	99875.36
Global scenario 3	day work motorway (3 lanes open) + night work over bridge	9980.39	152.26	99.12	63931.15	109386.92
Global scenario 4	day work motorway (3 lanes open) + day work over bridge	9976.07	153.30	99.36	64098.27	109575.56
Global scenario 5	night work motorway (2 lanes open)+ night work over bridge	9977.69	109.06	89.22	55470.25	99768.62
Global scenario 6	night work motorway (2 lanes open) + day work over bridge	9973.37	110.10	89.46	55637.37	99957.26
Global scenario 7	day work motorway (2 lanes open) + night work over bridge	46910.09	3591.16	849.72	157756.15	234212.42
Global scenario 8	day work motorway (2 lanes open) + day work over bridge	46905.77	3592.20	849.96	157923.27	234401.06
Global scenario 9	reduce day work motorway (2 lanes open) + night work over	24105.89	1452.76	379.92	106920.55	168682.52
Global scenario 10	reduce day work motorway (2 lanes open)+ day work over	24101.57	1453.80	380.16	107087.67	168871.16

Finally, for combined activity D, occurring in year 2083 with a total duration of 38 days, traffic is also affected over and under the bridge. In this case, also ten different global scenarios, as described in Table 11.18, were defined to combine each possible situation.

Table 11.18. Total emissions in work zone during operation stage (combined activity D)

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	night work motorway (3 lanes open)+ night work over bridge	3370.10	34.27	29.52	18086.05	32613.77
Global scenario 2	night work motorway (3 lanes open) + day work over bridge	3357.68	37.26	30.21	18566.52	33156.11
Global scenario 3	day work motorway (3 lanes open) + night work over bridge	3370.10	57.67	34.92	22451.41	37722.89
Global scenario 4	day work motorway (3 lanes open) + day work over bridge	3357.68	60.66	35.61	22931.88	38265.23
Global scenario 5	night work motorway (2 lanes open)+ night work over bridge	3369.02	34.63	29.88	18120.25	32651.93
Global scenario 6	night work motorway (2 lanes open) + day work over bridge	3356.60	37.62	30.57	18600.72	33194.27
Global scenario 7	day work motorway (2 lanes open) + night work over bridge	31649.18	2728.51	622.08	87710.77	120081.89
Global scenario 8	day work motorway (2 lanes open) + day work over bridge	31636.76	2731.50	622.77	88191.24	120624.23
Global scenario 9	reduce day work motorway (2 lanes open) + night work over	13365.86	1007.35	242.64	50600.53	74029.61
Global scenario 10	reduce day work motorway (2 lanes open)+ day work over	13353.44	1010.34	243.33	51081.00	74571.95

For the calculation of the total emissions in the operation stage, as indicated in the following sub-section, the best scenarios corresponding to each combined maintenance activity were considered.

11.5.3.4. Synthesis of the operation stage

The operation stage of the bridge took into account the estimated maintenance and rehabilitation activities according to Table 11.4. These activities occur over different time periods over the service life of the structure, as described in the previous sub-sections. However, due to a repeated number of processes, the tree diagram of Figure 11.8 aggregates the processes with same characteristics occurring at different time periods.

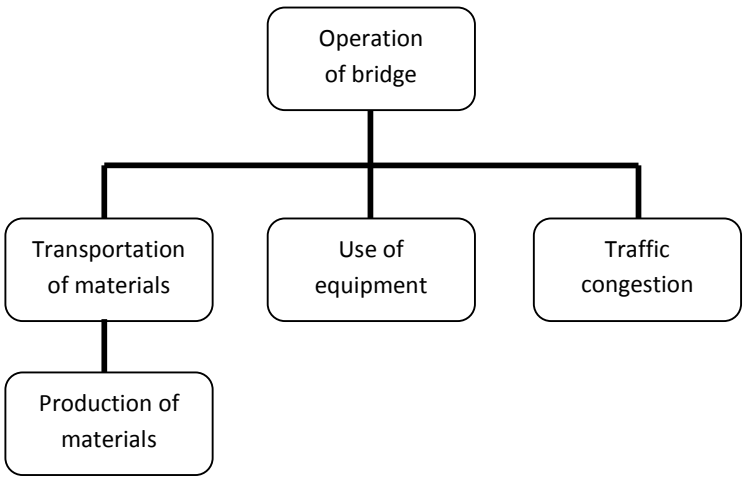

Figure 11.8. Operation stage of the bridge

The outcome of each combined activity is indicated in Table 11.19, Table 11.20, Table 11.21 and Table 11.22, respectively for combined activities A to D. Each table indicates total emissions per impact category and corresponding contribution of each process.

From Table 11.9 it is observed that the asphalt replacement contributes with a share of more than 50% for most impact categories, while traffic congestion represents a major contribution only for the impact category of photochemical oxidation. This combined activity affects only traffic over the bridge.

Table 11.19. Results of the operation stage per impact category (combined activity A)

Impact category	Unit	TOTAL	Asphalt replacement	Use of equipment	Traffic congestion
AD	kg Sb eq	297.8	75.7 %	0 %	24.3 %
AC	kg SO_2 eq	104.8	43.7 %	34.5 %	20.6 %
EU	kg NO_x eq	139.1	32.4 %	60.4 %	7.3 %
GW	kg CO_2 eq	27275.5	59.2 %	31.2 %	8.3 %
OD	kg CFC-11 eq	0.008	81.9 %	0 %	18.1 %
HT	kg 1,4-DB eq	2806.7	77.4 %	3.0 %	19.4 %
TT	kg 1,4-DB eq	3.3	77.6 %	0 %	22.4 %
Ph	kg C_2H_4	13.8	20.3 %	5.1 %	74.5 %

In the case of combined activity B, Table 11.20, the process that most contributes to major impact categories is clearly “traffic congestion”. Its contribution is always above 90%, except for the impact categories of acidification, eutrophication and global warming, for which an important contribution is also provided by the “use of equipment.

Table 11.20. Results of the operation stage per impact category (combined activity B)

Impact category	Unit	TOTAL	Concrete repair	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	1013.1	0.8 %	0.2 %	0 %	99.1 %
AC	kg SO_2 eq	423.3	1.4 %	0.2 %	29.2 %	69.2 %
EU	kg NO_x eq	410.4	2.0 %	0.2 %	68.1 %	29.7 %
GW	kg CO_2 eq	59764.0	5.9 %	0.4 %	46.6 %	47.1 %
OD	kg CFC-11 eq	0.019	0.6 %	0.2 %	0 %	99.2 %
HT	kg 1,4-DB eq	8182.9	3.4 %	0.4 %	3.6 %	92.6 %
TT	kg 1,4-DB eq	10.8	5.2 %	0.4 %	0 %	94.4 %
Ph	kg C_2H_4	84.5	0.3 %	0 %	2.9 %	96.8 %

The same conclusions may be drawn for the case of combined activity C, where the process that most contributes to major impact categories is again the “traffic congestion”, as indicated in Table 11.21.

Table 11.21. Results of the operation stage per impact category (combined activity C)

Impact category	Unit	TOTAL	Concrete rehabilitation	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	3084.1	1.3 %	0.3 %	0 %	98.5 %
AC	kg SO_2 eq	1180.8	2.5 %	0.3 %	22.0 %	75.3 %
EU	kg NO_x eq	1008.4	4.0 %	0.5 %	58.3 %	37.3 %
GW	ton CO_2 eq	163314.3	10.9 %	0.7 %	35.7 %	52.7 %
OD	kg CFC-11 eq	0.059	1.0 %	0.3 %	0 %	98.7 %
HT	ton1,4-DB eq	25086.5	5.5 %	0.6 %	2.5 %	91.4 %
TT	kg 1,4-DB eq	33.9	8.3 %	0.6 %	0 %	91.1 %
Ph	kg C_2H_4	271.8	0.4 %	0.1 %	1.9 %	97.7 %

Finally, in the case of combined activity D, the process of "traffic congestion" still has a major contribution to most impact categories, although the processes of "asphalt replacement" and "use of equipment" share some importance in a few impact categories.

Table 11.22. Results of the operation stage per impact category (combined activity D)

Impact category	Unit	TOTAL	Concrete repair	Asphalt replacem.	Transp. of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	1473.2	0.5 %	15.2 %	0.2 %	0 %	84.1 %
AC	kg SO_2 eq	576.1	1.0 %	7.9 %	0.2 %	28.0 %	62.9 %
EU	kg NO_x eq	571.5	1.4 %	7.8 %	0.4 %	63.6 %	26.9 %
GW	kg CO_2 eq	91861.5	3.9 %	17.4 %	0.4 %	40.0 %	38.4 %
OD	kg CFC-11 eq	0.030	0.4 %	20.7 %	0.2 %	0 %	78.7 %
HT	kg 1,4-DB eq	12211.3	2.3 %	17.7 %	0.4 %	3.1 %	76.5 %
TT	kg 1,4-DB eq	15.7	3.6 %	16.0 %	0.4 %	0 %	80.0 %
Ph	kg C_2H_4	116.9	0.2 %	2.4 %	0 %	2.7 %	94.7 %

The contribution of each combined activity to the aggregated result of the operation stage is illustrated in Figure 11.9, showing that combined activity C, which takes the longer period of time, has the major contribution in all impact categories.

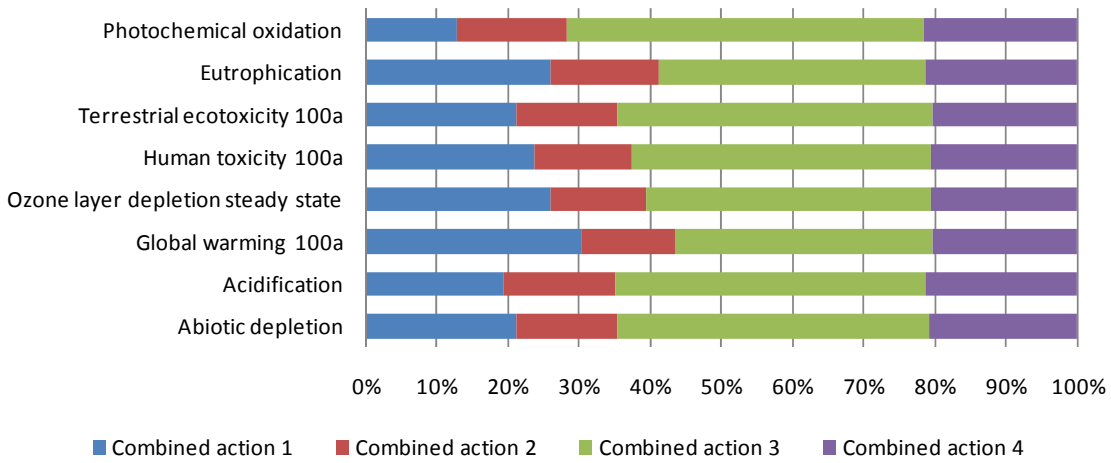

Figure 11.9. Contribution analysis of processes during the operation stage

11.5.4. End-of-life stage

11.5.4.1. Transportation of materials and equipments

Likewise, the distances considered in this case study for the transportation of materials and equipments, during the end-of-life stage, are the ones considered for the first case study (see Chapter 9).

11.5.4.2. Use of equipments

The quantification of emissions due to the use of construction equipment, which are indicated in Table 11.23, is based in the plan of demolition represented in Annex D, in the list of equipment provided by the constructor and emission factors from NONROAD2008 model described in Chapter 5.

The number of hours needed for each equipment were estimated from the time plan of demolition and in the work capacity of each equipment (assumed that each equipment was used at full capacity).

Table 11.23. Total emissions (in tonnes) due to diesel-fuelled equipment in the end-of-life stage

Activity	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
1st stage	0.005	0.024	0.060	0.005	0.004	0.001	6.900
2nd stage	0.002	0.013	0.034	0.002	0.002	0.001	3.528
3rd stage	0.026	0.099	0.212	0.020	0.019	0.005	23.096
TOTAL	0.034	0.137	0.306	0.027	0.026	0.007	33.524

11.5.4.3. Traffic over and under the bridge

11.5.4.3.1. Fuel consumption and vehicles' emissions

The characteristics of the traffic flow over and under the bridge for the end-of-life stage were indicated in Chapter 9, section 9.4.1.

For the calculation of fuel consumption and emissions during the end-of-life stage, five global scenarios were considered as described in Table 11.24. These global scenarios are based on the reference scenarios described in Chapter 9, section 9.5.4.

The demolition period is estimated to take 19 days (see Table 11.6). During this period it is estimated there were always four lanes of traffic in each direction, although with reduced speed, except for two working days (see demolition plan in Annex D), corresponding to the demolition of the central span. During this period a carriageway has to be closed to the traffic underneath and traffic has to be diverted to the other carriageway, resulting in three or, in the worst case, two lanes of traffic in each direction. Table 11.24 indicates the global scenarios resulting from the above considerations.

For the calculation of the total emissions in the end-of-life stage, the best scenario, that is global scenario 1, was considered.

Table 11.24. Total emissions in work zone during end-of-life stage

	Description	Emissions (kg)			Fuel (kg)	
		CO	HC	NOx	Gasoline	Diesel
Global scenario 1	Night work (3 lanes open)	2679.00	33.48	24.32	17683.98	30774.52
Global scenario 2	Day work (3 lanes open)	2679.00	36.68	25.04	18262.50	31464.92
Global scenario 3	Night work (3 lanes open)	2679.00	33.52	24.36	17688.14	30779.24
Global scenario 4	Day work (2 lanes open)	7169.92	461.60	118.64	28237.86	43825.00
Global scenario 5	Reduce day work (2 lanes open)	4171.88	179.76	56.48	22340.82	36586.84

11.5.4.4. Synthesis of the end-of-life stage

In this stage three scenarios are considered, according to Table 11.7. In all scenarios it is assumed that the bridge is demolished and the materials are sorted in the same place before being sent to their final destination. Therefore, no transportation is needed between the demolition place and the sorting plant. This is usually the procedure according to current legislation as referred in Chapter 2.

The first scenario assumes that the concrete is sent to a landfill of inert materials. The second scenario considers that 80% of concrete is recycled using an open-loop approach. The economic allocation procedure discussed in Chapter 5 was used. Finally, the third scenario is similar to the previous one, except in the allocation approach considered. In this case, a cut-off rule was used for all the materials sent for recycling. For the recycling of asphalt a cut-off rule was used in all end-of-life scenarios due to the lack of data in relation to the respective recycling process. In relation to steel reinforcement, it was assumed that it was recycled in all scenarios using the close-loop approach described in Chapter 5 for steel. Figure 11.10 represents the general unit processes included in this stage.

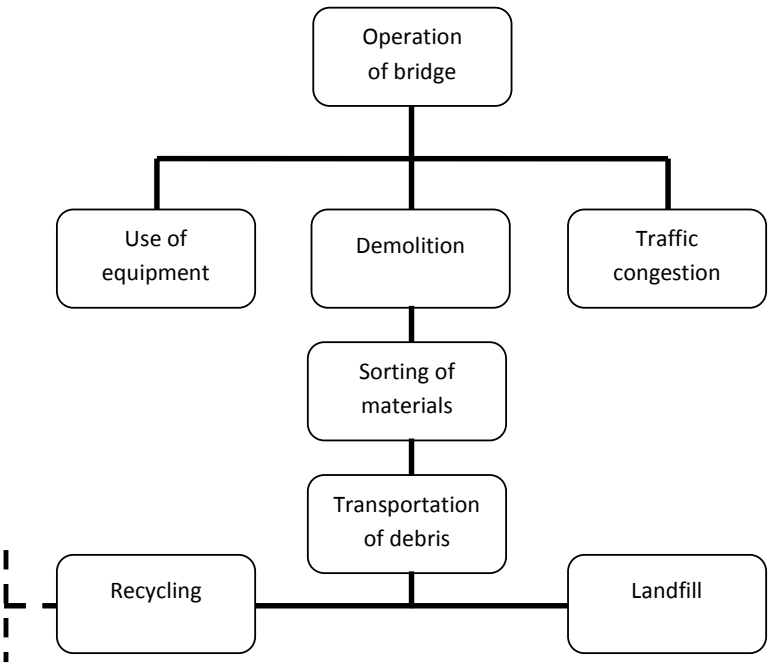

Figure 11.10. End-of-life stage

Taking into account end-of-life scenarios described in the previous paragraph, the gross amount of demolition waste produced in each case is indicated in Table 11.25. The efficiency of recycling processes was not considered, which would increase the amount of waste produced in all scenarios.

Table 11.25. Demolition waste produced in end-of-life stage

	1st scenario	2nd scenario	3rd scenario
Volume of demolition waste (ton)	3218	644	644

As in the previous case studies, the importance of recycling in the reduction of waste produced is noted from the previous table. However, as referred in the previous chapters, to avoid double counting of impacts, this indicator will not be further used.

Total emissions per impact category of this stage, considering the first end-of-life scenario, are indicated in Table 11.26. This table also indicates the contribution of each process per impact category.

Table 11.26. Results of the end-of-life stage per impact category

Impact category	Unit	TOTAL	Disassemble of structure	Transportation of materials	Use of equipment	Traffic congestion
AD	kg Sb eq	1633.0	14.4 %	13.1 %	0 %	72.5 %
AC	kg SO_2 eq	714.5	16.5 %	12.5 %	22.6 %	48.3 %
EU	kg NO_x eq	842.9	24.8 %	14.8 %	43.6 %	16.9 %
GW	kg CO_2 eq	115939.2	16.9 %	25.6 %	29.0 %	28.4 %
OD	kg CFC-11 eq	0.033	17.6 %	14.2 %	0 %	68.2 %
HT	kg 1,4-DB eq	20368.0	33.2 %	20.9 %	1.9 %	43.9 %
TT	kg 1,4-DB eq	21.2	16.4 %	26.7 %	0 %	56.9 %
Ph	kg C_2H_4	103.2	4.1 %	3.6 %	3.9 %	88.4 %

The contribution of each process per impact category is also illustrated in Figure 11.11, showing a major contribution from the “traffic congestion” as observed also for the previous stages.

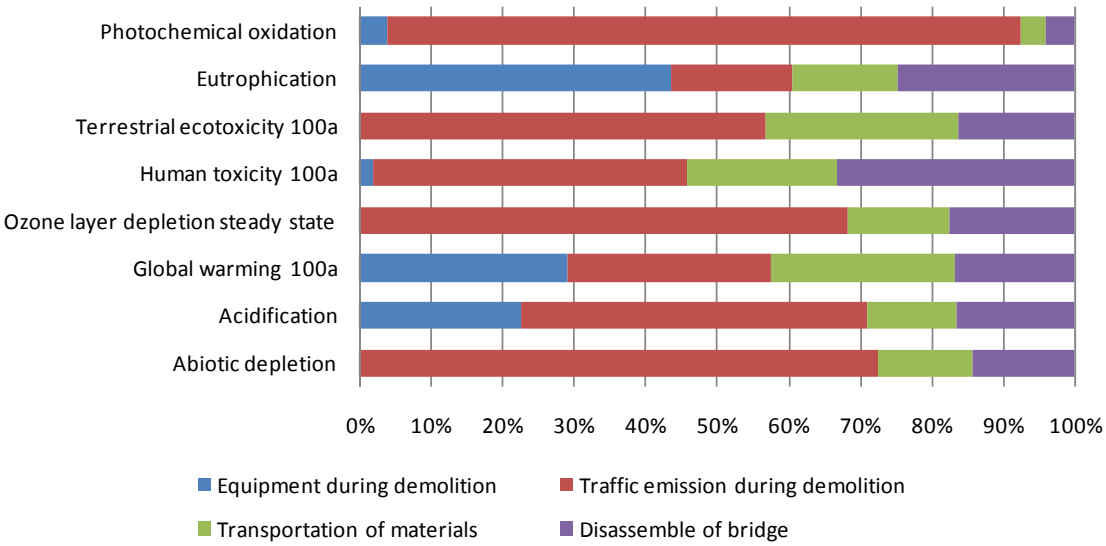

Figure 11.11. Contribution analysis of processes during the end-of-life stage

A comparison between end-of-life scenarios, for each impact category, is provided in Table 11.27.

Table 11.27. Comparison between end-of-life scenarios

Impact category	Unit	1st end-of-life scenario	2nd end-of-life scenario	3rd end-of-life scenario
AD	kg Sb eq	12020.84	11969.54	11798.54
AC	kg SO_2 eq	5863.10	5838.45	5753.46
EU	kg NO_x eq	5919.46	5877.07	5725.98
GW	kg CO_2 eq	1194961.20	1190961.50	1176755.60
OD	kg CFC-11 eq	0.23	0.23	0.23
HT	kg 1,4-DB eq	209670.92	208236.01	203398.01
TT	kg 1,4-DB eq	228.77	228.00	225.52
Ph	kg C_2H_4	936.22	935.28	932.29

11.5.5. Results of the environmental life-cycle analysis

11.5.5.1. Aggregate life-cycle results

In the previous sections, partial results per stage have been presented. In this sub-section the results of the different stages are summed up in the relation to each impact category. In this case the tree diagram is not presented due to the enormous amount of processes included which would make the diagram unreadable. The results are represented Table 11.28, considering the first end-of-life scenario.

In order to better understand the contribution of each stage to the aggregated result, the results are illustrated in a contribution graph represented in Figure 11.12.

Table 11.28. Life-cycle results per life cycle stage

Impact category	Unit	Total	Materials	Construction	Operation	End-of-life
AD	kg Sb eq	12020.8	8.4 %	19.3 %	58.7 %	13.6 %
AC	kg SO_2 eq	5863.1	24.6 %	17.1 %	46.1 %	12.2 %
EU	kg NO_x eq	5919.5	22.7 %	17.7 %	45.4 %	14.2 %
GW	ton CO_2 eq	1194961.0	41.0 %	11.5 %	37.8 %	9.7 %
OD	kg CFC-11 eq	0.231	2.8 %	19.4 %	63.4 %	14.4 %
HT	ton1,4-DB eq	209670.9	52.3 %	9.6 %	28.4 %	9.7 %
TT	kg 1,4-DB eq	228.8	45.9 %	11.4 %	33.5 %	9.2 %
Ph	kg C_2H_4	936.2	8.6 %	22.5 %	57.9 %	11.0 %

From the observation of the contribution analysis several conclusions may be taken. The operation stage is the stage with higher contribution to most impact categories, although above 50% only for the impact categories of Abiotic Depletion, Ozone Depletion and Photochemical Oxidation. The stage of material production has a significant contribution to the impact categories of Global Warming, Human Toxicity and Terrestrial Ecotoxicity. The end-of-life stage has a smaller contribution, less than 15%, to the life cycle analysis.

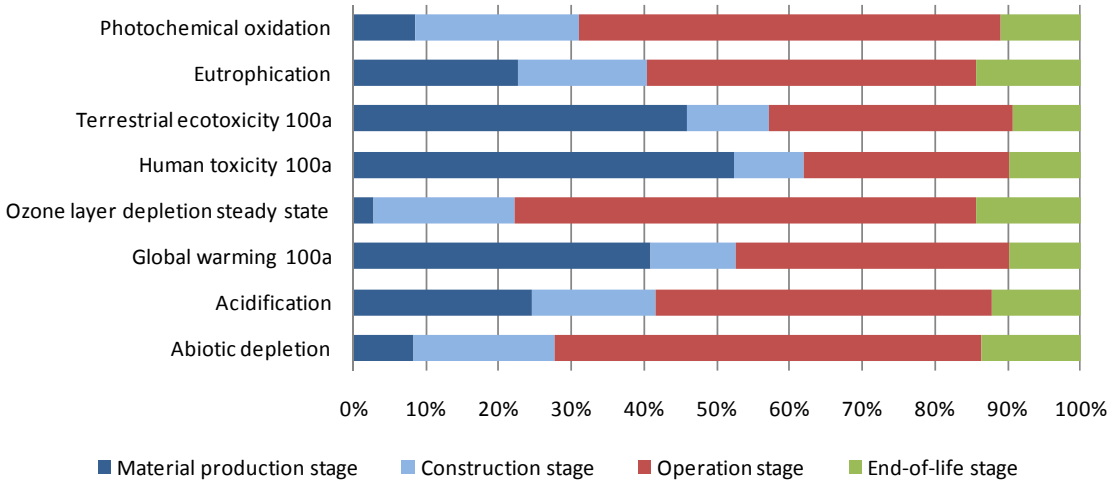

Figure 11.12. Contribution of each stage to impact category

Another important observation from the outcome of the LCEA is provided in terms of the aggregate contribution of main processes to the life cycle results. Thus, Figure 11.13 illustrates the contribution of the processes of material production, transportation, use of equipment and traffic congestion. Each of this main process aggregates the results obtained in each stage.

Traffic congestion resulting from work zones is the most important contributing process for the impact categories of Photochemical Oxidation, Ozone layer depletion and Abiotic Depletion. On the other hand, the production of materials is the most important contributing process (above 50%) for the impact categories of Terrestrial Ecotoxicity, Human Toxicity and Global Warming. The transportation of materials has a small contribution, while the use of equipment has a significant contribution to the impact categories of Eutrophication, Global Warming and Acidification.

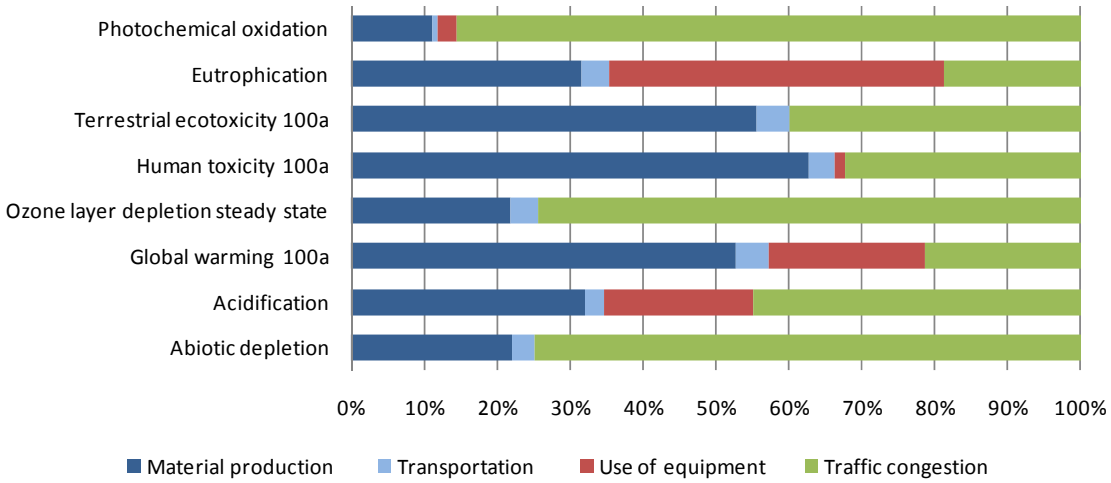

Figure 11.13. Contribution of each main process to impact category

From these results no conclusions may be taken in relation to the impact categories leading to higher and lower impacts. To enable such conclusions, normalization and weighting are performed, as described in the following sub-sections.

11.5.5.2. Normalized results

Using the normalized set of values proposed in Chapter 6, the values obtained for each impact categories are represented in the graph of Figure 11.14 considering the end-of-life scenarios described in Table 11.7.

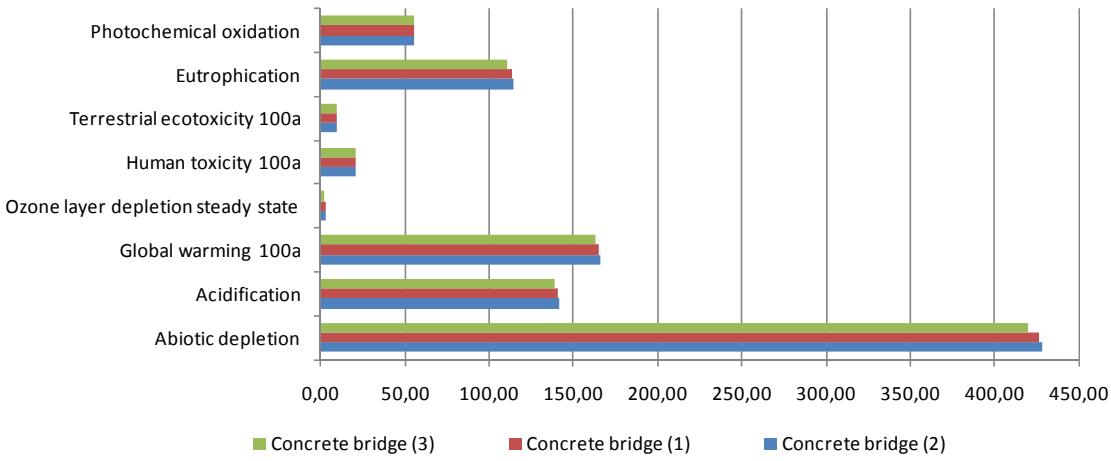

Figure 11.14. Normalized results for each impact category

From the previous graph it is observed that Abiotic depletion, Global warming, Acidification and Eutrophication are the most important environmental categories.

11.5.5.3. Weighted results

Finally, using the set of weights defined in Chapter 6, the resulting life cycle results are presented in Figure 11.15.

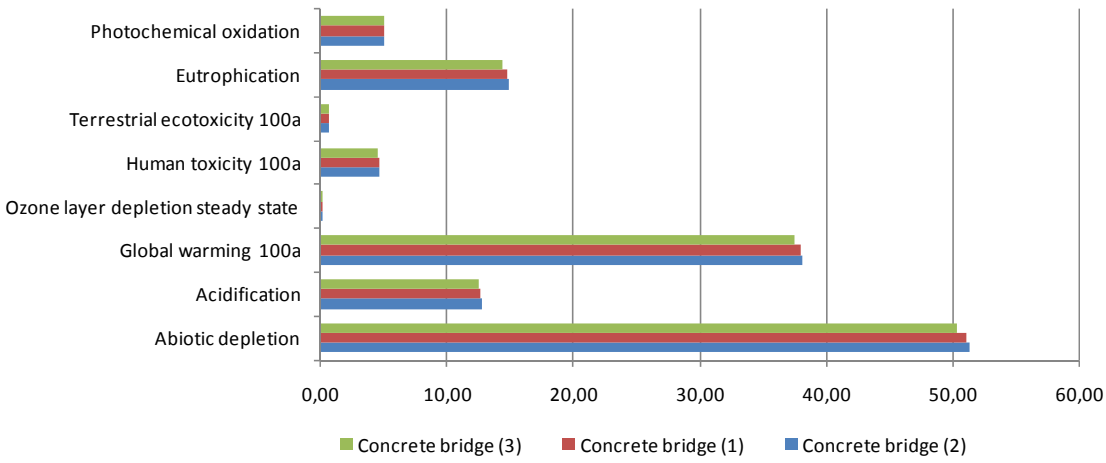

Figure 11.15. Weighted results for each impact category

Abiotic depletion and Global warming are still the most significant impact categories. Acidification and Eutrophication have also a significant value when compared with the remaining categories.

The same results divided by the area of the deck are indicated in Table 11.29. The first column refers to life-cycle results considering end-of-life scenario 1. This was considered the base

scenario. The other columns refer to life-cycle results considering the remaining end-of-life scenarios of Table 11.7 and the respective variation in relation to the results presented in the first column (base scenario). The results indicated in the 2nd column, corresponding to end-of-life scenario 2, have a small variation in relation to the base scenario, showing that recycling of concrete has little influence in the final results (less than 1%). Finally, the last column referred to end-of-life scenario 3, in which the "cut-off" rule was used. This rule is often considered as conservative (see discussion in Chapter 5). However, in this case, the results are lower than in the case of scenarios 1 and 2. Thus, in this case the "cut-off" rule despises potential impacts due to final disposition of demolition waste and recycling of materials.

Table 11.29. Life-cycle results of each impact category (per m^2)

Impact category	Concrete bridge (1)	Concrete bridge (2)		Concrete bridge (3)	
	Total	Total	Δ	Total	Δ
AD	6.60E-02	6.58E-02	-0.43%	6.48E-02	-1.85%
AC	1.64E-02	1.63E-02	-0.42%	1.61E-02	-1.87%
EU	1.91E-02	1.90E-02	-0.72%	1.85E-02	-3.27%
GW	4.90E-02	4.89E-02	-0.33%	4.83E-02	-1.52%
OD	1.63E-04	1.62E-04	-0.57%	1.59E-04	-2.40%
HT	5.93E-03	5.89E-03	-0.68%	5.76E-03	-2.99%
TT	8.37E-04	8.35E-04	-0.34%	8.25E-04	-1.42%
Ph	6.41E-03	6.41E-03	-0.10%	6.39E-03	-0.42%

The base scenario was selected taking account the current practice in the sector. However, considering that recycling has being increasingly promoted, it is predicted that in the near future recycling of concrete will be a standard practice. Therefore, life-cycle analysis, considering end-of-life scenario 2 will be used in the next section.

As for the two previous case studies, the operation stage is the most important stage in the life cycle of the bridge, as illustrated in Figure 11.16. In this case study, the material production stage has also a significant importance. These results are referred to end-of-life scenario 2.

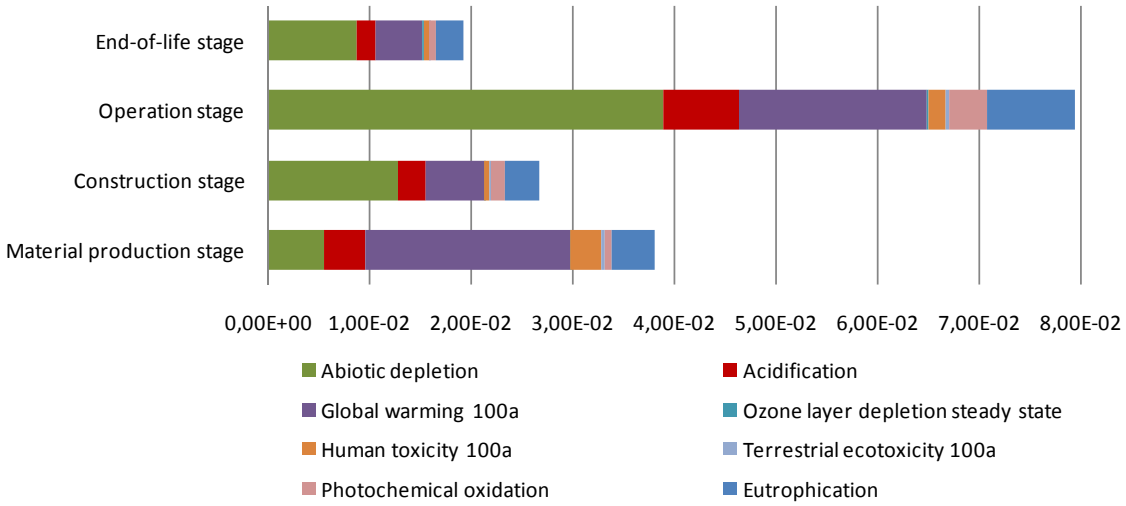

Figure 11.16. Weighted results per stage (considering end-of-life scenario 2)

11.5.6. Uncertainty analysis

The uncertainty analysis is performed using the same approach as the first case study (Chapter 9). Therefore, three types of uncertainties are hereby considered: parameter uncertainty, uncertainties due to choices and model uncertainties

The uncertainty analysis was performed by Monte Carlo simulations, considering 1000 iterations. The probabilistic analysis was performed by Microsoft Excel @Risk [11.2] add-in software package.

The life cycle environmental results of the simulation for the impact categories of Abiotic depletion, Acidification, Eutrophication and Global warming are represented in Figure 11.17 by the respective 90% confidence interval for the mean value. These results were obtained considering end-of-life scenario 2 (see Table 11.7).

