UNIVERSITAT POLITÈCNICA DE VALÈNCIA

DEPARTMENT OF CONSTRUCTION ENGINEERING AND ENGINEERING PROJECTS

PhD Thesis

LIFE CYCLE ASSESSMENT APPLIED TO THE SUSTAINABLE DESIGN OF PRESTRESSED BRIDGES IN COASTAL ENVIRONMENTS

Author:

Ignacio J. Navarro Martínez

Advisors:

Dr. Víctor Yepes Piqueras
Dr. José V. Martí Albiñana

Valencia, June 2019

A mis padres

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my advisors Dr. Víctor Yepes and Dr. José Vicente Martí for their priceless guidance and support throughout these years. I appreciate all their contributions of ideas and time to make my Ph.D. experience productive and stimulating.

I would also like to extend my gratitude to Juan José Clemente for all the invaluable and fine advices he gave me during the last years. His encouragement has been crucial for me not to faint in hard times.

I want to thank Dr. Leonardo Sierra for his valuable and inspiring comments that helped me to dive into the world of social impacts. I also want to acknowledge Vicent and Paqui for their patience and help at the beginning of my research.

I also want to acknowledge my job colleagues for being accomplices to my failures and successes. Special thanks to my beloved friends from the Department of Transport Engineering and Infrastructure Nacho, Pablo Salvador and Pablo Martínez. Believe it or not, I owe you part of what I am today. I wish to sincerely thank Patri, for her faith in my research has been essential for me during the difficult final period of this thesis. She made my fears banish and helped me believe in myself.

At last, I want to express my deep gratitude to my parents for their relentless support. I believe that what they keep teaching me is the most valuable knowledge I could ever get.

Abstract

Sustainability has gained relevant presence in our society since its first definition in 1987 by the Brundtland Commission. Ever since, the scientific community has put significant efforts in the development of standards, tools and criteria to reach sustainable designs. Notwithstanding the above, such efforts have not been enough to outline a truly sustainable future in the short term. As a response to the actual, insufficient state of development, the United Nations have recently established the Sustainable Development Goals to be reached by 2030. In such Goals, explicit attention is paid to the role of infrastructures, which are revealed as key elements to ensure the achievement of the mentioned Goals. However, despite the relevant implications of infrastructure design, and despite the fact that most infrastructures are designed to serve a significant group of people over an intergenerational period of time, the design of sustainable and resilient infrastructures is still lacking of a standarised methodology to determine their sustainability along their life cycles from a holistic perspective. Currently, both the environmental and the economic life cycle assessment methodologies show a relatively mature state of development. However, the social dimension is still considered to be in an embryonic state, thus compromising the use of multidimensional sustainability assessment methods.

The present thesis proposes an extended methodology based on the environmentally oriented ISO 14040 standard to evaluate the life cycle sustainability of infrastructures through the simultaneous and consistent consideration of the three dimensions of sustainability, namely environment, economy and society. A new methodology is suggested here so as to assess infrastructures from a social dimension, while integrating such assessments into an ISO 14040 based framework. A multi criteria decision making technique is then applied to integrate the three sustainability dimensions into one single assessment. So as to take into consideration the non-probabilistic uncertainties involved in subjective weighting techniques, a novel neutrosophic approach for group AHP weights determination is proposed here. The sustainable design of a prestressed concrete bridge in a coastal environment is assumed as a conducting case study on which to construct the proposed methodology. The holistic approach in the sustainability assessment of infrastructures reveals itself to be essential rather than the usually conducted sustainability assessments based on the sole consideration of the environmental dimension. It has been observed that preventive maintenance results in better life cycle sustainability performance values when compared with reactive maintenance strategies. This thesis provides a guide for the sustainable design of concrete structures, although the suggested methodology can be applied to any type of infrastructure.

Resumen

La sostenibilidad ha ido adquiriendo una presencia relevante en nuestra sociedad desde su primera definición en 1987 por parte de la Comisión Brundtland. Desde entonces, la comunidad científica ha llevado a cabo importantes esfuerzos en el desarrollo de normativas, herramientas y criterios para lograr diseños en esa línea. A pesar de ello, estos esfuerzos no han sido suficientes para lograr trazar un futuro realmente sostenible a corto plazo. Como respuesta al estado actual e insuficiente de desarrollo, las Naciones Unidas han establecido recientemente los Objetivos de Desarrollo Sostenible, los cuales deben alcanzarse en 2030. En dichos Objetivos se atiende explícitamente al papel de las infraestructuras, que se revelan como elementos clave para asegurar la consecución de los mencionados Objetivos. Sin embargo, a pesar de las relevantes implicaciones del diseño de infraestructuras, y a pesar de que la mayoría de las infraestructuras están diseñadas para servir a un grupo significativo de personas durante un periodo intergeneracional de tiempo, el diseño sostenible y resiliente de infraestructuras todavía carece de una metodología estandarizada que considere sus ciclos de vida desde una perspectiva holística. En la actualidad, tanto las metodologías de evaluación del ciclo de vida ambiental como las económicas muestran un estado de desarrollo relativamente maduro. Sin embargo, la dimensión social todavía se considera en estado embrionario, comprometiendo por tanto el empleo de métodos de evaluación multidimensionales de la sostenibilidad.

La presente tesis propone una metodología extendida basada en la norma ISO 14040 de enfoque puramente medioambiental para evaluar la sostenibilidad del ciclo de vida de las infraestructuras mediante la consideración simultánea y coherente de las tres dimensiones de la misma, a saber, el medio ambiente, la economía y la sociedad. Se propone aquí una nueva metodología para evaluar las infraestructuras desde la dimensión social, integrando al mismo tiempo dichas evaluaciones en un marco basado en la norma ISO 14040. A continuación, se aplica una técnica de toma de decisión multicriterio para integrar las tres perspectivas. Con el fin de tener en cuenta las incertidumbres no probabilísticas implicadas en la asignación de pesos al emplear dichas técnicas, se propone aquí un nuevo enfoque neutrosófico para la determinación de los pesos resultantes de la aplicación de la técnica AHP con grupos de decisores. Se ha considerado como caso de estudio el diseño sostenible de un puente de hormigón pretensado en un entorno costero para construir la metodología propuesta. El enfoque holístico en la evaluación de la sostenibilidad de las infraestructuras se revela esencial frente a las habituales evaluaciones basadas únicamente en la consideración de la dimensión medioambiental. Se ha observado que el mantenimiento preventivo resulta más sostenible a lo largo del ciclo de vida en comparación con las estrategias de mantenimiento reactivo. Esta tesis proporciona una guía para el diseño sostenible de estructuras de hormigón, aunque la metodología sugerida puede aplicarse a cualquier tipo de infraestructura.

Resum

La sostenibilitat ha anat adquirint una presència rellevant en la nostra societat des de la seva primera definició el 1987 per part de la Comissió Brundtland. Des de llavors, la comunitat científica ha dut a terme importants esforços en el desenvolupament de normatives, eines i criteris per aconseguir dissenys sostenibles. Tot i això, aquests esforços no han estat suficients per aconseguir traçar un futur realment sostenible a curt termini. Com a resposta a l'estat actual i insuficient de desenvolupament, les Nacions Unides han establert recentment els Objectius de Desenvolupament Sostenible, els quals s'han d'assolir en 2030. En aquests Objectius s'atén explícitament al paper de les infraestructures, que es revelen com a elements clau per assegurar la consecució dels esmentats Objectius. No obstant això, tot i les rellevants implicacions del disseny d'infraestructures, i tot i que la majoria de les infraestructures estan dissenyades per servir a un grup significatiu de persones durant un període intergeneracional de temps, el disseny sostenible i resilient d'infraestructures encara no té una metodologia estandarditzada per determinar la seva sostenibilitat al llarg dels seus cicles de vida des d'una perspectiva holística. En l'actualitat, tant les metodologies d'avaluació del cicle de vida ambiental com les econòmiques mostren un estat de desenvolupament relativament madur. No obstant això, la dimensió social encara es considera en estat embrionari, comprometent per tant el desenvolupament de mètodes d'avaluació multidimensionals de la sostenibilitat.

La present tesi proposa una metodologia basada en la norma ISO 14040 d'orientació mediambiental per avaluar la sostenibilitat del cicle de vida de les infraestructures mitjançant la consideració simultània i coherent de les tres dimensions de la sostenibilitat, és a dir, el medi ambient, l'economia i la societat. Es proposa aquí una nova metodologia per avaluar les infraestructures des de la dimensió social, integrant al mateix temps aquestes avaluacions en un marc basat en la norma ISO 14040. A continuació, s'aplica una tècnica de presa de decisió multicriteri per integrar les tres dimensions de la sostenibilitat. Per tal de tenir en compte les incerteses no probabilístiques implicades en l'assignació de pesos a l'emprar aquestes tècniques, es proposa aquí un nou enfocament neutrosófic per a la determinació dels pesos resultants de l'aplicació de la tècnica AHP amb grups de decisors. S'ha considerat com a cas d'estudi el disseny sostenible d'un pont de formigó pretesat en un entorn costaner per construir la metodologia proposada. L'enfocament holístic en l'avaluació de la sostenibilitat de les infraestructures es revela essencial en contrast a les habituals avaluacions de la sostenibilitat basades únicament en la consideració de la dimensió mediambiental. S'ha observat que el manteniment preventiu resulta en millors valors de rendiment de sostenibilitat del cicle de vida en comparació amb les estratègies de manteniment reactiu. Aquesta tesi proporciona una guia per al disseny sostenible d'estructures de formigó, encara que la metodologia sugerida pot aplicar-se a qualsevol tipus d'infraestructura.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1. Background

Sustainable development was first defined in 1987 by the Brundtland Commission as a way of satisfying the actual needs of the society without compromising the ability of future generations to meet their own needs (WCED, 1987). Since then, sustainability has been increasingly in the spotlight of the scientific community and significant efforts have been made so as to understand and assess the impacts of products on the three dimensions of sustainability, namely society, economy and environment.

Sustainable design of products takes particular relevance when considering the construction sector. The construction industry has become in recent times one of the main environmental stressors of our society, being responsible for 30% of global energy consumption, 30% of greenhouse gas emissions, and 40% of raw material extraction (Choi, 2019). It is estimated that the world's production rate of cement in 2030 will be 1.4 times greater than the production rates existing in year 2013 (Imbabi et al., 2013). On the other hand, infrastructure is recognised as a main promoter of the economic well-being and social development of countries, since they contribute to the adequate provision of services and to the territorial vertebration. According to estimates made by the International Monetary Fund, investing an additional 1% of Gross Domestic Product (GDP) in infrastructure will result in an average increase of 1.5% in World's GDP within four years. Such estimate is in line with the fact that about 20 per cent of World Bank loans in recent years have been allocated to transport infrastructure (Kyriacou et al., 2019). In addition, the construction sector constitutes approximately 9% of Europe's Gross Domestic Product, and provides 18 million direct jobs (Favier et al., 2018).

Taking into consideration the great economic, environmental and social impacts associated with the construction sector, particular attention has been paid during the past recent years to the sustainability of infrastructures. So, one of the 17 Sustainable Development Goals (SDGs) established by the United nations in 2015 to be reached by 2030, in particular the ninth goal, refers explicitly to the urgent need of developing reliable, sustainable and resilient infrastructure in the near future. In addition, designing infrastructures from the point of view of sustainability is recognised to have a direct, positive impact towards the achievement of other SDGs (NCE, 2016). So, building sustainable infrastructure creates jobs and boosts regional economies (SDG 8 – Decent work and economic growth). The jobs created shall ensure gender equality (SDG 5) and contribute to reducing social inequalities (SDG 10) by guaranteeing fair salaries. Taking into consideration the material consumption related to the construction sector, sustainable infrastructure building shall as well contribute to meet SDG 12 (Responsible consumption and production). Sustainable infrastructure is also central to SDG 11 (Sustainable cities and communities) on building resilient and sustainable cities. Given the environmental impacts associated to the construction sector, the use of adequate construction materials and construction processes are essential to help fighting climate change (SDG 13 – Climate action), while ensuring life on land (SDG 15) by preserving biodiversity and reducing land occupation. Considering the above, and according to NCE (2016), investing in sustainable infrastructure is crucial to meet the main challenges facing the global community, namely reaching the Sustainable Development Goals and reducing climate risks in line with the Paris Agreement.

Given the relevant implications of infrastructure design, and considering that most infrastructures are designed to serve a significant group of people over a long, intergenerational period of time, the design of sustainable and resilient infrastructures has revealed itself as a key factor to reach a sustainable future.

In this context, special attention require those infrastructures exposed to aggressive environments that might induce degrading processes that compromise their functionality and derive in significant maintenance demands along their service lives. Since concrete is the world's most used construction material, and the second most consumed material in the world after water, the degradation of concrete structures and the management of adequate maintenance strategies have been shown to be one of the most demanding challenges facing the construction industry in recent times (Gjørv, 2013). Only in Europe, the annual costs resulting from the repair activities of concrete structures exceeds 15x10^9 €, taking more than 50% of Europe's annual construction budget (Zewdu et al., 2013). The impacts derived from maintenance of concrete structures becomes particularly important when it comes to concrete structures exposed to coastal environments, where chloride-induced corrosion is recognised as the most critical threat to concrete. According to a report emitted by NACE (2016), the costs directly derived from corrosion are estimated to be 3.4% of the global Gross Domestic Product. According to this report, it is estimated that adequate corrosion control practices could result in economic savings of between 15 and 35% of the annual costs of corrosion. It shall be emphasized that the aforementioned maintenance needs associated with corrosion entail, in turn, considerable environmental emissions derived from the resulting increasing concrete and cement production demands. Only the production of cement for concrete takes around 8% of carbon dioxide emitted annually around the world (Olivier et al., 2016). In Europe, approximately 20% of the cement produced is consumed on average in maintenance and rehabilitation activities (Favier et al., 2018). In Western Europe, the cement consumption rates associated to rehabilitation works is increasing from 34% of total cement consumed in construction activities in 2007, to 44% in 2017.

Taking into account the aforementioned social, economic and environmental importance of the construction sector, and considering the relevant proportion of those impacts that result from corrosion problems as stated above, it is a matter of course that the sustainable design of the high maintenance-demanding concrete structures exposed to coastal environments is of paramount importance to achieve the goals established by the 2030 Agenda. The question arises as to what extent the consideration of sustainability criteria can affect the design choice for structures in marine environments.

Sustainable design requires the simultaneous consideration of the economic, environmental and social dimensions of sustainability. However, it is often recognised that nowadays the sustainability assessments of infrastructures are usually based on the sole economic or environmental perspectives, and that insufficient attention is paid to the social dimension (Diaz-Sarachaga et al., 2016). The holistic approach required by any sustainability assessment is hindered by an important knowledge gap existing regarding the evaluation of the social impacts derived along the life cycle of products (Jørgensen, 2013). So, while the environmental life cycle assessment (LCA) methodology has become highly standarised both methodologically (ISO, 2006a) and in terms of practical implementation (ISO, 2006b), social life cycle assessment (SLCA) is a quite new line of research that needs further efforts to be consistently developed (Sierra et al., 2018a). It should ne also acknowledged that the assessment of the social life cycle impacts in a sustainability context is a complex and highly subjective task. In past recent times, the United Nations Environmental Program has developed some methodological guidelines for consistent SLCA of products (UNEP/SETAC, 2009), as a first attempt to establish the foundations of a future standarised methodology for social assessments based on the ISO 14040 series.

Despite such efforts, the great discrepancies existing both in the definition of social criteria and in the application of evaluation techniques regarding SLCA show that greater emphasis must be put so as to build coherent methodologies consistent with the accepted LCA standards. In consequence, a consistent and universally accepted methodology to evaluate the sustainability of products from a holistic perspective is still missing. Despite of the existing tools and standards that aim guiding the life cycle assessment of products (ISO, 2006a, 2006b; UNEP/SETAC, 2009, 2013), no consensus has yet been reached on how to properly integrate them into the sustainability assessment of infrastructures along their life cycle.

1.2. Research objectives

The present PhD thesis aims to propose an integrated life cycle-oriented sustainability assessment to aid the design of structures. Focus is put here on concrete infrastructures, bridges in particular, exposed to marine environments, given the relevant impacts expected to result from the maintenance required to guarantee the provision of an adequate functionality along their long service lives. In view of the presented context, and given the knowledge gaps identified, several research questions shall be raised in relation to the sustainability assessment of infrastructures:

Q1. How could we effectively integrate the three dimensions of sustainability into an ISO 14040-oriented sustainability assessment of infrastructures?

Q2. Could we develop a sustainability life cycle assessment methodology oriented towards the attainment of the recently established Sustainable Development Goals?