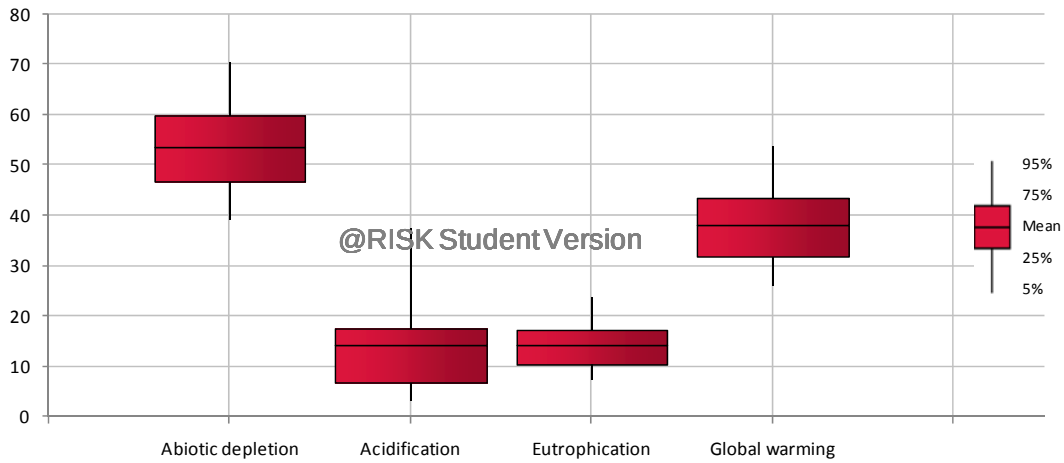

Figure 11.17. Results of the simulations for Abiotic depletion, Acidification, Eutrophication and Global warming

A distribution was fitted to the results of these simulations and the validity of the assumed distributions was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov*. The best-fit distributions for the impact categories represented in Figure 11.17 are indicated in Table 11.30.

Table 11.30. Best-fit distributions for the simulation results

	Abiotic depletion	Acidification	Eutrophication	Global warming
Distribution	lognormal	lognormal	lognormal	lognormal
Mean	53.46	14.29	14.30	38.13
SD	9.59	12.18	5.15	8.55

Likewise, the results for the remaining impact categories are represented in Figure 11.18 by the respective 90% confidence interval for the mean value.

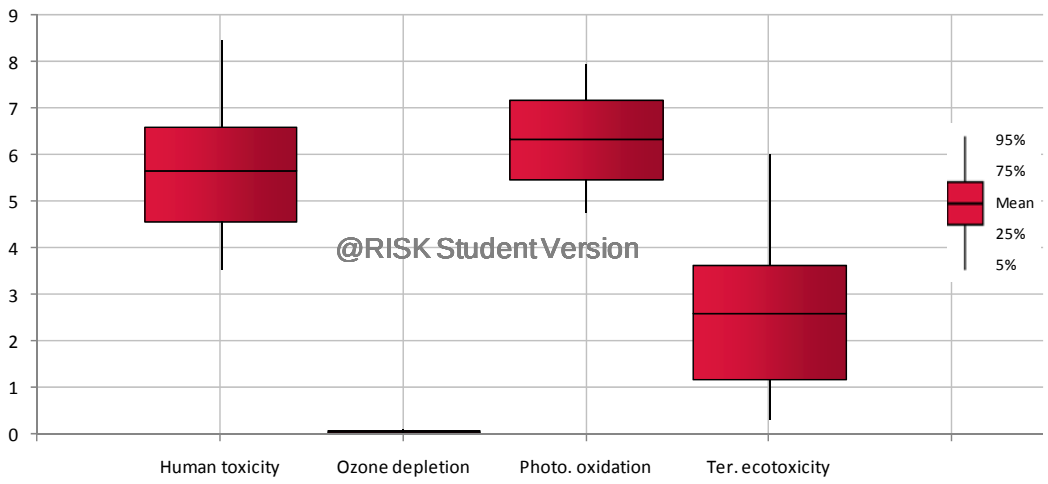

Figure 11.18. Results of the simulations for Human toxicity, Ozone layer depletion, Photochemical oxidation and Terrestrial ecotoxicity

In addition, a distribution was fitted to the results of these simulations and the validity of the assumed distributions was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov*. The best-fit distributions for these impact categories are indicated in Table 11.31.

Table 11.31. Best-fit distributions for the simulation results

	Human toxicity	Ozone layer depl.	Photo. oxidation	Terres. ecotoxicity
Distribution	lognormal	lognormal	betageneral	betageneral
Min/Max	-	-	3.76/9.35	0.05/17.98
Mean	5.68	0.06	6.35	2.62
SD	1.55	0.03	1.00	1.87

11.6. LIFE CYCLE COST ANALYSIS

11.6.1. Initial construction cost

The initial cost of the structure is 332 798.00 €, about 428.10 €/m^2, and it was calculated based on the bill of materials indicated in Table 11.1 and unit costs in Table 11.2.

11.6.2. Operation costs

Over the 100 years, the bridge is maintained and rehabilitated according to the scenario preview in Table 11.4. The costs per year are based on the unit costs and frequencies indicated in Chapter 9, Table 9.11. These costs are illustrated in Figure 11.19. The accumulated costs are also represented in the same figure, considering a discount rate of 3.5%.

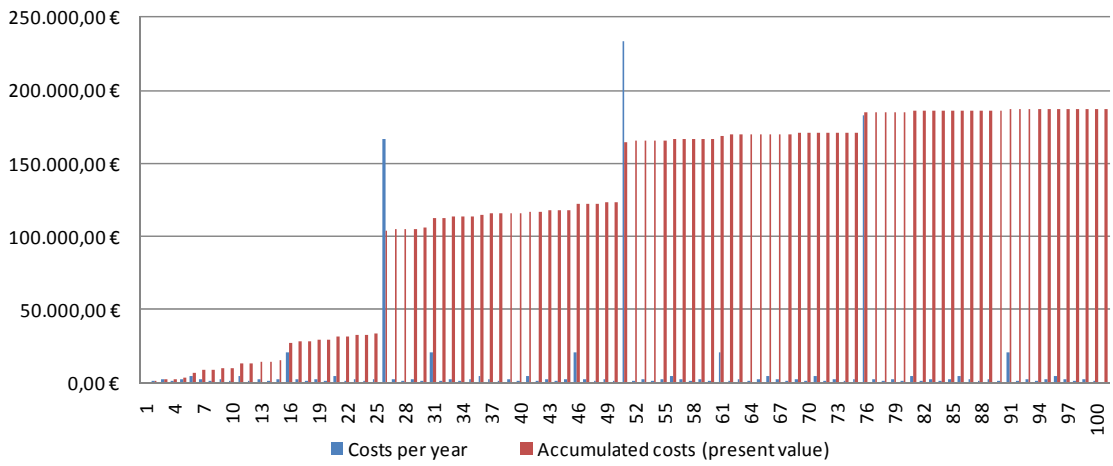

Figure 11.19. Operation costs of the bridge over its service life

The present value of the total cost for maintenance and rehabilitation for the period of 100 years is thus 187 556.44 €, which represents a cost of 241.27 €/m^2.

11.6.3. End-of-life cost

End-of-life costs encompasses the cost of labour work, cost of equipments, cost of road warning signage, cost of transportation and cost for deposition of materials and/or revenue due to recycling of materials.

From information provided by a construction company the cost for demolition of a similar bridge is about 100€/m^2. This cost includes the cost of labour, the cost of equipment and fuel, the cost of ancillary material, the cost of sorting the materials, the cost of all the necessary measures to ensure the safety of the work zone and the cost for cleaning the zone.

This stage includes also the transportation of materials to the disposal/recycling site and the cost or revenue due to landfill or recycling, respectively. According to current European legislation (list of waste), the demolition waste is classified into the following categories:

- (17 01 01) - Concrete;
- (17 03) - Bituminous mixtures, coal tar and tarred products;
- (17 04 05) - Iron and steel.

These wastes are sent for recycling or deposit in a landfill. The cost of transportation requires the estimation of the distances from the demolition place to the disposal/recycling place, the efficiency of the trucks and the price of the fuel. The cost for transportation is given in Table 11.32 assuming trucks with an average load of 25 tonnes.

Table 11.32. Cost for transportation of demolition waste materials

	Mass (tonnes)	No. of trucks	Distance to disposal/recycling site (km)	Fuel efficiency (l/km)	Cost of fuel (€/l)	Transportation fuel cost (€)
Concrete	2806.0	113	60	0.29(*)	1.065	3 490.00
Bituminous	76.6	3	20	0.29(*)	1.065	92.66
Iron and steel	67.7	3	100	0.29(*)	1.065	1 297.17
						4 879.83

(*) Considering the density of diesel 0.84 kg/l

The total cost for disposal is indicated in Table 11.33, assuming the disposal fees indicated in the same table.

Table 11.33. Cost of fees for land filling

	Mass (tonnes)	Fee for landfill (€/tonne)	Cost for landfill (€)
Concrete	2 806.0	10	28 060.00
Bituminous	76.6	50	3 830.00
			31 890.00

It is assumed that only 65% of the steel reinforcement is recovered. Thus, the money earned with the steel scrap is given in Table 11.34.

Table 11.34. Revenue due to scrap

	Mass (tonnes)	Price of scrap (€/tonne)	Scrap revenue (€)
Iron and steel	67.7	100	6 770.00

The total end-of-life cost is given by the sum of the previous components, leading to a total of 107 268.88 €. This cost is supposed to take place in year 100, and considering a discount rate of 3.5%, the present value is 3 439.05 €.

Considering the end-of-life scenarios indicated in Table 11.7, the end-of-life cost indicated in the previous paragraph relates to the first end-of-life scenario. For the second scenario, the fee for the disposal of concrete material is not considered. However, no value is available for the revenue of the inert material and hence this value was neglected. For the third scenario a cut-off rule is used and thus the scrap revenue is cut-off from the final accounting. The end-of-life costs for each scenario are summarized in Table 11.35.

Table 11.35. End-of-life costs for each scenario

	1st scenario	2nd scenario	3rd scenario
Total cost (€)	107 268.88	79 208.88	114 038.88
PV total cost (€)	3 439.05	2 539.45	3 656.10
PV Total cost (€/m^2)	4.42	3.27	4.70

11.6.4. Life cycle cost

The compilation of the costs calculated in the previous sections lead to the total life cycle present cost (PVLCC) of 523 793.28 €, using a discount rate of 3.5%. This represents a total cost of 673.79 €/m^2. The costs per year and the accumulated present value of the bridge are illustrated in Figure 11.20.

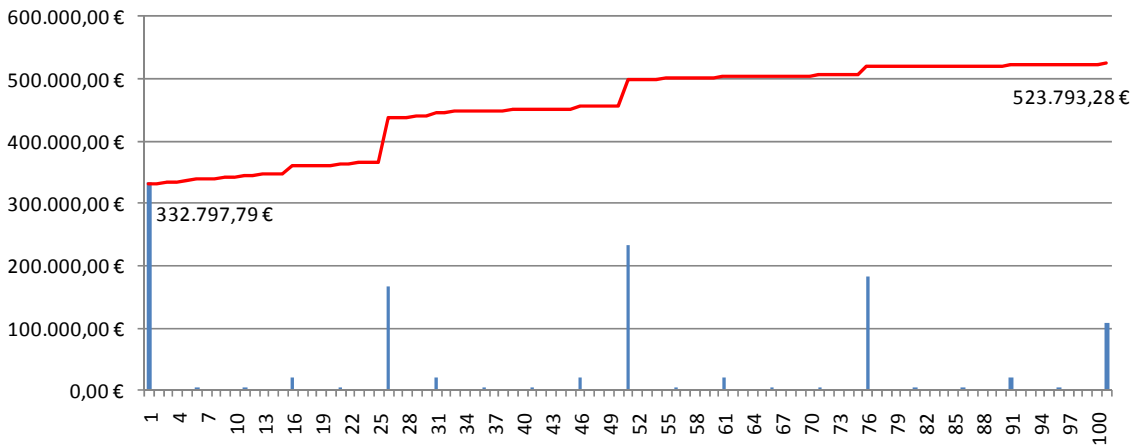

Figure 11.20. Life cycle costs of the composite bridge and accumulated present value (line in red)

Considering the three end-of-life scenarios, the respective life cycle net present costs (PVLCC) are summarized in Table 11.36.

Table 11.36. PVLCC considering different end-of-life scenarios

	1st scenario	2nd scenario	3rd scenario
PV LCC (€)	523 793.28	522 893.67	524 010.33
PV LCC (€/m^2)	673.79	672.63	674.67

11.6.5. Uncertainty analysis

11.6.5.1. Construction cost

The initial cost of the structure was calculated based on the bill of quantities provided by BRISA. Likewise, in order to take into consideration some variations, both in terms of quantities and in terms of costs, a lognormal distribution was assigned to each value (quantities and respective cost), with the mean values equal to the values indicated in Table 11.1 and Table 11.2, and a standard deviation of 10% and 25% of the mean values, for the quantities and the costs, respectively.

Hence, by running a Monte Carlo simulation with 10000 iterations, a mean value of 397 161.51€ and a standard deviation of 15 773.76€ were obtained. The probabilistic analysis was performed by Microsoft Excel @Risk [11.2] add-in software package. A distribution was fitted to the results of this simulation and the validity of the assumed distribution was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov*.

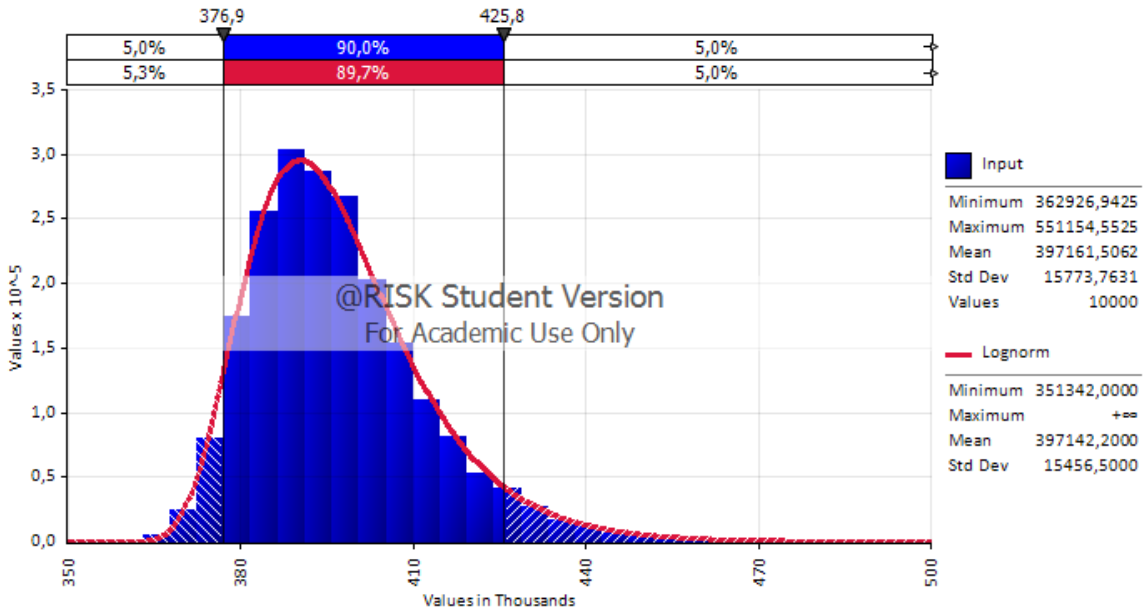

Figure 11.21. Best-fit distribution (in red) according to *chi-square* test and *Kolmogorov-Smirnov* test

In both tests the best distribution to fit the simulation was a lognormal distribution, as represented in Figure 11.21. Thus, for the initial cost of the structure lognormal distribution is considered with mean value 397 142.20€ and standard deviation of 15 456.50€.

11.6.5.2. Discount rate and time

Following the same approach of previous case studies, a triangular distribution with mean value of 3.5% and minimum and maximum values of 2.5% and 4.5%, respectively, is considered for the discount rate.

A triangular distribution was considered for the interval of time correspondent to the maintenance of concrete deck with a mean value of 25 years and minimum and maximum values of 20 and 30 years, respectively. In addition, a triangular distribution was considered for the interval of time correspondent to the replacement of the deck's surface, with a mean value of 15 years and minimum and maximum values of 12 and 18 years, respectively.

11.6.5.3. Probabilistic-based life cycle cost analysis of the bridge

For probabilistic life cycle cost analysis, a probability distribution was also assigned to each unit cost of Table 9.11 (see Chapter 9). In all variables, except for the unit cost of maintenance and rehabilitation of the concrete structure, a lognormal distribution was assigned with mean value equal to the value given in the table and a standard deviation of 10%. For the other two variables, a lognormal distribution was assigned with mean value equal to the value given in the table and a standard deviation of 30%

The total life cycle cost of the bridge was obtained by running a Monte Carlo simulation with 10000 iterations, leading to a mean value of 610 699.93 € and a 90% confidence interval of the mean value between 555 300.00 € and 675 800.00€. The probabilistic analysis was performed by Microsoft Excel @Risk [11.2] add-in software package.

The best distribution to fit the simulation is a lognormal distribution with mean value 610 693.10€ and standard deviation of 37 467.40€. The result of the simulation and the best-fitted distribution are both represented in Figure 11.22.

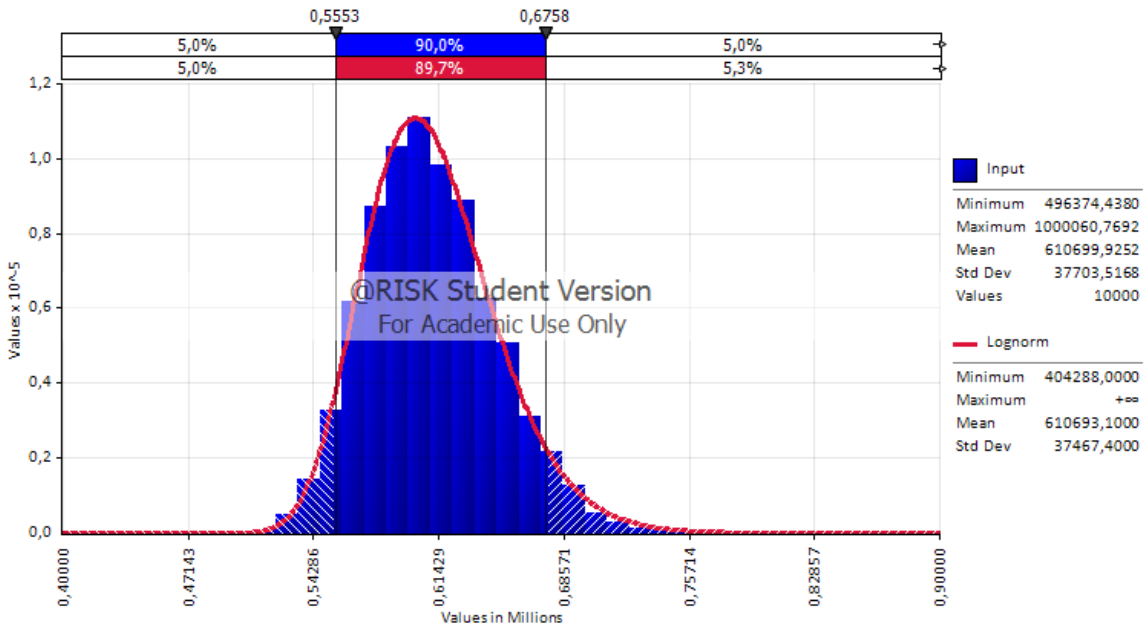

Figure 11.22. Lifecycle PVLCC of the bridge: best-fit distribution according to *chi-square* test and *Kolmogorov-Smirnov* test

The accumulated mean cost over the bridge life cycle is represented in the graph of Figure 11.23, together with the 90% confidence interval of the mean value.

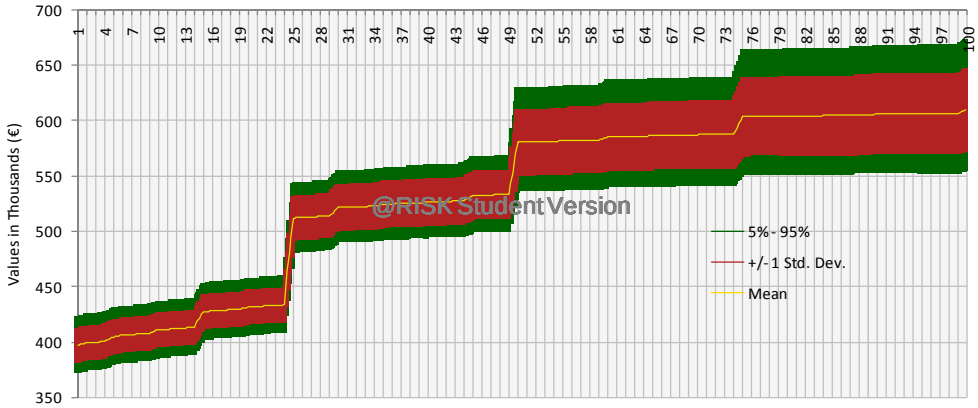

Figure 11.23. Accumulated present value cost (90% confidence interval)

These results are relative to the life cycle analysis considering the 1st end-of-life scenario. For the other scenarios, similar simulations were performed. In all cases a lognormal distribution was fitted to the results of the simulations. The mean value and standard deviation of each distribution are indicated in Table 11.37.

Table 11.37. Probability distributions of the PVLCC considering different end-of-life scenarios

	1st scenario	2nd scenario	3rd scenario
PV LCC (€)	LN(610693.10; 37467.40)	LN(609709.70; 37194.00)	LN(610894.90; 37659.90)

Likewise, to evaluate the importance of input parameters on the life cycle cost of the bridge, a sensitivity analysis is performed. The results of the Spearman rank correlation analysis are illustrated in Figure 11.24, showing that the most important variables are the discount rate, the construction cost and the interval of time for the maintenance/rehabilitation of the concrete structure.

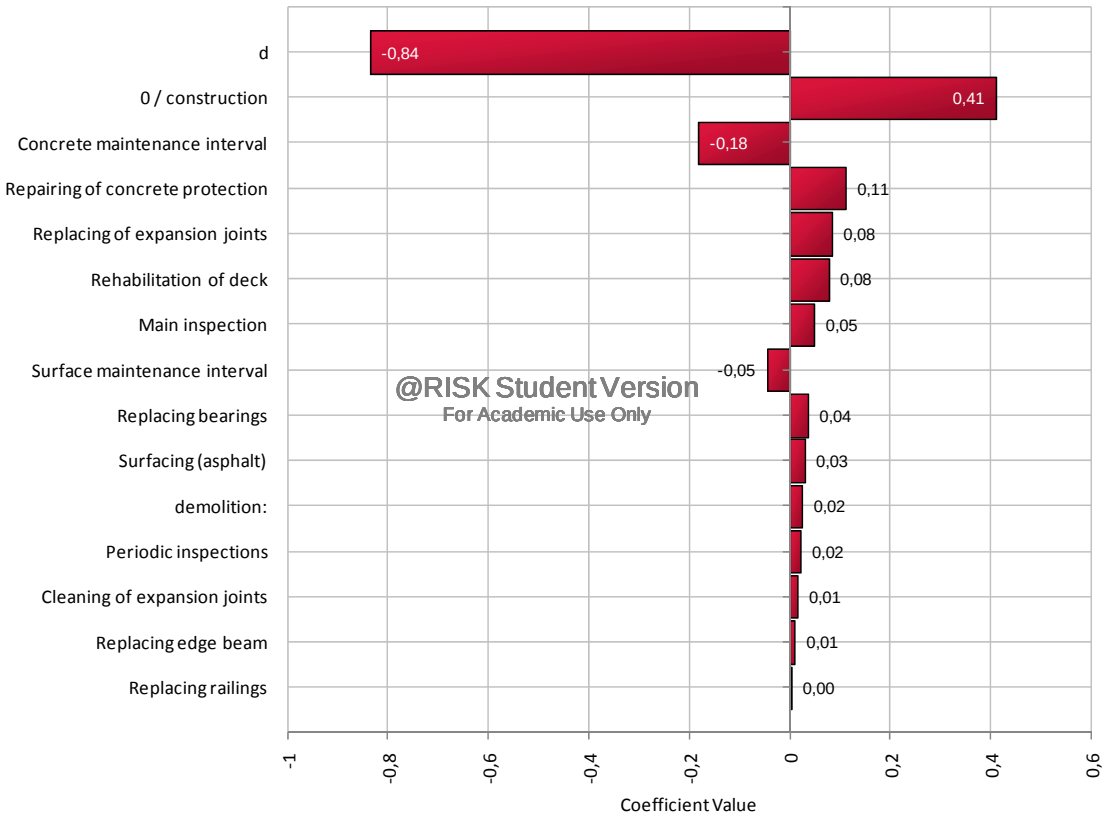

Figure 11.24. Sensitivity analysis of the PVLCC – Spearman rank

11.7. LIFE CYCLE SOCIAL ANALYSIS

11.7.1. Introduction

The impacts on the users of the motorway are quantified based on the methodology discussed in Chapter 8. Also, in this case study only the mandatory indicators are used, as no comprehensive data is currently available for the assessment of the optional indicators discussed in Chapter 8. Hence, three types of costs are hereby considered for all stages: the cost of vehicle operation (VOC), the cost of driver delay (DDC) and the cost of safety.

11.7.2. Social impacts due to construction

The construction of the bridge took 93 days as indicated in Table 11.3. Over this period of time traffic restrictions are imposed according to the requirements by the Portuguese Government regarding traffic conditions and safety of users through work zones (see Appendix A).

As already referred, the bridge is new; therefore, no traffic was considered over the bridge in this stage. Thus, the construction of the bridge only affects the traffic in the motorway.

The calculation of users' costs during the construction stage is based on the same reference scenarios considered for the previous case studies, which were detailed in Chapter 9 and on the same global scenarios described for the life cycle environmental analysis (see section 11.5.2).

However, as referred in section 11.5.2, two additional scenarios were considered (scenarios 1A and 1B in Table 11.38) due to the cast "in situ" of the concrete deck of the structure.

Hence, user costs, per day and per carriageway, are summarized in Table 11.38. The detail calculation of each cost is provided in Annex D.

Table 11.38. User costs (per day and per carriageway) in work zone during construction

Scen.	No. of lanes	No. of open lanes	Hours of rest. activ.	Hours of WZ activity	DDC (€/day)	VOC (€/day)	Safety (€/day)
1	2	2	0 - 24	6 - 20	904.91	1311.58	8.76
1A	2	2	0 - 24	18 - 10	1018.43	1466.88	9.71
1B	2	2	0 - 24	6 - 20	1318.17	1866.53	12.09
2	2	1	0 - 24	22 - 6	908.12	1316.34	8.79
3	2	1	0 - 24	6 - 22	3984.53	2841.3	14.64

Thus, total user costs for the construction stage are summarized in Table 11.39.

Table 11.39. Total user costs during construction stage

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	Night work (1 lane open)	168578.82	244321.60	1631.62
Global scenario 2	Day work (1 lane open)	206095.22	263420.42	1706.58

11.7.3. Social impacts during the operation of the bridge

The calculation of users' costs during the operation stage is based on the same reference scenarios considered for the previous case studies, which were detailed in Chapter 9, and on the same global scenarios described for the life cycle environmental analysis (see section 11.5.3). These costs are summarized in Table 11.40, Table 11.41, Table 11.42 and Table 11.43, for combined actions A, B, C and D, respectively.

Table 11.40. Total user costs for Combined Action A

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	Night work (1 lane open)	5477.70	8046.15	41.40
Global scenario 2	Day work (1 lane open)	6800.55	10007.40	51.90

Table 11.41. Total user costs for Combined Action B

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway + night work crossover.	78771.79	113799.11	559.92
Global scenario 2	night work motorway + day work crossover.	79477.31	114845.11	565.52
Global scenario 3	day work motorway + night work crossover.	266213.71	215276.99	823.80
Global scenario 4	day work motorway + day work crossover.	266919.23	216322.99	829.40
Global scenario 5	reduce day work motorway + night work crossover	155831.59	165906.95	705.72
Global scenario 6	reduce day work motorway + day work crossover	156537.11	166952.95	711.32

Table 11.42. Total user costs for Combined Action C

Scenario	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway (3 lanes open)+ night work crossover	295943.95	428225.27	2109.96
Global scenario 2	night work motorway (3 lanes open) + day work crossover	296649.47	429271.27	2115.56
Global scenario 3	day work motorway (3 lanes open) + night work crossover	332440.75	481787.87	2388.06
Global scenario 4	day work motorway (3 lanes open) + day work crossover	333146.27	482833.87	2393.66
Global scenario 5	night work motorway (2 lanes open)+ night work crossover	296250.85	428681.57	2112.66
Global scenario 6	night work motorway (2 lanes open) + day work crossover	296956.37	429727.57	2118.26
Global scenario 7	day work motorway (2 lanes open) + night work crossover	2441519.65	1110537.77	3678.66
Global scenario 8	day work motorway (2 lanes open) + day work crossover	2442225.17	1111583.77	3684.26
Global scenario 9	reduce day work motorway (2 lanes open) + night work crossover	1159815.25	774484.07	2966.76
Global scenario 10	reduce day work motorway (2 lanes open)+ day work crossover	1160520.77	775530.07	2972.36

Table 11.43. Total user costs for Combined Action D

Scenario	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway (3 lanes open)+ night work crossover	96667.69	139956.14	691.68
Global scenario 2	night work motorway (3 lanes open) + day work crossover	98696.06	142963.39	707.78
Global scenario 3	day work motorway (3 lanes open) + night work crossover	116509.45	167676.86	823.08
Global scenario 4	day work motorway (3 lanes open) + day work crossover	118537.82	170684.11	839.18
Global scenario 5	night work motorway (2 lanes open)+ night work crossover	96810.61	140168.18	692.76
Global scenario 6	night work motorway (2 lanes open) + day work crossover	98838.98	143175.43	708.86
Global scenario 7	day work motorway (2 lanes open) + night work crossover	1707106.81	595213.94	1670.52
Global scenario 8	day work motorway (2 lanes open) + day work crossover	1709135.18	598221.19	1686.62
Global scenario 9	reduce day work motorway (2 lanes open) + night work crossover	698800.45	353806.22	1189.56
Global scenario 10	reduce day work motorway (2 lanes open)+ day work crossover	700828.82	356813.47	1205.66

The summary of user costs per combined activity is represented in Figure 11.25, considering the best scenario in each case.

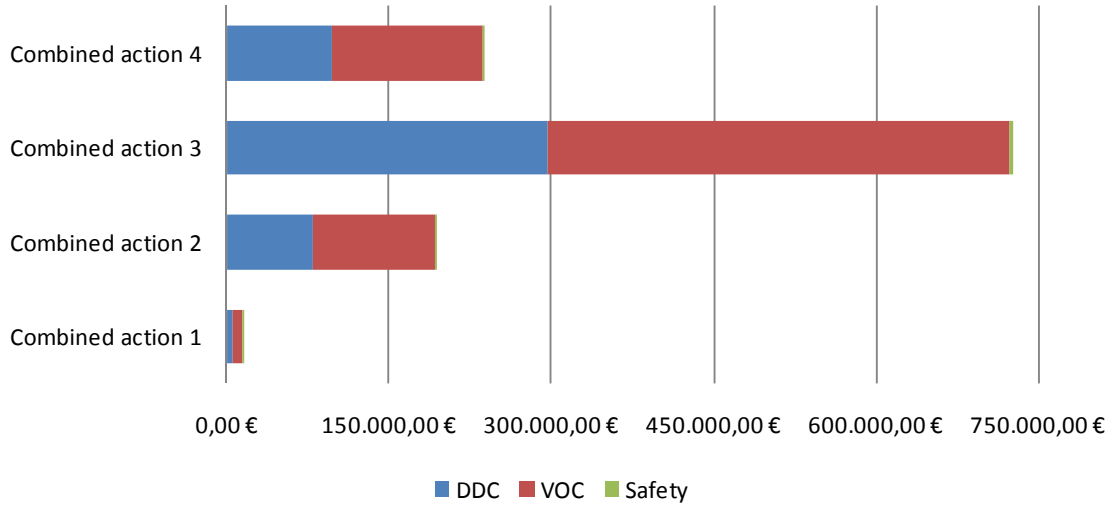

Figure 11.25. User costs per combined maintenance action

The user costs per year and the present value of the accumulated user costs are represented in Figure 11.26, considering a discount rate of 3.5%. These costs are also related to global scenario 1 in each combined activity.

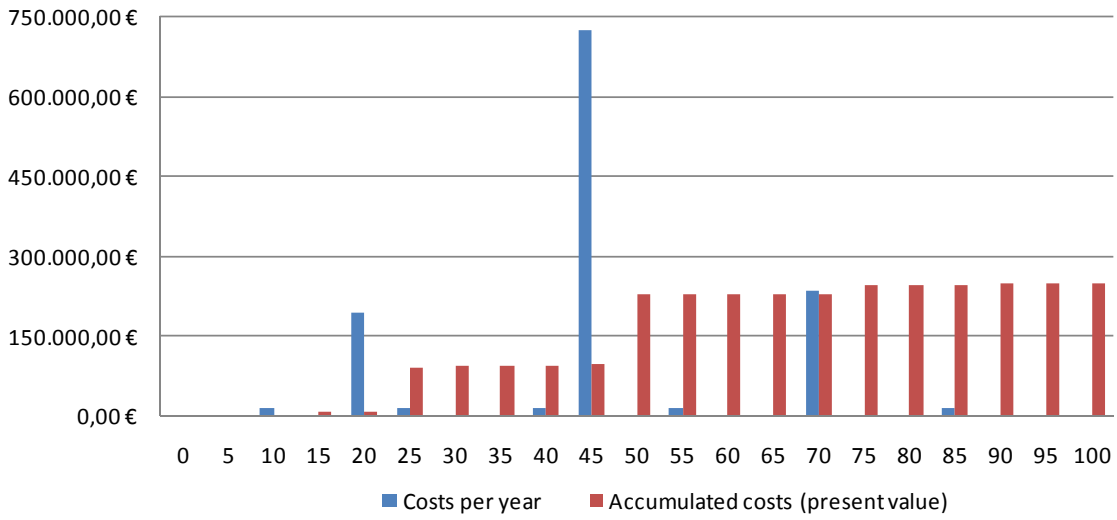

Figure 11.26. User costs of the bridge over its service life

11.7.4. Social impacts due to the demolition of the bridge

Like in the previous stages, the calculation of users' costs during the end-of-life stage is based on the same reference scenarios considered for the previous case studies, which were detailed in Chapter 9, and on the same global scenarios considered for the life cycle environmental analysis (see section 11.5.4). Therefore, no further description is provided in this section.

In addition, during this stage it is assumed that the traffic over the bridge is detoured to an alternative road and thus, no user costs are taken into consideration in this traffic analysis.

Therefore, total user costs for the end-of-life stage are indicated in Table 11.44.

Table 11.44. Total user costs during the demolition stage

	Description	User costs (€)		
		DDC	VOC	Safety
Global scenario 1	night work motorway (3 lanes open)	93149.56	134400.54	658.32
Global scenario 2	day work motorway (3 lanes open)	95905.48	138103.42	674.68
Global scenario 3	night work motorway (2 lanes open)	93167.12	134426.58	658.44
Global scenario 4	day work motorway (2 lanes open)	346563.20	202953.10	801.44
Global scenario 5	reduce day work motorway (2 lanes open)	182635.64	164767.10	727.16

11.7.5. Life cycle social impact

The compilation of the costs calculated in the previous sections lead to the total present value life cycle social cost of 669 744.00 €, which represents a cost of about 862.00 €/m^2. The costs per year and the accumulated present value cost of the bridge are illustrated in Figure 11.27. In this analysis a discount rate of 3.5% was considered.