Q3. How could we enhance the existing Multi-Criteria Decision-Making (MCDM) techniques applied to sustainable design so as to effectively deal with the experts' subjectivity along the decision making process?

Q4. Are there significant differences when assessing the design of maintenance-demanding structures in coastal environments from a holistic perspective or from one-dimensional approaches?

The present PhD thesis proposes an extended methodology based on the LCA-oriented ISO 14040 standard adapted for the holistic sustainability assessment and design of resilient structures. The methodology is applied for the assessment of alternative designs of particular coastal structures considering the different dimensions of sustainability.

Following objectives were established for this PhD thesis:

1. To review the existing literature regarding the current trends in sustainability assessment techniques used for evaluating infrastructures. Focus is put on both the application of Multi-Criteria Decision-Making (MCDM) techniques and on the particular criteria considered to characterise sustainability.
2. To propose a methodology for the evaluation of social impacts along the life

cycle of a structure on the methodological basis of the standarised environmental LCA.

3. To propose a methodology to integrate the economic, environmental and social life cycle assessments of a structure into a single, ISO 14040 based approach.
4. To extend into a neutrosophic environment the actual fuzzy AHP techniques used in MCDM assessments to derive criteria relevancies, so as to capture the non-probabilistic uncertainties related to decision making processes.
5. To apply the resulting sustainability assessment methodology for the design alternative selection of a structure in a coastal environment considering their associated sustainability performances.
6. On the basis of a case study, to evaluate how economically-, environmentally- or socially-oriented structure maintenance strategies affect the design choice. To compare the results derived from such one-dimensional approaches with the holistic approach proposed here.

1.3. Methodology

The research methodology followed to meet the objectives established for this PhD thesis is structured into three stages.

Firstly, the State of the Art regarding the sustainability assessment of infrastructures is systematically reviewed. The literature review is focused on two aspects, namely the characterisation of sustainability in the field of infrastructures, and the MCDM techniques used to assess them. With regards to the first aspect, attention is paid to the particular criteria that are considered by the scientific community so as to evaluate the three dimensions of sustainability, as well as to the particular impact assessment techniques considered. With regards to the second aspect, focus has been put on both the weighting techniques applied and the particular MCDM techniques applied. How the linguistic variables are handled throughout the decision making process has also been investigated.

Secondly, a holistic framework for the sustainability assessment of infrastructures is proposed. The sustainable design of a prestressed concrete bridge in a coastal environment is assumed as a conducting case study on which to construct the proposed methodology. Several design alternatives are evaluated with different durability performances against chloride-induced corrosion of steel rebars in concrete. Alternatives that are usually considered in such environments are considered, namely surface treatments, the use of different types of corrosion-resistant steel rebars, the use of different types of additions to concrete, or the increase of the steel bars cover, among others. Each of these alternative designs is intended to increase the durability of the resulting bridge deck design. The life-cycle economic, environmental and social impacts are analysed so as to draw conclusions in relation to their respective sustainability performance. The maintenance demands of each design option are evaluated on the basis of a reliability approach.

Prior to constructing a sustainability life cycle assessment methodology to evaluate infrastructures, a conventional life cycle assessment is performed. Such assessment is focused on the usually considered economic and socioeconomic dimensions of sustainability when handling with the design of bridge structures. Performing such assessment will serve to show the drawbacks and knowledge gaps existing in the conventional life cycle assessments, and show the contributions of the consistent and ISO14040-based holistic methodology developed and exposed in the present dissertation.

As a first step in the construction of the sustainability assessment method proposed here, an environmental LCA is performed on the basis of a particular case study, following the ISO 14040 standard. This will set the basis for the definition of a functional unit, system boundaries and unit processes on which to construct a consistent holistic methodology. Then, a second study shows the incorporation of the economic dimension into the life cycle approach defined in the first study. In this step, optimal reliability-based maintenance strategies in chloride laden environments are introduced and evaluated for each alternative design. The design choice resulting from an environmentally oriented perspective is compared with the choice derived from an economic design approach. In a third study, a methodology for the social assessment of resilient infrastructures is suggested. The application of such methodology is founded on the methodological basis established in the two previous studies. Conclusions are drawn on which designs are preferred from a social perspective, considering the optimal reliability-based maintenance strategy for each one.

Finally, once a consistent, three-dimensional impact assessment has been defined, an MCDM technique is applied to integrate the three sustainability dimensions into one single assessment. So as to take into consideration the non-probabilistic uncertainties involved in subjective weighting techniques, such as AHP, a novel neutrosophic approach for group AHP weights determination is proposed here. This study reveals how the environmental, economic and social dimensions are related to each other when assessing the sustainability of bridge deck designs in coastal environments from a holistic point of view. Results are compared to the previously obtained ones related to one-dimensional approaches.

1.4. Dissertation structure

The dissertation presents the research structured into 9 chapters:

- **Chapter 1** describes the research context, the objectives and main contributions of the actual PhD thesis, as well as the research methodology conducted.
- **Chapter 2** presents a literature review on the sustainability assessment of infrastructures, covering aspects such as the trends in the application of MCDM methods that are currently applied, the weighting techniques used, the criteria considered to characterise sustainable designs, and the mathematical handling

of linguistic variables throughout the decision-making process.

- **Chapter 3** presents a life cycle cost assessment applied for the selection of bridge design alternatives, including the consideration of the social dimension as usually done in such assessments. The methodology presented shows a series of drawbacks and limitations when compared with a consistent ISO 14040-based sustainability analysis such as the one proposed here, as will be highlighted in the discussion section.
- **Chapter 4** presents an ISO 14040-based life cycle assessment applied to evaluate the environmental performance of alternative designs for prestressed concrete bridge decks exposed to marine chlorides. This chapter serves to present the ISO 14040 assessment methodology, on which the latter proposed three-dimensional sustainability assessment will be based.
- **Chapter 5** incorporates the economic dimension to the assessment. The reliability-based determination of the maintenance needs is also introduced here.
- **Chapter 6** proposes a novel methodology to assess the social dimension of infrastructure sustainable designs, on the basis of ISO 14040 standard.
- **Chapter 7** applies TOPSIS MCDM technique to evaluate the sustainability of the alternative designs. A neutrosophic Analytic Hierarchy Process (AHP) is proposed to derive the criteria relevancies out of the judgements emitted by a panel of experts.
- **Chapter 8** presents a discussion of the results obtained in the previous chapters.
- **Chapter 9** summarises the main general and case-specific conclusions drawn from this PhD thesis and suggests future lines of research.

Chapter 2

A review of multi-criteria assessment techniques applied to sustainable infrastructures design

Authors: Ignacio J. Navarro; Víctor Yepes; José V. Martí

Status: Manuscript published

Journal: *Advances in Civil Engineering*, Article ID 6134803, 16 pages, 2019

DOI: 10.1155/2019/6134803

JCR IF (2018) 1.104

JCR Category	Ranking	Quartile
Construction & Building Technology	44/63	Q3
Engineering, Civil	96/132	Q3

Presentation: Post-print (author version)

Abstract

Given the great impacts associated with the construction and maintenance of infrastructures in both the environmental, the economic and the social dimensions, a sustainable approach to their design appears essential to ease the fulfilment of the Sustainable Development Goals set by the United Nations. Multi-criteria decision making methods are usually applied to address the complex and often conflicting criteria that characterise sustainability. The present study aims to review the current state of the art regarding the application of such techniques in the sustainability assessment of infrastructures, analysing as well the sustainability impacts and criteria included in the assessments. The Analytic Hierarchy Process is the most frequently used weighting technique. Simple Additive Weighting has turned out to be the most applied decision making method to assess the weighted criteria. Although a life cycle assessment approach is recurrently used to evaluate sustainability, standarised concepts, such as cost discounting, or presentation of the assumed functional unit or system boundaries, as required by ISO 14040, are still only marginally used. Additionally, a need for further research in the inclusion of fuzziness in the handling of linguistic variables is identified.

Keywords Multi-criteria Decision Making • Infrastructure • Sustainable design • Life Cycle Assessment • Construction

2.1. Introduction

Sustainable development was first defined in 1987 by the Brundtland Commission as a way to meet the present needs of the society without compromising the ability of future generations to meet their own needs. Sustainable actions and decisions shall therefore be based on the simultaneous consideration of their economic, environmental and social consequences over time. Sustainable design of products, as an application of the sustainability concept in the industry, takes particular relevance when considering the construction sector. In recent times, construction industry has become one of the main environmental stressors of our society, since it is responsible for 30% of global energy consumption, 40% of raw material extraction and 30% of greenhouse gas emissions (Choi, 2019). In particular, only the production of cement for concrete contributes around 8% of global annual CO_2 emissions (Olivier et al., 2016). On the other hand, investments in public capital, such as infrastructures, promote the economic well-being and social development of countries, since they contribute to the territorial vertebration of regions and to the adequate provision of services. For example, about 20 per cent of World Bank loans in recent years have been allocated to transport infrastructure (Kyriacou et al., 2019).

So, given the relevant implications of infrastructure design, and considering that most infrastructures are designed to serve a significant group of people over a long, intergenerational period of time, the assessment of the different dimensions of sustainability related to the infrastructure design has been in the spotlight of many researchers in recent times. Studies have been conducted on cost optimisation of infrastructure design (García-Segura et al., 2014a; Yepes et al., 2017) and maintenance (Frangopol, 2011; Safi et al., 2015). Attention has also been paid to the environmental impacts derived along the life cycle of structures, from bridges (Navarro et al., 2018c; Zhang et al., 2016; García-Segura et al., 2018) to buildings (Van den Heede & De Belie, 2014), as well as those derived from particular construction processes, such as concrete production (Braga et al., 2017). Social impacts related to the use of different building materials (Hossain et al., 2018) for building construction (Dong & Ng, 2015) and for road infrastructure projects (Sierra et al., 2018b) have also been assessed in recent years. However, the current state of science lacks an objective and universal methodology to properly assess the sustainability of a particular infrastructure design. Thus, although standarised tools exist to assess the different life cycle impacts of products, there is no consensus on how to cope with the simultaneous consideration of the three pillars that define sustainability, nor on what particular criteria should be considered in the decision-making process of sustainable infrastructure design (Montalbán-Domingo et al., 2018).

To deal with the assessment of the conflicting dimensions of sustainability in a multi-stakeholder and long-term context like infrastructure design, the use of multi-criteria decision-making (MCDM) techniques has revealed itself as the most suitable approach compared to other methods commonly used in infrastructure design, such as single- or multi-objective optimisation. MCDM techniques allow the decision maker to assess complex problems involving multiple and divergent criteria on the basis of the subjective judgements of a panel of experts or of stakeholders affected by the decision. Therefore, this paper is devoted to analysing the current trends regarding the application of MCDM techniques to the sustainability assessment of infrastructure design, paying special attention to the particular criteria considered in these assessments.

The rest of the paper is structured as follows. Section 2 presents the research methodology, exposing the research questions to be answered by means of this manuscript, as well as describing the data acquisition strategy followed in the review. Section 3 presents the results obtained. In particular, Section 3.1 provides a general overview of the gathered data; Section 3.2 presents the indicators selected to characterise each of the three dimensions of sustainability, as well as the methods considered to assess such impacts. Section 3.3 presents a brief review on how qualitative data is treated in the analysed manuscripts; Section 3.4 investigates the normalisation techniques found in the reviewed literature; Section 3.5 describes the weighting techniques used; Section 3.6 presents the methods used in the analysed studies to aggregate the weighted indicators; Section 3.7 offers an overview of the aspects object of sensitivity analyses in sustainability MCDM assessments; Section 3.8 presents how the subjectivity of the experts' judgements is handled throughout the whole decision making process. Finally, Section 4 provides the conclusions of the present literature review.

2.2. Materials and Methods

2.2.1. Research question

The present study formulates two research questions, namely, how MCDM methods have been applied for the sustainability assessment of infrastructures in recent times, and what particular impact criteria have been considered in these evaluations as representative of sustainability of an infrastructure design.

2.2.2. Data sampling strategy

The data collection process performed in the present literature review consists of two stages, as shown in Fig. 1. The objective of the first stage is to create a preliminary set of contributions to serve as a basis for the construction of a final set through an appropriate filtering and expanding process in a second stage.

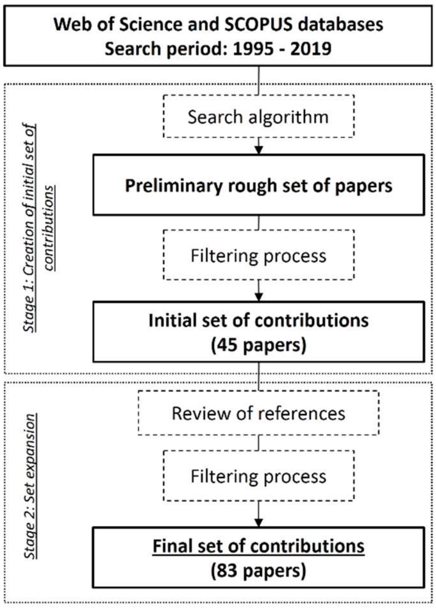


Figure 2.1.Systematic literature review

The search is carried out through the scientific bibliographic databases SCOPUS and Web of Science. The search period is established from 1995 to 2019, since there is no evidence of relevant contributions before that date. The search algorithm used to identify the articles conforming the preliminary set consists of a combination of the terms “Multi-criteria decision making”, “MCDM” and “Sustainability” along with other civil engineering-related terms, such as “Construction” or “Infrastructure”, by means of the Boolean operators “AND” and “OR”.

To filter the obtained results, some exclusion criteria have been followed to build the first set of papers. First, only original, peer-reviewed scientific articles and conference proceedings are included. Secondly, those manuscripts that do not clearly identify either the MCDM technique used or the sustainability criteria considered are excluded. Third, articles are required to consider at least two of the three dimensions of sustainability in the assessment through an appropriate selection of decision criteria. Finally, it should be taken into account that only articles written in English are considered in this study. This structured filtering process resulted in an initial set of 45 papers.

Once the initial set of contributions is generated, the references included in the selected manuscripts are then reviewed and analyzed. The set is then expanded by applying the filtering process exposed above to the articles referenced in the papers included in the first set, which results in a final and expanded set of manuscripts. This sampling technique has been used previously in other literature review works (Zamarrón-Mieza et al., 2017; Sierra et al., 2018). The expanded final set has resulted here in 83 contributions.

2.3. Results and Discussion

2.3.1. General overview of the retrieved data

Although in 2007 there was a first rebound in the number of publications regarding sustainability assessment of infrastructures, the number of contributions increases drastically in 2015 (Fig. 2.2). Over 50% of the publications applying MCDM techniques to sustainable infrastructure design were made between 2015 and the present. This increase is explained by the fact that it was in 2015 when the General Assembly of the United Nations established the Sustainable Development Goals for the first time. Among the 17 Goals set, some of them are related to sustainable economic growth, decent work, resilient and sustainable infrastructures, and climate action. This would explain the great efforts made by the scientific community since 2015 to contribute to providing tools that allow the sustainable design of infrastructures.