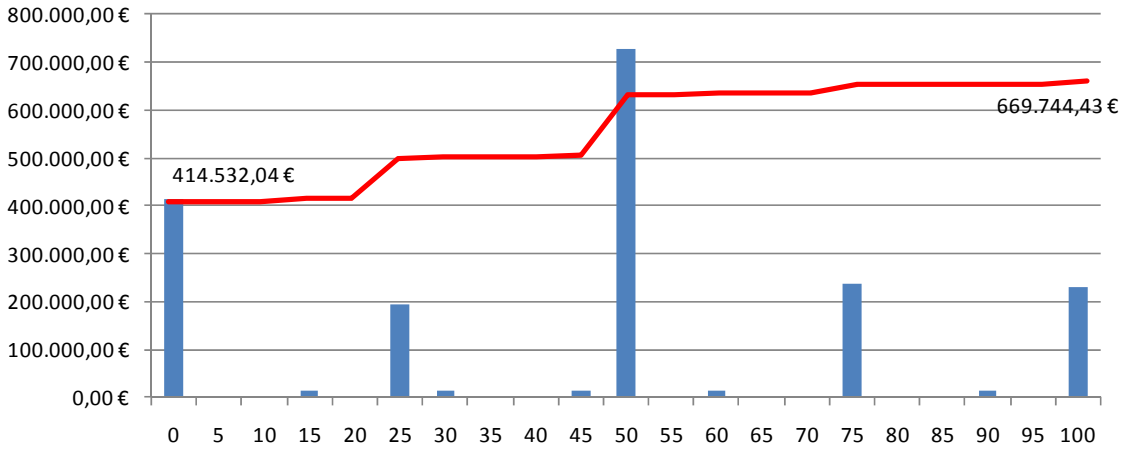

Figure 11.27. Life cycle social costs of the composite bridge

Considering the different stages over the life cycle of the bridge, the present value of the social cost per stage is indicated in Table 11.45.

Table 11.45. Social costs of the bridge per stage (present value)

Construction	Operation	End-of-life
414 532.04 €	247 896.01 €	7 316.39 €
533.24 €/m^2	318.88 €/m^2	9.41 €/m^2

The final value of the three indicators considered in the LCSA (the cost of vehicle operation (VOC), the cost of driver delay (DDC) and the cost of safety are indicated in Table 11.46.

Table 11.46. Life cycle social costs of the bridge (present value)

DDC	VOC	Safety
272 540.22 €	394 828.97 €	2 375.25 €
350.59 €/m^2	507.89 €/m^2	3.06 €/m^2

Life cycle social costs of the bridge were evaluated based on the best scenarios defined for each stage. As observed over the previous sections, the consideration of bad options in relation to traffic management may drastically increase the social costs. The accumulated life cycle user costs considering “best scenarios” and “worst scenarios” for each bridge intervention are indicated in Figure 11.28.

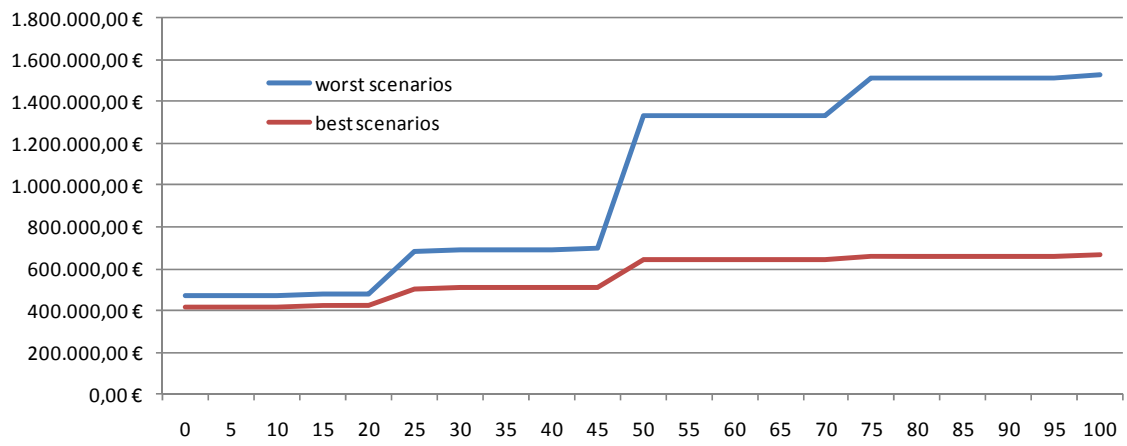

Figure 11.28. Accumulated life cycle user costs considering "best scenarios" and "worst scenarios"

As expected from the previous case-studies, a bad management of the construction work in the motorway increases significantly the life cycle social costs of the bridge.

11.7.6. Uncertainty analysis

The uncertainty analysis of life cycle social costs presented in this section took into account the uncertainties in the calculation of DDC, VOC and safety costs, which were discussed in Chapter 8, and the probability distributions of the discount rate and time of intervention indicated in section 11.6.5.

The total life cycle social cost of the bridge was obtained by running a Monte Carlo simulation with 10000 iterations, leading to a mean value of 674 352.18 € and a 90% interval of confidence of the mean value between 586 600.00 € and 772 900.00 €. The probabilistic analysis was performed by Microsoft Excel @Risk [11.2] add-in software package.

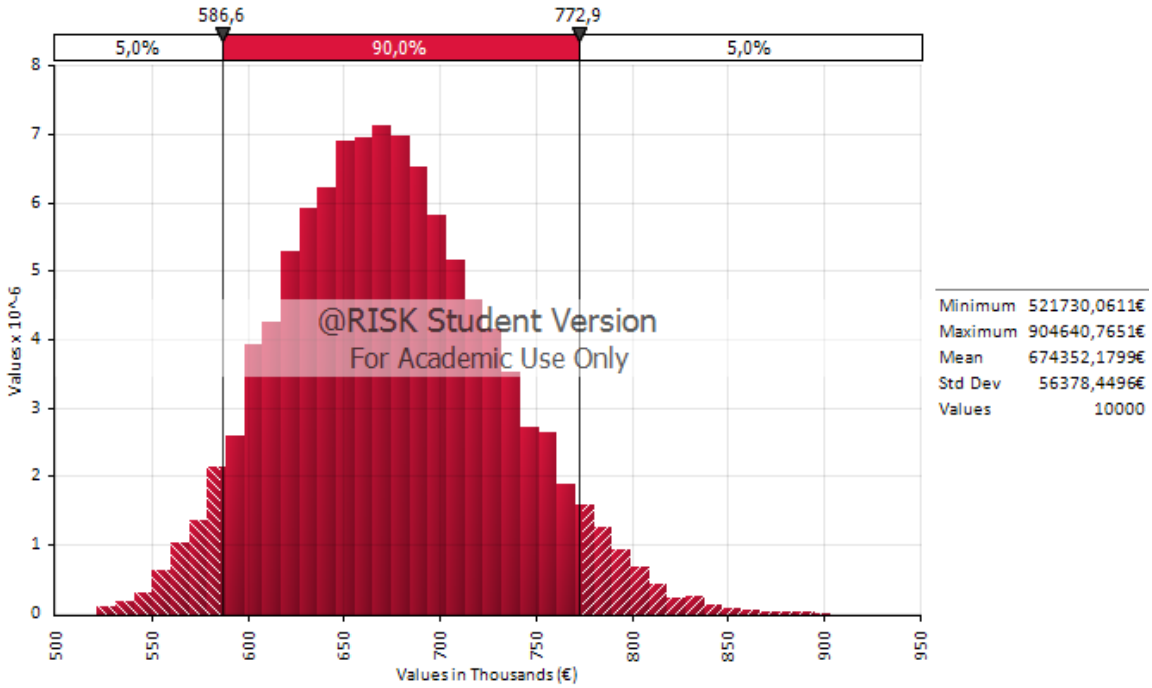

Figure 11.29. PVLCC of the bridge:

The accumulated mean cost over the bridge life cycle is represented in Figure 11.30 together with the 90% confidence interval of the mean value l.

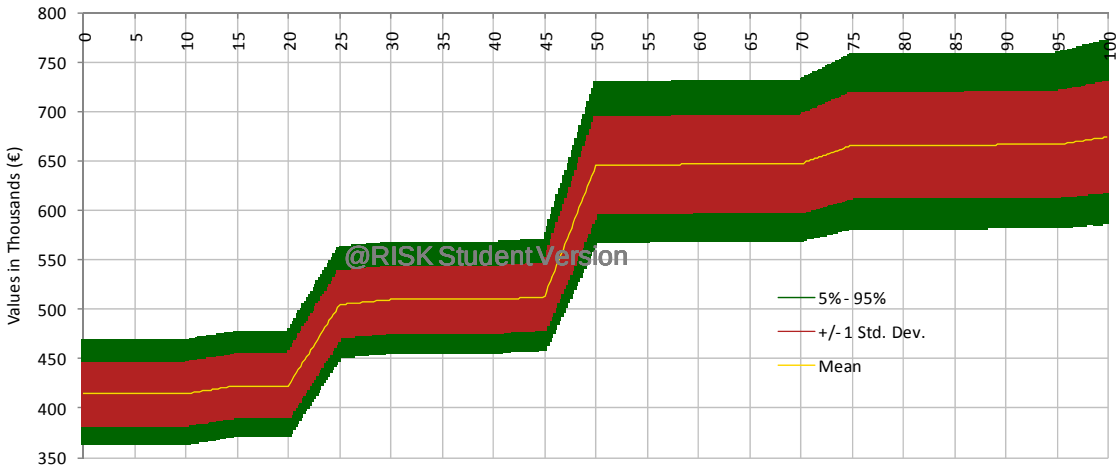

Figure 11.30. Accumulated present value cost (90% confidence interval)

Considering the total life cycle social cost divided by DDC, VOC and safety, the results obtained from the simulations are indicated in Table 11.47 together with the best-fit distributions in each case. The validity of the fitted distributions was verified by two *goodness-of-fit* tests: the *chi-square* and the *Kolmogorov-Smirnov.*

Table 11.47. Simulation results and best-fit distributions of life cycle social costs

		D.D.C.	V.O.C.	Safety
Simulation results	Mean	274 419.04 €	397 554.60€	2 388.57 €
	SD	30 869.23 €	35 781.43 €	206.03 €
Best-fit distribution: lognormal	Mean	274 419.00 €	397 554.70 €	2 388.61 €
	SD	30 883.70 €	35 806.80 €	206.08 €

11.8. CONCLUDING REMARKS

This chapter described the life cycle analysis of a concrete bridge cast “in situ”. In this analysis the environmental, economic and social criteria were taken into consideration.

As referred in the previous chapter, most of the comments, in relation to the application of the integral life cycle approach, provided in the end of Chapter 9 are also applicable to this case study. Therefore, they will not be referred in here to avoid repetition.

In this case study, the stages of material production and operation are the ones with major environmental impacts (see Figure 11.16). As in the previous case studies, “global warming” and “abiotic depletion” are the most important impact categories, followed by “acidification” and “eutrophication”.

In relation to life cycle costs, the total life cycle cost of the bridge (present value) represents more 57% of the initial cost of the structure; while the life cycle social cost (present value) represents more 62% of the initial social cost of the structure. It should be noted that in this case study, social costs outweigh the costs incurred by the concessionaire.

REFERENCES OF CHAPTER 11

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CHAPTER 12. MULTI-CRITERIA DECISION ANALYSIS

12.1. INTRODUCTION

In chapters 5 to 8 a framework for an integral life cycle analysis of bridges considering environmental, economical and social aspects was established. The general framework was based on ISO standard series 14040.

For each main aspect, several criteria were proposed and life-cycle based methodologies have been provided for its quantification. The output of the three main life-cycle analysis are a set of indicators, expressed in different units, which in spite of providing valuable information about the system, are not very helpful for deciding between alternative systems.

Hence, at this stage the problem is how to decide about the best bridge design considering the above criteria and the goals of Sustainable Development. It is noted that the Decision Maker (DM) may be the designer of the bridge, or the team of professionals working on the design, or even a panel of evaluators in a bidding process. Therefore, the aim of this chapter is to provide an approach to aid in the decision making process of selecting the most satisfactory solution in the aim of Sustainable Construction.

The definition of Sustainable Development (see Chapter 1) suggests a harmonization or simultaneous realisation of different (often contradictory) aspects.

Barbier [12.1] states that Sustainable Development implies the simultaneously maximization of biological, economic and social systems goals. However, as pointed out by Munda [12.2], it is generally impossible to maximise different objectives at the same time. Therefore, a compromise between different goals should be found and this can be achieved by a multi-criteria decision analysis. In this case, however a question may be raised in relation to the degree of compromise or compensation between different criteria.

Moreover, the consideration and management of uncertainty in the whole process is hereby regarded once more as an essential part of a good decision making practice. Hence, in this chapter one of the criteria for the adoption of an approach to aid in the decision making process is to enable the integration of the uncertainty information in the analysis.

These aspects will be addressed in the following sub-chapters. In the end of the chapter, the adopted approach is applied to the comparative analysis of the previous case studies.

Finally, based in the results of the comparative analysis, a set of recommendations for bridge design is provided, in the pursuit of sustainable construction.

12.2. THE DECISION MAKING PROBLEM

12.2.1. Introduction

According to Harris [12.3] decision making is the study of identifying and choosing alternatives based on the values and preferences of the decision maker. The process of decision-making implies the identification of all possible alternatives and the selection of the one that best fits the goals of the analysis. Because very few decisions are made with absolute certainty, as complete knowledge about all the alternatives is seldom possible, decision-making is also defined as "the process of sufficiently reducing uncertainty and doubt about alternatives to allow a reasonable choice to be made from among them". It should be noted that uncertainty is reduced rather than eliminated. This issue will be further addressed in the last section of this sub-chapter.

The main steps in a decision making process [12.4] are illustrated in the Figure 12.1 and they are further described in the following section.

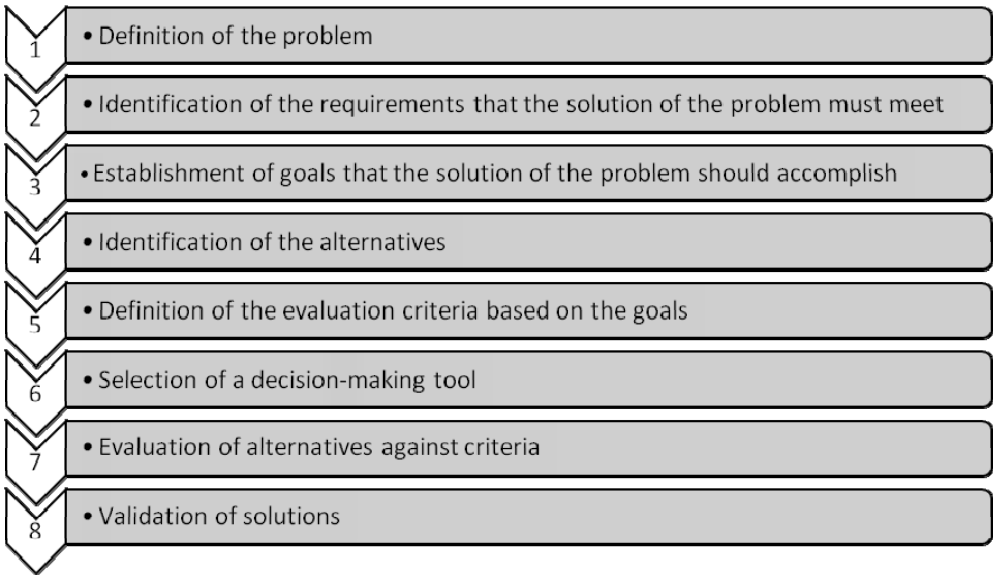


Figure 12.1. General Decision-Making process (adapted from [12.4])

12.2.2. Framework of the decision-making problem

12.2.2.1. Definition of the problem and respective requirements

The problem may be defined as the selection of a bridge design, with a service life of 100 years, considering the requirements of safety, and achieving a good global performance considering environmental, economical and social criteria, in the context of sustainable construction.

12.2.2.2. Definition of goal(s)

The goal is the design of a bridge offering the most favourable solution in terms of safety, environment, cost and society.

The safety of the bridge is hereby considered as an essential requirement that each alternative must meet and thus no differentiation is made in relation to this requirement for alternative designs.

As already referred, the simultaneously minimization of environmental, economical and social criteria is generally not possible to achieve. Therefore, the goal is the selection of a bridge design offering the most favourable solution in terms of environment, cost and social impacts. Naturally, a trade-off or compensation must be assumed, at least partially, between different criteria.

12.2.2.3. Selection and quantification of criteria

Criteria are used to discriminate among alternatives. Criteria must be based on the goals of the analysis and they should enable to measure how well each alternative achieves the goals. In this case, the criteria adopted for the evaluation of the environmental, economical and social criteria are the set of indicators presented in Chapters 6, 7 and 8, respectively. These indicators are summarized in the following table.

Table 12.1. Decision criteria for the evaluation of alternatives

Environmental	Economical	Social
Waste production	Construction costs	Vehicle operation cost
Abiotic depletion	Maintenance costs	Driver delay cost
Acidification	End-of-life costs	Safety cost
Eutrophication		Aesthetics
Global warming		Noise
Human toxicity		
Photochemical oxidation		
Ozone depletion layer		
Terrestrial ecotoxicity		

In order to achieve the goals of the analysis, most of these criteria are quantified over the life cycle of the bridge. Moreover, the sense of preferences for each indicator, except for Aesthetics, is decreasing: the lower the evaluation, the better the performance.

12.2.2.4. Identification and evaluation of alternatives

Any alternative must meet the requirements of the analysis. This step is similar to the functional unit, or the unit of comparison, in a life cycle approach, as referred in the previous chapters.

In this case three alternatives are evaluated: the three bridges described in the previous chapters. These bridges fulfil the requirements of the analysis. Furthermore, it is assumed that the bridges are alternatives to the same problem: the crossover of a dual carriageway with capacity for four lanes in each direction. As already stated the bridges were built in different locations. Although PS398 and PS390 were designed for the same segment of the motorway, they have different geometric characteristics due to the specific characteristics of the natural terrain and of the road segment, they were inserted. PS13 was built in a new motorway and it has characteristics that differ from the previous ones (for instance, the width of the cross-section). Nevertheless, in order to be assumed as different alternatives to the same problem, the unit of comparison has to be adequate and this issue will be further discussed in section 12.5.1.

All the three bridges were evaluated against the environmental, economical and social criteria indicated in Table 12.1. Moreover, in the context of sustainable construction, the evaluation of each subset of indicators in each main criterion was evaluated based in a life cycle approach, considering all the stages over the bridge life cycle, from raw material production to the demolition of the bridges in the end-of-life stage (chapters 9 to 11).

12.2.2.5. Selection of a decision making tool

In this decision making problem there are a finite number of criteria and a finite number of alternatives. Problems of this type are called multi-attribute decision-making problems. There are many different approaches to deal with this kind of problems, varying in terms of applicability and complexity, and naturally the selection of an appropriate approach is not an easy task. This issue will be further discussed in the following sub-chapter.

12.2.2.6. Validation of solutions against problem statement

After the application of the decision making approach, the alternatives have to be validated against the requirements and goals of the decision problem. It may happen that the decision making approach was misapplied or that further goals and/or requirements have to be added to the decision making model. This step may thus result in an iterative procedure.

12.2.3. Decision making under uncertainty

Usually decisions are taken based on deterministic analysis, without explicit evaluation of the uncertainties involved and possibly subjecting results and recommendations to a degree of sensitivity analysis.

However, as argued by Roy [12.5] a decision analysis cannot provide reliable results without taking into account the reasons and factors that can be responsible for contingency, arbitrariness and ignorance in the way the problem is envisaged and procedures are implemented.

On the previous chapters, procedures were adopted to address uncertainties in the evaluation of different criteria. It was concluded that an estimated range of values, given either by an interval of confidence or by a probability distribution, provided more reliable information than the estimation of a single value for each criterion. The uncertainties in the evaluation of criteria cannot be ignored in the decision making approach. Furthermore, the process of decision making by itself adds more uncertainty to the whole process.

Several attempts have been made to categorize different types of uncertainties in the context of decision making [12.6][12.7][12.8][12.9]. The common trend underlying such categorizations is the distinction between internal uncertainty and external uncertainty [12.10]. Internal uncertainties refer to both the structure of the model adopted and the judgmental inputs required by those models (for instance, the introduction of importance weights); whereas external uncertainty refers to the lack of knowledge about the consequences of a particular choice which may be outside of the control of the decision maker.

In this chapter, focus is given to internal uncertainties. Nevertheless, the boundary between external and internal uncertainties is fuzzy and under many circumstances, both types of uncertainties can be treated in much the same manner [12.10].

12.3. DECISION MAKING APPROACHES

12.3.1. Introduction

As previous referred, sustainability is a multidimensional concept including many and very often conflicting perspectives. MCDA is a very powerful tool for conflict management and has been successfully applied in many sustainability and management problems [12.2][12.11][12.12][12.13][12.14][12.15].

Multiple Criteria Decision Analysis (MCDA) can be divided into Multiple Attribute Decision Analysis (MADA) and Multiple Objective Optimization (MOO) methods [12.16], as represented in Figure 12.2. MOO are used for the synthesis of a preferred solution when the potential solution set is described by continuous variables and it is often used for operational planning. MOO is not associated with typical life cycle problems in which the alternatives have been predetermined [12.16] and therefore, it will not be further referred in this chapter.

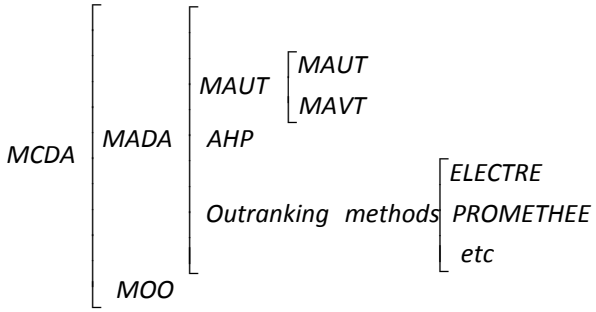


Figure 12.2. Classification of MCDA methodologies (adapted from [12.16])

Decision making problems in which the number of the criteria and alternatives is finite and alternatives are given explicitly are called Multi-Attribute Decision Analysis (MADA) [12.17] (also known as Multi-Attribute Decision Making). MADA methods can also be subdivided into Multi-Attribute Utility Theory (MAUT), Analytical Hierarchy Process (AHP) and outranking methods. The multi-attribute utility theory includes the Multi-Attribute Utility Theory (MAUT) itself and the Multi-Attribute Value Theory (MAVT). MAVT is applied for value measurement when there are no uncertainties about consequences of the alternatives, whereas MAUT is used under conditions of uncertainty.

AHP, which has already been used in the previous chapters, is similar to MAVT but its main point is that it allows decision makers to use so-called pairwise comparisons between the alternatives with qualitative expressions connected to a 1-9 scale.

Application of MAUT requires that the decision maker is able to decide which of two alternatives he/she prefers [12.16], whereas in the context of outranking methods this is not necessary.

In the outranking approaches an alternative Ai outranks Aj if on a great part of the criteria Ai performs at least as well as Aj, while its worst performance is still acceptable with respect to the other criteria [12.17]. After having determined for each pair of alternatives whether one alternative outranks another, these pairwise outranking assessments can be combined into a partial or complete ranking.

Generally, a multi-criteria problem involves [12.17] *m* criteria and *n* alternatives. Let $C_1,....,C_m$ and $A_1,....,A_n$ denote the criteria and alternatives, respectively. A standard feature of multi-attribute decision-making methodology is the decision table as shown in Figure 12.3. In the table each row belongs to a criterion and each column describes the performance of an alternative. The score a_{ij} describes the performance of alternative A_j against criterion C_i. Some criteria should be maximized and others minimized. For the sake of simplicity it is assumed that a higher score value means a better performance since any goal of minimization can be easily transformed into a goal of maximization.

$$\begin{array}{ccccc} & & x_1 & \cdots & x_n \\ & & A_1 & \cdots & A_n \\ w_1 & C_1 & a_{11} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ w_m & C_m & a_{m1} & \cdots & a_{mn} \end{array}$$

Figure 12.3. The decision table [12.17]

As shown in the decision table, weights $w_1,...,w_m$ are assigned to the criteria. Weight w_i reflects the relative importance of criterion C_i to the decision, and is assumed to be positive. The weights of the criteria are usually determined on a subjective basis. They represent the opinion of a single decision maker or synthesize the opinions of a group of experts using a group decision technique. The values $x_1,...,x_n$ associated with the alternatives in the decision table are used in the MAUT methods and are the final ranking values of the alternatives. Usually, higher ranking value means a better performance of the alternative, so the alternative with the highest ranking value is the best of the alternatives.

The next step in the multi-criteria analysis is the comparison between the alternatives against each criterion. The evaluation criterion by criterion has the advantage of keeping transparency; however it makes the evaluation difficult. Some criteria may be aggregated. In this case, the interpretation is easy but with less transparency. In the case of aggregation several approaches can be selected, some of which will be briefly referred in the following section.

12.3.2. Aggregation of criteria evaluations

12.3.2.1. Comparison of criteria

The DM preferences between two systems *a* and *b* may be represented by four elementary binary relations [12.18]:

i) *a* is indifferent to *b* (*a* I *b*) – indifference situation;

ii) *a* is strictly preferred to *b* (*a* P *b*) – strong preference situation;

iii) *a* is weakly preferred to *b* (*a* Q *b*) – weak preference situation, this situation is the hesitation between the indifference and preference situations and not being sure that *a* P *b*;

iv) *a* and *b* are incomparable (*a* R *b*) – incomparability situation, in this situation the hesitation is between *a* P *b* or *b* P *a*.

The criteria represent the consequences of the different systems that will allow one to judge them and preferences are based on the comparison of different criteria.

To take into account that the evaluation of criteria are subjected to imprecision, indetermination and uncertainty, threshold values are introduced [12.18]: the indifference threshold (q) representing the minimum margin of imprecision associated with a given criterion, the preference threshold (p) representing the maximum margin of error associated with the criterion in question, and the veto threshold (v), which allows the exclusion of a system if its evaluation for a given criterion is judged unacceptable to keep it as a solution to the problem. Moreover, the DM can establish that different criteria have different relative importance by assigning weighting factors to each criterion: the higher is the value of the weighting factor, the more important is the criterion.

Considering the comparison between two systems *a* and *b* and denoting g*(a)* the evaluation of the system *a* for the criterion *g*, the graphical representation of the criterion is illustrated in Figure 12.4 [12.19].

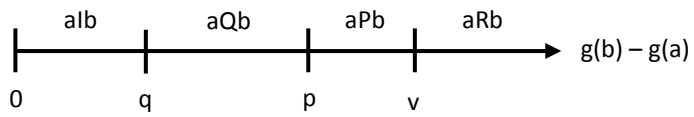


Figure 12.4. Representation of a criterion [12.19]

12.3.2.2. The single criterion approach

These methods assume that there exist a utility (or a value) function U to represent the DM preferences [12.26]. In this case, the task of the DM is to assess this function and then the ranking of alternatives is straightforward. The assessment of this function can be made in an additive mode, in a multiplicative mode, in a distributional mode, etc, and is based on the assumption that there is a partial utility function u_j according to each attribute *j*.

Among the usual aggregation functions there's the Multi Attribute Utility Theory (MAUT) [12.19]. These methods use a single synthesizing criterion approach and lead to a {P,I} preference structure. The AHP is also considered as a single synthesizing criterion approach. The final result of these methods can be completely described by the {P,I} preference structure and in some cases by {P,Q,I} structure.

Most of the utility assessment procedures use the trade-off mode to elucidate the DM preferences.

12.3.2.3. The outranking approach

The methods based on the outranking approach aim at the aggregation of the DM preferences established when comparing alternatives within each criterion [12.19]. The outranking relation aSb (*a* outranks *b*) holds when there is a strong reason to believe that with respect to all the criteria, a is at least as good as b. By the use of thresholds, the outranking approach leads to different structures depending on the preference relations taken into account. Contrarily to the previous approach, this one allows for incomparability.

Two of the most well known methods falling under this category are the ELECTRE family of methods [12.20] and PROMETHEE series of methods [12.21][12.22]. However, many other approaches are available, some of which based on the two previous ones: EXPROM (an extension of PROMETHEE) [12.23], MELCHIOR (an extension of ELECTRE IV) [12.24], NAIDE [12.25], ORESTE [12.26], REGIME [12.26], etc.

12.3.3. MCDA dealing with uncertainty

As already referred, the explicit consideration of uncertainty in MCDA is a very important issue and several approaches are found in the literature aiming to address this problem.

According to Stewart [12.10] internal uncertainty in decision making problems is commonly modelled by fuzzy set and related approaches. However, the author draws attention to the fact that the introduction of such, often complex, models to an already complex process may result in a loss of transparency to the decision maker, which is contrary to the nature of MCDA.

Fuzzy set approaches integrated with MCDA are increasingly being used in decision-making problems involving variables with high degree of uncertainty. For instance, the integration of fuzzy logic with the AHP in relation to environmental decision-making problems was used by Sadiqa and Husainb [12.27], Hung et al. [12.28], Kuo et al. [12.29] and Filippo et al. [12.30]. The same combination was used by Kuo et al. [12.31] for the selection of the location of a convenience store and by Yet et al. [12.32] for dredger dispatching.

A modified version of NAIADE was proposed by Benetto et al. [12.33] in order to comply with fuzzy and probabilistic uncertainty evaluations of LCA results.

An interval version of PROMETHEE was proposed by Le Téno and Mareschal [12.34] for the comparison of building products' design with ill-defined data for environmental use. Similarly, fuzzy logic was proposed to enhance PROMETHEE by considering fuzzy preferences, fuzzy scores and fuzzy weights simultaneously [12.35], and the approach was applied to a case study: the environmental assessment of sinter plants.

Probabilistic-based approaches are also gaining increasing popularity in dealing with uncertainty in MCDA.

A modified approach of ELECTRE, called ELECTRE-SS, was proposed by Hanandeh and El-Zein [12.36] using stochastic techniques to account for uncertainty in the weightings and threshold values of criteria. The proposed method was applied to a case of selecting a management strategy for the bio-degradable fraction in the municipal solid waste of Sydney.

A reliability-based approach was proposed by Hyde et al. [12.37] to enhance PROMETHEE by avoiding the need to define the generalized criterion functions. Also a probabilistic approach was proposed by Dorini et al. [12.38] by using Monte Carlo Simulations and Compromise Programming, and the approach was illustrated in the comparison of two options for electricity generation.

12.3.4. MCDA in the framework of sustainability

The aggregation of the alternatives evaluations implies some kind of "compensation ". There are no unanimous definitions to characterize the degree of compensation. However, according to Guitouni and Martel [12.26] any MCDA method can be either:

i) compensatory - where an absolute compensation between different evaluations can exist. In this case, a good performance on one criterion can easily counterbalance a poor one on another;

ii) non-compensatory – where no compensation is accepted between the different criteria. In this case, the criteria are considered to be important enough to refuse any kind of compensation or trade-offs;

iii) partially compensatory – in this case, some kind of compensation is accepted between the different criteria.

All single criterion methods fall into the category of compensatory methods, whereas the outranking methods are much less compensatory than the former [12.26].

Some authors [12.19] [12.33][12.35] argue that from the environmental point of view the compensation has to be avoided as much as possible, as a very serious environmental problem cannot be compensated by a less serious environmental problem. However, from a sustainable perspective when several dimensions are evaluated against each other, what is the degree of acceptable compensation?

Sustainable Development (SD) was introduced in the first chapter as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs". At the heart of this concept is the belief that social, economic and environmental objectives should be complementary and interdependent in the development process. The aim of SD is thus to balance the economic, social and environmental objectives of society – the three main pillars of SD [12.15]. Preferably, this should be achieved by integrating those objectives wherever possible, through mutually supportive policies and practices, but more usually it will require trade-offs [12.15].

Trade-offs or compensability plays an important role in the implementation of the concepts of strong and weak sustainability [12.2]. According to the concept of "strong sustainability", the existing stock of natural capital must be maintained and enhanced because the functions it performs cannot be duplicated by manufactured capital. The rationale is that some values are irreplaceable and thus, no trade-offs are admissible. On the other hand, the alternative concept of "weak sustainability", allows the replacement of natural capital by manufactured capital of equal value. Hence, the implementation of strong sustainability implies the use of non-compensatory multi-criterion algorithms [12.2].

Furthermore, according to Munda [12.2], complete compensability is not desirable in a method for dealing with sustainability decision problems and, in the framework of social decisions, criteria weights may be used in the form of importance coefficients and not as trade-offs.

In this chapter, completely compensatory approaches will not be considered for the decision-making problem in the context of sustainability and thus single criterion approaches will not be

further referred. However, it is considered that some kind of compensation is acceptable between different criteria.

Nevertheless, the range of available partially compensatory MCDA methods is still very wide. Guitouni and Martel [12.26] proposed a conceptual framework for tentative guidelines to choose an appropriate MCDA method and presented a comparative analysis of approaches based on those guidelines. According to the authors, the choice of a MCDA method is far from being a straightforward process and they propose to make comparative analysis between MCDA methods to identify in what circumstances one method is appropriate.

Salminen et al. [12.39] compared three different outranking approaches in the evaluation of real environmental problems in Finland to assess the applicability of the methods in aiding environmental decision-making. Although they concluded that the best approach is to make a sensitivity analysis using several methods for the same problem, their preference was for ELECTRE III (a method belonging to the family of ELECTRE approaches) due to its non-compensatory nature.

In the context of Life Cycle Environmental Assessment (LCEA) different MCDA methods were compared according to the criteria of non-compensatory degree, sensitivity to thresholds, practicability and workability [12.19]. The results of the analysis showed that there is not a single approach satisfying all the referred criteria and the choice of the MCDA approach depends on the characteristics of the LCEA.

12.3.5. Selection of the MCDA

As underlined in the previous section, to fulfil the aim of the proposed approach, outranking based methods are preferred to aggregating methods (or single criterion methods) because they involve weaker trade-offs.

As already referred, two of the most popular outranking approaches are ELECTRE and PROMETHEE series of methods. ELECTRE methods are very efficient in the operationalization of the outranking concept. However, this type of methods have also some drawbacks through its complexity and weak workability [12.19][12.35], which makes them difficult to use and to interpret the results.

When comparing criteria that are often subjective (in the evaluation) and incomplete (in lack of knowledge), such is the present case, it is important to maintain objectivity. Thus, the selected outranking approach should maintain transparency, should be easily understandable and should produce easily readable results [12.34][12.35].

Taking into account the above reasons, the method adopted in this work is the Preference Ranking Organization Methodology of Enrichment Evaluation (PROMETHEE) developed by Brans [12.40] and further extended by Vincke and Brans [12.41]. PROMETHEE belongs to the family of outranking methods and although not being the most non-compensatory approach, PROMETHEE is a quite simple ranking method in conception and application compared with the other methods for multi-criteria analysis [12.35][12.42]. One of the extensions of PROMETHEE (PROMETHEE II) enables a complete ranking of alternatives, while other approaches provide partial rankings including possible incomparabilities.

Moreover, PROMETHEE is a suitable approach for an integrated analysis thanks to its flexible algorithm enabling tailor-made enhancements to meet specific requirements for an integrated assessment approach, in particular, the explicit consideration of uncertainty in the input values (this issue will further developed in the following sections).

PROMETHEE has a widespread use in decision-making situations varying from environmental management to business and financial management, medical applications, etc. A comprehensive review of PROMETHEE methodologies and applications is provided in [12.43].

12.4. THE PROMETHEE METHOD

12.4.1. Theoretical basis

The solution of a multi-criteria problem depends on the basic data included in the evaluation of criteria and on the individual preferences of the decision-maker [12.44].