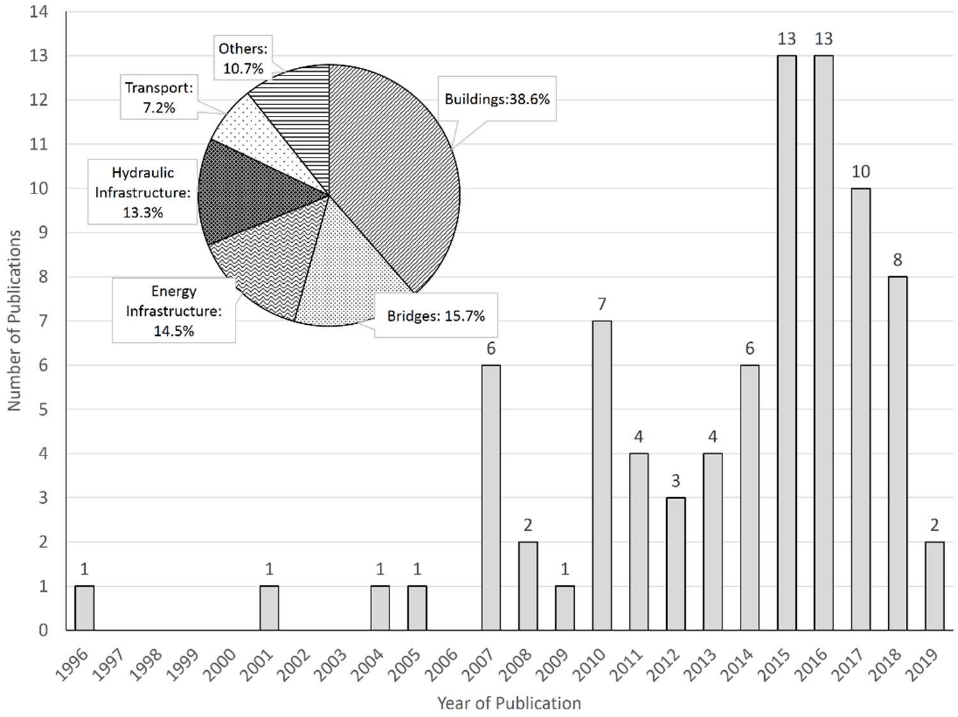


Figure 2.2. Distribution of contributions per year (1996 – 2019)

After reviewing the gathered data, 6 different main applications of MCDM techniques were identified:

- Buildings. 38.6% of the analysed contributions (32 papers) are devoted to assessing the sustainability of different aspects related to the design of buildings. While some authors have focused on the design assessment of particular elements of the building structure, such as slabs (Blanco et al., 2016; Reza et al., 2011), columns (Pons & De la Fuente, 2013) and beams (Mosalam et al., 2018), others pay attention to the sustainable design of building envelopes (Saparauskas et al., 2010; Perini & Rosasco, 2013; Jalaei et al., 2015; Gilani et al., 2017; Moussavi et al., 2017; Guzmán-Sánchez et al., 2018; Hashemkhani et al., 2018; Invidiata et al., 2018; Kamali et al., 2018). Pons and Aguado (2012), Akadiri et al. (2013), Motuziene et al. (2016), Samani et al. (2015), and Nassar et al. (2016) also compare the sustainability of the application of different construction materials to buildings. Research is also conducted on the development of indicators suitable to measure the sustainability of buildings (Alwaer & Clemens-Croome, 2010; Yu et al., 2012; Drejeris & Kavolynas, 2014; Ignatius et al., 2016; Mahdiraji et al., 2018).

Particular attention is paid to the sustainable design of industrial buildings (Lombera & Aprea, 2010; Cuadrado et al., 2015; Cuadrado et al., 2016; Heravi et al., 2017). Formisano and Mazzolani (2015), and Terracciano et al. (2015) evaluate the sustainability of different alternatives for energetic retrofitting of buildings in locations with high seismicity. Finally, other purposes are covered, such as restoration alternatives for derelict buildings (Zavadskas et al., 2007, 2010), or optimal building location (Hosseini et al., 2016).

- Bridges. 15.7% of the reviewed manuscripts (13 papers) deal with the sustainability assessment of bridges. Most of them focus either on the sustainability of bridge deck designs (Malekly et al., 2010; Farkas, 2011; Gervásio & Da Silva, 2012; Balali et al., 2014; Jakiel & Fabianowsky, 2015; Yepes et al., 2015a; Kripka et al., 2019) or on the selection of optimal maintenance strategies (Wang et al., 2008; Dabous & Alkass, 2008; Rashidi et al., 2016). Attention is also paid to the sustainability of different strengthening or repair schemes (Mikawi, 1996; Rashidi et al., 2017) and to the selection of the most sustainable construction method (Chen, 2014).

- Energy Infrastructure. 14.5 % of the papers (12 articles in total) deal with the sustainability of different topics related to energy infrastructure, such as the selection of the most sustainable energy production system (Begic & Afgan, 2007; Jovanovic et al., 2009; Kaya & Kahraman, 2010; Barros et al., 2015; Klein & Whalley, 2015; Montajabiha, 2016; Väisänen et al., 2016), the selection of the optimal location of energy production plants (Fetanat & Khorasaninejad, 2015; Medina-González et al., 2018), and the sustainability performance evaluation of different designs of wind turbines and towers (Gumus et al., 2016; De la Fuente et al., 2017a; Pons et al., 2017).

- Hydraulic Infrastructure. 13.3% of the publications handle with the sustainability of different hydraulic infrastructures, such as dams (Gento, 2004; Afshar et al., 2011; Sun et al., 2013), urban drainage (Martin et al., 2007; Dong et al., 2008; Tahmasebi & Yazdandoost, 2018), sewerage systems (De la Fuente et al., 2016b) and water supply systems (Jaber & Mohsen, 2001; Abrishamchi et al., 2005; Pascal et al., 2017;Chhipi-Shrestha et al., 2017).

- Transport Infrastructure. 7.2% of the manuscripts deal with the sustainability of different elements and topics related to transport systems, such as the sustainable design of road pavements (Kucukvar et al., 2014; Jato-Espino et al., 2014; Torres-Machí et al., 2015; Santos et al., 2019), the selection of the optimal road location (Hashemkhani et al., 2011) or the development of assessment tools for the evaluation of transport projects (Oses et al., 2017).

- Others. The remaining papers reviewed (10.7%) cover a variety of aspects related to sustainable infrastructure design, such as the assessment of tunnel projects (De la Fuente et al., 2016a; De la Fuente et al., 2017b), ports (Asgari et al., 2015), location of demolition waste facilities (Banias et al., 2010), the selection of coating materials for construction (Rochikashvili & Bongaerts, 2016), and the development of assessment tools for the evaluation of construction projects in general terms (Ugwu & Haupt, 2007; Saparauskas, 2007; Reyes et al., 2014; Dobrovolskiiene & Tamosiuniene, 2016).

2.3.1. Impact assessment and selection of indicators

As sustainability life cycle assessments are based on the life cycle impacts derived from the different activities considered in the analysis, it is essential to define in the early stages of the decision process not only which impacts (criteria) are going to be considered in the analysis, but also how those impacts are going to be assessed. Of the analysed publications, 74.7% (62 papers) base their assessments on the impacts derived from at least two different stages of the life cycle of the infrastructure under study. To evaluate the life cycle impacts and establish coherent impact categories, an objective methodology has been standarised in the environmental field (ISO, 2006a, 2006b) to allow a rigorous assessment of different alternatives. Although such an ISO standard does not yet exist for the economic field, life cycle costing shows a highly mature state of development (Hunkeler et al., 2008). However, the evaluation of the social dimension of sustainability is still under development. It was first in 2009 when an attempt was made to establish an objective methodology to identify and evaluate social impacts through the 'Guidelines for social life cycle assessment of products' (UNEP/SETAC, 2009), which relies on the ISO standarised methodology for environmental impact assessments. Notwithstanding the above, only 4 out of the 83 reviewed papers (4.8%) follow the ISO methodology, explicitly defining an adequate functional unit and the system boundaries assumed in the assessment (Reza et al., 2011; Motuziene et al., 2016; Samani et al., 2015; Väisänen et al., 2016). Although not strictly following the ISO methodology, other authors do explicitly define the functional unit and system boundaries (Invidiata et al., 2018; De la Fuente et al., 2016a, 2016b, 2017b; Kucukvar et al., 2014).

2.3.1.1 *Economic criteria*

Out of the 83 reviewed manuscripts, only 7 do not consider economic criteria in their sustainability assessments. Among the rest, three main economic impacts have been identified, namely the construction or implementation costs, the costs derived from maintenance and operation of the infrastructure, and the costs resulting from the end of life stage. 94.7% of the reviewed papers that take into account the economic dimension of sustainability assume the costs derived from the installation of the infrastructure relevant in the assessment. Only 13.3% of the reviewed papers consider the direct costs associated with the disposal of the infrastructure in their assessments, and 63.9% the costs of the maintenance and operation life cycle stage.

It shall be noted that, among the reviewed papers, only 5 explicitly present the assumed discount rates that allow to transform future costs into present currency values. In the field of building design, Mosalam et al. (2018) consider a discount rate of 3%, Jalei et al. (2015) assume a discount rate of 5%, and Perini and Rosasco (2013) evaluates three different economic scenarios, with discount rates that range from 4.5% to 5.5%. Torres-Machí et al. (2015), when assessing the sustainability of road pavement treatments, assume a discount rate of 5%. Klein and Whalley (2015) evaluate a cost discounting range that varies from 3% up to 10%.

2.3.1.2 *Environmental criteria*

Regarding the environmental dimension of sustainability, seven main impact categories have been found to be recurrent in the reviewed studies, namely emission of pollutants, energy consumption, resources depletion, waste generation, land use, eutrophication, and ozone layer depletion. Table 2.1 presents the main environmental indicators considered in the reviewed studies for the evaluation of the mentioned criteria.

The emission of pollutants as an indicator of the environmental impact of an infrastructure is the most used criterion within the reviewed papers. It considers the emissions derived from the production of construction materials and construction works, but also from the externalities associated with the construction of infrastructure and its maintenance, such as traffic congestion (Mikawi, 1996). While some authors explicitly focus on particular air pollutants, such as carbon dioxide (Perini & Rosasco, 2013; Moussavi et al., 2017; Invidiata et al., 2018; Kripka et al., 2019; De la Fuente et al., 2016a), SO_2 or NO_x (Begic & Afgan, 2007; Väisänen et al., 2016), or general greenhouse gases (Kamali et al., 2018; Gumus et al., 2016), attention is also paid to pollutants emitted to water (Martin et al., 2007; Dong et al., 2008; Tahmasebi & Yazdandoost, 2018) when dealing with urban water systems.

46.3% of the articles include energy consumptions as an additional measure of the environmental impact of an infrastructure. The majority of articles consider the energy needed to produce the construction materials and to construct the particular infrastructure under assessment (Kamali et al., 2018; Motuziene et al., 2016; Pons et al., 2017), while certain authors also consider the energy savings resulting from building envelope designs (Perini & Rosasco, 2013).

Environmental Criteria	Indicator	Assessment	References
Emission of pollutants	kg CO_2/output unit	Quantitative	Blanco et al. (2016), Reza et al. (2011), Pons & De la Fuente (2013), Gilani et al. (2017), Moussavi et al. (2017), Guzmán-Sánchez et al. (2018), Invidiata et al. (2018), Pons & Aguado (2012), Motuziene et al. (2016),

			Samani et al. (2015), Nassar et al. (2016), Yepes et al. (2015), Begic & Afgan (2007), Jovanovic et al. (2009), Barros et al. (2015), Klein & Whalley (2015), Väisänen et al. (2016), Medina-González et al. (2018), Pons et al. (2017), De la Fuente et al. (2016a, 2016b, 2017a, 2017b), Kucukvar et al. (2014), Jato-Espino et al. (2014), Torres-Machí et al. (2015), Santos et al. (2019), Oses et al. (2017)
	kg SO_2/output unit	Quantitative	Reza et al. (2011), Samani et al. (2015), Begic & Afgan (2007), Barros et al. (2015), Klein & Whalley (2015), Väisänen et al. (2016), Medina-González et al. (2018), Oses et al. (2017)
	kg NOx/output unit	Quantitative	Reza et al. (2011), Samani et al. (2015), Begic & Afgan (2007), Jovanovic et al. (2009), Jovanovic et al. (2009), Barros et al. (2015), Klein & Whalley (2015), Väisänen et al. (2016), Medina-González et al. (2018), Oses et al. (2017)
	€/kg pollutant removed	Quantitative	Perini & Rosasco (2013)
	Costs of medical care needs due to pollution (€)	Quantitative	Mikawi (1996)
	Oxygen, Nitrogen and Phosphates emitted to water	Quantitative	Dong et al. (2008)
	Asesment by experts through point scale	Qualitative	Saparauskas et al. (2010), Jalaei et al. (2015), Hashemkhani et al. (2018), Kamali et al. (2018), Akadiri et al. (2013), Yu et al. (2012), Drejeris & Kavolynas (2014), Mahdiraji et al. (2018), Cuadrado et al. (2015), Heravi et al. (2017), Farkas (2011), Balali et al. (2014), Jakiel & Fabianowski (2015), Wang et al. (2008), Dabous & Alkass (2008), Rashidi et al. (2016, 2017), Chen (2014), Kaya & Kahraman (2010), Montajabiha (2016), Fetanat & Khorasaninejad (2015), Gumus et al. (2016), Sun et al. (2013) Tahmasebi & Yazdandoost (2018), Jaber & Mohsen (2001), Pascal et al. (2017), Hashemkhani et al. (2011), Asgari et al. (2015), Rochikashvili & Bongaerts (2016), Ugwu & Haupt (2007), Reyes et al. (2014), Dobrovolskiiene & Tamosiuniene (2016)
Energy consumption	MJ (MWh)/output unit	Quantitative	Blanco et al. (2016), Reza et al. (2011), Gilani et al. (2017), Moussavi et al. (2017), Guzmán-Sánchez et al. (2018), Invidiata et al. (2018), Pons & Aguado (2012), Motuziene et al. (2016), Samani et al. (2015), Nassar et al. (2016), Medina-González et al. (2018), De la Fuente et al. (2017a) Gento

			(2004) De la Fuente et al. (2016b), Kucukvar et al. (2014), Jato-Espino et al. (2014), Santos et al. (2019), De la Fuente et al. (2016a, 2017b)
	€/year/output unit	Quantitative	Perini & Rosasco (2013)
	Tonnes of oil equivalent (TOE)	Quantitative	Saparauskas (2007)
	Asessment by experts through point scale	Qualitative	Jalaei et al. (2015), Hashemkhani et al. (2018), Kamali et al. (2018), Akadiri et al. (2013), Yu et al. (2012), Drejeris & Kavolynas (2014), Ignatius et al. (2016), Lombera & Aprea (2010), Heravi et al. (2017), Gumus et al. (2016), Asgari et al. (2015), Dobrovolskiiene & Tamosiuniene (2016)
Raw material consumption	Consumption/output unit	Quantitative	Blanco et al. (2016), Reza et al. (2011), Pons & De la Fuente (2013), Gilani et al. (2017), Moussavi et al. (2017), Guzmán-Sánchez et al. (2018), Samani et al. (2015), Klein & Whalley (2015), Medina-González et al. (2018), De la Fuente et al. (2017a) Gento (2004) Kucukvar et al. (2014), Jato-Espino et al. (2014), Santos et al. (2019), De la Fuente et al. (2016a, 2017b)
	Asessment by experts through point scale	Qualitative	Jalaei et al. (2015), Kamali et al. (2018), Akadiri et al. (2013), Yu et al. (2012), Drejeris & Kavolynas (2014), Ignatius et al. (2016), Lombera & Aprea (2010), Cuadrado et al. (2015), Heravi et al. (2017), De la Fuente et al. (2016b), Banias et al. (2010), Ugwu & Haupt (2007)
Waste generation	kg/output unit	Quantitative	Gilani et al. (2017), Pons & Aguado (2012), Samani et al. (2015), Medina-González et al. (2018), Kucukvar et al. (2014)
	Asessment by experts through point scale	Qualitative	Hashemkhani et al. (2018), Kamali et al. (2018), Akadiri et al. (2013), Yu et al. (2012), Drejeris & Kavolynas (2014), Lombera & Aprea (2010), Cuadrado et al. (2015), Heravi et al. (2017), Asgari et al. (2015), Banias et al. (2010), Ugwu & Haupt (2007), Reyes et al. (2014)
Land use	m^2/output unit		Klein & Whalley (2015)
	Asessment by experts through point scale	Qualitative	Perini & Rosasco (2013), Guzmán-Sánchez et al. (2018), Hashemkhani et al. (2018), Yu et al. (2012), Drejeris & Kavolynas (2014), Lombera & Aprea (2010), Heravi et al. (2017), Malekly et al. (2010), Jakiel & Fabianowski (2015), Kaya & Kahraman (2010), Montajabiha (2016), Fetanat & Khorasaninejad (2015), Gumus et al. (2016),

			Afshar et al. (2011) Sun et al. (2013) Hashemkhani et al. (2011), Banias et al. (2010), Ugwu & Haupt (2007)
	Aquatic ecotoxicity, salinity, biological indices	Quantitative	Väisänen et al. (2016), Martin et al. (2007), Dong et al. (2008)
Eutrophication	kg Phosphate/output unit	Quantitative	Samani et al. (2015), Nassar et al. (2016), Väisänen et al. (2016), Medina-González et al. (2018), Santos et al. (2019)
	Asessment by experts through point scale	Qualitative	Lombera & Aprea (2010), Afshar et al. (2011) Sun et al. (2013), Ugwu & Haupt (2007)
Ozone depletion	kg CFC (Chlorofluorocarbons)/output unit	Quantitative	Motuziene et al. (2016), Samani et al. (2015), Nassar et al. (2016), Väisänen et al. (2016), Medina-González et al. (2018), Santos et al. (2019)
	Asessment by experts through point scale	Qualitative	Akadiri et al. (2013), Lombera & Aprea (2010)

Table 2.1. Main environmental criteria and indicators

The depletion of natural resources is accepted as one of the main consequences of unsustainable construction practices. 32 studies account for the consumption of natural resources into construction materials in their sustainability assessments. Some authors take into consideration the positive environmental impact of using recycled materials (Jalaei et al., 2015; Guzmán-Sánchez et al., 2018; Jato-Espino et al., 2014) or using potentially reusable ones (Gilani et al., 2017; Akadiri et al., 2013; Nassar et al., 2016; Santos et al., 2019).