Therefore, additional information representing these preferences is required to provide the DM with useful decision aid. In the case of PROMETHEE it is necessary to add information between the criteria and within each criterion, as described in the following paragraphs.

Information between criteria is given by a set of weights $\{w_j, j = 1, 2,\ldots, k\}$ representing the relative importance of the different criteria. The higher the weighting factor the more important the criterion.

The information within each criterion, the preference structure, is based on pairwise comparisons [12.44]. The deviation between the evaluations of two alternatives on a particular criterion is considered. For small deviations, the decision-maker allocates a small preference to the best alternative or possibly no preference if the deviation is negligible. The larger the deviation the larger the preference. These preferences may vary between 0 and 1.

Thus, for each criterion, there is a function,

$$P_j(a,b) = F_j[d_j(a,b)], \forall a,b \in A, \tag{12.1}$$

where,

$$d_j(a,b) = g_j(a) - g_j(b) \tag{12.2}$$

and for which,

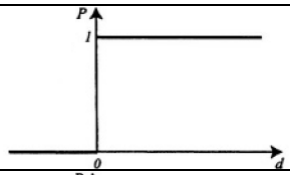
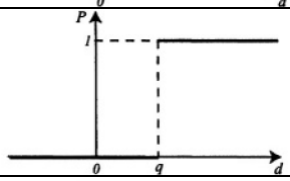
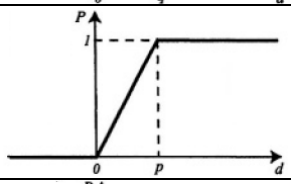
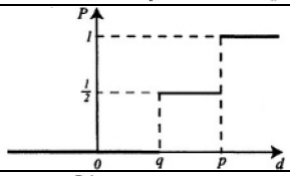
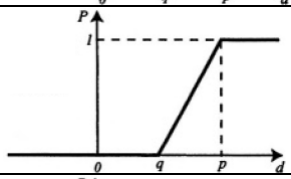
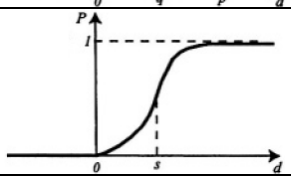
$$0 \le P_j(a,b) \le 1 \tag{12.3}$$

Expression (12.1) gives the preference of *a* over *b* for observed deviations between their evaluations on criterion $g_j(.)$, in case of a criterion to be maximised. For criteria to be minimised, the preference function should be reversed:

$$P_j(a,b) = F_j[-d_j(a,b)], \forall a,b \in A, \tag{12.4}$$

A generalised criterion $\{g_j(.), P_j(a,b)\}$ has to be defined for each criterion. Six types of particular preference functions are usually proposed [12.45], as shown in Table 12.2. However, other types of generalised criteria may also be considered.

Table 12.2. Types of generalised criteria

Type	Generalised criterion	Definition	Parameter to fix
Type I – Usual criterion		$P(d)=\begin{cases}0 & d\le 0\\ 1 & d>0\end{cases}$	-
Type II – Quasi criterion		$P(d)=\begin{cases}0 & d\le q\\ 1 & d>q\end{cases}$	q
Type III – Criterion with linear preference		$P(d)=\begin{cases}0 & d\le 0\\ d/p & 0<d\le p\\ 1 & d>p\end{cases}$	p
Type IV – Level criterion		$P(d)=\begin{cases}0 & d\le q\\ 1/2 & q<d\le p\\ 1 & d>p\end{cases}$	p,q
Type V – Criterion with linear preference and indifference area		$P(d)=\begin{cases}0 & d\le q\\ \dfrac{d-q}{p-q} & q<d\le p\\ 1 & d>p\end{cases}$	p,q
Type VI – Gaussian criterion		$P(d)=\begin{cases}0 & d\le 0\\ 1-\exp\left\{\dfrac{-d^2}{2s^2}\right\} & d>0\end{cases}$	s

Parameter q is the indifference threshold and represents the largest deviation which is considered as negligible by the decision maker. Parameter p is the preference threshold representing the smallest deviation which is considered as sufficient to generate a full preference. In the Gaussian criterion the preference function is monotonically increasing for all deviations and has no discontinuities. In this case, parameter s defines the inflection point of the preference function.

A number of variations of the PROMETHEE method have been developed. The PROMETHEE I and PROMETHEE II were developed by Brans [12.40]. PROMETHEE I provides a partial ranking, including possible incomparabilities, while PROMETHEE II shows a complete ranking of alternatives. PROMETHEE III and PROMETHEE IV provide a ranking based on intervals and in a continuous case, respectively. PROMETHEE V extends the application of PROMETHEE II to the problem of selection of several options, given a set of constraints, and PROMETHEE VI aims to represent the human brain. The Geometrical Analysis for Interactive Aid (GAIA) module provides a geometrical representation of the results obtained by the PROMETHEE methodology.

12.4.2. PROMETHEE I methodology

For the application of PROMETHEE two major actions are needed: the calculation of aggregated preference indices and outranking flows.

The aggregate preference indices π(a,b) expresses with which degree *a* is preferred to *b* over all the criteria, while π (b,a) indicates how *b* is preferred to *a*. Assuming a,b ∈ A,

$$\begin{cases} \pi(a,b) = \sum_{j=1}^{k} P_j(a,b) w_j \\ \pi(b,a) = \sum_{j=1}^{k} P_j(b,a) w_j \end{cases} \tag{12.5}$$

π(a,b) ≈ 0, implies a weak global preference of *a* over *b*, while, π(a,b) ≈ 1, implies a strong global preference of *a* over *b* [12.44].

Each alternative *a* faces (*n-1*) other alternatives in A. Two outranking flows can be defined:

i) the positive outranking flow,

$$\phi^{+}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a,x) \tag{12.6}$$

representing how an alternative *a* is outranking all the others. The higher ϕ^{+}(a), the better the better the alternative.

ii) the negative outranking flow,

$$\phi^{-}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x,a) \tag{12.7}$$

expressing how an alternative *a* is outranked by all the others. The lower ϕ^{-}(a), the better the better the alternative.

The PROMETHEE I partial ranking is obtained from the positive and negative outranking flows:

$$\begin{cases} aP^{I}b \quad if \begin{cases} \phi^{+}(a) > \phi^{+}(b) \quad and \quad \phi^{-}(a) < \phi^{-}(b), \quad or \\ \phi^{+}(a) = \phi^{+}(b) \quad and \quad \phi^{-}(a) < \phi^{-}(b), \quad or \\ \phi^{+}(a) > \phi^{+}(b) \quad and \quad \phi^{-}(a) = \phi^{-}(b), \quad or \end{cases} \\ aI^{I}b \qquad if\, \phi^{+}(a) = \phi^{+}(b) \quad and \quad \phi^{-}(a) = \phi^{-}(b) \\ aR^{I}b \quad if \begin{cases} \phi^{+}(a) > \phi^{+}(b) \quad and \quad \phi^{-}(a) > \phi^{-}(b), \quad or \\ \phi^{+}(a) < \phi^{+}(b) \quad and \quad \phi^{-}(a) < \phi^{-}(b) \end{cases} \end{cases} \tag{12.8}$$

where P^{I}, I^{I} and R^{I} represent the preference, indifference and incomparability, respectively. In the case of $aR^{I}b$, a higher power of one alternative is associated to a lower weakness of the

other. In this case, the information provided by both flows is not consistent and both alternatives are considered incomparable.

12.4.3. PROMETHEE II methodology

In case a complete ranking is necessary, then PROMETHEE II should be chosen. In this case the net outranking flow is defined as the balance between the positive and the negative outranking flows,

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a) \tag{12.9}$$

The higher the net flow, the better the alternative, so that:

$$\begin{cases} aP^{II}b & if \quad \phi(a) > \phi(b) \\ aI^{II}b & if \quad \phi(a) = \phi(b) \end{cases} \tag{12.10}$$

In PROMETHEE II all the alternatives are comparable, no incomparabilities remain [12.44]. When Ø(a)>0, *a* is more outranking all the alternatives on all the criteria, when Ø(a)<0 it is more outranked. For this reason, this version of PROMETHEE is adopted in the following sub-chapter.

However, Brans and Mareschal [12.44] recommend considering both PROMETHEE I and PROMETHEE II as the analysis of the incomparabilities often helps to finalise a proper solution.

12.5. DECISION MAKING IN RELATION TO BRIDGE DESIGN

12.5.1. Introduction

The decision making problem is the selection of the most favourable solution for the cross-over of a dual carriageway with the capacity of four lanes of traffic in each direction. Three different alternatives are analysed: a composite steel-concrete bridge (PS398), a concrete cast in situ bridge (PS390) and a precast concrete bridge (PS213). A comprehensive analysis of the three bridges has been performed in chapters 9, 10 and 11, respectively.

These three bridges are in fact real bridges built in motorways A1 (PS398 and PS390) and A17 (PS13) almost at the same time, and they have different structural characteristics (e.g. foundations and cross-section width) due to the location and respective road characteristics where they were built. Therefore, in spite of the fact that all bridges fulfil the above requirement, they are not directly comparable.

If the bridges were designed exactly for the same location and for the same road segment then the bridges would be comparable, and most probably they would have about the same length and the same width of the cross-section.

Therefore, a functional unit has to be adequate to account for this situation and to make the bridges comparable. To minimize this problem the results obtained for each indicator may be divided by the area of the deck of the respective bridge. This solution in itself does not make the results completely comparable as the need of materials, respective costs, use of equipment, etc,

do not vary linearly with bridge size. For instance, if there is a need for a cross-section 19 m wide, then the variation in terms of materials to a cross-section 11 m wide is not linear.

To account for different terrain characteristics, the analysis may take into account only the deck of the respective structures. However, this solution may distort the analysis as the number of columns and the type of abutments and foundations may also depend on the type of the deck.

Another solution to account for different deck dimensions could be to affect the functional unit by a factor considering the road capacity provided by each deck. The relationship between the deck size and the respective road capacity may be assumed to be almost linear. However, as already said, the relationship between the quantities of materials and the deck size is not linear.

Hence, in the current analysis each indicator was simply divided be the area of the deck, although acknowledging that this is not a perfect solution.

12.5.2. Deterministic analysis

12.5.2.1. Ranking of alternatives

The comparative analysis is based on the three previous case studies and in order to make the comparison more objective the criteria of “aesthetics” and “noise” were not considered in the evaluation of the alternatives due to their rather subjective nature.

The three alternative bridges (a_i) were analysed against fourteen criteria (g_j) indicated in Table 12.1, and the results (in m^2) are indicated in Table 12.3.

Table 12.3. Evaluation matrix

Criteria		Alternatives (a_i)		
		PS398	PS390	PS13
g_1	Abiotic depletion	6.30E-02	6.58E-02	8.50E-02
g_2	Acidification	1.52E-02	1.63E-02	1.78E-02
g_3	Global warming	4.72E-02	4.89E-02	4.63E-02
g_4	Ozone layer dep.	1.40E-04	1.62E-04	2.12E-04
g_5	Human toxicity	4.62E-03	5.89E-03	5.89E-03
g_6	Ecotoxicity	8.33E-04	8.35E-04	8.67E-04
g_7	Eutrophication	1.64E-02	1.90E-02	1.78E-02
g_8	Photochemical	6.60E-03	6.41E-03	8.69E-03
g_9	Construction cost (€)	571.30	428.10	451.00
g_{10}	Operation cost (€)	398.44	241.27	168.76
g_{11}	Demolition cost (€)	2.78	3.27	3.30
g_{12}	DDC (€)	266.79	350.59	689.70
g_{13}	VOC (€)	386.55	507.89	999.56
g_{14}	Accidents cost (€)	2.33	3.06	6.37

For all criteria, the sense of preferences is decreasing: the lower the evaluations, the better the performance. The indifference (q_j) thresholds were chosen in order to have 5% of the difference between the highest and lowest evaluation for each criterion: $\forall j$, $q_j = 0.05 \times [\max.g_j(i) - \min.g_j(i)]$; whereas, the preference (p_j) thresholds were chosen in order to have 60% of the difference between the highest and lowest evaluation for each criterion: $\forall j$, $p_j = 0.60 \times [\max.g_j(i) - \min.g_j(i)]$. The values of the s_j thresholds were chosen as intermediate values:

$\forall j$, $s_j = 0.30 \times [\max.g_j(i) - \min.g_j(i)]$.

It is up to the DM to decide whether different criteria have the same relative importance or not. In this approach the DM may express his/her choice by the weighting factors, which are defined based in a hierarchy structure, as represented in Figure 12.5. Three main criteria are used in the analysis: environmental, economical and social. These criteria are in the second level of the hierarchy structure. On the third level, there are the set of sub-criteria in each main criterion. The sub-criteria have already been weighted against each other in chapters 6, 7 and 8, respectively. In this chapter, weighting factors are established only for the second level.

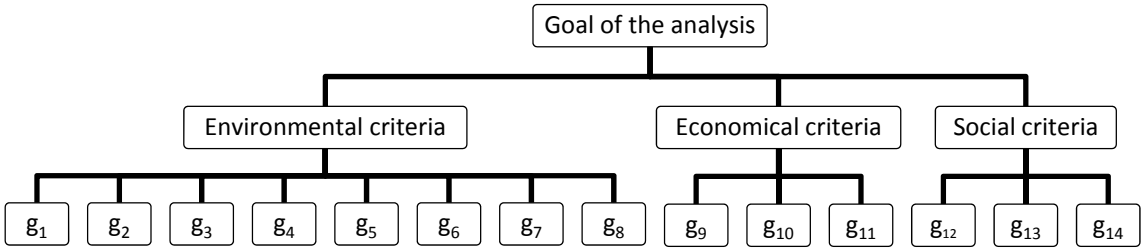


Figure 12.5. Hierarchy structure of weighting factors

In this case, it is considered that the three main criteria have equal importance. Hence, sub-criteria g_1 to g_8 are affected by a factor of (1/3)/8 = 0.0417, while sub-criteria g_9 to g_{14} are affected by a factor of (1/3)/3 = 0.111.

The evaluation of the matrix of the aggregate preference indices π(a,b), according to expressions (12.5), is represented in Table 12.4. In this evaluation a preference function corresponding to the Gaussian criterion (preference function type VI, see Table 12.2) was used.

Table 12.4. Aggregate preference indices π(a,b)

	PS398	PS390	PS13
PS398	0	0.341	0.724
PS390	0.215	0	0.539
PS13	0.239	0.118	0

From this matrix, the positive and negative flows are evaluated, according to expressions (12.6) and (12.7), respectively. The matrix of positive outranking flows is represented in Table 12.5.

Table 12.5. Positive outranking flow

	PS398	PS390	PS13
φ^+ (ai)	**0.5326**	0.3769	0.1788
φ^+_1 (ai)	**0.5371**	0.4932	0.0000
φ^+_2 (ai)	**0.8307**	0.4103	0.0000
φ^+_3 (ai)	0.4557	0.0000	**0.7346**
φ^+_4 (ai)	**0.6958**	0.4669	0.0000
φ^+_5 (ai)	**0.9961**	0.0000	0.0000
φ^+_6 (ai)	**0.5014**	0.4972	0.0000
φ^+_7 (ai)	**0.8928**	0.0000	0.3538
φ^+_8 (ai)	0.4955	**0.5150**	0.0000
φ^+_9 (ai)	0.0000	**0.5633**	0.4902
φ^+_{10} (ai)	0.0000	0.4629	**0.7106**
φ^+_{11} (ai)	**0.9941**	0.0121	0.0000
φ^+_{12} (ai)	**0.5961**	0.4859	0.0000
φ^+_{13} (ai)	**0.5959**	0.4860	0.0000
φ^+_{14} (ai)	**0.5805**	0.4881	0.0000

From this table, it is noted that the alternative with higher positive flow is PS398, this alternative has higher flows for most criteria except g_3, g_8 , g_9 and g_{10}. Alternative PS390 has higher flows for criteria g_8 and g_9, while alternative PS13 has higher flows for criteria g_3 and g_{10}.

Likewise, the matrix of negative outranking flows is represented in Table 12.6 and again the alternative with better global result is PS398. This alternative has lower negative flows for most criteria except g_3, g_8, g_9 and g_{10}. Alternative PS390 has lower flows for criteria g_8 and g_9, and alternative PS13 has lower flows for criteria g_3 and g_{10}.

Table 12.6. Negative outranking flow

	PS398	PS390	PS13
φ^- (ai)	**0.2271**	0.2295	0.6316
φ^-_1 (ai)	**0.0000**	0.0391	0.9912
φ^-_2 (ai)	**0.0000**	0.3326	0.9084
φ^-_3 (ai)	0.2365	0.9537	**0.0000**
φ^-_4 (ai)	**0.0000**	0.1977	0.9650
φ^-_5 (ai)	**0.0000**	0.4981	0.4981
φ^-_6 (ai)	**0.0000**	0.0034	0.9952
φ^-_7 (ai)	**0.0000**	0.8519	0.3947
φ^-_8 (ai)	0.0170	**0.0000**	0.9936
φ^-_9 (ai)	0.9883	**0.0000**	0.0652
φ^-_{10} (ai)	0.9610	0.2126	**0.0000**
φ^-_{11} (ai)	**0.0000**	0.4961	0.5101
φ^-_{12} (ai)	**0.0000**	0.0980	0.9840
φ^-_{13} (ai)	**0.0000**	0.0978	0.9840
φ^-_{14} (ai)	**0.0000**	0.0824	0.9861

The final ranking is given by the balance between the positive and negative outranking flows, according to expression (12.9), leading to the result indicated in Table 12.7.

Table 12.7. Net outranking flow

	PS398	PS390	PS13
φ (ai)	**0.3055**	0.1474	-0.4528
φ_1 (ai)	**0.5371**	0.4541	-0.9912
φ_2 (ai)	**0.8307**	0.0777	-0.9084
φ_3 (ai)	0.2191	-0.9537	**0.7346**
φ_4 (ai)	**0.6958**	0.2692	-0.9650
φ_5 (ai)	**0.9961**	-0.4981	-0.4981
φ_6 (ai)	**0.5014**	0.4938	-0.9952
φ_7 (ai)	**0.8928**	-0.8519	-0.0409
φ_8 (ai)	0.4786	**0.5150**	-0.9936
φ_9 (ai)	-0.9883	**0.5633**	0.4250
φ_{10} (ai)	-0.9610	0.2504	**0.7106**
φ_{11} (ai)	**0.9941**	-0.4840	-0.5101
φ_{12} (ai)	**0.5961**	0.3880	-0.9840
φ_{13} (ai)	**0.5959**	0.3882	-0.9840
φ_{14} (ai)	**0.5805**	0.4057	-0.9861

As expected, the better global alternative is PS398 and the better alternative per criterion (in bold) corresponds also to the results obtained by the positive and negative flows. Hence, the complete ranking of alternatives is represented in Figure 12.6.

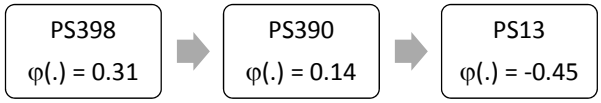


Figure 12.6. Ranking of alternatives

12.5.2.2. Sensitivity analysis

To assess the robustness of the analysis, a sensitivity analysis is made considering the use of other preference functions. Table 12.8 indicates the ranking of alternatives, based in the net outranking flow, for each preference function.

Table 12.8. Sensitivity analysis considering different preference functions

Preference function	Ranking of alternatives		
Type I	**PS398** [φ (.) = 0.47]	PS390 [φ (.) = 0.03]	PS13 [φ (.) = -0.50]
Type II	**PS398** [φ (.) = 0.45]	PS390 [φ (.) = 0.07]	PS13 [φ (.) = -0.52]
Type III	**PS398** [φ (.) = 0.33]	PS390 [φ (.) = 0.13]	PS13 [φ (.) = -0.47]
Type IV	**PS398** [φ (.) = 0.35]	PS390 [φ (.) = 0.15]	PS13 [φ (.) = -0.49]
Type V	**PS398** [φ (.) = 0.32]	PS390 [φ (.) = 0.14]	PS13 [φ (.) = -0.46]
Type VI	**PS398** [φ (.) = 0.31]	PS390 [φ (.) = 0.15]	PS13 [φ (.) = -0.45]

The ranking of alternatives is kept constant and alternative PS398 is always the preferred alternative independently of the preference function. However, as noted from Table 12.8, the use of preference function type VI provided a closer result between alternatives PS398 and PS390. Hence, a new sensitivity analysis is performed considering preference function type VI and different values for the threshold value (*s*), as indicated in Table 12.9

Table 12.9. Sensitivity analysis considering preference function VI and different threshold value (*s*)

Threshold value (*s*)	Ranking of alternatives		
0.1 x [max.g_j(i) – min.g_j(i)]	**PS398** [φ (.) = 0.43]	PS390 [φ (.) = 0.03]	PS13 [φ (.) = -0.46]
0.2 x [max.g_j(i) – min.g_j(i)]	**PS398** [φ (.) = 0.34]	PS390 [φ (.) = 0.10]	PS13 [φ (.) = -0.45]
0.3 x [max.g_j(i) – min.g_j(i)]	**PS398** [φ (.) = 0.31]	PS390 [φ (.) = 0.15]	PS13 [φ (.) = -0.45]
0.4 x [max.g_j(i) – min.g_j(i)]	**PS398** [φ (.) = 0.28]	PS390 [φ (.) = 0.15]	PS13 [φ (.) = -0.43]
0.5 x [max.g_j(i) – min.g_j(i)]	**PS398** [φ (.) = 0.25]	PS390 [φ (.) = 0.13]	PS13 [φ (.) = -0.38]

Likewise, the ranking of alternatives does not change and alternative PS398 is always the preferred alternative independently of the threshold value (*s*). However, as noted from Table 12.9, the higher the value of the threshold value (*s*), the closer is the result between alternatives PS398 and PS390. However, considering a value higher than the one indicated in the last row of Table 12.9, the distance between the two alternatives does not change significantly.

In the previous cases equal importance was given to the three main criteria. However, changing the relative importance of these criteria may also have same influence in the outcome of the analysis. Therefore, a new sensitivity analysis is performed considering different weights for the three main criteria, as indicated in Table 12.10.

Table 12.10. Sensitivity analysis considering different weights for main criteria

Weightings	Ranking of alternatives		
Env = Eco = Soc = 33.33%	**PS398** [φ (.) = 0.31]	PS390 [φ (.) = 0.15]	PS13 [φ (.) = -0.45]
Env = 50%; Eco = Soc = 25%	**PS398** [φ (.) = 0.39]	PS390 [φ (.) = 0.10]	PS13 [φ (.) = -0.49]
Eco = 50%; Env = Soc = 25%	**PS398** [φ (.) = 0.15]	**PS390** [φ (.) = 0.14]	PS13 [φ (.) = -0.29]
Soc = 50%; Env = Eco = 25%	**PS398** [φ (.) = 0.38]	PS390 [φ (.) = 0.21]	PS13 [φ (.) = -0.59]
Eco = 70%; Env = Soc = 15%	PS398 [φ (.) = -0.04]	**PS390** [φ (.) = 0.13]	PS13 [φ (.) = -0.09]

In the analysis the preference function type VI was considered. As observed from Table 12.10, the relative importance of the main criteria has a significant importance in the outcome of the analysis.

The weighting factors in the first row are intended to give the same importance to environmental, economical and social criteria, whereas, the factors indicated in the second, third and fourth rows give a slightly more importance to environmental, economical and social criteria, respectively. In all cases, the ranking of alternatives does not change, although the distance between the scores obtained by each alternative changes considerably. In fact, using the weighting factors in the third row would make the decision about bridges PS398 and PS390 very difficult.

The weighting factors in the last row, giving higher preference to the economical criteria, are the ones currently used in the daily practice. In this case, the alternative with the lower life cycle cost is considered the best alternative, which in this case is bridge PS390.

The sensitivity analysis performed in this sub-section highlighted the difficulty of the DM in dealing with different parameters of the adopted decision-making approach. The probabilistic decision-making approach, presented in the following section, allows to overcome some of these problems.

12.5.3. Probabilistic analysis

As already referred, a decision maker using a MCDA method has to deal with the uncertainty in the evaluation of the performance values for each criterion, the uncertainty in the choice of criteria weights and uncertainty in the parameters associated with the decision-making approach.

Therefore, using PROMETHEE two other sources of uncertainty are added to the analysis: the selection of generalized functions and their associated thresholds for each criterion. These two sources of uncertainty were highlighted in the sensitivity analysis performed in the previous section.

To address the above uncertainties in the use of PROMETHEE a probabilistic approach is adopted enabling a decision to be made with confidence that the alternative chosen is the best performing alternative under the range of probable circumstances. The probabilistic approach involves defining the uncertainty in the input values using probability distributions and running Monte Carlo simulations.

Moreover, in order to ascertain the relative importance of the introduction of the uncertainty in the performance values, two different probabilistic analysis are considered: the first analysis (Case A) considers uncertainty in the choice of criteria weights and in the selection of generalized functions; while the second analysis (Case B) adds the uncertainty in the evaluation of the performance values.

Hence, to perform the probabilistic analyses it is necessary to: (i) define the uncertainty in the criteria performance values, (ii) define the uncertainty in the criteria weights, and (iii) define the uncertainty in the generalized criterion functions.

The uncertainty and variability in the criteria performance values were dealt with in chapters 9, 10 and 11 for each alternative and they are hereby represented by the probability distributions achieved for each sub-criterion (g_i).

The uncertainty in the choice of the weighting values for the relative importance of each sub-criterion within each main criterion was already addressed in chapters 6, 7 and 8, respectively for environmental, economical and social criteria. This type of uncertainty is already included in the probability distributions referred in the previous paragraph. The uncertainty introduced by the weighting of the main criteria in this chapter is hereby addressed by a similar approach to the one used in the previous chapters. Thus, a range of values are assigned to each weighting value representing the set of possible values for those variables. In this case, and considering the sensitivity analysis performed in the previous section, uniform distributions are considered and the upper and lower bounds for the uniform distributions are indicated in Table 12.11.

Table 12.11. Upper and lower bounds of uniform distributions for weighting values

	Environmental	Economical	Social
Upper bound	15%	25%	15%
Lower bound	50%	70%	50%

Large weights for one criterion are associated with low weights for the others. Thus, a correlation analysis is undertaken and the results, which are indicated in Table 12.12, are incorporated in the distributions to ensure an accurate sampling from the distributions. Moreover, the random sample of preference values obtained from these distributions is normalized in order to guarantee that the sum of the values is 1.

Table 12.12. Correlation matrix of weighting values

	environmental	economical	social
environmental	1.00000	-0.73766	0.08830
economical		1.00000	-0.73766
social			1.00000

In relation to the uncertainty in the generalized criterion functions, Hyde et al. [12.37] propose to incorporate the uncertainty in input data (preference values) and to assign a type I generalized criterion function (usual criterion) to each criterion to enable the preference functions between alternatives to be established. This avoids the difficult task of selecting the generalized criterion functions and respective thresholds. This approach is also considered in this case. However, another alternative is hereby proposed: to use a generalized criterion function type VI and to assign a probability distribution to the parameter *s*. In the previous section, the parameter s was selected as an intermediate value between the indifference threshold and the preference threshold. A sensitivity analysis was performed to evaluate the importance of this parameter and the results confirmed its importance. Thus an uniform distribution is considered for parameter *s* with a lower bound of $\{0.1 \times [\max.g_j(i) - \min.g_j(i)]\}$ and an upper bound of $\{0.5 \times [\max.g_j(i) - \min.g_j(i)]\}$.

The output of the probabilistic analysis, by running a Monte Carlo simulation, enables the DM to assess the probability that an alternative achieves rank *n* based on all probable criteria input parameters.

Hence, in the first probabilistic analysis (Case A) and using the usual criterion (type I) and the Gaussian criterion (type VI), the probability of each alternative to achieve a certain rank is

represented in Table 12.13. The probabilistic analysis was performed by Microsoft Excel @Risk [12.46] add-in software package.

Table 12.13. Probability (%) of each alternative to achieve rank *i* (case A)

	Usual criterion			Gaussian criterion		
Rank	PS398	PS390	PS13	PS398	PS390	PS13
1	**90.9**	9.1	0	**79.9**	20.1	0
2	9.1	**90.9**	0	20.1	**79.9**	0
3	0	0	**100**	0	0	**100**

Based in [12.13], using criterion function type I, bridge PS398 has a probability of 90.9% of getting the first rank, while PS390 has the same probability of getting the second rank and PS13 has a probability of 100% of getting the third rank. Using criterion function type VI, similar results are obtained, although the probabilities of PS398 and PS390 of getting the first and second rank, respectively, are lower in comparison with the previous case. Like in the deterministic analysis, the probabilistic approach is also sensitive to the selection of the generalized criterion function; however, in this case the results are more reliable than in the previous analysis.

The second probabilistic analysis (Case B) is similar to the previous one, except that the uncertainty information in the criteria performance values is also included in the analysis. Likewise, the probabilistic analyses were performed by Microsoft Excel @Risk [12.46] add-in software package and the probability of each alternative to achieve a certain rank is represented in Table 12.14.

Table 12.14. Probability (%) of each alternative to achieve rank *i* (case B)

	Usual criterion			Gaussian criterion		
Rank	PS398	PS390	PS13	PS398	PS390	PS13
1	**58.0**	31.4	10.6	33.4	**57.8**	8.8
2	28.1	**53.7**	18.2	**47.3**	36.0	16.7
3	13.9	14.9	**71.2**	19.3	6.2	**74.5**

Based on Table 12.14, using criterion function type I, bridge PS398 has a probability of 58% of getting the first rank. However, using criterion function VI the probability of PS390 of getting the first rank is higher than PS398. In all cases, PS13 has the lowest rank, as already obtained from the previous case.

These analyses confirmed that PROMETHEE is very sensitive in relation to the selection of preference functions Moreover, the two probabilistic analyses performed in Case B showed that taking into account the uncertainty information in criteria performance values has a significant importance in the final ranking of alternatives. Taking into account the result of both probabilistic analyses, bridge PS398 showed advantages in relation to the other two alternatives. Naturally, the higher the importance of the economic criteria, the lower is the advantage of PS398 in relation to PS390.

The probabilistic approach is an improvement over the deterministic methodology as it enables to consider simultaneously the uncertainty in various input parameters. In this case, three types of uncertainties were addressed: uncertainty in the criteria performance values, uncertainty in the criteria weights, and uncertainty in the generalized criterion functions.

Furthermore, the probabilistic analysis enables a decision to be made with reasonable certainty that the alternative chosen is the best performing alternative under the range of probable

circumstances. In relation to the three case studies analyzed in this section, which were considered different alternatives of the same bridge, it would be possible to conclude that the bridge PS398 was the best alternative under all the assumed circumstances.

12.5.4. Concluding remarks

Multi-Criteria Decision Analysis (MCDA) is a methodology commonly used to aid in decision-making situations as it enables the participation of several stakeholders and collaborative decision-making. MCDA was introduced in this chapter as an approach suitable for a decision-making problem in the context of sustainability. The use of various evaluation criteria enables the evaluation exercise to be made based on a plurality of values, often controversial values.

Among several MCDA methodologies, the Preference Ranking Organization Methodology of Enrichment Evaluation (PROMETHEE) was adopted and its adoption was justified taking into account the aim of the proposed approach. In spite of allowing a balance between criteria, PROMETHEE is not a full compensatory method, which is in full agreement with the aims of Sustainable Development. The algorithm of PROMETHEE provides a clear understanding of the comparison between criteria, allowing an easily interpretation of the results. Moreover, this method was used in a deterministic-based approach and in a probabilistic-based approach. The latter has several advantages in relation to the former as it allows overcoming some limitations of the deterministic-based approach, namely, it allows considering uncertainty in several input parameters simultaneously. The robustness of the results of the probabilistic analysis enables decisions to be made with reasonable certainty that the alternative chosen is the best performing alternative under the range of probable circumstances.

PROMETHEE was used for the comparative analysis of the three bridges in order to select the bridge offering the best global performance. In spite of the case studies were not directly comparable, a functional unit divided per the area of the deck of each bridge was considered to make the comparative analysis more reliable. In this case, there were only three alternatives; however, the adopted methodology allows considering a higher number of alternatives.

With due acknowledge to the fact that the three bridges were not design for the same location and that the construction of the bridges was made under different circumstances, valuable information was obtained from the outcome of the analysis.

Within the three bridges the solution offering the best global performance was the composite steel-concrete bridge (PS398), followed by the concrete bridge that was cast “in situ” (PS390) and in last the precast bridge (PS13). Considering the three main criteria (environmental, economical and social) PS398 achieved the best performance in two main criteria (environmental and social), whereas in the economical criteria the other two solutions have a better performance.

The bridge with worst global performance is clearly PS13, although in this case a major reason for this to happen must be clarify. This bridge was design for a new motorway, therefore no care were taken for traffic in the motorway during construction as the motorway was not opened to traffic at that time. However, in the analysis of this bridge it was considered that, as for the other two bridges, the motorway was opened to traffic during construction. Naturally, this is the

main cause of having such a bad performance, particularly in the social indicators, although this is also reflected in the environmental analysis.

Comparing the other two bridges, the results are closer although, PS398 has a better environmental and social performance. The main reason for this to happen is due to the fact that the composite bridge enables a more efficient construction system, reducing the time needed for the erection of the structure and thus minimizing traffic affectation. Nevertheless, this type of bridge has a higher construction and maintenance costs.

12.6. RECOMMENDATIONS FOR BRIDGE DESIGN

The design of a bridge or any other construction system in the framework of sustainable construction has to consider not only the initial stage of construction but all the stages over its life cycle. Furthermore, the analysis should consider apart from safety requirements, at least the other main dimensions of sustainability: environmental, economical and social.

The importance of considering the complete life cycle of bridges instead of the initial stage was clearly illustrated in the analysis of the case studies in chapters 9, 10 and 11. Moreover, in the comparative analysis between the three bridges it was concluded that the alternative offering the best global performance was the one with a higher initial cost, which is usually the criteria for selection in the current practice.

One of the main barriers in the implementation of such approaches for construction systems is the long period of time that needs to be considered in the analysis, usually over 100 years. Naturally, it is very difficult to predict what is going to happen over such a long period of time. Hence, many assumptions have to be considered in relation to the performance of the structure (and related needs for maintenance and rehabilitation) but also in relation to the use of new materials, new equipment and technologies. To overcome this complex problem or at least to reduce it, the advice is to make all future assumptions based in present knowledge and today's engineering practice. Most probably, in 100 years new materials and new technologies will appear which will make present materials and technologies obsolete. However, to predict about future events based in predictions about future materials and technologies will make the analysis quite unrealistic and certainly not appropriate for decision making.

Traffic disruption and resulting congestion is one of the main causes of environmental and social impacts over the complete cycle of the bridge. Therefore, one of the main requirements in bridge design for an efficient life cycle performance is the use of a structural system that facilitates bridge construction, inspection, maintenance, upgrading and operation with minimum traffic disruption. For the society in general (and the users of the bridge, in particular), it is of great importance that maintenance and rehabilitation of a bridge is performed in such a way that all costs are minimized - not only the costs borne by the concessionaire of the bridge.

When the required service life is about 100 years, then the probability of the bridge to undergo a change in its functional requirements is high. This may lead the structure to become obsolete many years before the period of time for which the structure was designed. Thus, when thinking about a structural system for a bridge it would be beneficial to think about the best way a structure would accommodate a change in its requirements, for instance, the widening of the

deck due to an increase in traffic demand. This would reduce the time needed to perform such refurbishment work and simultaneously, extend the service life of the structure beyond the period of time it was originally designed for.