Given that the construction industry is considered one of the greatest producers of wastes in a global scale (Marzourk & Azab, 2014), efforts have been made to account their harmful impact in environmental assessments. 25.3% of the analysed manuscripts take into consideration the generation of waste resulting from the industrial processes involved in the production of construction materials or from the demolition works. Consideration is given to both solid wastes from construction materials (Mosalam et al., 2018; Gilani et al., 2017) and water wastes (Chhipi-Shrestha et al., 2017).

Land use is an environmental concept that implies both land occupation and transformation of land. Land use derived from the construction of infrastructures results in damage to ecosystems and loss of biodiversity. From the 83 reviewed articles, 25 (30.1%) take land use into account as an indicator of the environmental damage derived from infrastructures. The effects of land use have been accounted for as local ecosystem disturbances (Banias et al., 2010), destruction of wildlife habitats (Heravi et al., 2017; Hashemkhani et al., 2011), proximity to migratory paths (Fetanat & Khorasaninejad, 2015), effects on biodiversity (Guzmán-Sánchez et al., 2018; Väisänen et al., 2016).

Given the particular scope of their study, Perini and Rosasco (2013) consider the creation of habitats.

Eutrophication is the consequence of the emission of particular pollutants, mainly phosphate, derived from human activities to water, promoting an uncontrolled growth of algae that shall compromise the survival of other water species. This environmental impact has been considered by nine articles (10.8% of total)

Ozone layer is essential for life, as it hinders harmful solar ultraviolet radiation. Ozone layer depletion because of the emission of substances containing chlorine and bromine atoms has been accounted in eight studies as an additional indicator capable of measuring the environmental damage derived from infrastructures and their associated activities.

2.3.1.3 *Social criteria*

Regarding the social dimension of sustainability, the criteria assessed in the studies reviewed shall be grouped into eight main categories, namely social wellbeing, aesthetics, job creation, development of local economies, externalities, innovation, culture, and health. Table 2.2 presents the main social indicators considered in the reviewed studies for the evaluation of the mentioned criteria.

Social Criteria	Indicator	Assessment	References
Social wellbeing	Increase of income of local population (€/year)	Quantitative	Zavadskas & Antucheviciene (2007, 2010)
	Asessment by experts through point scale	Qualitative	Jalaei et al. (2015), Guzmán-Sánchez et al. (2018), Hashemkhani et al. (2018), Kamali et al. (2018), Nassar et al. (2016), Drejeris & Kavolynas (2014), Ignatius et al. (2016), Mahdiraji et al. (2018), Heravi et al. (2017), Kaya & Kahraman (2010), Montajabiha (2016), Fetanat & Khorasaninejad (2015), Gumus et al. (2016), Afshar et al. (2011) Sun et al. (2013) Tahmasebi & Yazdandoost (2018), Jato-Espino et al. (2014), Hashemkhani et al. (2011), Ugwu & Haupt (2007), Dobrovolskiiene & Tamosiuniene (2016)
	Habitability increase (m^2)	Quantitative	Pons & De la Fuente (2013)
	Comfort (hours/year)	Quantitative	Invidiata et al. (2018)
Aesthetics	Asessment by experts through point scale	Qualitative	Saparauskas et al. (2010), Perini & Rosasco (2013), Jalaei et al. (2015), Moussavi et al. (2017), Kamali et al. (2018), Akadiri et al. (2013), Yu et al. (2012), Ignatius et al. (2016), Lombera & Aprea (2010), Cuadrado et al.

			(2015), Malekly et al. (2010), Farkas (2011), Balali et al. (2014), Jakiel & Fabianowski (2015), Wang et al. (2008), Rashidi et al. (2017), Chen (2014), Barros et al. (2015), Fetanat & Khorasaninejad (2015), Gento (2004) Afshar et al. (2011) Tahmasebi & Yazdandoost (2018), Jato-Espino et al. (2014), Banias et al. (2010), Rochikashvili & Bongaerts (2016), Ugwu & Haupt (2007)
Job creation	Hours of work/output unit	Quantitative	Begic & Afgan (2007), Jovanovic et al. (2009), Klein & Whalley (2015), Väisänen et al. (2016), Kucukvar et al. (2014)
	Gross Value Added/hour worked	Quantitative	Saparauskas (2007)
	Unemployment rate	Quantitative	Banias et al. (2010)
	Employment increase (%)	Quantitative	Zavadskas & Antucheviciene (2007, 2010)
	Asessment by experts through point scale	Qualitative	Heravi et al. (2017), Kaya & Kahraman (2010), Montajabiha (2016), Gumus et al. (2016), Afshar et al. (2011)
Development of local economies	GDP increase (€)	Quantitative	Zavadskas & Antucheviciene (2007, 2010), Saparauskas (2007)
	Landn value degradation (€/m^2)	Quantitative	Banias et al. (2010)
	Asessment by experts through point scale	Qualitative	Kamali et al. (2018), Akadiri et al. (2013), Heravi et al. (2017), Barros et al. (2015), Fetanat & Khorasaninejad (2015), Gumus et al. (2016), Afshar et al. (2011) Sun et al. (2013), Ugwu & Haupt (2007)
Externalities	Noise pollution (dB)	Quantitative	Blanco et al. (2016), Santos et al. (2019), Oses et al. (2017), De la Fuente et al. (2016a), De la Fuente et al. (2017b), Banias et al. (2010)
	Traffic congestion (travel time)	Quantitative	Santos et al. (2019)
	Vehicle opertaing costs (€), User delay costs (€)	Quantitative	Gervásio & Da Silva (2012)
	Asessment by experts through point scale	Qualitative	Hashemkhani et al. (2018), Kamali et al. (2018), Drejeris & Kavolynas (2014), Lombera & Aprea (2010), Heravi et al. (2017), Malekly et al. (2010), Balali et al. (2014), Dabous & Alkass (2008), Rashidi et al. (2016), Chen (2014), Reyes et al. (2014)
Innovation	Asessment by experts through point scale	Qualitative	Yu et al. (2012), Drejeris & Kavolynas (2014), Ignatius et al. (2016), Heravi et al. (2017), Gento (2004), Ugwu & Haupt (2007)

Culture	Asessment by experts through point scale	Qualitative	Hashemkhani et al. (2018), Kamali et al. (2018), Yu et al. (2012), Heravi et al. (2017), Rashidi et al. (2017), Fetanat & Khorasaninejad (2015), Afshar et al. (2011), Ugwu & Haupt (2007)
Health and safety	Injuries/output unit	Quantitative	Jovanovic et al. (2009), Barros et al. (2015), Kucukvar et al. (2014)
	Fatalities/output unit	Quantitative	Klein & Whalley (2015)
	Particulate Matter (PM) concentration (PM2,5 / PM10)	Quantitative	Nassar et al. (2016), Santos et al. (2019)
	Safety costs (€)	Quantitative	Gervásio & Da Silva (2012)
	Asessment by experts through point scale	Qualitative	Blanco et al. (2016), Pons & De la Fuente (2013), Hashemkhani et al. (2018), Kamali et al. (2018), Pons & Aguado (2012), Akadiri et al. (2013), Drejeris & Kavolynas (2014), Lombera & Aprea (2010), Cuadrado et al. (2015), Heravi et al. (2017), Wang et al. (2008), Dabous & Alkass (2008), Rashidi et al. (2016), Gento (2004) Afshar et al. (2011) De la Fuente et al. (2016b), Pascal et al. (2017), Jato-Espino et al. (2014), Hashemkhani et al. (2011), De la Fuente et al. (2016a), De la Fuente et al. (2017b), Rochikashvili & Bongaerts (2016), Ugwu & Haupt (2007), Reyes et al. (2014), Dobrovolskiiene & Tamosiuniene (2016)

Table 2.2. Main social criteria and indicators

The impact of an infrastructure on the social wellbeing is included in 34 manuscripts (41% of total), and combines aspects such as public acceptance (Kamali et al., 2018; Hosseini et al., 2016; Kaya & Kahraman, 2010; Montajabiha, 2016; Väisänen et al., 2016; Dobrovolskiiene & Tamosiuniene, 2016), social welfare and income increase (Zavadskas et al., 2007; Fetanat & Khorasaninejad, 2015; Gumus et al., 2016; Tahmasebi & Yazdandoost, 2018), accessibility (Sun et al., 2013; Martin et al., 2007; Chhipi-Shrestha et al., 2017), or leisure (Gento, 2004). Assessments focused on building and road pavement design also account for the comfort of the users (Gilani et al., 2017; Moussavi et al., 2017; Invidiata et al., 2018; Heravi et al., 2017; Jato-Espino et al., 2014; Oses et al., 2017).

Aesthetics has also been identified as a main indicator for social sustainability, which is closely related to social acceptance of the project. The aesthetic, which has been assessed in 26 articles, includes not only the aesthetical perception of the infrastructure itself, but also its integration with the urban (Cuadrado et al., 2015; Hosseini et al., 2016) or rural environment (Zavadskas et al., 2007, 2010).

Direct and indirect working opportunities derived from the construction and maintenance of an infrastructure has been considered in 16 studies (19.3% of total), which is closely related to an increase of the social welfare. Although the methodological sheets for social life cycle assessments developed by UNEP/SETAC (2013) give preference not to the generated employment in general, but to that generated for the local communities, it is common practice in social life cycle assessments to use the generated employment in general terms as an indicator of social sustainability (Hunkeler et al., 2008; Navarro et al., 2018b).

16 studies take into consideration the effects of an infrastructure on the local development of a region, resulting from both the construction and maintenance activities, as well as from the serviceability provided by the infrastructure. Aspects such as the increase of the Gross Domestic Product (Zavadskas et al., 2010; Saparauskas, 2007), the increase in tourism (Afshar et al., 2011; Sun et al., 2013), or the regional economic benefits derived from the use of local materials and resources (Gilani et al., 2017; Akadiri et al., 2013; Väisänen et al., 2016; Ugwu & Haupt, 2007) have been included in this social impact category.

Externalities derived from infrastructure construction and, mainly, from infrastructure maintenance, have been considered in 33.7% of the reviewed studies. Effects such as traffic disruption (Balali et al., 2014; Mikawi, 1996; Rashidi et al., 2017; Chen, 2014; Santos et al., 2019), or the increase in vehicle operating costs due to detours (Gervásio & Da Silva, 2012; Dabous & Alkass, 2008; Mikawi, 1996) are found to be social indicators recurrently used when assessing the sustainability of bridge infrastructure. Other externalities frequently assessed are noise or dust pollution derived from construction works (Mosalam et al., 2018; Heravi et al., 2017).

The inclusion of innovative concepts in the infrastructure design is also accounted for as a social indicator, as it seeks to ensure the progress and technological development of the society. 9 articles have taken such aspect into account. The evaluation of this impact is based either on a binary indicator, which scores 1 if the design includes patented materials or solutions (Mosalam et al., 2018; De la Fuente et al., 2017a; Pons et al., 2017) or relies on the knowledge of the chosen panel of experts (Alwaer & Clemens-Croome, 2010; Ignatius et al., 2016).

13.3% of the reviewed manuscripts include culture as a measure of social sustainability, paying special attention to the respect for the cultural heritage of a region (Hashemkhani et al., 2018; Kamali et al., 2018; Alwaer & Clemens-Croome, 2010; Yu et al., 2012; Heravi et al., 2017; Rashidi et al., 2017), or for its traditional architecture (Gilani et al., 2017). Given the difficulties to quantitatively assess cultural indicators (UNEP/SETAC, 2013), most authors rely on the knowledge of the chosen panel of experts for the evaluation of cultural impacts (Heravi et al., 2017; Fetanat & Khorasaninejad, 2015; Afshar et al., 2011).

Health and safety include both the practices of construction and industry companies to protect the lives of their workers, but also the risk of accidents for users of an infrastructure. The impact of the activities associated with the construction and maintenance of an infrastructure on the safety of the involved workers, as well as the risks to the health of the users of the infrastructures, has been considered in 42 articles (50.6% of total).

2.3.2. Treatment of qualitative data

Once the indicators are selected that properly characterise the problem and condition the decision, the following step in a multi-criteria decision making problem consists in transforming them into quantitative values. While the numerical assessment of quantitative variables is straightforward, handling with qualitative criteria requires a certain pre-processing so as to transform such values into numerical ones. When dealing with qualitative criteria, such as aesthetics or comfort, many studies require the experts to evaluate such variables by assigning them scores on different scales ranging from 0 to 1, or from 0 to 10 in the most of the reviewed cases (Tahmasebi & Yazdandoost, 2018; Guzmán-Sánchez et al., 2018; Hosseini et al., 2016; Dobrovolskiiene & Tamosiuniene, 2016; Farkas, 2011).

In other cases, experts are required to evaluate qualitative criteria by choosing one of the different answer options provided by the decision maker in a closed form, which are then directly related to specific numerical values. This approach is often preferred when dealing with complex problems, where experts find it easier to reflect their judgements in linguistic terms rather than in the form of precise numbers. For example, (Gumus et al., 2016) bases the evaluation of each of the criteria assumed for the assessment of wind power plants on the mentioned translation of linguistic variables into numerical values. De la Fuente et al. (2016b) require experts to evaluate linguistically different functional and social aspects related to sewerage systems, such as surface degradation, risk of accidents, and the affection of pollutants and construction time on the wellbeing of the population. The use of linguistic variables has been used by De la Fuente et al. (2016a, 2017b) when assessing the risks derived from handling and installing precast tunnel segments. Heravi et al. (2017) also use a similar approach when handling the attitudes of experts towards different types of risks when establishing their judgements. Similar approaches have been conducted in other studies (Motuziene et al., 2016; Ignatius et al., 2016, Barros et al., 2015, Reyes et al., 2014, Balali et al., 2014, Kaya & Kahraman, 2010). Samani et al. (2015) use the PROMETHEE usual preference function to transform linguistic variables into numerical values.

Kripka et al. (2019) use the AHP method based on Saaty's fundamental scale to determine a normalised score for each of the qualitative criteria considered in the sustainability assessment, namely architectural value and security sensation. Other studies also base the scoring of qualitative data on such approach, such as (Rashidi et al., 2016, 2017; Jakiel et al., 2015).

2.3.1. Normalisation of the indicators

When dealing with indicators that are measured in different units, and prior to proceed to their aggregation into a final score, indicator values shall be normalised into dimensionless, comparable values. The most basic normalisation technique used is the so-called linear normalisation, and consists in dividing the indicator value x_{ij} of a particular alternative *i* associated to criterion *j* by the sum of the indicator values related to the complete set of alternatives:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sum_i x_{ij}}$$

Such approach is followed by the vast majority of studies reviewed (Yu et al., 2012; Ignatius et al., 2016; Zavadskas & Antucheviciene, 2010; Farkas, 2011; Väisänen et al., 2016; Torres-Machí et al., 2015; Asgari et al., 2015; Hashemkhani et al., 2018; Invidiata et al., 2018; Motuziene et al., 2016; Drejeris & Kavolynas, 2014; Mahdiraji et al., 2018; Jalaei et al., 2015; Terracciano et al., 2015). When the decision making problem involves the simultaneous consideration of both criteria with maximising and minimising optimal values, indicators are then normalised on the basis of the preferable optimum for each of them:

$$\bar{x}_{ij} = \frac{x_{ij}}{max_i\{x_{ij}\}}, where\ max_i\{x_{ij}\}\ is\ preferred$$

$$\bar{x}_{ij} = \frac{min_i\{x_{ij}\}}{x_{ij}}, where\ min_i\{x_{ij}\}\ is\ preferred$$

Such approach is followed by (Saparauskas et al., 2010; Dobrovolskiiene & Tamosiuniene, 2016; Guzmán-Sánchez et al., 2018; Malekly et al., 2010). This normalisation technique based on the preferred optimum of each criterion has been extended into the so-called Weitendorf's linear normalisation, so as to take into consideration their distance to the worst value (Klein & Whalley, 2015; Afshar et al., 2011; Pascal et al., 2017):

$$\bar{x}_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}}, for\ maximising\ optima$$

$$\bar{x}_{ij} = \frac{x_{max} - x_{ij}}{x_{max} - x_{min}}, for\ minimising\ optima$$

Other studies, such as (Nassar et al., 2016; Chhipi-Shrestha et al., 2017; Kamali et al., 2018; Gumus et al., 2016; Tahmasebi & Yazdandoost, 2018; Kucukvar et al., 2014), normalise the values of the decision variables by using a vector normalisation technique, where each element x_{ij} of the decision matrix is normalised by dividing it by its norm:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_i {x_{ij}}^2}}$$

Particular value functions have been also used to normalise the indicator values into dimensionless values. So, studies based on the Simple Additive Weighting technique called MIVES (Blanco et al., 2016; Pons & De la Fuente, 2013; Gilani et al., 2017; Pons & Aguado, 2012; Lombera & Aprea, 2010; Cuadrado et al., 2015, 2016; Hosseini et al., 2016; Barros et al., 2015; De la Fuente et al., 2016a, 2016b, 2017a, 2017b; Pons et al., 2017; Jato-Espino et al., 2014; Oses et al., 2017; Reyes et al., 2014) use exponential value functions defined as:

$$\bar{x}_{ij} = \left[1 - e^{-K_i\left(\frac{x_{ij} - x_{opt}}{c_i}\right)^{Pi}}\right] \cdot \left[1 - e^{-K_i\left(\frac{x_{opt} - x_{ij}}{c_i}\right)^{Pi}}\right]$$

where x_{opt} is the least preferable value of the indicator under evaluation, P_i is a shape factor that makes the value function be concave, linear, convex or S-shaped, C_i is the curve's inflexion point, and K_i tends towards x_{ij} at the inflexion point.