Another very important idea to keep in mind during the design of the bridge is to think about the way the structure will be demolished. Bridges are privileged structures in relation to buildings where the complexity of the material involved is much higher. Nevertheless, thinking about the way the materials incorporated in the structure may be recovered during demolition increases the chance for further reuse or recycling of those waste materials. For instance, bolted joints instead of welded joints in steel structures may increase the chance for further reusing of some structural components. Deconstruction or selective demolition aims to enhance the percentage of construction and demolition waste that is re-used or recycled, reducing the waste sent to a landfill and avoiding the production of natural resources; and therefore, it should be promoted.

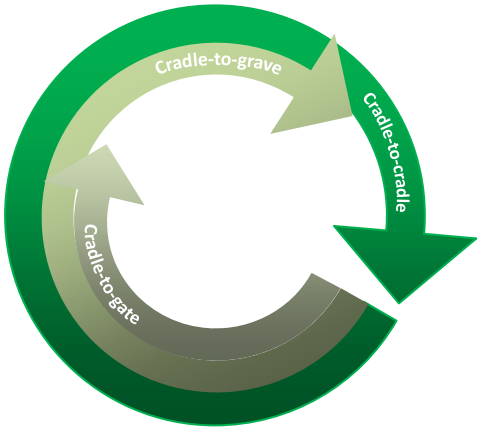


Figure 12.7. Closing the loop in the life cycle of structures

As referred in the first chapter of this dissertation, the consumption of raw materials and the production of construction and demolition waste are two of the most important contributing factors in the sustainability of the construction sector. Therefore, the sustainability of the sector can only be achieved if these two factors are considered. The use of materials with recycling content and the use of materials with recycling potential contribute to the minimization of these factors. Hence, in the selection of the materials of the bridge, preference should be given to such materials. Moreover, the re-use of structural elements or parts of the structure allows closing the loop of the structure (see Figure 12.7). The re-use of structures (or parts of it) further reduces the two factors referred above, as it avoids the need for recycling and enables to extend the service life of structures. Naturally, it plays a privileged role in the pursuit of a sustainable construction system.

In Table 12.15 some recommendations for sustainable bridge design are summarized, according to the construction stage they relate to and in relation to processes that are common to most stages (such as traffic and transportation).

Table 12.15. Summary of recommendation for a sustainable bridge design

Stage	Description
Design	Take into account the complete life cycle of the structure in the evaluation of environmental, economical and social criteria.
	Privilege a design providing the best global performance, that is, the most favourable solution in terms of between environmental, economical and social criteria.
	Privilege the use of materials with recycling content, recycling or re-use potential.
Construction	Privilege the use of pre-fabricated structural elements in order to reduce the time of construction and the safety of the work zone.
	When using fresh concrete consider the proximity of the concrete plant to the construction site in order to reduce the distance travelled by the trucks
Operation	Consider the adaptability of the structure for future demands/requirements.
	Consider the durability of the materials in order to reduce the need for maintenance and rehabilitation.
End-of-life	Detail the structure to enable the deconstruction.
	Consider the use of C&DW (e.g. recycled concrete in foundations) in the site before send it to a recycling plant or a landfill.
Transportation	Privilege the use of local materials in order to reduce transportation distances
Traffic	Avoid traffic disruption in work zones whenever possible.
	If traffic disruption is unavoidable then consider a careful planning of the construction activity in the work zone in order to reduce the impacts: - avoid the queue formation (queue formation increases exponentially the environmental impacts and user costs); - avoid to have work activity during the peak hours of the traffic (an intense work activity in the work zone usually implies a speed reduction and thus a reduction in the traffic capacity of the motorway); - avoid complete traffic diversion (traffic diversion usually implies an increase in environmental impacts and user costs); - if the work zone is not located in a residential area, privilege the construction activity during the night period (with due consideration for the safety of drivers and workers) or during the periods of time with lower traffic flows; - consider a careful plan of the safety measures of workers and drivers at every situation

The design of a bridge in the framework of sustainable construction comprehends the simultaneously consideration of many and often contradictory aspects. In general, it is not possible to consider all the best options in terms of environmental aspects without affecting the economical and/or social aspects and vice versa. Hence, a sustainable bridge design is a design providing the best compromise between the involved criteria over the complete life cycle of the bridge.

12.7. SYNOPSIS OF THE CHAPTER

The main aim of this chapter was to provide an approach that would be able to compare alternative bridges in the context of sustainability.

Therefore, in the first part of the chapter, following a discussion of several multi-criteria decision approaches, an approach was selected based on its suitability to fulfil the aims of the proposed integral approach. Consequently, the Preference Ranking Organization Methodology of Enrichment Evaluation (PROMETHEE) was adopted.

Moreover, a probabilistic-based approach of PROMETHEE was proposed in order to overcome some limitations provided by the deterministic-based approach. The probabilistic approach enables the simultaneous consideration of the uncertainty in various input parameters and therefore, allows decisions to be made with a more reasonable certainty.

The adopted approach was used for the comparison of the three case studies analyzed in the three previous chapters, in order to select the bridge offering the best global performance considering the environmental, economical social performances.

Whilst the bridges were not directly comparable, as clearly stated in the text, valuable information was provided from the outcome of the analysis.

Based on the results of the life cycle analysis performed in chapters 9 to 11 and on the outcome of the comparative analysis performed in this chapter, some recommendation for bridge design were provided in the end of this chapter. These recommendations aim to provide bridge engineers, at the initial stage of bridge design, guidelines for an efficient design of the bridge, leading to a better life cycle performance of the structure and thus, contributing to the sustainability of the construction sector.

A last note to make clear that the purpose of the comparative analysis presented in this chapter was not to show the supremacy of a structural system over another. The conclusions presented in chapters 9 to 12 were based on the analysis of three case studies, which correspond to three different construction systems, and with due recognition that several assumptions were needed to perform such analysis. If the analysis had been made on different case studies, then different conclusions could be obtained in relation to the most efficient structural system. Nevertheless, the recommendations provided in the end of this chapter are general, and although the structural system is an important factor to the lifetime performance of the bridge, provided that an adequate life cycle design is considered then any structural system can achieve a good life cycle performance.

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CHAPTER 13. CONCLUSIONS AND FUTURE DEVELOPMENTS

13.1. CONCLUSIONS

The main goal of this thesis was the application of life cycle analysis, as a decision making tool, to aid engineers throughout the design process of civil engineering infrastructures in the pursuit of a sustainable design. This goal was achieved by the establishment of a comprehensive life cycle approach, integrating environmental, economical and social criteria; to be used by designers in the early stage of design.

The strategy followed to pursuit this primary goal is described in the following paragraphs.

In the first part of this thesis the general aim of Sustainable Development was introduced in order to contextualize its implications in the construction sector. It was concluded that life cycle thinking is the basis for the development of current policies leading to the implementation of sustainable goals. An extend state-of-art of current legislation and methodologies was also provided, showing the amount of importance given to this topic by major institutions, such as the European Union. Although the integration of the multi-dimensional concept of sustainable construction is acknowledged in every speech, its effective implementation in the practice is far from being real. Several issues were identified as being the main barriers to the implementation of such a methodology, being the primary cause the lack of such comprehensive approach.

Therefore, in Chapter 5 a framework for life cycle assessment integrating the environmental, economical and social criteria was introduced, based on the well established methodology for life cycle environmental analysis according to ISO standards. It was concluded that the best approach would be to quantify the three criterions in a independent way. However, the same scope and assumptions should be used for all dimensions, and the integration should be made in the following step by means of a multi-criteria decision analysis. The general framework covering the three main dimensions of sustainability was further validated in the case studies.

Hence, the three following chapters focused on the life cycle analysis of each criterion, namely, environmental, economical and social.

In Chapter 6, cut-off rules were proposed based on contribution analysis in order to reduce the amount of time needed to perform this type of life cycle environmental analysis. The production of construction materials is usually the unit process that most contributes to environmental impacts, in any stage where it is considered; the quantification of the main materials that constitute the bridge are enough to proper characterize the environmental performance of the bridge in the first stage of the analysis. The environmental profile of a bridge is characterized by local/ global impacts and present/future impacts. To overcome the lack of spatial and temporal data in inventory data, a weighting set was defined, based on the Analytical Hierarchy Process, to clearly reflect the preferences of the bridge designer towards the different environmental problems.

Chapter 7 focused on the economical component. It was observed that maintenance and rehabilitation strategies have a deep influence in the result of the life cycle cost. Scenario

analysis and sensibility analysis are recommended to have a consistent life cycle result. From the sensitivity analysis performed in the case studies, the most important aspects of the life cycle economical analysis are the construction cost and the selection of the discount rate.

The social component in Chapter 8 was divided into mandatory indicators and optional indicators. Mandatory indicators are those that are recommended to take into account in normal cases. Optional indicators are indicators that might have importance in specific circumstances but are not usually necessary to take into account in normal situations. User costs, which are mandatory indicators, proved to be extremely importance in a life cycle analysis. The user costs over the life cycle period may be twice the life cycle capital costs of the bridge. A careful management of work activities in relation to traffic is essential for the minimization of user costs.

The aggregation of the three criteria was performed by the Multi-Criteria Decision Aid (MCDA) method PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations). This method although being a partial compensate method is also a quite simple ranking method in conception and application compared with other methods for multi-criteria analysis, which makes it suitable for a practical application. The probabilistic approach of PROMETHEE enables to consider simultaneously the uncertainty in various input parameters. Furthermore, it enables a decision to be made with reasonable certainty that the alternative chosen is the best performing alternative under the range of probable circumstances.

The integral life cycle approach was validated by its application to three case studies. These case studies were selected in order represent distinct structural systems in terms of materials and construction processes. Based in the results of the case studies, the following recommendations are listed:

- Preference should be given to materials with low environmental profile and/or with high potential for recycling/reuse;
- The durability of the materials is very important in order to reduce the need for rehabilitation; although, a structural system needs also to be flexible to account for a change in the functional requirement of the bridge;
- The use of prefabricate structural elements should be privileged in relation to other systems in order to reduce the time for construction or replacement;
- The number of maintenance/rehabilitation activities should be optimized in order to reduce capital costs and costs on the users of the bridge;
- A bridge design that potentially offers the best option in terms of sustainability is the one that enables to close the loop, considering a “cradle-to-cradle” approach.

13.2. FUTURE DEVELOPMENTS

During the development of this thesis several aspects were identified as deserving further developments and improvements. This topics are here provided as a basis for possible further developments.

For the present research several assumptions were necessary in order to complete the life cycle analysis, particularly, in the case of the operation and end-of-life stages. There´s a lack of historical data in relation to bridge maintenance and rehabilitation in Portugal (due to the relative young stock of infrastructures) and the existing data in relation to current practices in other countries can be misleading when transposed to the Portuguese situation. To further validate the models and assumptions taken along the present research more consistent data is needed. Some of this data can be provided by "in situ" measurements, such as air emissions to the atmosphere and noise emissions during construction activities. Other type of data, like the structural performance over time of new structural systems, can be obtained from data from other countries complemented by theoretical models predicting the time behavior of structures.

The present research was based mainly on the point of view of the author, considering herself as a bridge designer. Her view has influence the development of the methodology, particularly, in regard of the preferences taken for the development of the weighting set and multi-criteria analysis. These steps are determinant for the result of the overall analysis. In order to further extent the application of the methodology to other interested parties, such as bridge managers, constructors, etc; and even for its application to public procurement, a more comprehensive approach is needed. This could be accomplished by the development of surveys or panel discussions within the interested parties regarding the preferences and views of each stakeholder in relation to the various matters integrating the methodology.

The methodology developed in this thesis contributes to the implementation of life cycle thinking in relation to the process of decision making of bridge design. Such an approach should be preferably used in the early stage of design, as discussed in Chapter 1. In order to further facilitate and widespread its use to bridge engineers or any other interested party, a practical software tool could be implemented. This tool could be a internet-based approach integrating a database, which could be continuously updated with data from the users themselves.

The integration of environmental, social and economical criteria into the same analysis is a fundamental base step. As a next step, one could also consider the optimization of the entire process. The optimization of bridge design taking into account the economic restraint is an issue that have been intensively addressed by many authors (see Chapter 5 for references). Taking into consideration the goal of a sustainable design, the environmental and social criteria are recommended to be taken along the optimization process, introducing further restraints in the analysis.

Finally, in a more comprehensive research step, the developed methodology could be further extended in order to encompass the design and/or optimization of a complete network of infrastructures, contributing to a more efficient management of the construction sector and leading to a more sustainable society. This was the major motivation of the author to pursuit this research.

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ANNEX A - WORK ZONES

A.1 SAFETY MEASURES IN WORK ZONES

Mandatory measures introduced by the Portuguese government [A.1][A.2] in order to improve the traffic conditions and safety of users through work zones in national motorways and other major roads.

General rules:

i) the length of the work zone should be less than 10 km in each direction of the motorway and in each segment of the motorway;

ii) there should be always two lanes of traffic in each direction;

iii) the width of the carriageway, in the work zone, cannot be less than two thirds of the original width;

iv) in work zones longer than 5 km, it is mandatory to include shoulders;

v) the maximum speed through the work zone must be higher than two thirds of the speed under normal conditions in the same location;

vi) a place for emergency parking should be provided in each 2 km;

vii) in urban and suburban areas, the work should be performed preferentially during the nocturnal period (from 9 p.m. to 7 a.m.).

Nocturnal work:

i) In case of works due to demolition, construction or maintenance of bridges, performed over the nocturnal period, it is allowed to provide only one lane of traffic in each direction;

ii) In this case, the width of the lane should not be less than one third of the original width of the carriageway; and the maximum speed through the work zone must be higher than one third of the speed under normal conditions in the same location;

iii) the length of the work zone should be less than 3.5 km.

A.2 TRAFFIC EMISSIONS AND USER COSTS IN WORK ZONES

A.1.10. Characteristics of work zones (Model QUEWZ)

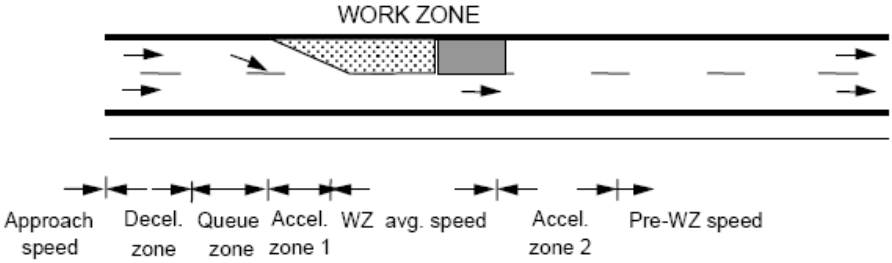


Figure A.1. Traffic behaviour associated with queue formation near a Work Zone

A.1.11. Reference scenarios in work zones

Ref. no.	Scen.	ADT	year	Stage	No. lanes/open	Traffic control	Work activiy
1	1	31522	2008	Construction	2/2	24 hours	Day
2	2	31522	2008	Construction	2/1	24 hours	Night
3	3	31522	2008	Construction	2/1	24 hours	Day
4	1	62547	2033	Operation	3/3	24 hours	Day
5	2	62547	2033	Operation	3/2	24 hours	Night
6	3	62547	2033	Operation	3/2	24 hours	Day
7	4	62547	2033	Operation	3/2	24 hours	Reduce day
8	1	70287	2058	Operation	4/4	24 hours	Day
9	2	70287	2058	Operation	4/3	24 hours	Night
10	3	70287	2058	Operation	4/3	24 hours	Day
11	4	70287	2058	Operation	4/2	24 hours	Night
12	5	70287	2058	Operation	4/2	24 hours	Day
13	6	70287	2058	Operation	4/2	24 hours	Reduce day
14	1	75807	2083	Operation	4/4	24 hours	Day
15	2	75807	2083	Operation	4/3	24 hours	Night
16	3	75807	2083	Operation	4/3	24 hours	Day
17	4	75807	2083	Operation	4/2	24 hours	Night
18	5	75807	2083	Operation	4/2	24 hours	Day
19	6	75807	2083	Operation	4/2	24 hours	Reduce day
20	1	79723	2108	End-of-life	4/4	24 hours	Day
21	2	79723	2108	End-of-life	4/3	24 hours	Night
22	3	79723	2108	End-of-life	4/3	24 hours	Day
23	4	79723	2108	End-of-life	4/2	24 hours	Night
24	5	79723	2108	End-of-life	4/2	24 hours	Day
25	6	79723	2108	End-of-life	4/2	24 hours	Reduce day

Table A.1. Emissions and user costs in WZ (Ref. 8)

Time	Hourly traffic (	Workzone			Excess emissions			Excess fuel		User costs					
		C_{wz}	v_a	queue	CO	HC	NO_x	gasoline	diesel	DDC		VOC		Safety cost	
	(vph)	(vph)	(kw/h)	l_q (km)	(kg)	(kg)	(kg)	(liters)	(liters)	LTveh.	HWveh.	LTveh.	HWveh.	LTveh.	HWveh.
0-1	178	7200	118,9		0,67	0,00	0,00	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
1-2	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
2-3	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
3-4	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
4-5	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
5-6	379	7200	117,6		1,39	0,00	0,01	3,67	7,55	5,59 €	10,71 €	10,41 €	13,78 €	0,10 €	0,03 €
6-7	1672	6600	109,5	0,00	3,87	0,03	0,03	22,27	38,35	35,08 €	56,48 €	63,19 €	70,01 €	0,53 €	0,13 €
7-8	3579	6600	97,6	0,00	3,99	0,09	0,04	64,91	93,58	104,73 €	143,19 €	184,20 €	170,85 €	1,43 €	0,28 €
8-9	1650	6600	109,7	0,00	3,85	0,03	0,03	21,87	37,76	34,44 €	55,59 €	62,07 €	68,94 €	0,52 €	0,13 €
9-10	1594	6600	110,0		3,80	0,03	0,03	20,90	36,31	32,87 €	53,37 €	59,30 €	66,28 €	0,50 €	0,12 €
10-11	1516	6600	110,5		3,71	0,03	0,03	19,56	34,28	30,72 €	50,30 €	55,50 €	62,60 €	0,47 €	0,12 €
11-12	1561	6600	110,2		3,76	0,03	0,03	20,32	35,44	31,95 €	52,05 €	57,66 €	64,70 €	0,49 €	0,12 €
12-13	2274	6600	105,8	0,00	4,20	0,05	0,04	33,86	54,76	53,85 €	81,79 €	96,07 €	99,98 €	0,78 €	0,18 €
13-14	1812	6600	108,7	0,00	3,98	0,04	0,04	24,79	42,04	39,15 €	62,14 €	70,34 €	76,76 €	0,59 €	0,14 €
14-15	2018	6600	107,4		4,10	0,05	0,04	28,70	47,63	45,48 €	70,74 €	81,44 €	86,96 €	0,67 €	0,16 €
15-16	2408	6600	104,9	0,00	4,23	0,06	0,04	36,67	58,55	58,44 €	87,71 €	104,07 €	106,90 €	0,84 €	0,19 €
16-17	3155	6600	100,3	0,00	4,15	0,08	0,04	53,96	80,56	86,73 €	122,42 €	153,13 €	147,09 €	1,20 €	0,24 €
17-18	3456	6600	98,4	0,00	4,04	0,09	0,04	61,66	89,78	99,38 €	137,11 €	174,97 €	163,91 €	1,36 €	0,27 €
18-19	2810	6600	102,4	0,00	4,23	0,07	0,04	45,64	70,21	73,08 €	106,02 €	129,50 €	128,20 €	1,03 €	0,22 €
19-20	1840	6600	108,5	0,00	4,00	0,04	0,04	25,31	42,79	39,98 €	63,28 €	71,81 €	78,13 €	0,60 €	0,14 €
20-21	1293	7200	111,9		3,44	0,02	0,03	15,48	28,20	24,19 €	41,10 €	43,94 €	51,49 €	0,38 €	0,10 €
21-22	677	7200	115,8		2,24	0,01	0,02	7,06	13,92	10,87 €	19,93 €	20,04 €	25,41 €	0,19 €	0,05 €
22-23	379	7200	117,6		1,39	0,00	0,01	3,67	7,55	5,59 €	10,71 €	10,41 €	13,78 €	0,10 €	0,03 €
23-24	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
	TOTAL				**68,56**	**0,76**	**0,61**	**520,10**	**840,06**	**826,96 €**	**1.253,96 €**	**1.475,87 €**	**1.533,75 €**	**12,08 €**	**2,73 €**

Table A.2. Emissions and user costs in WZ (Ref. 9)

Time	Hourly traffic (	Workzone			Excess emissions			Excess fuel		User costs					
		C_{wz}	v_a	queue	CO	HC	NO_x	gasoline	diesel	DDC		VOC		Safety cost	
	(vph)	(vph)	(kw/h)	l_q (km)	(kg)	(kg)	(kg)	(liters)	(liters)	LTveh.	HWveh.	LTveh.	HWveh.	LTveh.	HWveh.
0-1	178	4455	118,9		0,70	0,00	0,01	1,69	3,52	2,56 €	4,97 €	4,79 €	6,43 €	0,05 €	0,01 €
1-2	178	4455	118,9		0,70	0,00	0,01	1,69	3,52	2,56 €	4,97 €	4,79 €	6,43 €	0,05 €	0,01 €
2-3	178	4455	118,9		0,70	0,00	0,01	1,69	3,52	2,56 €	4,97 €	4,79 €	6,43 €	0,05 €	0,01 €
3-4	178	4455	118,9		0,70	0,00	0,01	1,69	3,52	2,56 €	4,97 €	4,79 €	6,43 €	0,05 €	0,01 €
4-5	178	4455	118,9		0,70	0,00	0,01	1,69	3,52	2,56 €	4,97 €	4,79 €	6,43 €	0,05 €	0,01 €
5-6	379	4455	117,6		1,39	0,00	0,01	3,92	7,80	5,99 €	11,09 €	11,11 €	14,24 €	0,11 €	0,03 €
6-7	1672	6600	109,5	0,00	3,87	0,03	0,03	22,27	38,35	35,08 €	56,48 €	63,19 €	70,01 €	0,53 €	0,13 €
7-8	3579	6600	97,6	0,00	3,99	0,09	0,04	64,91	93,58	104,73 €	143,19 €	184,20 €	170,85 €	1,43 €	0,28 €
8-9	1650	6600	109,7	0,00	3,85	0,03	0,03	21,87	37,76	34,44 €	55,59 €	62,07 €	68,94 €	0,52 €	0,13 €
9-10	1594	6600	110,0		3,80	0,03	0,03	20,90	36,31	32,87 €	53,37 €	59,30 €	66,28 €	0,50 €	0,12 €
10-11	1516	6600	110,5		3,71	0,03	0,03	19,56	34,28	30,72 €	50,30 €	55,50 €	62,60 €	0,47 €	0,12 €
11-12	1561	6600	110,2		3,76	0,03	0,03	20,32	35,44	31,95 €	52,05 €	57,66 €	64,70 €	0,49 €	0,12 €
12-13	2274	6600	105,8	0,00	4,20	0,05	0,04	33,86	54,76	53,85 €	81,79 €	96,07 €	99,98 €	0,78 €	0,18 €
13-14	1812	6600	108,7	0,00	3,98	0,04	0,04	24,79	42,04	39,15 €	62,14 €	70,34 €	76,76 €	0,59 €	0,14 €
14-15	2018	6600	107,4		4,10	0,05	0,04	28,70	47,63	45,48 €	70,74 €	81,44 €	86,96 €	0,67 €	0,16 €
15-16	2408	6600	104,9	0,00	4,23	0,06	0,04	36,67	58,55	58,44 €	87,71 €	104,07 €	106,90 €	0,84 €	0,19 €
16-17	3155	6600	100,3	0,00	4,15	0,08	0,04	53,96	80,56	86,73 €	122,42 €	153,13 €	147,09 €	1,20 €	0,24 €
17-18	3456	6600	98,4	0,00	4,04	0,09	0,04	61,66	89,78	99,38 €	137,11 €	174,97 €	163,91 €	1,36 €	0,27 €
18-19	2810	6600	102,4	0,00	4,23	0,07	0,04	45,64	70,21	73,08 €	106,02 €	129,50 €	128,20 €	1,03 €	0,22 €
19-20	1840	6600	108,5	0,00	4,00	0,04	0,04	25,31	42,79	39,98 €	63,28 €	71,81 €	78,13 €	0,60 €	0,14 €
20-21	1293	6600	111,9		3,44	0,02	0,03	15,91	28,63	24,88 €	41,76 €	45,15 €	52,28 €	0,39 €	0,10 €
21-22	677	6600	115,8		2,24	0,01	0,02	7,18	14,03	11,06 €	20,11 €	20,37 €	25,62 €	0,19 €	0,05 €
22-23	379	4455	117,6		1,39	0,00	0,01	3,92	7,80	5,99 €	11,09 €	11,11 €	14,24 €	0,11 €	0,03 €
23-24	178	4455	118,9		0,70	0,00	0,01	1,69	3,52	2,56 €	4,97 €	4,79 €	6,43 €	0,05 €	0,01 €
	TOTAL				**68,56**	**0,77**	**0,62**	**521,46**	**841,45**	**829,16 €**	**1.256,08 €**	**1.479,74 €**	**1.536,28 €**	**12,11 €**	**2,73 €**

Table A.3. Emissions and user costs in WZ (Ref. 10)

Time	Hourly traffic (	Workzone			Excess emissions			Excess fuel		User costs					
		C_{wz}	v_a	queue	CO	HC	NO_x	gasoline	diesel	DDC		VOC		Safety cost	
	(vph)	(vph)	(kw/h)	l_q (km)	(kg)	(kg)	(kg)	(liters)	(liters)	LTveh.	HWveh.	LTveh.	HWveh.	LTveh.	HWveh.
0-1	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
1-2	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
2-3	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
3-4	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
4-5	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
5-6	379	7200	117,6		1,39	0,00	0,01	3,67	7,55	5,59 €	10,71 €	10,41 €	13,78 €	0,10 €	0,03 €
6-7	1672	4350	109,5	0,00	3,80	0,05	0,04	26,67	42,83	42,18 €	63,32 €	75,68 €	78,19 €	0,63 €	0,14 €
7-8	3579	4350	97,6	0,00	3,87	0,17	0,06	87,56	117,51	143,06 €	181,78 €	248,47 €	214,54 €	1,88 €	0,34 €
8-9	1650	4350	109,7	0,00	3,78	0,05	0,04	26,16	42,12	41,35 €	62,25 €	74,23 €	76,90 €	0,62 €	0,14 €
9-10	1594	4350	110,0	0,00	3,73	0,05	0,04	24,90	40,38	39,33 €	59,59 €	70,66 €	73,72 €	0,59 €	0,14 €
10-11	1516	4350	110,5	0,00	3,65	0,05	0,04	23,18	37,97	36,56 €	55,93 €	65,78 €	69,32 €	0,55 €	0,13 €
11-12	1561	4350	110,2	0,00	3,70	0,05	0,04	24,16	39,34	38,13 €	58,01 €	68,55 €	71,82 €	0,57 €	0,13 €
12-13	2274	4350	105,8	0,00	4,09	0,09	0,05	42,00	63,04	66,98 €	94,45 €	119,18 €	115,10 €	0,96 €	0,20 €
13-14	1812	4350	108,7	0,00	3,90	0,06	0,04	29,96	47,30	47,48 €	70,17 €	85,01 €	86,36 €	0,70 €	0,16 €
14-15	2018	4350	107,4	0,00	4,01	0,07	0,04	35,11	54,15	55,81 €	80,70 €	99,64 €	98,87 €	0,81 €	0,18 €
15-16	2408	4350	104,9	0,00	4,11	0,10	0,05	45,80	67,84	73,16 €	101,90 €	129,98 €	123,86 €	1,04 €	0,21 €
16-17	3155	4350	100,3	0,00	4,01	0,14	0,05	69,64	96,50	112,01 €	146,78 €	197,61 €	176,19 €	1,55 €	0,29 €
17-18	3456	4350	98,4	0,00	3,89	0,15	0,05	80,47	108,90	129,71 €	166,33 €	228,35 €	198,83 €	1,77 €	0,33 €
18-19	2810	4350	102,4	0,00	4,09	0,12	0,05	58,07	82,85	93,12 €	125,34 €	164,77 €	151,27 €	1,30 €	0,25 €
19-20	1840	4350	108,5	0,00	3,92	0,06	0,04	30,63	48,21	48,57 €	71,57 €	86,93 €	88,02 €	0,72 €	0,16 €
20-21	1293	4350	111,9	0,00	3,39	0,03	0,03	18,54	31,31	29,12 €	45,86 €	52,62 €	57,17 €	0,45 €	0,11 €
21-22	677	4350	115,8	0,00	2,22	0,01	0,02	7,90	14,77	12,22 €	21,23 €	22,42 €	26,96 €	0,20 €	0,05 €
22-23	379	7200	117,6		1,39	0,00	0,01	3,67	7,55	5,59 €	10,71 €	10,41 €	13,78 €	0,10 €	0,03 €
23-24	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
	TOTAL				**67,14**	**1,26**	**0,73**	**647,89**	**970,91**	**1.034,82 €**	**1.455,94 €**	**1.838,50 €**	**1.772,65 €**	**14,83 €**	**3,10 €**

Table A.4. Emissions and user costs in WZ (Ref. 11)

Time	Hourly traffic (V	Workzone			Excess emissions			Excess fuel		User costs					
		C_{wz}	v_a		CO	HC	NO_x	gasoline	diesel	DDC		VOC		Safety cost	
	(vph)	(vph)	(kw/h)	l_q (km)	(kg)	(kg)	(kg)	(liters)	(liters)	LTveh.	HWveh.	LTveh.	HWveh.	LTveh.	HWveh.
0-1	178	2970	118,9		0,70	0,00	0,01	1,76	3,60	2,68 €	5,09 €	4,99 €	6,57 €	0,05 €	0,01 €
1-2	178	2970	118,9		0,70	0,00	0,01	1,76	3,60	2,68 €	5,09 €	4,99 €	6,57 €	0,05 €	0,01 €
2-3	178	2970	118,9		0,70	0,00	0,01	1,76	3,60	2,68 €	5,09 €	4,99 €	6,57 €	0,05 €	0,01 €
3-4	178	2970	118,9		0,70	0,00	0,01	1,76	3,60	2,68 €	5,09 €	4,99 €	6,57 €	0,05 €	0,01 €
4-5	178	2970	118,9		0,70	0,00	0,01	1,76	3,60	2,68 €	5,09 €	4,99 €	6,57 €	0,05 €	0,01 €
5-6	379	2970	117,6		1,38	0,01	0,01	4,24	8,13	6,51 €	11,59 €	12,03 €	14,84 €	0,11 €	0,03 €
6-7	1672	6600	109,5	0,00	3,87	0,03	0,03	22,27	38,35	35,08 €	56,48 €	63,19 €	70,01 €	0,53 €	0,13 €
7-8	3579	6600	97,6	0,00	3,99	0,09	0,04	64,91	93,58	104,73 €	143,19 €	184,20 €	170,85 €	1,43 €	0,28 €
8-9	1650	6600	109,7	0,00	3,85	0,03	0,03	21,87	37,76	34,44 €	55,59 €	62,07 €	68,94 €	0,52 €	0,13 €
9-10	1594	6600	110,0	0,00	3,80	0,03	0,03	20,90	36,31	32,87 €	53,37 €	59,30 €	66,28 €	0,50 €	0,12 €
10-11	1516	6600	110,5	0,00	3,71	0,03	0,03	19,56	34,28	30,72 €	50,30 €	55,50 €	62,60 €	0,47 €	0,12 €
11-12	1561	6600	110,2	0,00	3,76	0,03	0,03	20,32	35,44	31,95 €	52,05 €	57,66 €	64,70 €	0,49 €	0,12 €
12-13	2274	6600	105,8	0,00	4,20	0,05	0,04	33,86	54,76	53,85 €	81,79 €	96,07 €	99,98 €	0,78 €	0,18 €
13-14	1812	6600	108,7	0,00	3,98	0,04	0,04	24,79	42,04	39,15 €	62,14 €	70,34 €	76,76 €	0,59 €	0,14 €
14-15	2018	6600	107,4	0,00	4,10	0,05	0,04	28,70	47,63	45,48 €	70,74 €	81,44 €	86,96 €	0,67 €	0,16 €
15-16	2408	6600	104,9	0,00	4,23	0,06	0,04	36,67	58,55	58,44 €	87,71 €	104,07 €	106,90 €	0,84 €	0,19 €
16-17	3155	6600	100,3	0,00	4,15	0,08	0,04	53,96	80,56	86,73 €	122,42 €	153,13 €	147,09 €	1,20 €	0,24 €
17-18	3456	6600	98,4	0,00	4,04	0,09	0,04	61,66	89,78	99,38 €	137,11 €	174,97 €	163,91 €	1,36 €	0,27 €
18-19	2810	6600	102,4	0,00	4,23	0,07	0,04	45,64	70,21	73,08 €	106,02 €	129,50 €	128,20 €	1,03 €	0,22 €
19-20	1840	6600	108,5	0,00	4,00	0,04	0,04	25,31	42,79	39,98 €	63,28 €	71,81 €	78,13 €	0,60 €	0,14 €
20-21	1293	6600	111,9	0,00	3,44	0,02	0,03	15,91	28,63	24,88 €	41,76 €	45,15 €	52,28 €	0,39 €	0,10 €
21-22	677	6600	115,8	0,00	2,24	0,01	0,02	7,18	14,03	11,06 €	20,11 €	20,37 €	25,62 €	0,19 €	0,05 €
22-23	379	2970	117,6	0,00	1,38	0,01	0,01	4,24	8,13	6,51 €	11,59 €	12,03 €	14,84 €	0,11 €	0,03 €
23-24	178	2970	118,9	0,00	0,70	0,00	0,01	1,76	3,60	2,68 €	5,09 €	4,99 €	6,57 €	0,05 €	0,01 €
	TOTAL				**68,53**	**0,78**	**0,62**	**522,54**	**842,55**	**830,89 €**	**1.257,76 €**	**1.482,80 €**	**1.538,28 €**	**12,13 €**	**2,73 €**

Table A.5. Emissions and user costs in WZ (Ref. 12)

Time	Hourly raffic (V	Workzone			Excess emissions			Excess fuel		User costs					
		C_{wz}	v_a		CO	HC	NO_x	gasoline	diesel	DDC		VOC		Safety cost	
	(vph)	(vph)	(kw/h)	l_q (km)	(kg)	(kg)	(kg)	(liters)	(liters)	LTveh.	HWveh.	LTveh.	HWveh.	LTveh.	HWveh.
0-1	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
1-2	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
2-3	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
3-4	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
4-5	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
5-6	379	7200	117,6		1,39	0,00	0,01	3,67	7,55	5,59 €	10,71 €	10,41 €	13,78 €	0,10 €	0,03 €
6-7	1672	2900	109,5	0,00	3,69	0,08	0,05	33,13	49,39	52,59 €	73,36 €	94,01 €	90,18 €	0,77 €	0,16 €
7-8	3579	2900	97,6	1,04	79,33	7,14	1,57	345,95	432,06	2.260,21 €	2.401,15 €	981,70 €	788,83 €	3,82 €	0,67 €
8-9	1650	2900	109,7	1,04	38,19	3,10	0,70	128,06	172,94	952,85 €	1.023,98 €	363,39 €	315,74 €	1,53 €	0,29 €
9-10	1594	2900	110,0	0,00	3,63	0,08	0,04	30,77	46,34	48,79 €	68,71 €	87,32 €	84,61 €	0,72 €	0,15 €
10-11	1516	2900	110,5	0,00	3,56	0,07	0,04	28,49	43,37	45,12 €	64,18 €	80,84 €	79,17 €	0,67 €	0,14 €
11-12	1561	2900	110,2	0,00	3,60	0,07	0,04	29,78	45,06	47,20 €	66,75 €	84,51 €	82,27 €	0,70 €	0,15 €
12-13	2274	2900	105,8	0,00	3,93	0,14	0,06	53,95	75,19	86,24 €	113,01 €	153,08 €	137,28 €	1,22 €	0,24 €
13-14	1812	2900	108,7	0,00	3,78	0,10	0,05	37,54	55,01	59,70 €	81,95 €	106,52 €	100,43 €	0,87 €	0,18 €
14-15	2018	2900	107,4	0,00	3,87	0,11	0,05	44,52	63,72	70,98 €	95,32 €	126,32 €	116,33 €	1,02 €	0,20 €
15-16	2408	2900	104,9	0,00	3,93	0,16	0,06	61,46	84,59	100,05 €	129,30 €	174,41 €	154,45 €	1,34 €	0,26 €
16-17	3155	2900	100,3	0,39	34,32	2,69	0,59	198,17	274,90	925,18 €	1.089,69 €	562,34 €	501,90 €	2,63 €	0,50 €
17-18	3456	2900	98,4	1,63	112,77	10,32	2,29	425,77	511,29	3.182,07 €	3.282,49 €	1.208,21 €	933,50 €	4,48 €	0,75 €
18-19	2810	2900	102,4	2,34	127,40	11,65	2,60	421,36	495,87	3.513,46 €	3.563,50 €	1.195,70 €	905,35 €	4,40 €	0,73 €
19-20	1840	2900	108,5	1,10	44,38	3,67	0,82	150,44	200,21	1.124,76 €	1.201,58 €	426,91 €	365,53 €	1,79 €	0,34 €
20-21	1293	2900	111,9	0,00	3,32	0,05	0,04	22,41	35,24	35,35 €	51,86 €	63,58 €	64,34 €	0,53 €	0,12 €
21-22	677	2900	115,8	0,00	2,20	0,02	0,02	8,96	15,84	13,92 €	22,87 €	25,42 €	28,92 €	0,23 €	0,06 €
22-23	379	7200	117,6	0,00	1,39	0,00	0,01	3,67	7,55	5,59 €	10,71 €	10,41 €	13,78 €	0,10 €	0,03 €
23-24	178	7200	118,9	0,00	0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
	TOTAL				**478,89**	**39,47**	**9,07**	**2037,88**	**2636,92**	**12.544,52 €**	**13.380,45 €**	**5.782,89 €**	**4.814,38 €**	**27,19 €**	**5,08 €**

Table A.6. Emissions and user costs in WZ (Ref. 13)

Time	Hourly raffic (V	Workzone			Excess emissions			Excess fuel		User costs					
		C_{wz}	v_a		CO	HC	NO_x	gasoline	diesel	DDC		VOC		Safety cost	
	(vph)	(vph)	(kw/h)	l_q (km)	(kg)	(kg)	(kg)	(liters)	(liters)	LTveh.	HWveh.	LTveh.	HWveh.	LTveh.	HWveh.
0-1	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
1-2	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
2-3	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
3-4	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
4-5	178	7200	118,9		0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
5-6	379	7200	117,6		1,39	0,00	0,01	3,67	7,55	5,59 €	10,71 €	10,41 €	13,78 €	0,10 €	0,03 €
6-7	1672	6600	109,5	0,00	3,87	0,03	0,03	22,27	38,35	35,08 €	56,48 €	63,19 €	70,01 €	0,53 €	0,13 €
7-8	3579	6600	97,6	0,00	3,99	0,09	0,04	64,91	93,58	104,73 €	143,19 €	184,20 €	170,85 €	1,43 €	0,28 €
8-9	1650	6600	109,7	0,00	3,85	0,03	0,03	21,87	37,76	34,44 €	55,59 €	62,07 €	68,94 €	0,52 €	0,13 €
9-10	1594	2900	110,0	0,00	3,63	0,08	0,04	30,77	46,34	48,79 €	68,71 €	87,32 €	84,61 €	0,72 €	0,15 €
10-11	1516	2900	110,5	0,00	3,56	0,07	0,04	28,49	43,37	45,12 €	64,18 €	80,84 €	79,17 €	0,67 €	0,14 €
11-12	1561	2900	110,2	0,00	3,60	0,07	0,04	29,78	45,06	47,20 €	66,75 €	84,51 €	82,27 €	0,70 €	0,15 €
12-13	2274	2900	105,8	0,00	3,93	0,14	0,06	53,95	75,19	86,24 €	113,01 €	153,08 €	137,28 €	1,22 €	0,24 €
13-14	1812	2900	108,7	0,00	3,78	0,10	0,05	37,54	55,01	59,70 €	81,95 €	106,52 €	100,43 €	0,87 €	0,18 €
14-15	2018	2900	107,4	0,00	3,87	0,11	0,05	44,52	63,72	70,98 €	95,32 €	126,32 €	116,33 €	1,02 €	0,20 €
15-16	2408	2900	104,9	0,00	3,93	0,16	0,06	61,46	84,59	100,05 €	129,30 €	174,41 €	154,45 €	1,34 €	0,26 €
16-17	3155	2900	100,3	0,39	34,32	2,69	0,59	198,17	274,90	925,18 €	1.089,69 €	562,34 €	501,90 €	2,63 €	0,50 €
17-18	3456	2900	98,4	1,63	112,77	10,32	2,29	425,77	511,29	3.182,07 €	3.282,49 €	1.208,21 €	933,50 €	4,48 €	0,75 €
18-19	2810	6600	102,4	1,24	23,74	1,73	0,38	199,74	271,80	632,64 €	787,07 €	566,81 €	496,24 €	2,56 €	0,48 €
19-20	1840	6600	108,5	0,00	4,00	0,04	0,04	25,31	42,79	39,98 €	63,28 €	71,81 €	78,13 €	0,60 €	0,14 €
20-21	1293	6600	111,9	0,00	3,44	0,02	0,03	15,91	28,63	24,88 €	41,76 €	45,15 €	52,28 €	0,39 €	0,10 €
21-22	677	6600	115,8	0,00	2,24	0,01	0,02	7,18	14,03	11,06 €	20,11 €	20,37 €	25,62 €	0,19 €	0,05 €
22-23	379	7200	117,6	0,00	1,39	0,00	0,01	3,67	7,55	5,59 €	10,71 €	10,41 €	13,78 €	0,10 €	0,03 €
23-24	178	7200	118,9	0,00	0,70	0,00	0,01	1,63	3,47	2,47 €	4,89 €	4,63 €	6,33 €	0,05 €	0,01 €
	TOTAL				**225,51**	**15,71**	**3,85**	**1284,77**	**1762,32**	**5.474,17 €**	**6.209,63 €**	**3.645,78 €**	**3.217,56 €**	**20,34 €**	**4,02 €**

REFERENCES

[A.1] *Lei no. 24/2007 de 18 de Julho - Define direitos dos utentes nas vias rodoviárias classificadas como auto -estradas concessionadas, itinerários principais e itinerários complementares* (in Portuguese).

[A.2] *Decreto Regulamentar n.º 12/2008 de 9 de Junho - Regula a Lei n.º 24/2007, de 18 de Junho* (in Portuguese).

ANNEX B – SUPPORT INFORMATION TO 1ST CASE STUDY

B.1. PLANS OF CONSTRUCTION, MAINTENANCE AND DEMOLITION

Table B.1. Construction plan

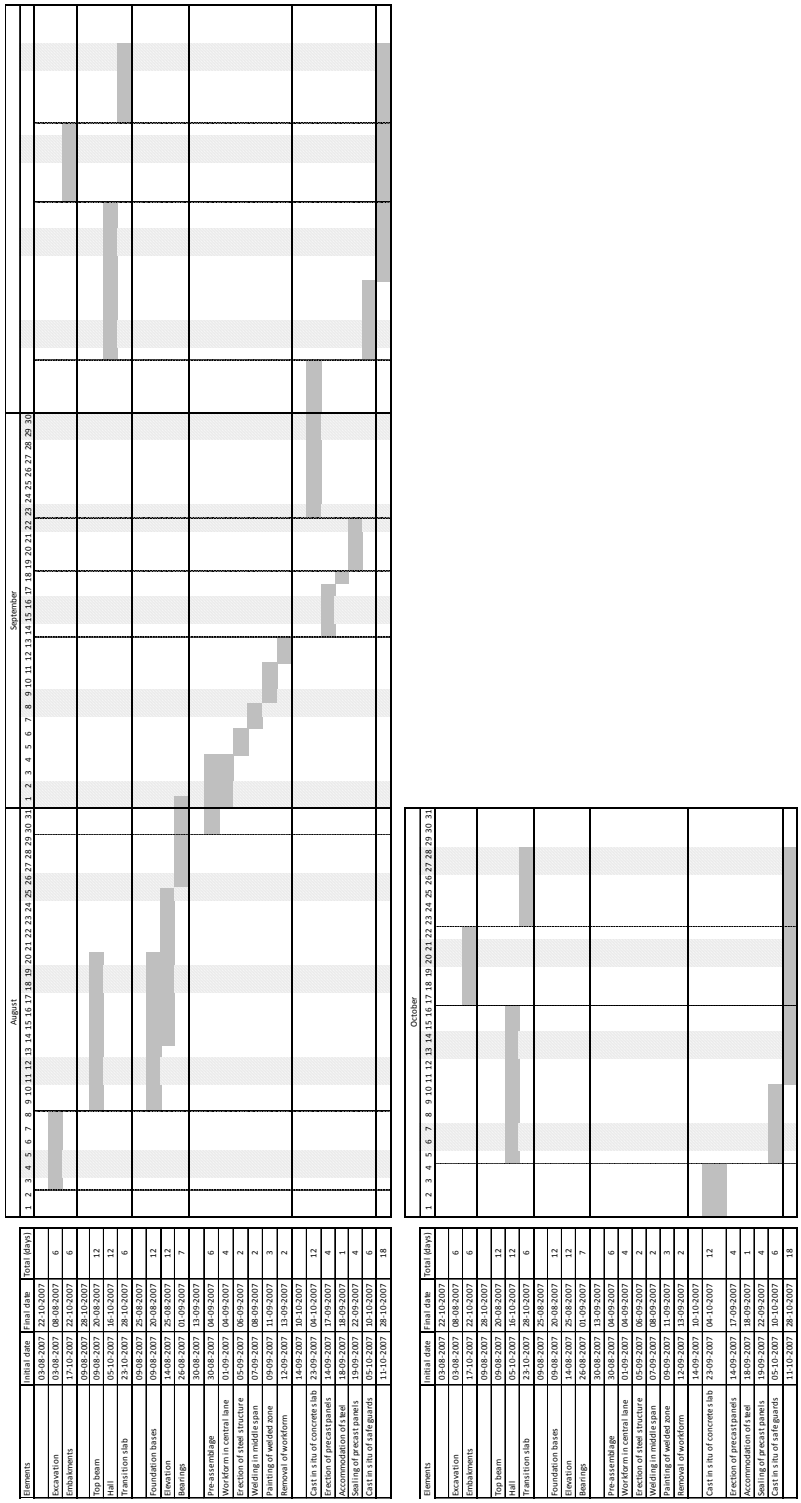


Table B.2. Maintenance plan

Main activity	Working days	Total (days)
rollers	4	8
pavers	4	4
milling (paving equipment)	4	4
Combined action 1		16
New surface protection	11	15
Re-coating of steel beams	13	17
Replacement of expansion joints	7	11
Replacement of bearings	16	22
Replacement of rails and protection	9	11
Replacement of edge beams	16	22
Combined action 2		22
Rehabilitation of concrete structure	54	74
Re-coating of steel beams	13	17
Replacement of expansion joints	7	11
Replacement of bearings	16	22
Replacement of rails and protection	9	11
Replacement of edge beams	16	22
Combined action 3		74
New surface protection	11	15
Re-coating of steel beams	13	17
Replacement of expansion joints	7	11
Replacement of bearings	16	22
Replacement of rails and protection	9	11
Replacement of edge beams	16	22
rollers	4	4
pavers	4	6
milling (paving equipment)	4	6
Combined action 4		38

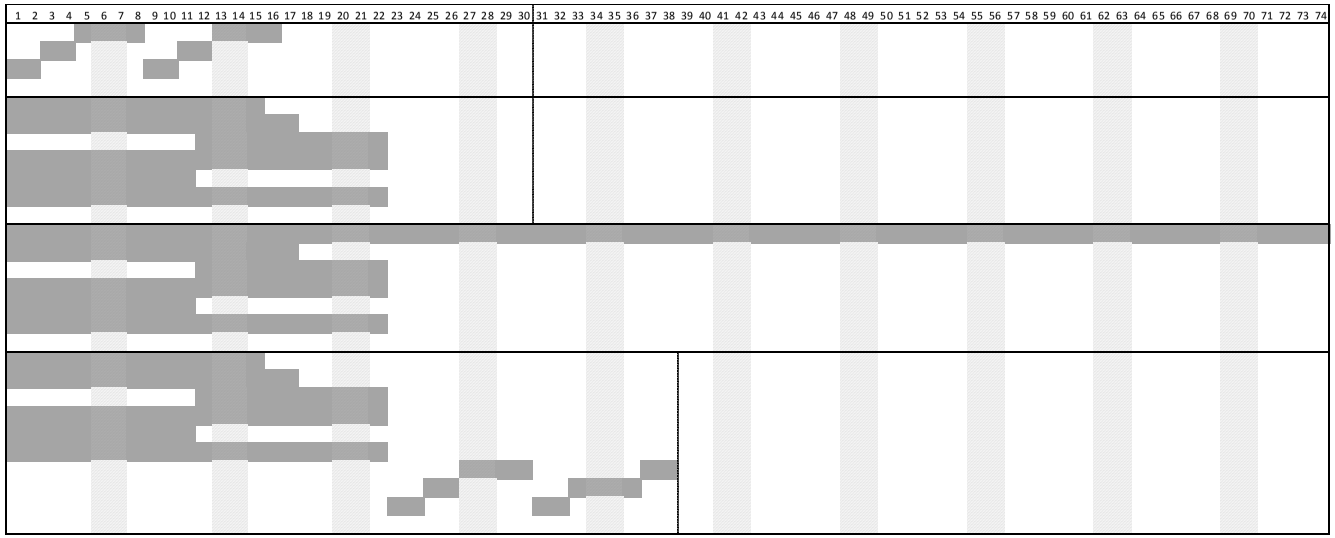
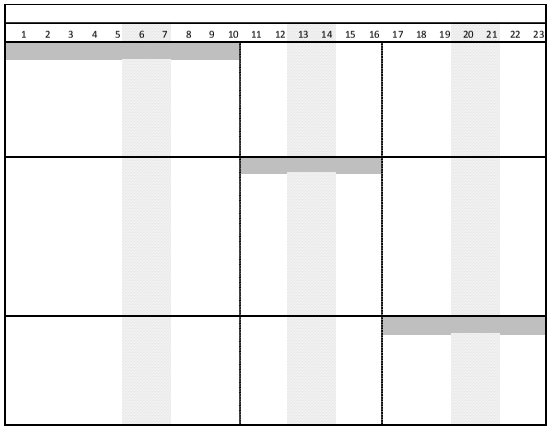


Table B.3. Demolition plan

Main Activity	Elements	Initial date	Final date	Working days	Total (days)
1st stage		-	-	8	10
	Preparation of base supports for scaffolding	-	-		
	Preparation of terrain for deposit of concrete pieces	-	-		
	Erection of scaffolding	-	-		
	Transversal cuts in deck	-	-		
	Longitudinal cuts of deck (partialy)	-	-		
2nd stage		-	-	4(*)	6
	Dismantling of the left part of concrete slab	-	-		
	Deposition of concrete pieces in the side terrain	-	-		
	Dismantling of the left part of steel structure				
	Deposition of steel strcuture in the side terrain				
	Dismantling of the right part of concrete slab	-	-		
	Deposition of concrete pieces in the side terrain				
	Dismantling of the right part of steel structure				
	Deposition of steel strcuture in the side terrain	-	-		
3rd stage		-	-	5	7
	Dismantling of scaffolding	-	-		
	Demolition of the concrete pieces from the deck	-	-		
	Demolition "in situ" of piers and abutments	-	-		
	Removal and transportation of materials	-	-		
	Cleaning of the area	-	-		



B.2. NON-MOBILE EMISSIONS

Table B.4. Non-mobile emissions during construction stage

Type of construction equipment	Assumptions					Emissions factors [gr/(hp-hrs)]							Total emissions (tonnes)						
	no. Units	hp rated	hrs/day	days	Total hp-hrs	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
excavators	2	300	1,3	1	780	0,278	1,224	3,653	0,253	0,245	0,115	535,989	0,000	0,001	0,003	0,000	0,000	0,000	0,418
dump trucks	25	175	1	1	4375	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,005	0,017	0,031	0,004	0,004	0,001	2,726
Excavation													**0,005**	**0,018**	**0,034**	**0,004**	**0,004**	**0,001**	**3,145**
concrete pumps	2	400	1,2	1	960	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,003	0,005	0,000	0,000	0,000	0,514
vibrators	4	2	6	1	48	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,029
compressor	1	2	6	1	12	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,007
concrete mixer truck	74	335	0,7	1	17353	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,008	0,036	0,110	0,006	0,005	0,002	9,191
Piers and abutments													**0,008**	**0,039**	**0,116**	**0,006**	**0,006**	**0,002**	**9,741**
cranes	3	175	6	2	6300	0,343	1,062	4,598	0,267	0,259	0,114	530,002	0,002	0,007	0,029	0,002	0,002	0,001	3,339
generator (60 KVA)	1	64	12	4	3072	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,002	0,012	0,015	0,002	0,002	0,000	1,826
generator (45 KVA)	1	48	12	4	2304	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,001	0,009	0,012	0,001	0,001	0,000	1,370
Steel structure													**0,005**	**0,028**	**0,056**	**0,005**	**0,005**	**0,001**	**6,535**
cranes	2	175	8	2	5600	0,343	1,062	4,598	0,267	0,259	0,114	530,002	0,002	0,006	0,026	0,001	0,001	0,001	2,968
concrete pumps	2	400	0,2	1	160	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,000	0,001	0,000	0,000	0,000	0,086
vibrators	2	2	1	1	4	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,002
concrete mixer truck	7	335	0,7	1	1641,5	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,001	0,003	0,010	0,001	0,001	0,000	0,869
compressor	1	2	1	1	2	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,001
generator 1	1	64	12	2	1536	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,001	0,006	0,008	0,001	0,001	0,000	0,913
generator 2	1	48	12	2	1152	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,001	0,005	0,006	0,001	0,001	0,000	0,685
concrete pumps	2	400	0,4	1	320	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,001	0,002	0,000	0,000	0,000	0,171
vibrators	2	2	2	1	8	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,005
concrete mixer truck	14	335	0,7	1	3283	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,001	0,007	0,021	0,001	0,001	0,000	1,739
compressor	1	2	2	1	4	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,002
Concrete deck													**0,006**	**0,028**	**0,073**	**0,005**	**0,005**	**0,002**	**7,442**
concrete pumps	2	400	0,3	1	240	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,001	0,001	0,000	0,000	0,000	0,129
vibrators	2	2	1,5	1	6	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,004
compressor	1	2	1,5	1	3	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,002
concrete mixer truck	11	335	0,7	1	2579,5	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,001	0,005	0,016	0,001	0,001	0,000	1,366
concrete pumps	2	400	0,1	1	80	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,000	0,000	0,000	0,000	0,000	0,043
vibrators	2	2	0,4	1	1,6	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,001
compressor	1	2	0,4	1	0,8	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,000
concrete mixer truck	4	335	0,7	1	938	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,000	0,002	0,006	0,000	0,000	0,000	0,497
rollers	1	300	5	3	4500	0,310	1,348	4,159	0,278	0,269	0,115	535,891	0,001	0,006	0,019	0,001	0,001	0,001	2,412
pavers	1	300	5	3	4500	0,302	1,308	4,042	0,271	0,263	0,115	535,916	0,001	0,006	0,018	0,001	0,001	0,001	2,412
Finishing & abutments													**0,004**	**0,020**	**0,061**	**0,004**	**0,004**	**0,001**	**6,864**
												TOTAL	**0,029**	**0,134**	**0,340**	**0,024**	**0,023**	**0,007**	**33,727**

Table B.5. Non-mobile emissions during operation stage

Type of construction equipment	Assumptions					Emissions factors [gr/(hp-hrs)]							Total emissions (tonnes)						
	no. Units	hp rated	hrs/day	days	Total hp-hrs	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
rollers	1	300	5	4	6000	0,310	1,348	4,159	0,278	0,269	0,115	535,891	0,002	0,008	0,025	0,002	0,002	0,001	3,215
pavers	1	300	5	4	6000	0,302	1,308	4,042	0,271	0,263	0,115	535,916	0,002	0,008	0,024	0,002	0,002	0,001	3,215
milling (paving equipment)	1	300	5	4	6000	0,337	1,509	4,463	0,299	0,290	0,115	535,810	0,002	0,009	0,027	0,002	0,002	0,001	3,215
Combined action 1													**0,006**	**0,025**	**0,076**	**0,005**	**0,005**	**0,002**	**9,646**
New surface protection	1	300	6	11	19548	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,007	0,030	0,088	0,006	0,006	0,002	10,474
Re-coating of steel beams	1	300	4	13	15552	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,005	0,024	0,070	0,005	0,005	0,002	8,333
Replacement of expansion joints	1	300	4	7	8229	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,003	0,013	0,037	0,002	0,002	0,001	4,409
Replacement of bearings	1	300	1	16	4800	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,007	0,022	0,001	0,001	0,001	2,572
Replacement of rails and protection	1	300	2	9	5130	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,008	0,023	0,002	0,002	0,001	2,749
Replacement of edge beams	1	300	2	16	9600	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,003	0,015	0,043	0,003	0,003	0,001	5,144
Combined action 2													**0,021**	**0,097**	**0,284**	**0,019**	**0,018**	**0,007**	**33,679**
Rehabilitation of concrete structure	1	300	4	54	65160	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,022	0,100	0,294	0,020	0,019	0,007	34,913
Re-coating of steel beams	1	300	4	13	15552	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,005	0,024	0,070	0,005	0,005	0,002	8,333
Replacement of expansion joints	1	300	4	7	8229	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,003	0,013	0,037	0,002	0,002	0,001	4,409
Replacement of bearings	1	300	1	16	4800	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,007	0,022	0,001	0,001	0,001	2,572
Replacement of rails and protection	1	300	2	9	5130	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,008	0,023	0,002	0,002	0,001	2,749
Replacement of edge beams	1	300	2	16	9600	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,003	0,015	0,043	0,003	0,003	0,001	5,144
Combined action 3													**0,037**	**0,167**	**0,490**	**0,033**	**0,032**	**0,012**	**58,118**
New surface protection	1	300	6	11	19548	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,007	0,030	0,088	0,006	0,006	0,002	10,474
Re-coating of steel beams	1	300	4	13	15552	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,005	0,024	0,070	0,005	0,005	0,002	8,333
Replacement of expansion joints	1	300	4	7	8229	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,003	0,013	0,037	0,002	0,002	0,001	4,409
Replacement of bearings	1	300	1	16	4800	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,007	0,022	0,001	0,001	0,001	2,572
Replacement of rails and protection	1	300	2	9	5130	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,008	0,023	0,002	0,002	0,001	2,749
Replacement of edge beams	1	300	2	16	9600	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,003	0,015	0,043	0,003	0,003	0,001	5,144
rollers	1	300	5	4	6000	0,310	1,348	4,159	0,278	0,269	0,115	535,891	0,002	0,008	0,025	0,002	0,002	0,001	3,215
pavers	1	300	5	4	6000	0,302	1,308	4,042	0,271	0,263	0,115	535,916	0,002	0,008	0,024	0,002	0,002	0,001	3,215
milling (paving equipment)	1	300	5	4	6000	0,337	1,509	4,463	0,299	0,290	0,115	535,810	0,002	0,009	0,027	0,002	0,002	0,001	3,215
Combined action 4													**0,027**	**0,122**	**0,360**	**0,024**	**0,023**	**0,009**	**43,325**
												TOTAL	**0,091**	**0,410**	**1,209**	**0,081**	**0,079**	**0,031**	**144,768**

Table B.6. Non-mobile emissions during end-of-life stage

Type of construction equipment	Assumptions					Emissions factors [gr/(hp-hrs)]							Total emissions (tonnes)						
	no. Units	hp rated	hrs/day	days	Total hp-hrs	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
backhoe	1	175	2	1	350	1,099	4,300	6,553	0,727	0,705	0,134	623,215	0,000	0,002	0,002	0,000	0,000	0,000	0,218
generator	1	60	4	4	960	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,001	0,004	0,005	0,001	0,001	0,000	0,571
dump trucks	1	175	2	1	350	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,000	0,001	0,002	0,000	0,000	0,000	0,218
roller	1	175	4	2	1400	0,350	1,589	4,353	0,347	0,337	0,115	535,771	0,000	0,002	0,006	0,000	0,000	0,000	0,750
concrete saw	2	300	4	4	9600	0,350	1,598	4,591	0,311	0,301	0,115	535,772	0,003	0,015	0,044	0,003	0,003	0,001	5,143
1st stage													**0,005**	**0,024**	**0,060**	**0,005**	**0,004**	**0,001**	**6,900**
generator	2	60	12	4	5760	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,003	0,023	0,029	0,004	0,003	0,001	3,424
crane	2	175	6	2	4200	0,343	1,062	4,598	0,267	0,259	0,114	530,002	0,001	0,004	0,019	0,001	0,001	0,000	2,226
telescopic crane	1	420	6	4	10080	0,309	1,453	5,259	0,246	0,239	0,114	530,104	0,003	0,015	0,053	0,002	0,002	0,001	5,343
2nd stage													**0,008**	**0,042**	**0,101**	**0,007**	**0,007**	**0,002**	**10,993**
backhoe	1	175	15	1	2625	1,099	4,300	6,553	0,727	0,705	0,134	623,215	0,003	0,011	0,017	0,002	0,002	0,000	1,636
tractor/loader	1	300	30	1	9000	0,290	1,256	3,860	0,262	0,255	0,115	535,953	0,003	0,011	0,035	0,002	0,002	0,001	4,824
excavators	2	300	2	5	6000	0,278	1,224	3,653	0,253	0,245	0,115	535,989	0,002	0,007	0,022	0,002	0,001	0,001	3,216
crushing equipment	2	300	2	5	6000	0,309	0,924	4,446	0,211	0,205	0,114	530,107	0,002	0,006	0,027	0,001	0,001	0,001	3,181
dump tracks	75	175	0,6	1	7875	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,009	0,031	0,056	0,007	0,007	0,001	4,908
3rd stage													**0,018**	**0,067**	**0,156**	**0,014**	**0,013**	**0,004**	**17,764**
												TOTAL	**0,031**	**0,134**	**0,317**	**0,025**	**0,025**	**0,008**	**35,657**

B.3. TRAFFIC EMISSIONS

Table B.7. Traffic emissions during construction stage

Traffic scenario	Emissions [kg/day]			Fuel [kg/day]		Emissions [kg]			Fuel [kg]	
	CO	HC	NO_x	Gasoline	Diesel	CO	HC	NO_x	Gasoline	Diesel
Scenario 1 - motorway	33,21	0,33	0,29	167,92	308,35	5380,02	53,46	46,98	27203,04	49952,70
Scenario 2 - motorway	33,20	0,34	0,30	168,68	309,20	398,40	4,08	3,60	2024,16	3710,40
Scenario 3 - motorway	80,68	4,75	1,22	388,16	625,89	968,16	57,00	14,64	4657,92	7510,68
	night work motorway					5778,42	57,54	50,58	29227,20	53663,10
	day work motorway					6348,18	110,46	61,62	31860,96	57463,38

Table B.8. Traffic emissions during end-of-life stage

Traffic scenario	Emissions [kg/day]			Fuel [kg/day]		Emissions [kg]			Fuel [kg]	
	CO	HC	NO_x	Gasoline	Diesel	CO	HC	NO_x	Gasoline	Diesel
Scenario 1 - motorway	70,50	0,88	0,64	465,23	809,70	2679,00	33,44	24,32	17678,74	30768,60
Scenario 2 - motorway	70,50	0,89	0,64	466,54	811,18	564,00	7,12	5,12	3732,32	6489,44
Scenario 3 - motorway	70,50	1,69	0,82	611,17	983,78	564,00	13,52	6,56	4889,36	7870,24
Scenario 4 - motorway	70,50	0,90	0,65	467,58	812,36	564,00	7,20	5,20	3740,64	6498,88
Scenario 5 - motorway	1193,23	107,92	24,22	3105,01	4073,80	9545,84	863,36	193,76	24840,08	32590,40
Scenario 6 - motorway	443,72	37,46	8,68	1630,75	2264,26	3549,76	299,68	69,44	13046,00	18114,08
	night work motorway (3 lanes open)					3243,00	40,56	29,44	21411,06	37258,04
	day work motorway (3 lanes open)					3243,00	46,96	30,88	22568,10	38638,84
	night work motorway (2 lanes open)					3243,00	40,64	29,52	21419,38	37267,48
	day work motorway (2 lanes open)					12224,84	896,80	218,08	42518,82	63359,00
	reduce day work motorway (2 lanes open)					6228,76	333,12	93,76	30724,74	48882,68

Table B.9. Traffic emissions during operation stage

Traffic scenario	Emissions [kg/day]			Fuel [kg/day]		Emissions [kg]			Fuel [kg]	
	CO	HC	NO_x	Gasoline	Diesel	CO	HC	NO_x	Gasoline	Diesel
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	0,00	0,00	0,00	0,00	0,00
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	361,12	1,76	2,88	1028,48	2139,04
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	352,48	3,84	3,36	1362,72	2516,32
	night work crossover					361,12	1,76	2,88	1028,48	2139,04
	day work crossover					352,48	3,84	3,36	1362,72	2516,32
Combined action 1										
Scenario 1 - motorway	53,30	0,69	0,49	371,88	640,05					
Scenario 2 - motorway	53,30	0,70	0,49	373,17	641,51	1812,20	23,80	16,66	12687,78	21811,34
Scenario 3 - motorway	135,05	7,74	1,95	776,82	1230,44	4591,70	263,16	66,30	26411,88	41834,96
Scenario 4 - motorway	84,08	3,28	1,00	578,16	947,86	2858,72	111,52	34,00	19657,44	32227,24
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	248,27	1,10	1,98	705,21	1468,50
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	248,27	1,21	1,98	707,08	1470,59
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	242,33	2,64	2,31	936,87	1729,97
	night work motorway + night work crossover					2308,74	26,11	20,62	14100,07	24750,43
	night work motorway + day work crossover					2302,80	27,54	20,95	14329,86	25009,81
	day work motorway + night work crossover					5088,24	265,47	70,26	27824,17	44774,05
	day work motorway + day work crossover					5082,30	266,90	70,59	28053,96	45033,43
	reduce day work motorway + night work crossover					3355,26	113,83	37,96	21069,73	35166,33
	reduce day work motorway + day work crossover					3349,32	115,26	38,29	21299,52	35425,71
Combined action 2										
Scenario 1 - motorway	68,56	0,76	0,61	390,07	699,35	2742,40	30,40	24,40	15602,80	27974,00
Scenario 2 - motorway	68,56	0,77	0,62	391,09	700,51	4799,20	53,90	43,40	27376,30	49035,70
Scenario 3 - motorway	68,56	1,26	0,73	485,91	808,29	4799,20	88,20	51,10	34013,70	56580,30
Scenario 4 - motorway	68,53	0,78	0,62	391,90	701,42	4797,10	54,60	43,40	27433,00	49099,40
Scenario 5 - motorway	478,89	39,47	9,07	1528,41	2195,24	33522,30	2762,90	634,90	106988,70	153666,80
Scenario 6 - motorway	225,51	15,71	3,85	963,57	1467,13	15785,70	1099,70	269,50	67449,90	102699,10
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	248,27	1,10	1,98	705,21	1468,50
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	248,27	1,21	1,98	707,08	1470,59
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	242,33	2,64	2,31	936,87	1729,97
	night work motorway (3 lanes open)+ night work crossover					8038,14	86,61	71,76	44391,39	79948,79
	night work motorway (3 lanes open) + day work crossover					8032,20	88,04	72,09	44621,18	80208,17
	day work motorway (3 lanes open) + night work crossover					8038,14	120,91	79,46	51028,79	87493,39
	day work motorway (3 lanes open) + day work crossover					8032,20	122,34	79,79	51258,58	87752,77
	night work motorway (2 lanes open)+ night work crossover					8036,04	87,31	71,76	44448,09	80012,49
	night work motorway (2 lanes open) + day work crossover					8030,10	88,74	72,09	44677,88	80271,87
	day work motorway (2 lanes open) + night work crossover					36761,24	2795,61	663,26	124003,79	184579,89
	day work motorway (2 lanes open) + day work crossover					36755,30	2797,04	663,59	124233,58	184839,27
	uce day work motorway (2 lanes open) + night work crosso					19024,64	1132,41	297,86	84464,99	133612,19
	duce day work motorway (2 lanes open)+ day work crossov					19018,70	1133,84	298,19	84694,78	133871,57
Combined action 3										
Scenario 1 - motorway	69,79	0,83	0,63	433,43	763,56					
Scenario 2 - motorway	69,79	0,84	0,63	434,61	764,90	2372,86	28,56	21,42	14776,74	26006,60
Scenario 3 - motorway	69,79	1,49	0,78	555,87	906,82	2372,86	50,66	26,52	18899,58	30831,88
Scenario 4 - motorway	69,76	0,85	0,64	435,56	765,96	2371,84	28,90	21,76	14809,04	26042,64
Scenario 5 - motorway	855,32	75,68	17,09	2368,63	3194,57	29080,88	2573,12	581,06	80533,42	108615,38
Scenario 6 - motorway	347,45	27,87	6,55	1337,79	1915,34	11813,30	947,58	222,70	45484,86	65121,56
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	248,27	1,10	1,98	705,21	1468,50
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	609,39	2,97	4,86	1735,56	3609,63
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	594,81	6,48	5,67	2299,59	4246,29
	night work motorway (3 lanes open)+ night work crossover					3230,52	32,63	28,26	17217,51	31084,73
	night work motorway (3 lanes open) + day work crossover					3215,94	36,14	29,07	17781,54	31721,39
	day work motorway (3 lanes open) + night work crossover					3230,52	54,73	33,36	21340,35	35910,01
	day work motorway (3 lanes open) + day work crossover					3215,94	58,24	34,17	21904,38	36546,67
	night work motorway (2 lanes open)+ night work crossover					3229,50	32,97	28,60	17249,81	31120,77
	night work motorway (2 lanes open) + day work crossover					3214,92	36,48	29,41	17813,84	31757,43
	day work motorway (2 lanes open) + night work crossover					29938,54	2577,19	587,90	82974,19	113693,51
	day work motorway (2 lanes open) + day work crossover					29923,96	2580,70	588,71	83538,22	114330,17
	uce day work motorway (2 lanes open) + night work crosso					12670,96	951,65	229,54	47925,63	70199,69
	duce day work motorway (2 lanes open)+ day work crossov					12656,38	955,16	230,35	48489,66	70836,35
Combined action 4										