The aggregation technique PROMETHEE also bases the normalisation step on the construction of preference functions. Vincke & Brans (1985)proposed six basic types of preference functions. Depending on the nature of the criteria to be assessed, different value functions shall be used. For example, Balali et al. (2014) combines the use of V-shaped preference functions and linear preference functions. Samani et al. (2015) use the usual preference function for qualitative criteria, and the V-shaped function for the quantitative ones. Other preference functions are also used, such as exponential functions (Gervásio & Da Silva, 2012; Montajabiha, 2016; Gento, 2004). One of the main advantages of using such exponential functions is that they are continuously defined and consequently easier to use when compared to the other discrete, stepped preference functions.

Finally, it shall be highlighted that the normalisation of indicator values only makes sense when the involved indicators are measured in different units. Thus, those studies based on the qualitative criteria assessment of experts, who set scores for each criterion based on their expertise (Rashidi et al., 2016, 2017; Sun et al., 2013), do not require such normalisation step prior to their aggregation.

2.3.2. Weighting techniques

Weighting the criteria is an essential step in a decision making process, as it will condition the results of an assessment. Fig. 2.3 shows the weighting methods identified among the reviewed publications, as well as the number of times that each one has been applied. By far, the Analytic Hierarchy Process (AHP) is the most used method to determine the weights of the criteria considered in a decision making process, used by 65.1% of the authors. This widely used method allows to transform, through a systematic procedure, the pairwise judgements emitted by a single or a group of decision makers into a relevance score, which will be used in the later assessment of the impacts. No particular relationship has been identified between the use of this weighting technique and either the year of publication or the type of infrastructure assessed.

The direct allocation of weights has been identified as the second most used method (16 papers, 19.3% of the publications). By using this technique, the evaluator directly sets the score that represents the importance of each criterion on the decision making problem. Shanon Entropy methods are used to provide weightings less based on the subjectivity inherent in the previously mentioned techniques by measuring the uncertainty associated to the provided judgements (Saparauskas et al., 2010; Jalaei et al., 2015; Balali et al., 2014; Gumus et al., 2016; Kucukvar et al., 2014). Similar results have been previously reported regarding the application frequency of AHP, Direct allocation and Entropy methods in relation to the social sustainability of infrastructures (Zamarrón-Mieza et al., 2017).

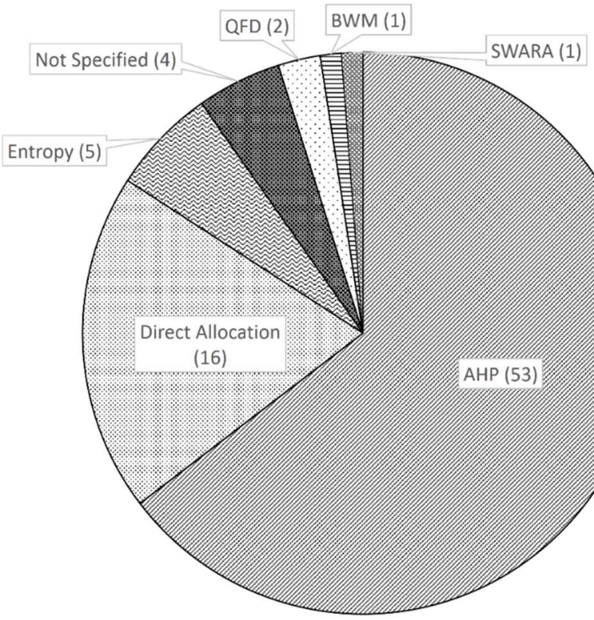


Figure 2.3. Weighting techniques applied within the reviewed papers

At last, three other techniques have been marginally used, namely the Best-Worst method (BWM) (Mahdiraji et al., 2018), the Quality Function Deployment (QFD) (Ignatius et al., 2016; Malekly et al., 2010) and the SWARA method (Hashemkhani et al., 2018) to assess the sustainability criteria weights. While the methodology related to the Best-Worst technique is close to the AHP, the Quality Function Deployment method has been used as a means to handle with complex and conflicting criteria, such as those describing sustainability, which can often be difficult to assess by decision makers. SWARA method is a so-called order relation technique based on the direct assignation of criteria relevance by a group of experts. It shall be noted that 4 contributions do not explicitly report the methodology used in the criteria weights assignation.

2.3.3. Aggregation of indicators

Once the relevance of each criterion is established, the next step in a decision making process is to assess the obtained results. Fig. 2.4 shows the frequency of use of the multi-criteria assessment techniques applied in the reviewed contributions, as well as the specific infrastructure field in which they have been applied. The most frequently used technique is the Simple Additive Weighting (SAW) or direct aggregation of the criteria

(Shin et al., 2013), which has been applied by 43 publications (51.8% of total). The popularity of this technique is based on its ease of application, as it consists in the simple addition of the normalised criteria scores weighted by their corresponding relevance factors obtained in a previous step. SAW is a compensatory technique that is revealed as a very intuitive tool for decision makers, based on an extremely simple and transparent calculation procedure. However, SAW is limited by the fact that it can only deal with maximising, positive defined criteria (Velasquez & Hester, 2013). Minimising criteria should be properly converted to maximising ones before being used. Similar conversions should be applied to negative defined criteria. The results of the assessments using SAW technique depend therefore on the transformation applied (Velasquez & Hester, 2013). Thus, to overcome such limitations when handling with more complex criteria, other MCDM methods are used. Among them, the most applied one is TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), used by 15.7% (13 studies) of the reviewed papers. TOPSIS allows to rank different alternatives in a multi-criteria context, considering the fact that the most preferred solution should have the shortest geometric distance to the positive ideal solution, and the longest distance to the less preferred solution (Penadés-Plà et al., 2019).

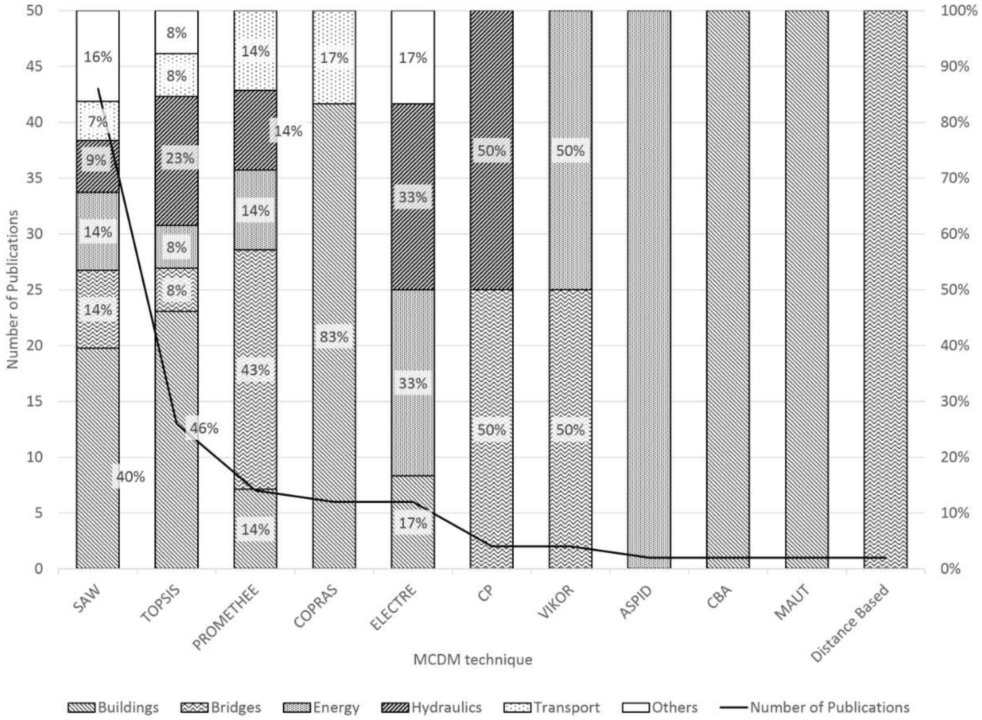


Figure 2.4. MCDM assessment techniques applied within the reviewed papers

TOPSIS technique is based on a simple, comprehensible concept that aims to represent the rationale of human decision processes (Roszkowska, 2011). Its high flexibility to accommodate to further extensions based on fuzzy sets or grey theory, for example, as well as its computational efficiency are additionally recognised advantages of this method (Hung & Chen, 2009). Transparency along the decision making process is revealed as an essential requirement when choosing an adequate MCDM method (Goodwin & Wright, 2000). The traceability of the analysis, i.e. the ability to investigate into the different analysis steps to identify strengths and weaknesses of each alternative under evaluation, is considered as a main source to provide argumentation in a decision making process. The transparency associated to TOPSIS is one of the main advantages of this technique (Hung & Chen, 2009).

PROMETHEE has been applied in 8.4% of the papers reviewed. This outranking method has suffered different modifications over the course of time, so as to overcome some of its initial limitations. PROMETHEE III, for example, does not even require the variables to be normalised, and is applicable when information is missing (Pires et al., 2011). However, PROMETHEE techniques are recognised to be very time consuming and not intuitive, making it often difficult to keep an overview over the problem when a significant number of criteria are involved (Kabir et al., 2014). In addition, in some cases the ranking of alternatives can drastically change and even reverse when a new alternative is introduced (Gervásio & Da Silva, 2012), which is one of the main disadvantages of these techniques.

7.2% of the studies reviewed use ELECTRE in their assessments. ELECTRE is another outranking technique based on concordance analysis. This noncompensatory method is particularly useful when ordinal scales are used to measure criteria (Chhipi-Shrestha et al., 2017). It has the ability to include vagueness and uncertainty in the assessments, but, as with PROMETHEE, outcomes can be hard to explain (Velasquez & Hester, 2013). As the outcomes are provided as an ordinal ranking, ELECTRE does not allow the decision makers to identify the particular strengths and weaknesses of the assessed alternatives, or even determine how much better an alternative is over the rest (Ahmine et al., 2014). One of the advantages of ELECTRE methods is that, in contrast to PROMETHEE techniques, they do not rely on the selection or construction of appropriate utility functions by the decision makers, which are not always straightforward and may condition the assessment results.

COPRAS has also turned out to be one of the most used techniques in sustainability assessment of infrastructures. As ELECTRE method, COPRAS has been applied in 7.2% of the papers reviewed. COPRAS is recognised to be simple to calculate and, in contrast with SAW, adequate when dealing with both maximising and minimising criteria values (Podvezko, 2011). Other MCDM techniques, such as Cost-Benefit Analysis (CBA) (Perini & Rosasco, 2013), Compromise Programming (CP) (Mikawi, 1996; Abrishamchi et al., 2005), Multi-Attribute Utility Theory (MAUT) (Mosalam et al., 2018), Analysis and Synthesis of Parameters under Information Deficiency (ASPID) (Begic & Afgan, 2007), Distance Based methods (Yepes et al., 2015a) and VIKOR technique (Kripka et al., 2019; Kaya & Kahraman, 2010) have been marginally applied to assess the sustainability of particular infrastructure designs.

It shall be noted that the proportions found in the present review regarding the use of MCDM techniques for the sustainability assessment of infrastructures have also been found in other fields of application. As an example, Kaya et al. (2018) report that 44% of the studies dealing with the assessment of energy policies use SAW technique, 23% use TOPSIS, 8% PROMETHEE and 6% ELECTRE, results that are quite similar to the ones obtained in the present review. Likewise, Mardani et al. (2015) focus on the use of MCDM techniques to solve management problems associated to of construction, risk and safety, report that 33% of the reviewed studies use SAW, 11% TOPSIS, 8% ELECTRE and 6% PROMETHEE. Similar results are reported by other studies, dealing with application fields such as mining and mineral processing (Sitorus et al., 2019).

Besides SAW, TOPSIS is revealed as the most used method to assess MCDM problems in different fields, such as supplier selection (Renganath & Suresh, 2016), manufacturing and product recovery (Ilgin et al., 2015), supply chain management (Khan et al., 2018), or material selection in the automotive industry (Noryani et al., 2018), just to cite some examples. After analysing the use of MCDM in other fields of application, it shall be concluded that the trends detected in the field of sustainability assessment of infrastructures are quite similar to those popular in other fields.

2.3.1. Sensitivity analysis

An important step in MCDM problems is to perform sensitivity analyses on those aspects that might alter significantly the conclusions of the assessment, so as to ensure the consistency of the final decision. From the total of the reviewed studies, only 18 (21.7%) include a sensitivity analysis in their assessments.

The majority of them (13 out of 18 manuscripts) focus their attention on the results sensitivity against the chosen criteria weights. This evidences that the weighting is considered as a great source of uncertainty in MCDM problems, usually derived from the subjectivity inherent to weighting based on experts' judgements (Scholten et al., 2015). The unprobabilistic uncertainty introduced in MCDM problems through experts' opinions is greater the more complex is the problem. So, when dealing with sustainability assessments, where criteria are often conflicting and usually of very different nature, decision makers might be unable to provide precise judgements and become overwhelmed by the problem to be assessed.

The usual way to proceed is to make one of the involved decision criteria predominant with respect to the rest, and compare the results with the ones obtained after the conventional weighting (Guzmán-Sánchez et al., 2018; De la Fuente et al., 2016a, 2016b, 2017b; Barros et al., 2015; Asgari et al., 2015; Pons & De la Fuente, 2013; Afshar et al., 2011). This allows the decision makers identify those criteria where the subjectivity is greater and are therefore more sensitive to experts' biases. Mosalam et al., (2018) analyse different weighting scenarios where the weighting of one of the criteria is changed continuously, from 0% to 100%. By doing so, the decision maker is able to determine for which weights the results are more prone to change and check if the weights obtained in his/her analysis are close to such thresholds or not.

Heravi et al. (2017) and Ignatius et al. (2016) perform a sensitivity analysis on the power assigned to each of the involved experts in the decision making problem. Several authors also focus on the sensitivity that the obtained results have on the parameters defining the aggregation techniques that they are using. So, Gervásio & Da Silva (2012) evaluate the sensitivity of the results on the PROMETHEE preference function used to normalise the indicator values. In addition, a second sensitivity analysis is also conducted on the criteria weights. Similarly, Martin et al. (2007) conduct a sensitivity analysis not only on the criteria weights, but on the selected indifference, preference and veto thresholds assumed when using the ELECTRE method.

2.3.2. Dealing with the experts' subjectivity

MCDM problems have a highly subjective component, since they are generally based on the cognitive capacity of the decision makers, who are usually required to provide the relevance of each criterion and even to assign performance values to the selected criteria indicators, as derived from the results shown in the present literature review. However, during the application of the described steps inherent in a decision making process, it is common practice to handle with so-called crisp or bi-valued data. This is proved by 72.3% of the analysed manuscripts (60 papers), as shown in Fig. 2.5. Such crisp approach to MCDM problems presumes the information provided by the judgements emitted by the decision makers to be absolutely precise and certain, and has been therefore subject to strong criticism for not being able to reflect the vague and qualitative nature of human thinking (Radwan et al., 2016). So, when dealing with complex problems such as sustainability assessments, with criteria that are usually conflicting and only difficultly to be compared, neglecting the fuzziness of human thinking may lead to erroneous conclusions (Radwan et al., 2016). So as to deal with the mentioned non-probabilistic uncertainties associated with human thinking, efforts have been made by several authors to apply different mathematical approaches to deal with the information resulting from the judgements of the decision makers. So, since 2007, 17 manuscripts (20.5% of total) have been found to apply the fuzzy sets theory (Zadeh, 1965) in the MCDM process for the sustainability assessment of infrastructures combined with a variety of weighting and

MCDM techniques (AHP, TOPSIS, VIKOR, SAW, PROMETHEE, ELECTRE, COPRAS). As an alternative, grey numbers have been recently applied by Heravi et al. (2017) in the assessment of the sustainability of industrial buildings.

The fuzzy theory was further developed by Atanassov (1986) into the intuitionistic fuzzy sets theory, which has been used in sustainability MCDM assessments of infrastructures only since 2013 (Chen, 2014; Montajabiha, 2016; Gumus et al., 2016; Kucukvar et al., 2014). At the present, the intuitionistic approach has been further generalised into the neutrosophic sets approach, developed by Smarandache in 1999 (Smarandache, 1999). No application of the neutrosophic approach has yet been found to be applied in MCDM related to the infrastructure assessment.

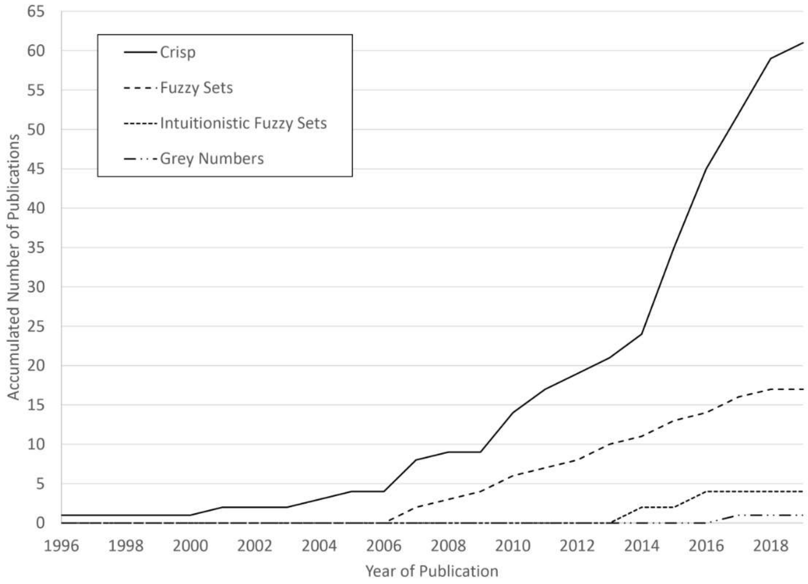


Figure 2.5. Handling of linguistic variables within the reviewed papers

2.4. Conclusions

This study presents a systematic literature review on the sustainability assessment of infrastructure projects and designs developed by means of MCDM techniques. Given the complex characterisation of sustainability, MCDM is revealed as a useful tool to integrate decision criteria related to the different dimensions of sustainability, namely economy, environment and society. MCDM has gained relevance to evaluate sustainability mainly since 2015, when the Sustainable Development Goals were set by the United Nations. In particular, MCDM has been found to be mainly applied for the assessment of buildings (38.6%), bridges (15.7%), energy (14.5%), hydraulic (13.3%), and transport infrastructures (7.2%). In view of the results, more efforts should be put in the sustainability analysis of infrastructures where long lasting, intergenerational service lives are required, such as bridges or dams. In those cases, where the required service life frequently exceeds 100 years, and where the magnitude of the impacts is not negligible given the dimensions of the infrastructures and their material and maintenance demands, evaluating the sustainability throughout their life cycle acquires an essential relevance.

AHP is revealed as the most used weighting technique to identify the relevance of the decision criteria, being applied in 65.1% of the analysed studies. Regarding the assessment technique used to evaluate the final sustainability scores of the design alternatives under consideration, SAW has resulted to be by far the preferred option, used by 51.8% of the authors. This technique, despite its undoubted advantages, such as its ease of use, is limited by the fact that it can only deal with positive defined, maximizing criteria. Given the complex relations between sustainability criteria, and their often conflicting nature, other techniques have been used by the scientific community, being TOPSIS the most applied (15.7% of the contributions).

Regarding the mathematical handling of the linguistic variables involved in MCDM process, where the main variables to derive the criteria weights are usually the judgements and opinion of experts, it has been found that the vast majority of manuscripts assume a crisp approach. It is first since 2007 when authors have started to implement the fuzziness of human judgments into the decision making process. Although fuzzy sets theory, and to some extent even intuitionistic fuzzy sets theory, have been applied in the sustainability assessment of infrastructures, the recently developed and more generalised neutrosophic sets have not been used to date for such purpose.

Regarding the criteria considered in the assessments, it shall be said that 74.7% base their definition on the framework of the life cycle of the infrastructure, which is in good accordance with the temporal dimension of sustainability. However, although recognised standards exist that provide guidelines for coherent and robust life cycle analyses, it has been found that only 4.8% of the publications base their studies on such standards, properly defining basic concepts such as the functional unit or the system boundaries assumed in the evaluation. It shall also be noted that none of the studies base the definition of the social criteria and indicators on the ‘Guidelines for social life cycle assessment of products’, which provides, at the present, the most recognised methodology to perform social life cycle assessments. With regards to life cycle costing, only 6.1% of the authors take into consideration the discounting of costs related to time.

In view of the obtained review results, further research is required to integrate the existing life cycle impact assessment methodologies (both economic, environmental and social) into the multi-criteria sustainability assessment of infrastructures, so as to provide robust and integral assessment tools based on a universal, systematic and transparent methodology. In addition, further efforts should be made to consider the fuzziness of experts' judgments in future assessment models.

Chapter 3

Life Cycle Cost Assessment of preventive strategies applied to prestressed concrete bridges exposed to chlorides

Authors: Ignacio J. Navarro; Víctor Yepes; José V. Martí

Status: Manuscript published

Journal: *Sustainability,* Volume 10 (3), March 2018

DOI: 10.3390/su10030845

JCR IF (2018) 2.592

JCR Category	Ranking	Quartile
Environmental Sciences	105/250	Q2
Environmental Studies	44/116	Q2
Green & Sustainable Science & Technology	20/35	Q3

Presentation: Post-print (author version)

Abstract

This paper applies Life Cycle Assessment methodology to aid decision making to select the preventive measure against chloride corrosion in concrete structures that works best for the socio-economic context of the structure. The assumed model combines the concepts of Life Cycle Cost Analysis and Social Life Cycle Analysis, assessing the impacts on users derived from the maintenance activities associated with each alternative analysed in terms of economic costs. The model has been applied to a prestressed concrete bridge, obtaining in the study a preventive measure that can reduce the total costs incurred over the period of analysis up to 58.5% compared to the cost of the current solution.

Keywords Life Cycle Assessment; Social Life Cycle Analysis; reinforced concrete; chloride corrosion; preventive measures

3.1. Introduction

Corrosion of reinforcing steel in concrete structures is one of the most important durability problems associated with this material. In the present, construction companies of different countries state that the refurbishment and maintenance of buildings represent up to 30% of the activity of the construction sector (Gil et al., 2015). The poor durability of many concrete structures, which results in short structural service lives, is not sustainable (Gao & Wang, 2017) neither in social nor in economic terms. In recent times, it has been common practice to deal with concrete deterioration mechanisms once the problem is detected and not before it arises. Such kind of strategy results in greater socio-economic impacts, since it is more material demanding in the long term than a design based on prevention. Although there are several mechanisms that may degrade concrete in severe environments, experience demonstrates that the most critical threat to concrete structures exposed to marine environments is chloride-induced corrosion of the reinforcing steel bars (Šavija & Schlangen, 2012; Maes & De Belie, 2014; Miyazato & Otsuki, 2010). Research has been carried out on this specific mechanism for many years (Yang et al., 2017; Zhu et al., 2016; Shaheen & Pradhan, 2015; Cheng et al., 2018), leading to the development of different preventive measures to increase resistance to corrosion from the beginning of the structure life cycle, thus resulting in less maintenance demanding solutions.

Some of the measures developed to prevent chloride corrosion focus on the reinforcement itself and others seek to prevent corrosion by reducing the porosity of the concrete cover. Corrosion can also be prevented by isolating the structure from the environment by means of surface protection treatments or by altering the kinetics of the reactions or electrochemical potential of the affected metals. Although the degree of knowledge associated with some of these measures is still precarious, the use of preventive measures such as those mentioned above is common when a concrete structure is exposed to chlorides. It is the task of the designer to find the solution that entails the lowest cost and consumption of resources (Martí et al., 2013, 2015, 2016; Yepes et al, 2015b). Regarding durability, decision support techniques, such as Life Cycle Cost Assessment (LCCA) can be used to find a durable solution with the minimum associated costs (Penadés-Plà et al., 2017).

Cost comparison is the usual procedure for selecting the best design alternative. However, when only considering the costs derived from implementing a particular solution, it may happen that the costs associated to the maintenance operations of the structure can exceed the initial investment, thus tilting the balance in favor of other alternatives with higher initial investment costs (Yepes et al., 2016) but lesser maintenance. This leads to the consideration of LCCA techniques in order to evaluate the costs generated throughout every stage of the life cycle of a structure. In addition, the economic costs deferred over time have associated social costs that can also be evaluated by means of Social Life Cycle Assessment (SLCA) techniques. When applied to the choice of the most appropriate prevention measure, it is common practice to overlook the social impacts generated. In urban environments, this impact may lead to adopt preventive measures that are more expensive in economic terms, but that require fewer interventions and consequently generate less social costs. Thus, the integration of social criteria in decision making is presented as an effective way towards a sustainable structural design (Sierra et al., 2016; Penadés-Plà et al., 2018).

It is possible to integrate both methodologies when choosing between different prevention measures. The present paper proposes a LCCA based methodology for decision-making regarding the most appropriate preventive measure for concrete structures exposed to chlorides, taking into account economic and social criteria. The economic and social costs considered in the proposed methodology are described below.

3.2. Materials and Methods

3.2.1. Case Study Description

In the present paper, some of the most usual preventive strategies against chloride corrosion are applied to a particular bridge deck. The subject in this case study is the bridge of Illa de Arosa, in Galicia – Spain. A cross section of the bridge deck is shown in Fig. 3.1. The input data regarding the durability and geometry characterization of this structure has been obtained from the literature (León et al., 2013). The concrete mix of the bridge deck has a cement content of 485 kg/m^3, and a water/cement ratio w/c=0.45. The concrete cover of the deck is 30 mm. A steel amount of 100 kg/m^3 of concrete has been assumed, as usual for these type of prestressed structures. This quantity does not include the steel of the prestressing tendons. The deck has a width of 13 m and a section depth of 2.3 m. The deck, with a span of 50 m, is located 9.6 m over the high tide sea water level. It is worth noting that according to the Spanish regulations for marine environments the deck is designed for no cracking of concrete, i.e. concrete remains uncracked.

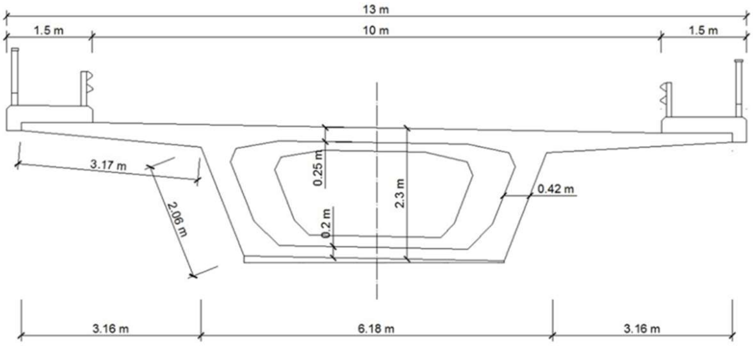


Figure 3.1. Cross section of the Arosa's concrete bridge deck

The particular preventive measures evaluated in the present study are as follows. Firstly, it has been considered an increase in the reinforcement concrete cover to 35 mm, 45 mm and to 50 mm (measures R35, R40 and R50 respectively henceforth). It has been taken into account that the more concrete cover is considered, the greater the steel amount needed to guarantee the proper structural behavior of the bridge deck. The steel amounts considered are 112 kg/m for R35, 136 kg/m for R45 and 147 kg/m for R50. A second group of measures consists in the addition to the existing concrete mixture of fly ash, silica fume or polymers. The resulting concrete mixes have been assumed to be applied to the whole deck, although only the properties of the cover will affect the durability performance of the design alternative. Additions of 10% and 20% of fly ash (measures CV10 and CV20), additions of 5% and 10% of silica fume (measures HS5 and HS10) and additions of 10% and 20% of Styrene-butadiene rubber (SBR) latex (measures HMP10 and HMP20) have been assumed in the analysis. The mentioned percentages are expressed in relation to the cement content of the reference concrete mix design. In the cases where fly ash or silica fume are added, the amount of cement is partially substituted by those components, as they contribute to the resistance development of the resulting concrete. The cement amount considered in the mix proportions of those alternatives is reduced according to the efficiency factor associated to the specific addition. In the present study, efficiency factors of K=0.3 and K=2 have been assumed for fly ash and silica fume additions, respectively. In the present study, efficiency factors of K=0.3 and K=2 have been assumed for fly ash and silica fume additions, respectively. It is worth noting that the addition of silica fume may reduce the critical chloride threshold (Manera et al., 2008). This effect, which is a consequence of the decrease in the chloride binding capacity of the resulting concrete when such additions are considered, has been taken into account in the present study. Thirdly, it has been considered a decrement in the water/cement ratio to w/c=0.40 and to w/c=0.35 (measures AC40 and AC35). When the water/cement ratio is reduced, it is common practice to add special additives in order to increase concrete workability. As these products may increase the economic impacts of the measure, the addition of superplasticisers has been considered in the definition of measures AC40 and AC35. The concrete mixes corresponding to the design alternatives presented above are shown in Table 3.1. It shall be noted that, in order to make alternatives comparable, they shall not only guarantee the same service life under an appropriate maintenance, but the resulting design should also have the same mechanical strength as the reference design. According to the mix proportions reported by León et al. (2013), the reference design has a mean compressive strength fcm equal to 40 MPa, with a modulus of elasticity E_c equal to 29 GPa. The alternative concrete mixes have been designed in order to reach the reference compressive strength and elastic modulus.

	Cement (kg/m^3)	Water (l/m^3)	w/b (%)	Fly Ash (kg/m^3)	Silica Fume (kg/m^3)	Polymer (SBR) (kg/m^3)	Plasticiser (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)
REF [1]	485.6	218.5	0.45	-	-	-	-	926.7	827.9
AC40	500	200	0.40	-	-	-	7.5	948	844.1
AC35	500	175	0.35	-	-	-	10	976.7	882.8
CV10	471	218.5	0.45	48.6	-	-	-	926.7	798.3
CV20	456.4	218.5	0.45	97.1	-	-	-	926.7	768.7
HS5	437	218.5	0.45	-	24.3	-	-	926.7	849.1
HS10	388.4	218.5	0.45	-	48.6	-	-	926.7	870.2
HMP10	485.6	218.5	0.45	-	-	48.6	-	926.7	827.9
HMP20	485.6	218.5	0.45	-	-	97.1	-	926.7	827.9

[1] This mix is also considered in alternatives R35, R45, R50, INOX, GALV, HIDRO and SEAL

Table 3.1. Concrete mix design for the different alternatives

At last, it has been considered the replacement of the existing ordinary steel with galvanized steel (measure GALV) and with stainless steel (measure INOX). Finally, it has been considered to treat the exposed deck surface with a generic silane-based hydrophobic impregnation (measure HIDRO) and with a silicate-based sealant product (measure SEAL). A total of 15 preventive measures are considered. It shall be said that there are other ways to deal with corrosion in severe environments, such as cathodic protection. These also relevant measures have been excluded from the present analysis, as their performance is hardly to be assessed in the same terms as the presented strategies

3.2.2. Durability performance of the preventive measures

The assessment of the durability of the structure requires a criterion indicating the time at which it becomes necessary to perform a maintenance operation. In the case of prestressed concrete bridges, it is usual to consider the time to corrosion initiation (Fig. 3.2) as proposed by Tuutti (1982) as the time where maintenance activities shall be held.

The time to corrosion initiation is the time where chlorides reach a concentration high enough to start the corrosive process of the reinforcement. Consequently, this maintenance criterion guarantees that, when maintenance operations are performed, the reinforcing steel is still not damaged by corrosion, and it is not necessary to replace it.