B.4. USER COSTS

Table B.10. Life cycle user costs

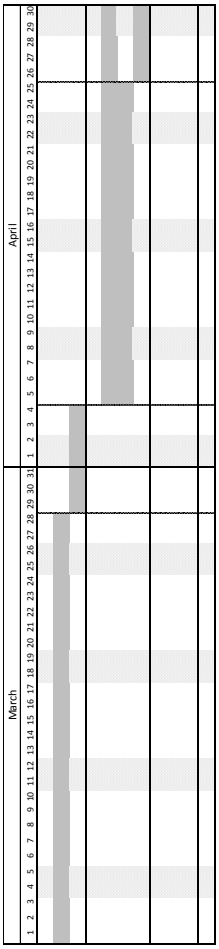
Traffic scenario	User costs [€/day]			User costs [€]		
	DDC	VOC	Safety	DDC	VOC	Safety
Scenario 1 - motorway	904,91	1311,58	8,76	146595,42	212475,96	1419,12
Scenario 2 - motorway	908,12	1316,34	8,79	10897,44	15796,08	105,48
Scenario 3 - motorway	3984,53	2841,3	14,64	47814,36	34095,60	175,68
night work motorway				157492,86	228272,04	1524,60
day work motorway				194409,78	246571,56	1594,80
Construction						
Scenario 1 - crossover	364,45	535,33	2,76	0,00	0,00	0,00
Scenario 2 - crossover	365,18	536,41	2,76	5842,88	8582,56	44,16
Scenario 3 - crossover	453,37	667,16	3,46	7253,92	10674,56	55,36
night work crossover				5842,88	8582,56	44,16
day work crossover				7253,92	10674,56	55,36
Combined action 1						
Scenario 1 - motorway	1949,64	2810,74	13,75			
Scenario 2 - motorway	1955,1	2818,83	13,79	66473,40	95840,22	468,86
Scenario 3 - motorway	7161,82	5637,66	21,12	243501,88	191680,44	718,08
Scenario 4 - motorway	4095,65	4266,27	17,84	139252,10	145053,18	606,56
Scenario 1 - crossover	364,45	535,33	2,76	4008,95	5888,63	30,36
Scenario 2 - crossover	365,18	536,41	2,76	4016,98	5900,51	30,36
Scenario 3 - crossover	453,37	667,16	3,46	4987,07	7338,76	38,06
night work motorway + night work crossover				74499,33	107629,36	529,58
night work motorway + day work crossover				75469,42	109067,61	537,28
day work motorway + night work crossover				251527,81	203469,58	778,80
day work motorway + day work crossover				252497,90	204907,83	786,50
reduce day work motorway + night work crossover				147278,03	156842,32	667,28
reduce day work motorway + day work crossover				148248,12	158280,57	674,98
Combined action 2						
Scenario 1 - motorway	2080,92	3009,63	14,81	83236,80	120385,20	592,40
Scenario 2 - motorway	2085,24	3016,02	14,84	145966,80	211121,40	1038,80
Scenario 3 - motorway	2490,76	3611,16	17,93	174353,20	252781,20	1255,10
Scenario 4 - motorway	2088,65	3021,09	14,87	146205,50	211476,30	1040,90
Scenario 5 - motorway	25924,97	10597,27	32,27	1814747,90	741808,90	2258,90
Scenario 6 - motorway	11683,81	6863,34	24,36	817866,70	480433,80	1705,20
Scenario 1 - crossover	364,45	535,33	2,76	4008,95	5888,63	30,36
Scenario 2 - crossover	365,18	536,41	2,76	4016,98	5900,51	30,36
Scenario 3 - crossover	453,37	667,16	3,46	4987,07	7338,76	38,06
night work motorway (3 lanes open)+ night work crossover				237229,53	343295,74	1691,92
night work motorway (3 lanes open) + day work crossover				238199,62	344733,99	1699,62
day work motorway (3 lanes open) + night work crossover				265615,93	384955,54	1908,22
day work motorway (3 lanes open) + day work crossover				266586,02	386393,79	1915,92
night work motorway (2 lanes open)+ night work crossover				237468,23	343650,64	1694,02
night work motorway (2 lanes open) + day work crossover				238438,32	345088,89	1701,72
day work motorway (2 lanes open) + night work crossover				1906010,63	873983,24	2912,02
day work motorway (2 lanes open) + day work crossover				1906980,72	875421,49	2919,72
reduce day work motorway (2 lanes open) + night work crossover				909129,43	612608,14	2358,32
reduce day work motorway (2 lanes open)+ day work crossover				910099,52	614046,39	2366,02
Combined action 3						
Scenario 1 - motorway	2295,03	3314,46	16,26			
Scenario 2 - motorway	2300,05	3321,91	16,3	78201,70	112944,94	554,20
Scenario 3 - motorway	2851,21	4091,93	19,95	96941,14	139125,62	678,30
Scenario 4 - motorway	2304,02	3327,8	16,33	78336,68	113145,20	555,22
Scenario 5 - motorway	47034,47	15967,96	43,49	1599171,98	542910,64	1478,66
Scenario 6 - motorway	19025,96	9262,19	30,13	646882,64	314914,46	1024,42
Scenario 1 - crossover	364,45	535,33	2,76	4008,95	5888,63	30,36
Scenario 2 - crossover	365,18	536,41	2,76	9859,86	14483,07	74,52
Scenario 3 - crossover	453,37	667,16	3,46	12240,99	18013,32	93,42
night work motorway (3 lanes open)+ night work crossover				92070,51	133316,64	659,08
night work motorway (3 lanes open) + day work crossover				94451,64	136846,89	677,98
day work motorway (3 lanes open) + night work crossover				110809,95	159497,32	783,18
day work motorway (3 lanes open) + day work crossover				113191,08	163027,57	802,08
night work motorway (2 lanes open)+ night work crossover				92205,49	133516,90	660,10
night work motorway (2 lanes open) + day work crossover				94586,62	137047,15	679,00
day work motorway (2 lanes open) + night work crossover				1613040,79	563282,34	1583,54
day work motorway (2 lanes open) + day work crossover				1615421,92	566812,59	1602,44
reduce day work motorway (2 lanes open) + night work crossover				660751,45	335286,16	1129,30
reduce day work motorway (2 lanes open)+ day work crossover				663132,58	338816,41	1148,20
Combined action 4						
Scenario 1 - motorway	2450,72	3535,99	17,32	93127,36	134367,62	658,16
Scenario 2 - motorway	2456,27	3544,22	17,36	19650,16	28353,76	138,88
Scenario 3 - motorway	3145,25	4469,94	21,45	25162,00	35759,52	171,60
Scenario 4 - motorway	2460,66	3550,73	17,39	19685,28	28405,84	139,12
Scenario 5 - motorway	65809,68	20682,36	53,14	526477,44	165458,88	425,12
Scenario 6 - motorway	24827,79	11135,86	34,57	198622,32	89086,88	276,56
Scenario 1 - crossover				0,00	0,00	0,00
Scenario 2 - crossover				0,00	0,00	0,00
Scenario 3 - crossover				0,00	0,00	0,00
night work motorway (3 lanes open)				112777,52	162721,38	797,04
day work motorway (3 lanes open)				118289,36	170127,14	829,76
night work motorway (2 lanes open)				112812,64	162773,46	797,28
day work motorway (2 lanes open)				619604,80	299826,50	1083,28
reduce day work motorway (2 lanes open)				291749,68	223454,50	934,72
End-of-life						

ANNEX C – SUPPORT INFORMATION TO 2ND CASE STUDY

C.1. PLANS OF CONSTRUCTION, MAINTENANCE AND DEMOLITION

Table C.1. Construction plan

Main Activity	Elements	Initial date	Final date	Total (days)
Excavation		01-03-2006	04-04-2006	
	Excavation	01-03-2006	28-03-2006	28
	Casting of piles	29-03-2006	04-04-2006	7
Casting "in situ"		05-04-2006	16-05-2006	
	Abutments	05-04-2006	16-05-2006	42
	Foundation bases	05-04-2006	25-04-2006	21
	Piers	26-04-2006	16-05-2006	21
Deck		17-05-2006	11-07-2006	
	Pre-cast beams + pre-stressed	17-05-2006	30-05-2006	14
	Pre-slabs + casting of slab	31-05-2006	27-06-2006	28
Finishings		14-06-2006	11-07-2006	29



Main Activity	Elements	Initial date	Final date	Total (days)
Excavation		01-03-2006	04-04-2006	
	Excavation	01-03-2006	28-03-2006	28
	Casting of piles	29-03-2006	04-04-2006	7
Casting "in situ"		05-04-2006	16-05-2006	
	Abutments	05-04-2006	16-05-2006	42
	Foundation bases	05-04-2006	25-04-2006	21
	Piers	26-04-2006	16-05-2006	21
Deck		17-05-2006	11-07-2006	
	Pre-cast beams + pre-stressed	17-05-2006	30-05-2006	14
	Pre-slabs + casting of slab	31-05-2006	27-06-2006	28
Finishings		14-06-2006	11-07-2006	29

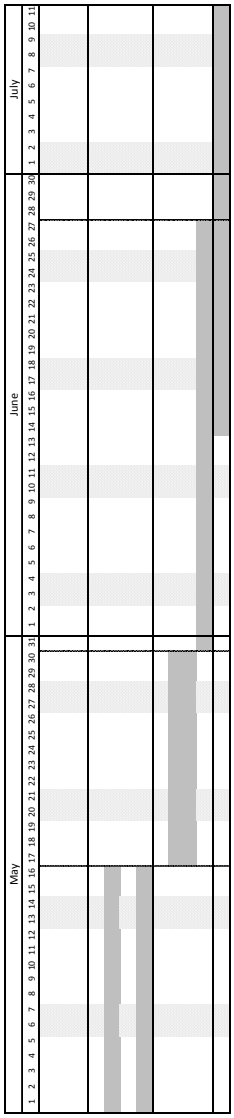


Table C.2. Maintenance plan

Main activity	Working days	Total (days)
rollers	2	2
pavers	2	2
milling (paving equipment)	2	4
Combined action 1		8
New surface protection	7	9
Replacement of rails and protection	7	9
Replacement of edge beams	14	18
Combined action 2		18
Rehabilitation of concrete structure	31	43
Replacement of rails and protection	7	9
Replacement of edge beams	14	18
Combined action 3		43
New surface protection	7	9
Replacement of rails and protection	7	9
Replacement of edge beams	14	18
rollers	2	4
pavers	2	2
milling (paving equipment)	2	2
Combined action 4		26

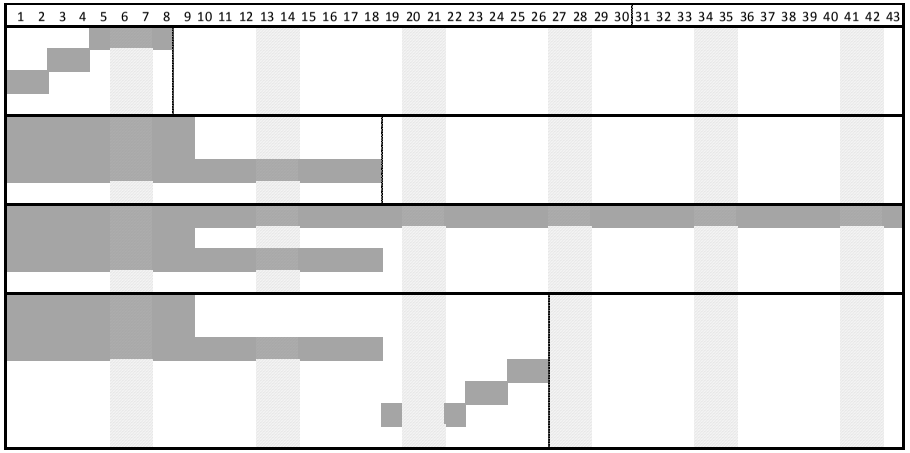
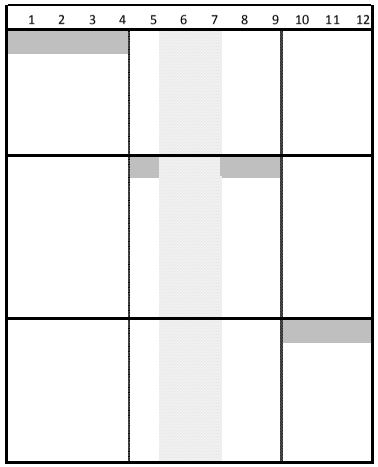


Table C.3. Demolition plan

Main Activity	Elements	Initial date	Final date	Working days	Total (days)
1st stage		-	-	4	4
	Preparation of base supports for scaffolding	-	-		
	Preparation of terrain for deposit of concrete pieces	-	-		
	Erection of scaffolding	-	-		
	Transversal cuts in deck	-	-		
2nd stage		-	-	3	5
	Dismantling of the first part of central span	-	-		
	Deposition of concrete pieces in the side terrain	-	-		
	Dismantling of the second part of central span	-	-		
	Deposition of concrete pieces in the side terrain	-	-		
	Dismantling of the middle pier				
	Deposition of concrete pieces in the side terrain				
3rd stage		-	-	3	3
	Dismantling of scaffolding	-	-		
	Demolition of the concrete pieces from the deck	-	-		
	Demolition "in situ" of piers and abutments	-	-		
	Removal and transportation of materials	-	-		
	Cleaning of the area	-	-		



C.2. NON-MOBILE EMISSIONS

Table C.4. Non-mobile emissions during construction stage

Type of construction equipment						Emissions factors [gr/(hp-hrs)]							Total emissions (tonnes)						
	no. Units	hp rated	hrs/day	days	Total hp-hrs	VOC	CO	NOx	PM-10	PM-2.5	SO2	CO2	VOC	CO	NOx	PM-10	PM-2.5	SO2	CO2
excavators	2	300	0,2	1	120	0,278	1,224	3,653	0,253	0,245	0,115	535,989	0,000	0,000	0,000	0,000	0,000	0,000	0,064
dump trucks	5	300	1	1	1500	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,002	0,006	0,011	0,001	0,001	0,000	0,935
bore/drill	1	300	1	2	600	0,531	2,041	6,412	0,412	0,399	0,114	529,434	0,000	0,001	0,004	0,000	0,000	0,000	0,318
concrete pumps	2	400	0,1	1	80	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,000	0,000	0,000	0,000	0,000	0,043
vibrators	2	2	0,35	1	1,4	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,001
compressor	1	2	0,35	1	0,7	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,000
concrete mixer truck	3	335	0,7	1	703,5	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,000	0,001	0,004	0,000	0,000	0,000	0,373
Excavation and piles													**0,002**	**0,009**	**0,020**	**0,002**	**0,002**	**0,000**	**1,733**
concrete pumps	2	400	0,4	1	320	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,001	0,002	0,000	0,000	0,000	0,171
vibrators	4	2	1,75	1	14	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,008
compressor	1	2	1,75	1	3,5	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,002
concrete mixer truck	13	335	0,7	1	3048,5	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,001	0,006	0,019	0,001	0,001	0,000	1,615
Abutments and bases													**0,002**	**0,007**	**0,021**	**0,001**	**0,001**	**0,000**	**1,797**
concrete pumps	2	400	0,15	1	120	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,000	0,001	0,000	0,000	0,000	0,064
vibrators	2	2	0,6	1	2,4	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,001
compressor	1	2	0,6	1	1,2	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,001
concrete mixer truck	4	335	0,7	1	938	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,000	0,002	0,006	0,000	0,000	0,000	0,497
Abutments and piers													**0,000**	**0,002**	**0,007**	**0,000**	**0,000**	**0,000**	**0,563**
cranes	2	175	8	1	2800	0,343	1,062	4,598	0,267	0,259	0,114	530,002	0,001	0,003	0,013	0,001	0,001	0,000	1,484
cranes	1	175	2	10	3500	0,343	1,062	4,598	0,267	0,259	0,114	530,002	0,001	0,004	0,016	0,001	0,001	0,000	1,855
cranes	1	175	4	10	7000	0,343	1,062	4,598	0,267	0,259	0,114	530,002	0,002	0,007	0,032	0,002	0,002	0,001	3,710
concrete pumps	2	400	0,65	1	520	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,001	0,003	0,000	0,000	0,000	0,279
vibrators	4	2	3	1	24	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,014
concrete mixer truck	23	335	0,7	1	5393,5	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,002	0,011	0,034	0,002	0,002	0,001	2,857
compressor	1	2	3	1	6	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,004
Deck													**0,007**	**0,027**	**0,098**	**0,006**	**0,005**	**0,002**	**10,202**
tractors/loaders	2	300	0,75	1	450	1,007	3,851	6,305	0,645	0,626	0,134	623,491	0,000	0,002	0,003	0,000	0,000	0,000	0,281
dump trucks	18	300	1	1	5400	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,006	0,022	0,038	0,005	0,004	0,001	3,365
rollers	1	300	5	1,5	2250	0,310	1,348	4,159	0,278	0,269	0,115	535,891	0,001	0,003	0,009	0,001	0,001	0,000	1,206
pavers	1	300	5	1,5	2250	0,302	1,308	4,042	0,271	0,263	0,115	535,916	0,001	0,003	0,009	0,001	0,001	0,000	1,206
Finishings													**0,008**	**0,029**	**0,059**	**0,006**	**0,006**	**0,001**	**6,057**
												TOTAL	**0,019**	**0,075**	**0,206**	**0,015**	**0,014**	**0,004**	**20,353**

Table C.5. Non-mobile emissions during operation stage

Type of construction equipment	Assumptions					Emissions factors [gr/(hp-hrs)]							Total emissions (tonnes)						
	no. Units	hp rated	hrs/day	days	Total hp-hrs	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
rollers	1	300	5	2	3000	0,310	1,348	4,159	0,278	0,269	0,115	535,891	0,001	0,004	0,012	0,001	0,001	0,000	1,608
pavers	1	300	5	2	3000	0,302	1,308	4,042	0,271	0,263	0,115	535,916	0,001	0,004	0,012	0,001	0,001	0,000	1,608
milling (paving equipment)	1	300	5	2	3000	0,337	1,509	4,463	0,299	0,290	0,115	535,810	0,001	0,005	0,013	0,001	0,001	0,000	1,607
Combined action 1													**0,003**	**0,012**	**0,038**	**0,003**	**0,002**	**0,001**	**4,823**
New surface protection	1	300	6	6	11417,4	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,004	0,018	0,052	0,003	0,003	0,001	6,117
Replacement of rails and protection	1	300	2	7	4320	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,001	0,007	0,020	0,001	0,001	0,000	2,315
Replacement of edge beams	1	300	2	14	8358	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,003	0,013	0,038	0,003	0,002	0,001	4,478
Combined action 2													**0,008**	**0,037**	**0,109**	**0,007**	**0,007**	**0,003**	**12,910**
Rehabilitation of concrete structure	1	300	4	32	38058	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,013	0,058	0,172	0,012	0,011	0,004	20,391
Replacement of rails and protection	1	300	2	7	4320	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,001	0,007	0,020	0,001	0,001	0,000	2,315
Replacement of edge beams	1	300	2	14	8358	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,003	0,013	0,038	0,003	0,002	0,001	4,478
Combined action 3													**0,017**	**0,078**	**0,229**	**0,015**	**0,015**	**0,006**	**27,184**
New surface protection	1	300	6	6	11417,4	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,004	0,018	0,052	0,003	0,003	0,001	6,117
Replacement of rails and protection	1	300	2	7	4320	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,001	0,007	0,020	0,001	0,001	0,000	2,315
Replacement of edge beams	1	300	2	14	8358	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,003	0,013	0,038	0,003	0,002	0,001	4,478
rollers	1	300	5	2	3000	0,310	1,348	4,159	0,278	0,269	0,115	535,891	0,001	0,004	0,012	0,001	0,001	0,000	1,608
pavers	1	300	5	2	3000	0,302	1,308	4,042	0,271	0,263	0,115	535,916	0,001	0,004	0,012	0,001	0,001	0,000	1,608
milling (paving equipment)	1	300	5	2	3000	0,337	1,509	4,463	0,299	0,290	0,115	535,810	0,001	0,005	0,013	0,001	0,001	0,000	1,607
Combined action 4													**0,011**	**0,050**	**0,147**	**0,010**	**0,010**	**0,004**	**17,733**
												TOTAL	**0,039**	**0,177**	**0,523**	**0,035**	**0,034**	**0,013**	**62,650**

Table C.6. Non-mobile emissions during end-of-life stage

Type of construction equipment	Assumptions					Emissions factors [gr/(hp-hrs)]							Total emissions (tonnes)						
	no. Units	hp rated	hrs/day	days	Total hp-hrs	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
backhoe	1	175	2	1	350	1,099	4,300	6,553	0,727	0,705	0,134	623,215	0,000	0,002	0,002	0,000	0,000	0,000	0,218
generator	1	60	4	2	480	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,000	0,002	0,002	0,000	0,000	0,000	0,285
dump trucks	1	175	2	1	350	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,000	0,001	0,002	0,000	0,000	0,000	0,218
roller	1	175	4	1	700	0,350	1,589	4,353	0,347	0,337	0,115	535,771	0,000	0,001	0,003	0,000	0,000	0,000	0,375
concrete saw	2	300	4	2	4800	0,350	1,598	4,591	0,311	0,301	0,115	535,772	0,002	0,008	0,022	0,001	0,001	0,001	2,572
1st stage													**0,003**	**0,014**	**0,032**	**0,003**	**0,003**	**0,001**	**3,668**
generator	1	60	12	3	2160	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,001	0,009	0,011	0,001	0,001	0,000	1,284
telescopic crane	1	420	6	2	5040	0,309	1,453	5,259	0,246	0,239	0,114	530,104	0,002	0,007	0,027	0,001	0,001	0,001	2,672
2nd stage													**0,003**	**0,016**	**0,037**	**0,003**	**0,002**	**0,001**	**3,956**
backhoe	1	175	12	1	2100	1,099	4,300	6,553	0,727	0,705	0,134	623,215	0,002	0,009	0,014	0,002	0,001	0,000	1,309
tractor/loader	1	300	12	1	3600	0,290	1,256	3,860	0,262	0,255	0,115	535,953	0,001	0,005	0,014	0,001	0,001	0,000	1,929
excavators	2	300	2	3	3600	0,278	1,224	3,653	0,253	0,245	0,115	535,989	0,001	0,004	0,013	0,001	0,001	0,000	1,930
crushing equipment	2	300	2	3	3600	0,309	0,924	4,446	0,211	0,205	0,114	530,107	0,001	0,003	0,016	0,001	0,001	0,000	1,908
dump tracks	41	175	0,6	1	4305	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,005	0,017	0,030	0,004	0,004	0,001	2,683
3rd stage													**0,010**	**0,038**	**0,087**	**0,008**	**0,008**	**0,002**	**9,759**
												TOTAL	**0,016**	**0,068**	**0,157**	**0,013**	**0,013**	**0,004**	**17,383**

C.3. TRAFFIC EMISSIONS

Table C.7. Traffic emissions during construction stage

Traffic scenario	Emissions [kg/day]			Fuel [kg/day]		Emissions [kg]			Fuel [kg]	
	CO	HC	NO_x	Gasoline	Diesel	CO	HC	NO_x	Gasoline	Diesel
Scenario 1 - motorway	33,21	0,33	0,29	167,92	308,35	7505,46	74,58	65,54	37949,92	69687,10
Scenario 2 - motorway	33,20	0,34	0,30	168,68	309,20	1328,00	13,60	12,00	6747,20	12368,00
Scenario 3 - motorway	80,68	4,75	1,22	388,16	625,89	3227,20	190,00	48,80	15526,40	25035,60
	night work motorway					8833,46	88,18	77,54	44697,12	82055,10
	day work motorway					10732,66	264,58	114,34	53476,32	94722,70

Table C.8. Traffic emissions during end-of-life stage

Traffic scenario	Emissions [kg/day]			Fuel [kg/day]		Emissions [kg]			Fuel [kg]	
	CO	HC	NO_x	Gasoline	Diesel	CO	HC	NO_x	Gasoline	Diesel
Scenario 1 - motorway	70,50	0,88	0,64	465,23	809,70	1269,00	15,84	11,52	8374,14	14574,60
Scenario 2 - motorway	70,50	0,89	0,64	466,54	811,18	423,00	5,34	3,84	2799,24	4867,08
Scenario 3 - motorway	70,50	1,69	0,82	611,17	983,78	423,00	10,14	4,92	3667,02	5902,68
Scenario 4 - motorway	70,50	0,90	0,65	467,58	812,36	423,00	5,40	3,90	2805,48	4874,16
Scenario 5 - motorway	1193,23	107,92	24,22	3105,01	4073,80	7159,38	647,52	145,32	18630,06	24442,80
Scenario 6 - motorway	443,72	37,46	8,68	1630,75	2264,26	2662,32	224,76	52,08	9784,50	13585,56
	night work motorway (3 lanes open)					1692,00	21,18	15,36	11173,38	19441,68
	day work motorway (3 lanes open)					1692,00	25,98	16,44	12041,16	20477,28
	night work motorway (2 lanes open)					1692,00	21,24	15,42	11179,62	19448,76
	day work motorway (2 lanes open)					8428,38	663,36	156,84	27004,20	39017,40
	reduce day work motorway (2 lanes open)					3931,32	240,60	63,60	18158,64	28160,16

Table C.9. Traffic emissions during operation stage

Traffic scenario	Emissions [kg/day]			Fuel [kg/day]		Emissions [kg]			Fuel [kg]	
	CO	HC	NO_x	Gasoline	Diesel	CO	HC	NO_x	Gasoline	Diesel
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	0,00	0,00	0,00	0,00	0,00
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	180,56	0,88	1,44	514,24	1069,52
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	176,24	1,92	1,68	681,36	1258,16
	night work crossover					180,56	0,88	1,44	514,24	1069,52
	day work crossover					176,24	1,92	1,68	681,36	1258,16
Combined action 1										
Scenario 1 - motorway	53,30	0,69	0,49	371,88	640,05					
Scenario 2 - motorway	53,30	0,70	0,49	373,17	641,51	959,40	12,60	8,82	6717,06	11547,18
Scenario 3 - motorway	135,05	7,74	1,95	776,82	1230,44	2430,90	139,32	35,10	13982,76	22147,92
Scenario 4 - motorway	84,08	3,28	1,00	578,16	947,86	1513,44	59,04	18,00	10406,88	17061,48
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	406,26	1,80	3,24	1153,98	2403,00
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	0,00	0,00	0,00	0,00	0,00
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	0,00	0,00	0,00	0,00	0,00
	night work motorway + night work crossover					1365,66	14,40	12,06	7871,04	13950,18
	night work motorway + day work crossover					1365,66	14,40	12,06	7871,04	13950,18
	day work motorway + night work crossover					2837,16	141,12	38,34	15136,74	24550,92
	day work motorway + day work crossover					2837,16	141,12	38,34	15136,74	24550,92
	reduce day work motorway + night work crossover					1919,70	60,84	21,24	11560,86	19464,48
	reduce day work motorway + day work crossover					1919,70	60,84	21,24	11560,86	19464,48
Combined action 2										
Scenario 1 - motorway	68,56	0,76	0,61	390,07	699,35	1645,44	18,24	14,64	9361,68	16784,40
Scenario 2 - motorway	68,56	0,77	0,62	391,09	700,51	2742,40	30,80	24,80	15643,60	28020,40
Scenario 3 - motorway	68,56	1,26	0,73	485,91	808,29	2742,40	50,40	29,20	19436,40	32331,60
Scenario 4 - motorway	68,53	0,78	0,62	391,90	701,42	2741,20	31,20	24,80	15676,00	28056,80
Scenario 5 - motorway	478,89	39,47	9,07	1528,41	2195,24	19155,60	1578,80	362,80	61136,40	87809,60
Scenario 6 - motorway	225,51	15,71	3,85	963,57	1467,13	9020,40	628,40	154,00	38542,80	58685,20
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	406,26	1,80	3,24	1153,98	2403,00
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	0,00	0,00	0,00	0,00	0,00
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	0,00	0,00	0,00	0,00	0,00
	night work motorway (3 lanes open)+ night work crossover					4794,10	50,84	42,68	26159,26	47207,80
	night work motorway (3 lanes open) + day work crossover					4794,10	50,84	42,68	26159,26	47207,80
	day work motorway (3 lanes open) + night work crossover					4794,10	70,44	47,08	29952,06	51519,00
	day work motorway (3 lanes open) + day work crossover					4794,10	70,44	47,08	29952,06	51519,00
	night work motorway (2 lanes open)+ night work crossover					4792,90	51,24	42,68	26191,66	47244,20
	night work motorway (2 lanes open) + day work crossover					4792,90	51,24	42,68	26191,66	47244,20
	day work motorway (2 lanes open) + night work crossover					21207,30	1598,84	380,68	71652,06	106997,00
	day work motorway (2 lanes open) + day work crossover					21207,30	1598,84	380,68	71652,06	106997,00
	uce day work motorway (2 lanes open) + night work crosso					11072,10	648,44	171,88	49058,46	77872,60
	duce day work motorway (2 lanes open)+ day work crossov					11072,10	648,44	171,88	49058,46	77872,60
Combined action 3										
Scenario 1 - motorway	69,79	0,83	0,63	433,43	763,56					
Scenario 2 - motorway	69,79	0,84	0,63	434,61	764,90	1256,22	15,12	11,34	7822,98	13768,20
Scenario 3 - motorway	69,79	1,49	0,78	555,87	906,82	1256,22	26,82	14,04	10005,66	16322,76
Scenario 4 - motorway	69,76	0,85	0,64	435,56	765,96	1255,68	15,30	11,52	7840,08	13787,28
Scenario 5 - motorway	855,32	75,68	17,09	2368,63	3194,57	15395,76	1362,24	307,62	42635,34	57502,26
Scenario 6 - motorway	347,45	27,87	6,55	1337,79	1915,34	6254,10	501,66	117,90	24080,22	34476,12
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	406,26	1,80	3,24	1153,98	2403,00
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	180,56	0,88	1,44	514,24	1069,52
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	176,24	1,92	1,68	681,36	1258,16
	night work motorway (3 lanes open)+ night work crossover					1843,04	17,80	16,02	9491,20	17240,72
	night work motorway (3 lanes open) + day work crossover					1838,72	18,84	16,26	9658,32	17429,36
	day work motorway (3 lanes open) + night work crossover					1843,04	29,50	18,72	11673,88	19795,28
	day work motorway (3 lanes open) + day work crossover					1838,72	30,54	18,96	11841,00	19983,92
	night work motorway (2 lanes open)+ night work crossover					1842,50	17,98	16,20	9508,30	17259,80
	night work motorway (2 lanes open) + day work crossover					1838,18	19,02	16,44	9675,42	17448,44
	day work motorway (2 lanes open) + night work crossover					15982,58	1364,92	312,30	44303,56	60974,78
	day work motorway (2 lanes open) + day work crossover					15978,26	1365,96	312,54	44470,68	61163,42
	uce day work motorway (2 lanes open) + night work crosso					6840,92	504,34	122,58	25748,44	37948,64
	duce day work motorway (2 lanes open)+ day work crossov					6836,60	505,38	122,82	25915,56	38137,28
Combined action 4										

C.4. USER COSTS

Table C.10. Life cycle user costs

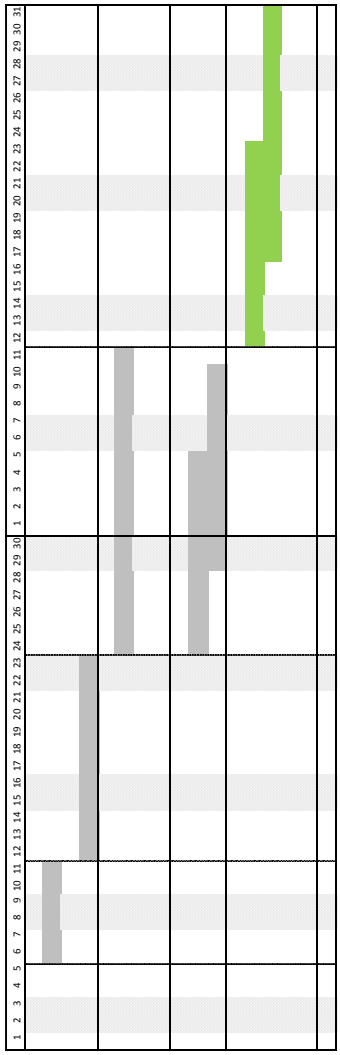
Traffic scenario	User costs [€/day]			User costs [€]		
	DDC	VOC	Safety	DDC	VOC	Safety
Scenario 1 - motorway	904,91	1311,58	8,76	204509,66	296417,08	1979,76
Scenario 2 - motorway	908,12	1316,34	8,79	36324,80	52653,60	351,60
Scenario 3 - motorway	3984,53	2841,3	14,64	159381,20	113652,00	585,60
Motorway detour (night)	4232,33	6274,79	299,08	0,00	0,00	0,00
Motorway detour (day)	31171,00	46213,62	2202,70	0,00	0,00	0,00
night work motorway				240834,46	349070,68	2331,36
day work motorway				363890,86	410069,08	2565,36
Construction						
Scenario 1 - motorway						
Scenario 2 - motorway						
Scenario 3 - motorway						
Scenario 4 - motorway						
Scenario 1 - crossover	364,45	535,33	2,76	0,00	0,00	0,00
Scenario 2 - crossover	365,18	536,41	2,76	2921,44	4291,28	22,08
Scenario 3 - crossover	453,37	667,16	3,46	3626,96	5337,28	27,68
night work crossover				2921,44	4291,28	22,08
day work crossover				3626,96	5337,28	27,68
Combined action 1						
Scenario 1 - motorway	1949,64	2810,74	13,75			
Scenario 2 - motorway	1955,1	2818,83	13,79	35191,80	50738,94	248,22
Scenario 3 - motorway	7161,82	5637,66	21,12	128912,76	101477,88	380,16
Scenario 4 - motorway	4095,65	4266,27	17,84	73721,70	76792,86	321,12
Scenario 1 - crossover	364,45	535,33	2,76	6560,10	9635,94	49,68
Scenario 2 - crossover	365,18	536,41	2,76	0,00	0,00	0,00
Scenario 3 - crossover	453,37	667,16	3,46	0,00	0,00	0,00
night work motorway + night work crossover				41751,90	60374,88	297,90
night work motorway + day work crossover				41751,90	60374,88	297,90
day work motorway + night work crossover				135472,86	111113,82	429,84
day work motorway + day work crossover				135472,86	111113,82	429,84
reduce day work motorway + night work crossover				80281,80	86428,80	370,80
reduce day work motorway + day work crossover				80281,80	86428,80	370,80
Combined action 2						
Scenario 1 - motorway	2080,92	3009,63	14,81	49942,08	72231,12	355,44
Scenario 2 - motorway	2085,24	3016,02	14,84	83409,60	120640,80	593,60
Scenario 3 - motorway	2490,76	3611,16	17,93	99630,40	144446,40	717,20
Scenario 4 - motorway	2088,65	3021,09	14,87	83546,00	120843,60	594,80
Scenario 5 - motorway	25924,97	10597,27	32,27	1036998,80	423890,80	1290,80
Scenario 6 - motorway	11683,81	6863,34	24,36	467352,40	274533,60	974,40
Scenario 1 - crossover	364,45	535,33	2,76	6560,10	9635,94	49,68
Scenario 2 - crossover	365,18	536,41	2,76	0,00	0,00	0,00
Scenario 3 - crossover	453,37	667,16	3,46	0,00	0,00	0,00
night work motorway (3 lanes open)+ night work crossover				139911,78	202507,86	998,72
night work motorway (3 lanes open) + day work crossover				139911,78	202507,86	998,72
day work motorway (3 lanes open) + night work crossover				156132,58	226313,46	1122,32
day work motorway (3 lanes open) + day work crossover				156132,58	226313,46	1122,32
night work motorway (2 lanes open)+ night work crossover				140048,18	202710,66	999,92
night work motorway (2 lanes open) + day work crossover				140048,18	202710,66	999,92
day work motorway (2 lanes open) + night work crossover				1093500,98	505757,86	1695,92
day work motorway (2 lanes open) + day work crossover				1093500,98	505757,86	1695,92
reduce day work motorway (2 lanes open) + night work crossover				523854,58	356400,66	1379,52
reduce day work motorway (2 lanes open)+ day work crossover				523854,58	356400,66	1379,52
Combined action 3						
Scenario 1 - motorway	2295,03	3314,46	16,26			
Scenario 2 - motorway	2300,05	3321,91	16,3	41400,90	59794,38	293,40
Scenario 3 - motorway	2851,21	4091,93	19,95	51321,78	73654,74	359,10
Scenario 4 - motorway	2304,02	3327,8	16,33	41472,36	59900,40	293,94
Scenario 5 - motorway	47034,47	15967,96	43,49	846620,46	287423,28	782,82
Scenario 6 - motorway	19025,96	9262,19	30,13	342467,28	166719,42	542,34
Scenario 1 - crossover	364,45	535,33	2,76	6560,10	9635,94	49,68
Scenario 2 - crossover	365,18	536,41	2,76	2921,44	4291,28	22,08
Scenario 3 - crossover	453,37	667,16	3,46	3626,96	5337,28	27,68
night work motorway (3 lanes open)+ night work crossover				50882,44	73721,60	365,16
night work motorway (3 lanes open) + day work crossover				51587,96	74767,60	370,76
day work motorway (3 lanes open) + night work crossover				60803,32	87581,96	430,86
day work motorway (3 lanes open) + day work crossover				61508,84	88627,96	436,46
night work motorway (2 lanes open)+ night work crossover				50953,90	73827,62	365,70
night work motorway (2 lanes open) + day work crossover				51659,42	74873,62	371,30
day work motorway (2 lanes open) + night work crossover				856102,00	301350,50	854,58
day work motorway (2 lanes open) + day work crossover				856807,52	302396,50	860,18
reduce day work motorway (2 lanes open) + night work crossover				351948,82	180646,64	614,10
reduce day work motorway (2 lanes open)+ day work crossover				352654,34	181692,64	619,70
Combined action 4						
Scenario 1 - motorway	2450,72	3535,99	17,32	44112,96	63647,82	311,76
Scenario 2 - motorway	2456,27	3544,22	17,36	14737,62	21265,32	104,16
Scenario 3 - motorway	3145,25	4469,94	21,45	18871,50	26819,64	128,70
Scenario 4 - motorway	2460,66	3550,73	17,39	14763,96	21304,38	104,34
Scenario 5 - motorway	65809,68	20682,36	53,14	394858,08	124094,16	318,84
Scenario 6 - motorway	24827,79	11135,86	34,57	148966,74	66815,16	207,42
night work motorway (3 lanes open)				58850,58	84913,14	415,92
day work motorway (3 lanes open)				62984,46	90467,46	440,46
night work motorway (2 lanes open)				58876,92	84952,20	416,10
day work motorway (2 lanes open)				438971,04	187741,98	630,60
reduce day work motorway (2 lanes open)				193079,70	130462,98	519,18
End-of-life						