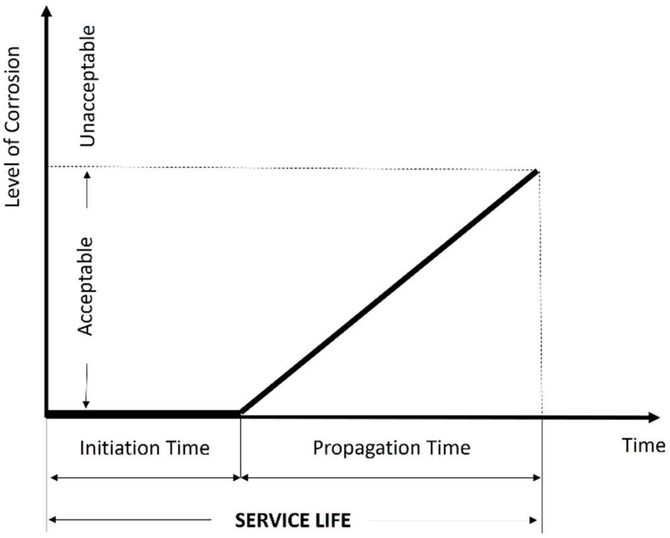


Figure 3.2. Service life definition based on Tuutti's model of corrosion

The calculation of the initiation time requires a physical model that describes how chloride ions move through the concrete cover. Existing models for the prediction of the required time to initiate corrosion are based on Fick's second law of diffusion, and assume that the porous concrete cover is a homogeneous material in which ions migrate through a diffusion process. A deterministic solution of the Fick's equation for the diffusion of chlorides in the concrete cover is used in this analysis, namely the one proposed in Fib Bulletin 34 (Fib, 2006) that assumes a constant, time independent surface chloride concentration. So, the chloride concentration to be expected in the concrete cover at a specific depth x and in a particular time t is expressed as:

$$\boldsymbol{C(x,t) = C_0 + (C_{s,\Delta x} - C_0) \cdot \left(1 - erf\,\frac{x-\Delta x}{2\sqrt{D_{app,C} \cdot t}}\right)} \qquad (1)$$

where *C(x,t)* is the chloride concentration (wt.%/binder) at concrete depth *x* (mm) and time t (years); $C_{s,\Delta x}$ is the chloride concentration at depth Δx (wt.%/binder); Δx is the depth of the convection zone (mm), which is the surface layer depth for which the process of chloride penetration differs from Fick's second law of diffusion; *erf(.)* is the Gauss error function; and $D_{app,C}$ is the apparent coefficient of chloride diffusion through concrete (mm^2/years). Note that if Δx is considered to be zero, the term $C_{s,\Delta x} = C_s$ is the chloride concentration at the concrete surface. The model proposed by Fib Bulletin 34 (Fib, 2006) assumes that the chloride front advances in only one direction. However, this hypothesis is not true when specific bars are exposed to two simultaneously advancing fronts, as the case of reinforcing bars located at the edges of the studied section. In such cases, the use of one-dimensional models results in inaccurate, overestimated service lives. In the present study, the Fib model has been slightly modified in order to consider the two-dimensional advance of chlorides, the so-called corner effect:

$$\boldsymbol{C(x,y,t) = C_0 + (C_s - C_0)\cdot\left(1 - erf\frac{x-\Delta x}{2\sqrt{D_{app,C,x}\cdot t}}\cdot erf\frac{y-\Delta y}{2\sqrt{D_{app,C,y}\cdot t}}\right)} \tag{2}$$

The concrete cover in the y-direction (r_y) is assumed to be constant and equal to 50 mm for every alternative analyzed, while the cover in the x-direction (r_x) is assumed to vary between 30 mm and 50 mm depending on the prevention alternative studied. The apparent diffusion coefficient is obtained from the experimental non-steady state migration coefficient using the equation proposed by Fib (2006):

$$\boldsymbol{D_{app,C} = exp\left(b_e\cdot\left(\frac{1}{T_{ref}} - \frac{1}{T_{real}}\right)\right)\cdot D_{RCM,0}\cdot k_t\cdot\left(\frac{t_0}{t}\right)^{\alpha}} \tag{3}$$

where b_e is a regression variable (constant); T_{ref} is the standard test temperature (ºC); T_{real} is the temperature of the structural element (ºC); $D_{RCM,0}$ is the non-steady state chloride migration coefficient (mm^2/years); k_t is a transfer parameter (constant); t_0 is a reference point of time (years); and α is an age factor, which is assumed to be equal to 0.5 according to the Spanish concrete code EHE-08 (Spanish Ministry of Public Works, 2008). In the present study, T_{ref} and T_{real} are assumed to be the same, and the transfer variable is considered to be $k_t = 1$ as suggested by Fib (2006). The age factor α determines the way the diffusion coefficient varies with the time. As reference time, t_0 = 0.0767 years (namely 28 days) has been considered. Table 3.2 shows the value of the parameters that allow for the characterization of the analysed measures in terms of durability.

Design alternative	Description	$D_{RCM,0}$ (x10^{-12} m^2/s)	C_{crit} (%)	r_x (mm)	Service Life (years)	Reference
REF	Current bridge design	10	0.6	30	7.1	Spanish Ministry of Public Works (2008)
R35		10	0.6	35	11.2	
R45		10	0.6	45	21.1	
R50		10	0.6	50	26.5	
AC40	w/c=0,40	6.15	0.6	30	18.8	Cheewaket et al. (2014), Vedalakshmi et al. (2009)
AC35	w/c=0,35	4.32	0.6	30	43.1	

INOX	Stainless steel reinforcement bars	10	5	30	>100	Bertolini et al. (1996)
GALV	Galvanized steel reinforcement bars	10	1.2	30	23.4	Darwin et al. (2009)
HMP10	Polymer modified concrete (10%)	7.32	0.6	30	13.2	Ohama (1995), Yang et al. (2009)
HMP20	Polymer modified concrete (20%)	3.04	0.6	30	75.6	
HS5	5% Silica Fume	3.31	0.38	30	36.2	Manera et al. (2008), Frederiksen (2000)
HS10	10% Silica Fume	1.38	0.22	30	>100	
CV10	10% Fly Ash	6.16	0.6	30	18.6	Otsuki et al. (2014)
CV20	20% Fly Ash	5.23	0.6	30	26.1	
HIDRO	Hydrophobic surface treatment	7.73	0.6	30	5[1]	Zhang & Buenfeld (2000), Liu et al. (2005)
SEAL	Sealant surface treatment	4.87	0.6	30	5[1]	Medeiros et al. (2012)

[1] In the present study, the service life of surface treatments (HIDRO and SEAL) is limited to 5 years according to manufacturer specifications

Table 3.2. Durability characterization of the analysed preventive strategies

It is assumed that the surface concentration of chlorides and the age coefficient is the same for all the alternatives evaluated. Back to the Tuutti model presented above, the time to corrosion initiation can be obtained by equalizing the chloride concentration at the rebar depth $C(r_x, r_y, t)$ to the critical chloride concentration for each specific measure. In the calculations, and on the basis of the distance between the bridge deck bottom surface and the mean sea water level, a surface chloride content of C_s=3.34% is assumed for the evaluation of the bridge deck. Table 3.2 shows the resulting expected service lives for the analysed prevention alternatives considering the durability parameters assumed in the present study. It shall be noted that the effectiveness of the surface treatments depends greatly on the porosity of the substrate (Baltazar et al., 2014). Consequently, the diffusion coefficients presented in Table 3.2 for HIDRO and SEAL have been obtained considering the w/c ratio of the REF alternative, namely w/c = 0.45. However, the durability performance of these treatments is very sensitive to ageing and weathering as derived from the existing literature (Medeiros et al., 2012; Courard et al., 2014). In particular, conventional treatments are very affected by microcracking of the concrete cover, for when those cracks are deeper than the treatment thickness, barrier properties are lost and the impregnation becomes ineffective (Pan et al., 2017; Dai et al., 2010). Periodic reapplication of surface treatments is therefore desirable, in order to reestablish the protective effect of these measures. For these reasons, the present study limits the service life of surface treatments to 5 years according to manufacturer specifications

3.2.3. Life Cycle Cost Analysis (LCCA)

In general, the economic costs associated with a structure, can be divided into initial investment and maintenance costs. The investment costs, which correspond to the costs incurred at the initial moment of the economic analysis. Four main categories are usually distinguished chronologically: planning costs, land acquisition costs, construction costs and interruption costs. The present study only considers the costs derived from the construction activities. It shall be noted that many of the investment costs are very similar between the different alternatives to be evaluated, for example the costs associated to excavation or piles construction. Only those costs that are different between alternatives are considered in the present paper, as they are the ones that will have an influence on the final decision.

The maintenance costs, which are generated throughout the service life of the structure, are necessary for the infrastructures to be in operating conditions throughout the required service life of the project, ant they directly depend on the durability performance of the structure against the dominating degradation mechanism. Maintenance operations include the activities of hydrodemolition of the concrete cover, cleaning of the outermost reinforcement and shotcreting with the corresponding concrete mixture to restore the original cover. In the case of surface treatment, maintenance operations consist only in the reapplication of the treatment.

The unitary costs assumed in the present study for the basic materials considered in the evaluation of both initial investment and maintenance costs are shown in Table 3.3. These costs are usual for the Spanish construction sector.

Parameter	**Cost**	
Ordinary Portland Cement	87.77	€/t
Sand	13.98	€/t
Gravel	16.36	€/t
Fly Ash	38	€/t
Silica Fume	1.14	€/kg
SBR Latex	4.7	€/l
Superplastiziser	1.38	€/kg
Reinforcing Steel - B 500 S	0.8	€/kg
Reinforcing Steel - Stainless	4.5	€/kg
Hydrophobic surface treatment	19.01	€/m2
Sealant surface treatment	29.04	€/m2

Table 3.3. Parameters considered in LCCA

3.2.4. Social Life Cycle Assessment (SLCA)

The social costs of a construction over its lifetime are difficult to quantify in monetary terms. These costs affect both users of the infrastructure and third parties who do not make use of it. For the road bridge case study, the main social costs affecting users (Torres-Machí et al., 2017; Penadés-Plà et al., 2017) of the infrastructure are quantified. The user related costs considered in the present study are the Vehicle Operating Costs and the Vehicle Delay Costs. The Vehicle Operating Costs (*VOC*) are those costs arising from the normal use of the vehicles and which must be borne by its users, such as fuel consumption, tyre wear and maintenance. These costs can be quantified as the cost increase derived from the circulation in zones affected by the construction or maintenance of the bridge with regard to the costs associated to the circulation in normal, unaffected travelling conditions. According to Seshadri and Harrison (1993), the traffic behavior along a zone affected by maintenance or construction works allows us to identify five different sections, as shown in Figure 3.3.

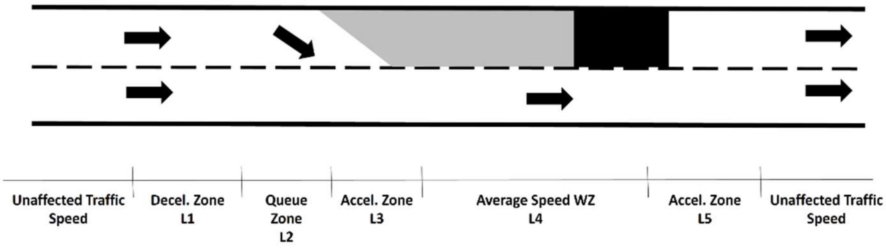


Figure 3.3. Traffic behavior along a Working Zone (WZ), according to Seshadri and Harrison (1993)

The value of the vehicle's operating costs can be defined by the following equation (Gervásio & Da Silva, 2013):

$$\boldsymbol{VOC = \sum_{j=1}^{24}\left(\sum_{k=1}^{5}\left(L_k - \frac{S_{ak}}{S_n}\cdot L_k\right)\cdot HT\cdot\sum_{i=1}^{4}(VOC_i\cdot p_i)\right)} \tag{4}$$

where L_k is the length of the affected zone k depending on the behaviour of the traffic involved as shown in Fig. 3.3, S_{ak} is the traffic speed in the zone k affected by maintenance works, S_{an} stands for the traffic speed under normal, unaffected conditions, HT is the average hourly traffic, p_i is the percentage of class i vehicles with respect to the total vehicle flow and VOC_i represents the operating costs associated to class i vehicles, defined as the sum of the costs derived from fuel consumption, tyre consumption and maintenance costs. In the present paper, the assumed parameter values regarding the characterization of the traffic behaviour along the Working Zone are shown in Table 3.4. In the analysis, a traffic speed under normal conditions of S_{an}=80 km/h has been considered. The vehicle classes assumed in the present methodology are described in Table 3.5.

Section	Section Length (m)	Traffic speed (km/h)
L1 - Deceleration Zone	100	60
L2 - Queue Zone	75	20
L3 - Acceleration Zone	50	30
L4 - Average Speed	250	40
L5 - Acceleration zone	50	50

Table 3.4. Characterization of the Working Zone traffic behaviour

Vehicle class	Class description	Cost of driver's working time (€ /h)	Cost of passenger's leisure time (€ /h)	Occupation rate
Class 1	Motorcycles and vehicles with vertical height from the first axle of 1.10 m	22.34	7.15	2
Class 2	Vehicles with two axles and a vertical height greater than 1.10 m	22.34	-	1
Class 3	Vehicles with three axles and a vertical height greater than 1.10 m	17.93	5.13	24
Class 4	Vehicles with more than three axles and a vertical height greater than 1.10 m	17.93	-	1

Note: For every vehicle class, it is assumed that 1 passenger is working. For vehicle classes 1 and 3, additional 1 and 23 passengers are assumed to be "not working" respectively, according to Gervásio (2010)

Table 3.5. Cost per hour of a person travelling, with regard to their objective, according to De Rus (2010)

On the other hand, the economic quantification of the delays generated by maintenance operations on road users (*VDC*) is calculated by assessing the difference between the costs derived from the time spent by the driver on crossing the section affected by the works and those resulting from the time spent under normal operating conditions. In addition, the reason for the driver's travel is also assessed and different estimates are made if the journey is for work or for other reasons. The value of the vehicle's delay costs (*VDC*) can be defined by the following equation:

$$\boldsymbol{VDC} = \sum_{\boldsymbol{j=1}}^{\boldsymbol{24}} \left(\sum_{\boldsymbol{k=1}}^{\boldsymbol{5}} \left(\frac{\boldsymbol{L_k}}{\boldsymbol{S_{ak}}} - \frac{\boldsymbol{L_k}}{\boldsymbol{S_n}} \right) \cdot \boldsymbol{HT} \cdot \sum_{\boldsymbol{i=1}}^{\boldsymbol{4}} \boldsymbol{DTC_i} \cdot \boldsymbol{p_i} \right) \tag{5}$$

where the meaning of the different variables is the same as that presented in the definition of *VOC*. In Eq. 5, DTC_i is the hourly cost associated to a class *i* vehicle user and depends on the user's reason for travelling. This concept can be evaluated as:

$$\boldsymbol{DTC_i} = \sum_{\boldsymbol{m}} (\boldsymbol{TC_m} \cdot \boldsymbol{OR_{i,m}}) \tag{6}$$

where $OR_{i,m}$ is the ocupation rate of passengers inside a class *i* vehicle that are travelling with a particular objective m, and TC_m is the hourly cost of a person travelling with a particular objective m as shown in Table 3.5. Two travel objectives are assumed, namely

m=1 for working reasons and m=2 for non-working reasons. The relation between both costs, when no data is available, can be estimated as

$$TC_{m=2} = 0.25 \cdot TC_{m=1} \tag{7}$$

Equations presented to evaluate VOC and VDC are based on the model developed by Gervásio (2010). For both the quantification of VOC and VDC, it is assumed that the maintenance operations only affect a 300 m long road section, and that the repair activities last six weeks. The average daily traffic is assumed to be 6000 vehicles per day, with an average traffic speed of 80 km/h. The costs derived from the use of vehicles are shown in Table 3.6.

Vehicle class	Class 1		Class 2	Class 3	Class 4
Traffic composition	11%		78%	3%	8%
Fuel type	Gasoline	Diesel	Diesel	Diesel	Diesel
Fuel consumption (l/100 km)	5.9	4.8	4.5	44	44
Fuel cost (€/l)	1.33	1.13	1.13	1.13	1.13
Average service life for vehicles (years)[1]	10		8	12	12
Service life of tyres (km)[1]	40000		40000	75000	200000
Tyre cost (€)[1]	73		62	333	463.6
Mean travel distance km/year[1]	20000		30000	70000	85000
Yearly vehicle maintenance cost (€)[1]	1575		1860	16316	28027
Vehicle depreciation (€)[1]	17177		11563	21653	84451

[1] This data has been obtained from Gervásio (2010)

Table 3.6. Costs associated to the assumed vehicle classes

Both the economic and the social costs, all transformed into monetary terms, will occur in different time instants, depending on the initiation time resulting for each of the treatment alternatives considered. In the resolution of the proposed model, the temporality of the maintenance actions is taken into account through the following concepts: selection of an appropriate period of analysis, consideration of a residual benefit and cost discounting to present values.