ANNEX D – SUPPORT INFORMATION TO 3RD CASE STUDY

D.1. PLANS OF CONSTRUCTION, MAINTENANCE AND DEMOLITION

Table D.1. Construction plan

Main Activity	Elements	Initial date	Final date	Total (days)
Excavation		06-09-2007	22-11-2007	
	Excavation	06-09-2007	11-09-2007	6
	Embakments	17-11-2000	22-11-2000	6
	Casting of piles	12-09-2007	23-09-2007	12
Casting of abutments		24-09-2007	28-11-2007	
	Top beam	24-09-2007	11-10-2007	18
	Hall	05-11-2007	16-11-2007	12
	Transition slab	23-11-2007	28-11-2007	6
Piers		24-09-2007	10-10-2007	
	Foundation bases	24-09-2007	05-10-2007	12
	Elevation	29-09-2007	10-10-2007	12
Casting of deck		12-10-2007	13-11-2007	
	Workform	12-10-2007	23-10-2007	12
	Reinforcement steel	17-10-2007	03-11-2007	18
	Concrete	04-11-2007	04-11-2007	1
	Prestress steel	12-11-2007	13-11-2007	2
Finishings		14-11-2007	07-12-2007	24



Main Activity	Elements	Initial date	Final date	Total (days)
Excavation		06-09-2007	22-11-2007	
	Excavation	06-09-2007	11-09-2007	6
	Embakments	17-11-2000	22-11-2000	6
	Casting of piles	12-09-2007	23-09-2007	12
Casting of abutments		24-09-2007	28-11-2007	
	Top beam	24-09-2007	11-10-2007	18
	Hall	05-11-2007	16-11-2007	12
	Transition slab	23-11-2007	28-11-2007	6
Piers		24-09-2007	10-10-2007	
	Foundation bases	24-09-2007	05-10-2007	12
	Elevation	29-09-2007	10-10-2007	12
Casting of deck		12-10-2007	13-11-2007	
	Workform	12-10-2007	23-10-2007	12
	Reinforcement steel	17-10-2007	03-11-2007	18
	Concrete	04-11-2007	04-11-2007	1
	Prestress steel	12-11-2007	13-11-2007	2
Finishings		14-11-2007	07-12-2007	24

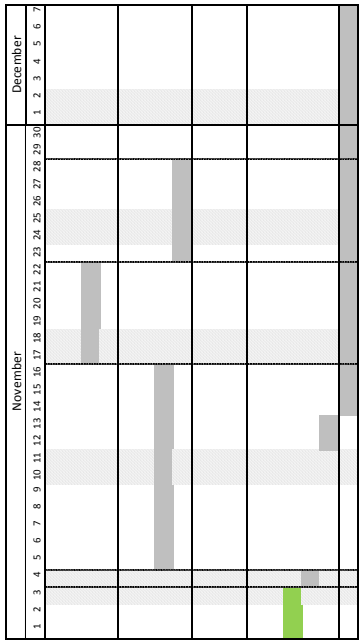


Table D.2. Maintenance plan

Main activity	Working days	Total (days)
rollers	3	8
pavers	4	4
milling (paving equipment)	4	3
Combined action 1		15
New surface protection	14	18
Replacement of expansion joints	6	8
Replacement of bearings	16	22
Replacement of rails and protection	9	11
Replacement of edge beams	17	23
Combined action 2		23
Rehabilitation of concrete structure	67	93
Replacement of expansion joints	6	8
Replacement of bearings	16	22
Replacement of rails and protection	9	11
Replacement of edge beams	17	23
Combined action 3		93
New surface protection	14	18
Replacement of expansion joints	6	8
Replacement of bearings	16	22
Replacement of rails and protection	9	11
Replacement of edge beams	17	23
rollers	3	3
pavers	4	8
milling (paving equipment)	4	4
Combined action 4		38

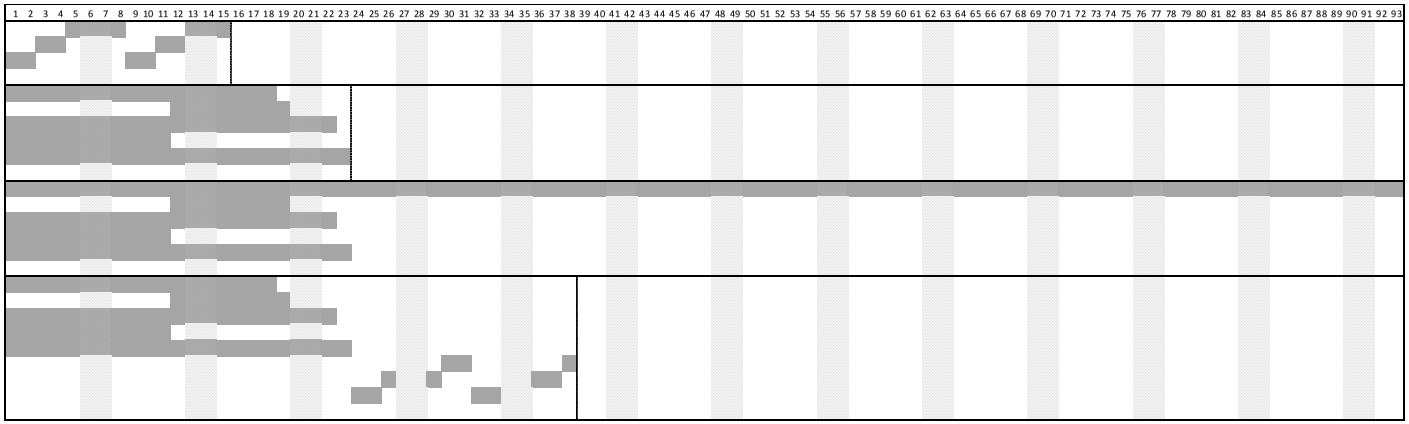
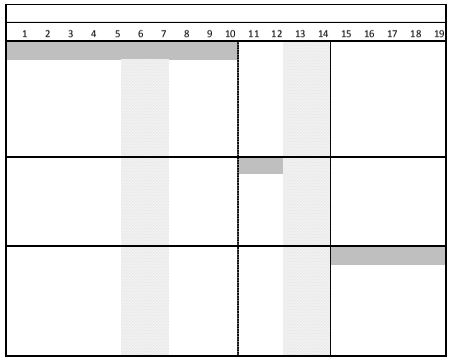


Table D.3. Demolition plan

Main Activity	Elements	Initial date	Final date	Working days	Total (days)
1st stage		-	-	8	10
	Preparation of base supports for scaffolding	-	-		
	Preparation of terrain for deposit of concrete pieces	-	-		
	Erection of scaffolding	-	-		
	Transversal cuts in deck	-	-		
	Longitudinal cuts of deck (partialy)	-	-		
2nd stage		-	-	2	4
	Dismantling of the first part of central span	-	-		
	Deposition of concrete pieces in the side terrain	-	-		
	Dismantling of the second part of central span	-	-		
	Deposition of concrete pieces in the side terrain	-	-		
3rd stage		-	-	5	5
	Dismantling of scaffolding	-	-		
	Demolition of the concrete pieces from the deck	-	-		
	Demolition "in situ" of piers and abutments	-	-		
	Removal and transportation of materials	-	-		
	Cleaning of the area	-	-		



D.2. NON-MOBILE EMISSIONS

Table D.4. Non-mobile emissions during construction stage

Type of construction equipment	Assumptions					Emissions factors [gr/(hp-hrs)]							Total emissions (tonnes)						
	no. Units	hp rated	hrs/day	days	Total hp-hrs	VOC	CO	NOx	PM-10	PM-2.5	SO2	CO2	VOC	CO	NOx	PM-10	PM-2.5	SO2	CO2
excavators	2	300	2,5	1	1500	0,278	1,224	3,653	0,253	0,245	0,115	535,989	0,000	0,002	0,005	0,000	0,000	0,000	0,804
dump trucks	60	300	1	1	18000	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,020	0,072	0,127	0,015	0,015	0,002	11,217
bore/drill	1	175	1	4	700	0,531	2,041	6,412	0,412	0,399	0,114	529,434	0,000	0,001	0,004	0,000	0,000	0,000	0,371
concrete pumps	2	400	0,3	1	240	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,001	0,001	0,000	0,000	0,000	0,129
vibrators	2	2	1,4	1	5,6	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,003
compressor	1	2	1,4	1	2,8	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,002
concrete mixer truck	11	335	0,7	1	2579,5	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,001	0,005	0,016	0,001	0,001	0,000	1,366
Excavation and piles													**0,022**	**0,081**	**0,155**	**0,017**	**0,016**	**0,003**	**13,892**
concrete pumps	2	400	1	1	800	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,002	0,004	0,000	0,000	0,000	0,429
vibrators	2	2	4,6	1	18,4	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,011
compressor	1	2	4,6	1	9,2	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,005
concrete mixer truck	34	335	0,7	1	7973	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,004	0,016	0,051	0,003	0,002	0,001	4,223
Piers and abutments													**0,004**	**0,019**	**0,055**	**0,003**	**0,003**	**0,001**	**4,668**
cranes	2	175	4	16	22400	0,343	1,062	4,598	0,267	0,259	0,114	530,002	0,008	0,024	0,103	0,006	0,006	0,003	11,872
concrete pumps	2	400	3,5	1	2800	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,001	0,008	0,015	0,001	0,001	0,000	1,500
vibrators	6	2	15	1	180	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,001	0,001	0,000	0,000	0,000	0,107
concrete mixer truck	112	335	0,7	1	26264	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,012	0,054	0,167	0,008	0,008	0,003	13,911
compressor	1	2	15	1	30	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,018
generator 1	1	64	15	1	960	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,001	0,004	0,005	0,001	0,001	0,000	0,571
generator 2	1	48	15	1	720	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,000	0,003	0,004	0,000	0,000	0,000	0,428
Deck													**0,022**	**0,094**	**0,295**	**0,017**	**0,016**	**0,006**	**28,407**
tractors/loaders	2	300	0,5	1	300,000	1,007	3,851	6,305	0,645	0,626	0,134	623,491	0,000	0,001	0,002	0,000	0,000	0,000	0,187
dump trucks	12	300	1	1	3600	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,004	0,014	0,025	0,003	0,003	0,000	2,243
concrete pumps	2	400	0,15	1	120	0,384	2,725	5,480	0,378	0,367	0,115	535,668	0,000	0,000	0,001	0,000	0,000	0,000	0,064
vibrators	2	2	0,7	1	2,8	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,002
compressor	1	2	0,7	1	1,4	0,768	6,219	4,871	0,695	0,674	0,128	593,831	0,000	0,000	0,000	0,000	0,000	0,000	0,001
concrete mixer truck	6	335	0,7	1	1407	0,453	2,056	6,365	0,322	0,313	0,114	529,670	0,001	0,003	0,009	0,000	0,000	0,000	0,745
rollers	1	300	5	2,5	3750	0,310	1,348	4,159	0,278	0,269	0,115	535,891	0,001	0,005	0,016	0,001	0,001	0,000	2,010
pavers	1	300	5	2,5	3750	0,302	1,308	4,042	0,271	0,263	0,115	535,916	0,001	0,005	0,015	0,001	0,001	0,000	2,010
Finishing & abutments													**0,007**	**0,029**	**0,068**	**0,006**	**0,006**	**0,002**	**7,262**
												TOTAL	**0,055**	**0,222**	**0,573**	**0,042**	**0,041**	**0,012**	**54,228**

Table D.5. Non-mobile emissions during operation stage

Type of construction equipment	Assumptions					Emissions factors [gr/(hp-hrs)]							Total emissions (tonnes)						
	no. Units	hp rated	hrs/day	days	Total hp-hrs	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
rollers	1	300	5	3	4500	0,310	1,348	4,159	0,278	0,269	0,115	535,891	0,001	0,006	0,019	0,001	0,001	0,001	2,412
pavers	1	300	5	4	6000	0,302	1,308	4,042	0,271	0,263	0,115	535,916	0,002	0,008	0,024	0,002	0,002	0,001	3,215
milling (paving equipment)	1	300	5	4	6000	0,337	1,509	4,463	0,299	0,290	0,115	535,810	0,002	0,009	0,027	0,002	0,002	0,001	3,215
Combined action 1													**0,005**	**0,023**	**0,070**	**0,005**	**0,005**	**0,002**	**8,842**
New surface protection	1	300	6	13	23941,08	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,008	0,037	0,108	0,007	0,007	0,003	12,828
Replacement of expansion joints	1	300	4	6	7200	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,011	0,033	0,002	0,002	0,001	3,858
Replacement of bearings	1	300	1	16	4800	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,007	0,022	0,001	0,001	0,001	2,572
Replacement of rails and protection	1	300	2	9	5400	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,008	0,024	0,002	0,002	0,001	2,893
Replacement of edge beams	1	300	2	17	10380	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,004	0,016	0,047	0,003	0,003	0,001	5,562
Combined action 2													**0,018**	**0,079**	**0,233**	**0,016**	**0,015**	**0,006**	**27,712**
Rehabilitation of concrete structure	1	300	4	67	79803,6	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,027	0,123	0,360	0,024	0,023	0,009	42,759
Replacement of expansion joints	1	300	4	6	7200	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,011	0,033	0,002	0,002	0,001	3,858
Replacement of bearings	1	300	1	16	4800	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,007	0,022	0,001	0,001	0,001	2,572
Replacement of rails and protection	1	300	2	9	5400	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,008	0,024	0,002	0,002	0,001	2,893
Replacement of edge beams	1	300	2	17	10380	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,004	0,016	0,047	0,003	0,003	0,001	5,562
Combined action 3													**0,037**	**0,165**	**0,486**	**0,033**	**0,032**	**0,012**	**57,643**
New surface protection	1	300	6	13	23941,08	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,008	0,037	0,108	0,007	0,007	0,003	12,828
Replacement of expansion joints	1	300	4	6	7200	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,011	0,033	0,002	0,002	0,001	3,858
Replacement of bearings	1	300	1	16	4800	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,007	0,022	0,001	0,001	0,001	2,572
Replacement of rails and protection	1	300	2	9	5400	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,002	0,008	0,024	0,002	0,002	0,001	2,893
Replacement of edge beams	1	300	2	17	10380	0,341	1,537	4,514	0,303	0,294	0,115	535,797	0,004	0,016	0,047	0,003	0,003	0,001	5,562
rollers	1	300	5	3	4500	0,310	1,348	4,159	0,278	0,269	0,115	535,891	0,001	0,006	0,019	0,001	0,001	0,001	2,412
pavers	1	300	5	4	6000	0,302	1,308	4,042	0,271	0,263	0,115	535,916	0,002	0,008	0,024	0,002	0,002	0,001	3,215
milling (paving equipment)	1	300	5	4	6000	0,337	1,509	4,463	0,299	0,290	0,115	535,810	0,002	0,009	0,027	0,002	0,002	0,001	3,215
Combined action 4													**0,023**	**0,102**	**0,303**	**0,020**	**0,020**	**0,008**	**36,554**
												TOTAL	**0,082**	**0,370**	**1,092**	**0,073**	**0,071**	**0,028**	**130,751**

Table D.6. Non-mobile emissions during end-of-life stage

Type of construction equipment	Assumptions					Emissions factors [gr/(hp-hrs)]							Total emissions (tonnes)						
	no. Units	hp rated	hrs/day	days	Total hp-hrs	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2	VOC	CO	NO_x	PM-10	PM-2.5	SO_2	CO_2
backhoe	1	175	2	1	350	1,099	4,300	6,553	0,727	0,705	0,134	623,215	0,000	0,002	0,002	0,000	0,000	0,000	0,218
generator	1	60	4	4	960	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,001	0,004	0,005	0,001	0,001	0,000	0,571
dump trucks	1	175	2	1	350	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,000	0,001	0,002	0,000	0,000	0,000	0,218
roller	1	175	4	2	1400	0,350	1,589	4,353	0,347	0,337	0,115	535,771	0,000	0,002	0,006	0,000	0,000	0,000	0,750
concrete saw	2	300	4	4	9600	0,350	1,598	4,591	0,311	0,301	0,115	535,772	0,003	0,015	0,044	0,003	0,003	0,001	5,143
1st stage													**0,005**	**0,024**	**0,060**	**0,005**	**0,004**	**0,001**	**6,900**
generator	1	60	12	2	1440	0,570	4,039	5,036	0,611	0,592	0,128	594,430	0,001	0,006	0,007	0,001	0,001	0,000	0,856
telescopic crane	1	420	6	2	5040	0,309	1,453	5,259	0,246	0,239	0,114	530,104	0,002	0,007	0,027	0,001	0,001	0,001	2,672
2nd stage													**0,002**	**0,013**	**0,034**	**0,002**	**0,002**	**0,001**	**3,528**
backhoe	1	175	34	1	5950	1,099	4,300	6,553	0,727	0,705	0,134	623,215	0,007	0,026	0,039	0,004	0,004	0,001	3,708
tractor/loader	1	300	34	1	10200	0,290	1,256	3,860	0,262	0,255	0,115	535,953	0,003	0,013	0,039	0,003	0,003	0,001	5,467
excavators	2	300	2	5	6000	0,278	1,224	3,653	0,253	0,245	0,115	535,989	0,002	0,007	0,022	0,002	0,001	0,001	3,216
crushing equipment	2	300	2	5	6000	0,309	0,924	4,446	0,211	0,205	0,114	530,107	0,002	0,006	0,027	0,001	0,001	0,001	3,181
dump tracks	115	175	0,6	1	12075	1,108	3,989	7,060	0,851	0,826	0,134	623,186	0,013	0,048	0,085	0,010	0,010	0,002	7,525
3rd stage													**0,026**	**0,099**	**0,212**	**0,020**	**0,019**	**0,005**	**23,096**
												TOTAL	**0,034**	**0,137**	**0,306**	**0,027**	**0,026**	**0,007**	**33,524**

D.3. TRAFFIC EMISSIONS

Table D.7. Traffic emissions during construction stage

Traffic scenario	Emissions [kg/day]			Fuel [kg/day]		Emissions [kg]			Fuel [kg]	
	CO	HC	NO_x	Gasoline	Diesel	CO	HC	NO_x	Gasoline	Diesel
Scenario 1 - motorway	33,21	0,33	0,29	167,92	308,35	5712,12	56,76	49,88	28882,24	53036,20
Scenario 1A - motorway	32,86	0,48	0,33	192,25	337,18	65,72	0,96	0,66	384,50	674,36
Scenario 1B - motorway	32,07	0,86	0,41	254,69	411,69	64,14	1,72	0,82	509,38	823,38
Scenario 2 - motorway	33,20	0,34	0,30	168,68	309,20	398,40	4,08	3,60	2024,16	3710,40
Scenario 3 - motorway	80,68	4,75	1,22	388,16	625,89	968,16	57,00	14,64	4657,92	7510,68
	night work motorway					6176,24	61,80	54,14	31290,90	57420,96
	day work motorway					6744,42	115,48	65,34	34049,54	61370,26

Table D.8. Traffic emissions during end-of-life stage

Traffic scenario	Emissions [kg/day]			Fuel [kg/day]		Emissions [kg]			Fuel [kg]	
	CO	HC	NO_x	Gasoline	Diesel	CO	HC	NO_x	Gasoline	Diesel
Scenario 1 - motorway	70,50	0,88	0,64	465,23	809,70	2397,00	29,92	21,76	15817,82	27529,80
Scenario 2 - motorway	70,50	0,89	0,64	466,54	811,18	282,00	3,56	2,56	1866,16	3244,72
Scenario 3 - motorway	70,50	1,69	0,82	611,17	983,78	282,00	6,76	3,28	2444,68	3935,12
Scenario 4 - motorway	70,50	0,90	0,65	467,58	812,36	282,00	3,60	2,60	1870,32	3249,44
Scenario 5 - motorway	1193,23	107,92	24,22	3105,01	4073,80	4772,92	431,68	96,88	12420,04	16295,20
Scenario 6 - motorway	443,72	37,46	8,68	1630,75	2264,26	1774,88	149,84	34,72	6523,00	9057,04
	night work motorway (3 lanes open)					2679,00	33,48	24,32	17683,98	30774,52
	day work motorway (3 lanes open)					2679,00	36,68	25,04	18262,50	31464,92
	night work motorway (2 lanes open)					2679,00	33,52	24,36	17688,14	30779,24
	day work motorway (2 lanes open)					7169,92	461,60	118,64	28237,86	43825,00
	reduce day work motorway (2 lanes open)					4171,88	179,76	56,48	22340,82	36586,84

Table D.9. Traffic emissions during operation stage

Traffic scenario	Emissions [kg/day]			Fuel [kg/day]		Emissions [kg]			Fuel [kg]	
	CO	HC	NO_x	Gasoline	Diesel	CO	HC	NO_x	Gasoline	Diesel
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	0,00	0,00	0,00	0,00	0,00
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	338,55	1,65	2,70	964,20	2005,35
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	330,45	3,60	3,15	1277,55	2359,05
	night work crossover					338,55	1,65	2,70	964,20	2005,35
	day work crossover					330,45	3,60	3,15	1277,55	2359,05
Combined action 1										
Scenario 1 - motorway	53,30	0,69	0,49	371,88	640,05					
Scenario 2 - motorway	53,30	0,70	0,49	373,17	641,51	1918,80	25,20	17,64	13434,12	23094,36
Scenario 3 - motorway	135,05	7,74	1,95	776,82	1230,44	4861,80	278,64	70,20	27965,52	44295,84
Scenario 4 - motorway	84,08	3,28	1,00	578,16	947,86	3026,88	118,08	36,00	20813,76	34122,96
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	338,55	1,50	2,70	961,65	2002,50
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	180,56	0,88	1,44	514,24	1069,52
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	176,24	1,92	1,68	681,36	1258,16
	night work motorway + night work crossover					2437,91	27,58	21,78	14910,01	26166,38
	night work motorway + day work crossover					2433,59	28,62	22,02	15077,13	26355,02
	day work motorway + night work crossover					5380,91	281,02	74,34	29441,41	47367,86
	day work motorway + day work crossover					5376,59	282,06	74,58	29608,53	47556,50
	reduce day work motorway + night work crossover					3545,99	120,46	40,14	22289,65	37194,98
	reduce day work motorway + day work crossover					3541,67	121,50	40,38	22456,77	37383,62
Combined action 2										
Scenario 1 - motorway	68,56	0,76	0,61	390,07	699,35	3290,88	36,48	29,28	18723,36	33568,80
Scenario 2 - motorway	68,56	0,77	0,62	391,09	700,51	6170,40	69,30	55,80	35198,10	63045,90
Scenario 3 - motorway	68,56	1,26	0,73	485,91	808,29	6170,40	113,40	65,70	43731,90	72746,10
Scenario 4 - motorway	68,53	0,78	0,62	391,90	701,42	6167,70	70,20	55,80	35271,00	63127,80
Scenario 5 - motorway	478,89	39,47	9,07	1528,41	2195,24	43100,10	3552,30	816,30	137556,90	197571,60
Scenario 6 - motorway	225,51	15,71	3,85	963,57	1467,13	20295,90	1413,90	346,50	86721,30	132041,70
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	338,55	1,50	2,70	961,65	2002,50
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	180,56	0,88	1,44	514,24	1069,52
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	176,24	1,92	1,68	681,36	1258,16
	night work motorway (3 lanes open)+ night work crossover					9980,39	108,16	89,22	55397,35	99686,72
	night work motorway (3 lanes open) + day work crossover					9976,07	109,20	89,46	55564,47	99875,36
	day work motorway (3 lanes open) + night work crossover					9980,39	152,26	99,12	63931,15	109386,92
	day work motorway (3 lanes open) + day work crossover					9976,07	153,30	99,36	64098,27	109575,56
	night work motorway (2 lanes open)+ night work crossover					9977,69	109,06	89,22	55470,25	99768,62
	night work motorway (2 lanes open) + day work crossover					9973,37	110,10	89,46	55637,37	99957,26
	day work motorway (2 lanes open) + night work crossover					46910,09	3591,16	849,72	157756,15	234212,42
	day work motorway (2 lanes open) + day work crossover					46905,77	3592,20	849,96	157923,27	234401,06
	luce day work motorway (2 lanes open) + night work crosso					24105,89	1452,76	379,92	106920,55	168682,52
	educe day work motorway (2 lanes open)+ day work crossov					24101,57	1453,80	380,16	107087,67	168871,16
Combined action 3										
Scenario 1 - motorway	69,79	0,83	0,63	433,43	763,56					
Scenario 2 - motorway	69,79	0,84	0,63	434,61	764,90	2512,44	30,24	22,68	15645,96	27536,40
Scenario 3 - motorway	69,79	1,49	0,78	555,87	906,82	2512,44	53,64	28,08	20011,32	32645,52
Scenario 4 - motorway	69,76	0,85	0,64	435,56	765,96	2511,36	30,60	23,04	15680,16	27574,56
Scenario 5 - motorway	855,32	75,68	17,09	2368,63	3194,57	30791,52	2724,48	615,24	85270,68	115004,52
Scenario 6 - motorway	347,45	27,87	6,55	1337,79	1915,34	12508,20	1003,32	235,80	48160,44	68952,24
Scenario 1 - crossover	22,57	0,10	0,18	64,11	133,50	338,55	1,50	2,70	961,65	2002,50
Scenario 2 - crossover	22,57	0,11	0,18	64,28	133,69	519,11	2,53	4,14	1478,44	3074,87
Scenario 3 - crossover	22,03	0,24	0,21	85,17	157,27	506,69	5,52	4,83	1958,91	3617,21
	night work motorway (3 lanes open)+ night work crossover					3370,10	34,27	29,52	18086,05	32613,77
	night work motorway (3 lanes open) + day work crossover					3357,68	37,26	30,21	18566,52	33156,11
	day work motorway (3 lanes open) + night work crossover					3370,10	57,67	34,92	22451,41	37722,89
	day work motorway (3 lanes open) + day work crossover					3357,68	60,66	35,61	22931,88	38265,23
	night work motorway (2 lanes open)+ night work crossover					3369,02	34,63	29,88	18120,25	32651,93
	night work motorway (2 lanes open) + day work crossover					3356,60	37,62	30,57	18600,72	33194,27
	day work motorway (2 lanes open) + night work crossover					31649,18	2728,51	622,08	87710,77	120081,89
	day work motorway (2 lanes open) + day work crossover					31636,76	2731,50	622,77	88191,24	120624,23
	luce day work motorway (2 lanes open) + night work crosso					13365,86	1007,35	242,64	50600,53	74029,61
	educe day work motorway (2 lanes open)+ day work crossov					13353,44	1010,34	243,33	51081,00	74571,95
Combined action 4										

D.4. USER COSTS

Table D.10. Life cycle user costs

Traffic scenario	User costs [€/day]			User costs [€]		
	DDC	VOC	Safety	DDC	VOC	Safety
Scenario 1 - motorway	904,91	1311,58	8,76	155644,52	225591,76	1506,72
Scenario 1A - motorway	1018,43	1466,88	9,71	2036,86	2933,76	19,42
Scenario 1B - motorway	1318,17	1866,53	12,09	2636,34	3733,06	24,18
Scenario 2 - motorway	908,12	1316,34	8,79	10897,44	15796,08	105,48
Scenario 3 - motorway	3984,53	2841,3	14,64	47814,36	34095,60	175,68
night work motorway				168578,82	244321,60	1631,62
day work motorway				206095,22	263420,42	1706,58
Construction						
Scenario 1 - crossover	364,45	535,33	2,76	0,00	0,00	0,00
Scenario 2 - crossover	365,18	536,41	2,76	5477,70	8046,15	41,40
Scenario 3 - crossover	453,37	667,16	3,46	6800,55	10007,40	51,90
night work crossover				5477,70	8046,15	41,40
day work crossover				6800,55	10007,40	51,90
Combined action 1						
Scenario 1 - motorway	1949,64	2810,74	13,75			
Scenario 2 - motorway	1955,1	2818,83	13,79	70383,60	101477,88	496,44
Scenario 3 - motorway	7161,82	5637,66	21,12	257825,52	202955,76	760,32
Scenario 4 - motorway	4095,65	4266,27	17,84	147443,40	153585,72	642,24
Scenario 1 - crossover	364,45	535,33	2,76	5466,75	8029,95	41,40
Scenario 2 - crossover	365,18	536,41	2,76	2921,44	4291,28	22,08
Scenario 3 - crossover	453,37	667,16	3,46	3626,96	5337,28	27,68
night work motorway + night work crossover				78771,79	113799,11	559,92
night work motorway + day work crossover				79477,31	114845,11	565,52
day work motorway + night work crossover				266213,71	215276,99	823,80
day work motorway + day work crossover				266919,23	216322,99	829,40
reduce day work motorway + night work crossover				155831,59	165906,95	705,72
reduce day work motorway + day work crossover				156537,11	166952,95	711,32
Combined action 2						
Scenario 1 - motorway	2080,92	3009,63	14,81	99884,16	144462,24	710,88
Scenario 2 - motorway	2085,24	3016,02	14,84	187671,60	271441,80	1335,60
Scenario 3 - motorway	2490,76	3611,16	17,93	224168,40	325004,40	1613,70
Scenario 4 - motorway	2088,65	3021,09	14,87	187978,50	271898,10	1338,30
Scenario 5 - motorway	25924,97	10597,27	32,27	2333247,30	953754,30	2904,30
Scenario 6 - motorway	11683,81	6863,34	24,36	1051542,90	617700,60	2192,40
Scenario 1 - crossover	364,45	535,33	2,76	5466,75	8029,95	41,40
Scenario 2 - crossover	365,18	536,41	2,76	2921,44	4291,28	22,08
Scenario 3 - crossover	453,37	667,16	3,46	3626,96	5337,28	27,68
night work motorway (3 lanes open)+ night work crossover				295943,95	428225,27	2109,96
night work motorway (3 lanes open) + day work crossover				296649,47	429271,27	2115,56
day work motorway (3 lanes open) + night work crossover				332440,75	481787,87	2388,06
day work motorway (3 lanes open) + day work crossover				333146,27	482833,87	2393,66
night work motorway (2 lanes open)+ night work crossover				296250,85	428681,57	2112,66
night work motorway (2 lanes open) + day work crossover				296956,37	429727,57	2118,26
day work motorway (2 lanes open) + night work crossover				2441519,65	1110537,77	3678,66
day work motorway (2 lanes open) + day work crossover				2442225,17	1111583,77	3684,26
reduce day work motorway (2 lanes open) + night work crossover				1159815,25	774484,07	2966,76
reduce day work motorway (2 lanes open)+ day work crossover				1160520,77	775530,07	2972,36
Combined action 3						
Scenario 1 - motorway	2295,03	3314,46	16,26			
Scenario 2 - motorway	2300,05	3321,91	16,3	82801,80	119588,76	586,80
Scenario 3 - motorway	2851,21	4091,93	19,95	102643,56	147309,48	718,20
Scenario 4 - motorway	2304,02	3327,8	16,33	82944,72	119800,80	587,88
Scenario 5 - motorway	47034,47	15967,96	43,49	1693240,92	574846,56	1565,64
Scenario 6 - motorway	19025,96	9262,19	30,13	684934,56	333438,84	1084,68
Scenario 1 - crossover	364,45	535,33	2,76	5466,75	8029,95	41,40
Scenario 2 - crossover	365,18	536,41	2,76	8399,14	12337,43	63,48
Scenario 3 - crossover	453,37	667,16	3,46	10427,51	15344,68	79,58
night work motorway (3 lanes open)+ night work crossover				96667,69	139956,14	691,68
night work motorway (3 lanes open) + day work crossover				98696,06	142963,39	707,78
day work motorway (3 lanes open) + night work crossover				116509,45	167676,86	823,08
day work motorway (3 lanes open) + day work crossover				118537,82	170684,11	839,18
night work motorway (2 lanes open)+ night work crossover				96810,61	140168,18	692,76
night work motorway (2 lanes open) + day work crossover				98838,98	143175,43	708,86
day work motorway (2 lanes open) + night work crossover				1707106,81	595213,94	1670,52
day work motorway (2 lanes open) + day work crossover				1709135,18	598221,19	1686,62
reduce day work motorway (2 lanes open) + night work crossover				698800,45	353806,22	1189,56
reduce day work motorway (2 lanes open)+ day work crossover				700828,82	356813,47	1205,66
Combined action 4						
Scenario 1 - motorway	2450,72	3535,99	17,32	83324,48	120223,66	588,88
Scenario 2 - motorway	2456,27	3544,22	17,36	9825,08	14176,88	69,44
Scenario 3 - motorway	3145,25	4469,94	21,45	12581,00	17879,76	85,80
Scenario 4 - motorway	2460,66	3550,73	17,39	9842,64	14202,92	69,56
Scenario 5 - motorway	65809,68	20682,36	53,14	263238,72	82729,44	212,56
Scenario 6 - motorway	24827,79	11135,86	34,57	99311,16	44543,44	138,28
night work motorway (3 lanes open)				93149,56	134400,54	658,32
day work motorway (3 lanes open)				95905,48	138103,42	674,68
night work motorway (2 lanes open)				93167,12	134426,58	658,44
day work motorway (2 lanes open)				346563,20	202953,10	801,44
reduce day work motorway (2 lanes open)				182635,64	164767,10	727,16
End-of-life						