The analysis period is the time frame in which the different alternatives are compared. The choice of the analysis period greatly influences the results of the socio-economic evaluation: choosing a period equal to the shorter service life of the alternatives may not capture the differences in the behavior of the alternatives in the long term, penalizing those that have longer service lives. This period should be long enough to adequately reflect the existing performance differences between the alternatives being compared. The current LCCA includes the impacts derived for an analysis period of the first 100 years of bridge life. This is the required service life for bridge structures according to European Committee for Standarization (2002). The consideration of the durability performance shown in Table 3.2 results in the number of maintenance operations to be held during the analysis period.

The residual benefit represents the monetary value of the alternative at the end of the analysis period. This value should be taken into account in the evaluation of projects where the solution has a longer service life than the analysis period considered in the economic evaluation (Walls & Smith, 1998). In a simplified way, the economic value of the structure in its optimum state corresponds to the value of the initial investment. From this point onwards, the structure loses value as the end of its useful life approaches, when its state becomes inadmissible from the point of view of durability and its residual value becomes zero. In cost accounting, this residual value of a solution when the end of the analysis period is reached is considered as a benefit, thus reducing the life cycle costs.

The criterion assumed to determine the residual value of an alternative is to take into account the advance of the critical chloride content. By calculating the depth reached by the critical chloride content at the end of the analysis period, it is possible to estimate the residual value of the alternative in question: if the critical chloride content has reached the reinforcement depth, the residual value of the structure is zero. If not, it is assumed that the residual value of the structure is a fraction of the installation costs of the alternative. In particular, this fraction is proportional to the penetration depth of the chlorides in relation to the concrete cover of the design.

Finally, the temporary aspect of costs and benefits remains to be addressed. Over time, the value of money varies depending on financial concepts such as the interest rates of the investment or the inflation rates. In order to properly compare two alternatives, it is necessary to convert the costs generated over time into comparable monetary values. As a criterion, the comparison is made in terms of present monetary value, using the discount rate. The equation for calculating costs in terms of present costs is as follows:

$$\boldsymbol{LCC} = \sum_{\boldsymbol{t}=\boldsymbol{t_0}}^{\boldsymbol{t_{SL}}} \boldsymbol{C_i} \cdot \frac{\mathbf{1}}{(\mathbf{1}+\boldsymbol{d})^{\boldsymbol{t}-\boldsymbol{t_0}}} \tag{8}$$

where *LCC* is the Life Cycle Cost of the structure, C_i represents the economic costs associated to time *t*, t_0 is the time associated to the beginning of the analysis period, t_{SL} is the number of years considered in the analysis, and d is the discount rate. In Europe, the European Commission proposes a discount rate of between 3.5% and 5.5% for project evaluation. In the present paper, a discount rate of 5% is considered.

3.3. Results and Discussion

According to the methodology proposed, the resulting installation and maintenance costs per meter of bridge deck are presented in Fig. 3.4 for the preventive strategies analysed in this study. As explained above, since the assumed maintenance criterion is to repair when the initiation time is reached, the reinforcement will not have been affected by corrosion, and consequently the maintenance operation will consist on removing the chloride contaminated concrete cover and executing it again. Regarding the surface treatments (HIDRO and SEAL), the maintenance activities consist in the reapplication of the treatment, without demolishing the existing concrete cover.

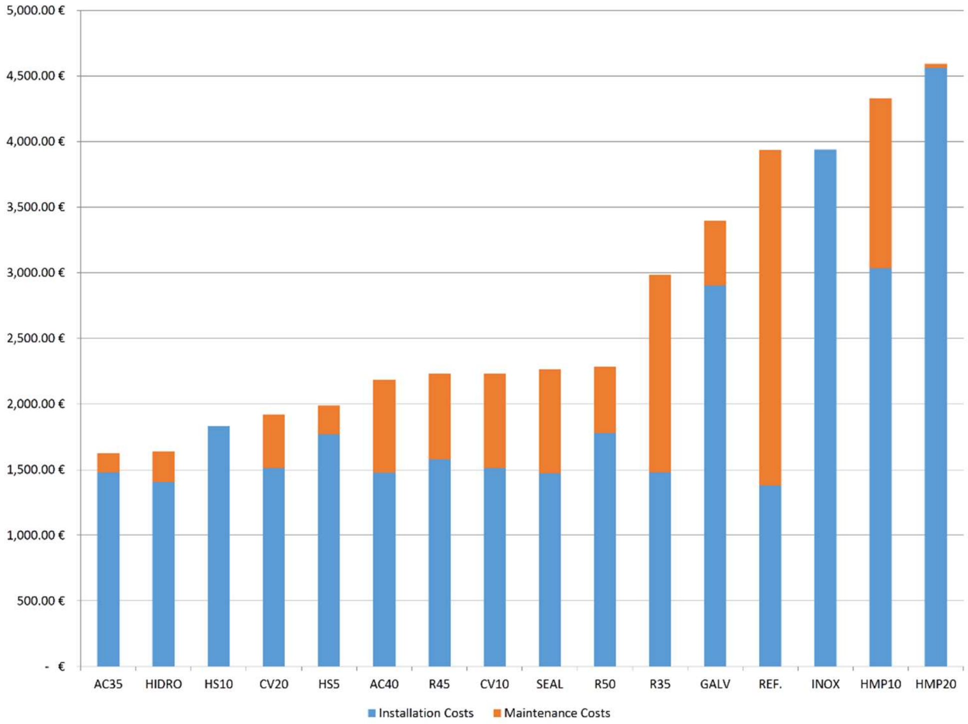


Figure 3.4. Installation and maintenance costs, in €/m of deck

It is observed that there are several alternatives with initial costs very similar to the installation costs of the reference alternative. Those are the alternatives where the cost of the materials is very close to the reference case, namely the ones based on surface treatments (hydrophobic and sealant treatments), the addition of fly ash, the reduction of the water/cement ratio and the increase of the concrete cover up to 35 mm.

The addition of silica fume in the concrete mix results in solutions with initial costs significantly greater than the ones of the reference alternative, namely 28% to 33% greater. It is observed that an excessive concrete cover (R45 and R50) leads to great initial costs as well, due to the associated increase in the reinforcing steel demand. On the other hand, those solutions where the reinforcement material is modified, namely by using galvanized or stainless steel reinforcements, result in almost the highest initial costs, due to the high costs of materials (Mistry et al., 2016). At last, it is observed that the most expensive solutions in terms of initial costs are those where the reference concrete is modified with polymers. Such conclusion is in good accordance with Fowler

(1999), and is derived from the high costs of this material. Consequently, the economic limitation of polymer modified concretes or stainless steel used as reinforcement is only assumable in cases where good durability is required. As can be observed, the service life of both HMP10 and HMP20 solutions is considerable, and this results in less or almost no maintenance costs. In the case of INOX, no maintenance is required.

Focusing on the costs generated during the service stage of the bridge, the results show that the alternatives with the least number of interventions are, in general, the ones with the lowest maintenance costs, as expected. An exception to the foregoing is made by alternatives involving surface treatments: as explained above, such alternatives require a considerably frequent maintenance. The costs associated with each of these maintenance operations are, however, small if compared to the cost of repair for any of the other alternatives. This means that, despite demanding a high number of repairs, they are preferable in terms of economic costs if compared to the other alternatives. It is also interesting to highlight the significant maintenance costs associated with the reference solution, which almost doubles the maintenance costs of the next more expensive alternative. However, it is worth noting that an increase of only 5 mm in the concrete cover may reduce the maintenance costs of the reference alternative up to 40%.

Analyzing the social impact of the different alternatives in terms of user costs (Fig. 3.5), it can be observed that those measures that require a greater number of interventions are the ones that generate the greatest social impact. Thus, alternatives HIDRO and SEAL, despite requiring faster maintenance operations, generate the greatest social costs, exceeding the ones resulting from the reference alternative. The reference alternative, which also requires intensive maintenance throughout its service life, results in high social costs as well. The rest of the analysed measures show a significantly lower social impact.

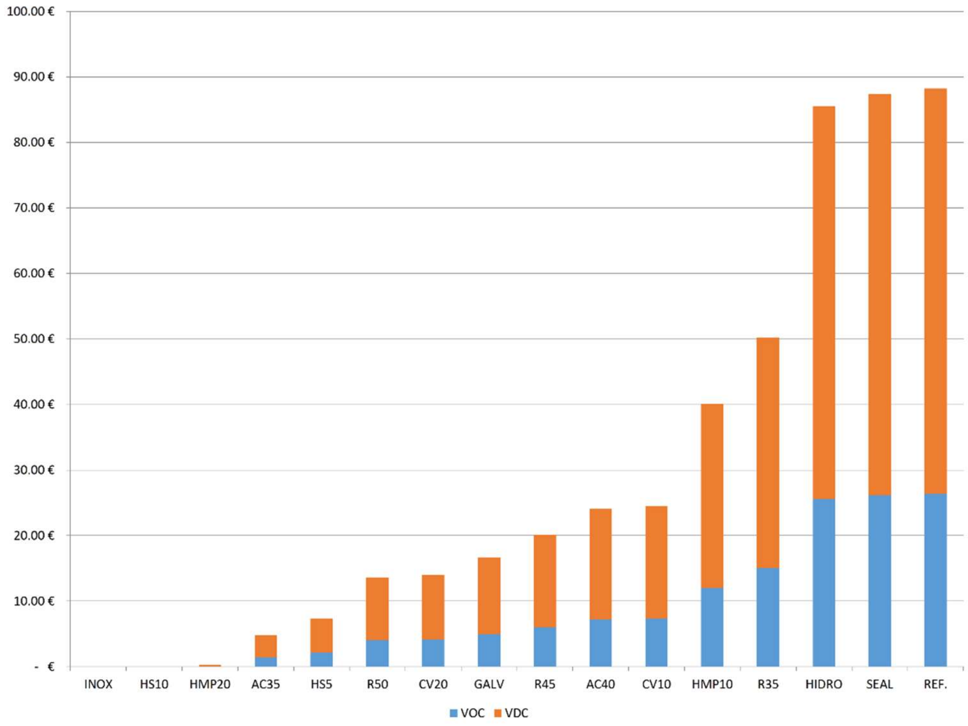


Figure 3.5. User costs of the analysed preventive measures, in €/m of deck

Table 3.7 shows the discounted total costs in which incurs each of the different designs. It is observed that the user costs are significantly lower than the costs derived from maintenance. These costs depend on the socio-economic context of the infrastructure, and on the traffic intensity registered. When considering both installation, maintenance and user costs, it is concluded that using polymer modified concrete is the most expensive prevention alternative, with a resulting cost that is even greater than the costs derived from the reference design. The difference between the cost of both strategies is, however, less than 15%. The use of stainless steel shows similar economic impact to the reference alternative. In this case, the same as in the case of HMP20, the total costs are mainly those associated to the installation phase of the structure, i.e. neither of them incurs in maintenance costs (INOX) or maintenance costs are generated in a far future (HMP20).

Alternative	**Investment Costs**	**Maintenance Costs**	**VOC**	**VDC**	**Residual Value**	**Total**
AC35	1,481.67 €	143.84 €	1.44 €	3.37 €	-7.66 €	1,622.65 €
HIDRO	1,406.91 €	230.92 €	25.61 €	59.93 €	-10.70 €	1,712.68 €

HS10	1,832.96 €	- €	- €	- €	-2.24 €	1,830.72 €
CV20	1,511.39 €	409.19 €	4.19 €	9.80 €	-1.94 €	1,932.63 €
HS5	1,768.90 €	219.50 €	2.18 €	5.11 €	-3.20 €	1,992.50 €
AC40	1,475.82 €	707.39 €	7.22 €	16.88 €	-7.64 €	2,199.66 €
R45	1,579.74 €	654.04 €	6.02 €	14.09 €	-3.13 €	2,250.76 €
CV10	1,514.56 €	720.65 €	7.34 €	17.16 €	-7.18 €	2,252.53 €
R50	1,778.83 €	507.79 €	4.08 €	9.54 €	-3.06 €	2,297.17 €
SEAL	1,471.19 €	795.83 €	26.17 €	61.22 €	-11.19 €	2,343.22 €
R35	1,480.19 €	1,506.24 €	15.02 €	35.14 €	-0.80 €	3,035.79 €
GALV	2,903.18 €	494.98 €	4.98 €	11.64 €	-16.04 €	3,398.74 €
INOX	3,941.28 €	- €	- €	- €	-29.97 €	3,911.31 €
REF.	1,380.64 €	2,555.78 €	26.43 €	61.83 €	-9.61 €	4,015.07 €
HMP10	3,033.84 €	1,296.54 €	12.02 €	28.12 €	-9.79 €	4,360.72 €
HMP20	4,560.74 €	32.59 €	0.08 €	0.19 €	-23.49 €	4,570.11 €

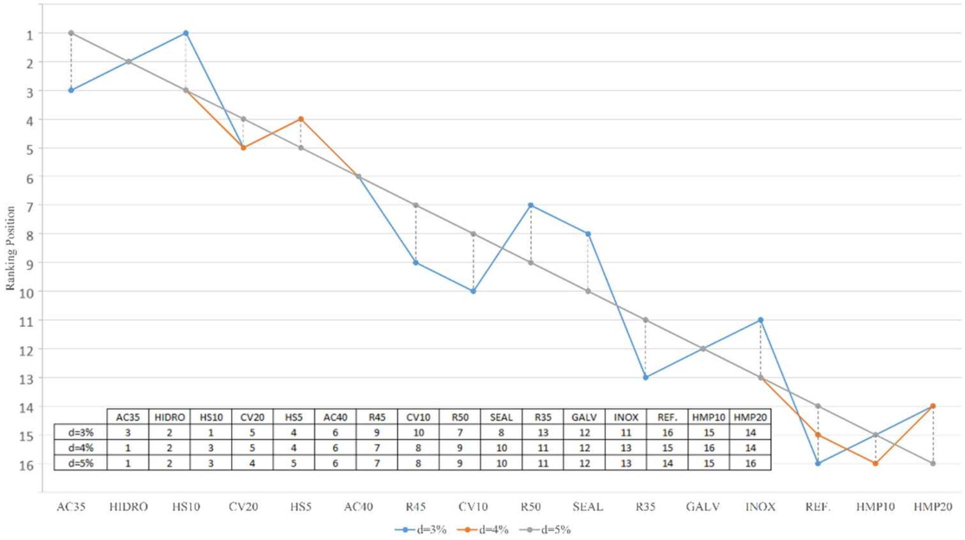
Table 3.7. Total socio-economic costs of the analysed alternatives, in €/m of deck

On the other hand, it shall be noted the high cost of maintenance derived from the reference design. For this alternative, the costs that are generated over the service life almost double the initial investment. Something similar happens for those alternatives in which the modification of the solution does not significantly affect the durability of the solution, as is the case with alternative R35. While this slight increase in the concrete cover significantly reduces maintenance costs, they still carry a significant weight on the final cost of the solution. Obviously, the more a solution contributes to improving the durability performance of the structure against corrosion, the lower the maintenance costs will be.

The prevention strategies that generate less costs throughout the life cycle of the structure, considering both economic and social costs on users, are those based on reducing the water to cement ratio of the original concrete mix (AC35), applying hydrophobic surface treatments on the deck surface (HIDRO) and adding of silica fume and fly ash on the concrete mix design (HS10, HS5 and CV20). As can be observed, the durability performance of both AC35 and HIDRO is far below the performance of other, more expensive solutions such as HMP20 or INOX. However, the resulting life cycle costs are the lowest, namely between 41.5% and 42.6% of the costs associated to the reference design. This is due to the fact that material costs in both cases are very competitive. Consequently, the combined effect of the inexpensive maintenance activities together with the more than acceptable durability performance in the case of AC35, and the low costs of maintenance in the case of HIDRO design, make them the most desirable strategies. It shall be highlighted that the life cycle costs of these alternatives only differs between 11% and 15% with the costs derived from alternatives

HS10 and CV20, making them also very cost-efficient solutions in chloride laden environments. It has to be noted that the design HS10 does not incur in any costs related to maintenance, as the service life associated to this alternative is greater than the required service life.

The results presented above are based on the assumption of a discount rate d=5%. However, the assumed discount rate is highly uncertain when considering a period of analysis of 100 years. Taking into account that uncertainties about discount rate tends to be a key contributor on LCCA results when considered (Lee et al., 2011; Harvey et al., 2012), a sensitivity analysis on this parameter is performed, taking into account three discount rates within the usual range for infrastructures in Europe, namely d=3%, d=4% and d=5%. For these three scenarios, the different preventive strategies have been ranked, based on the resulting life cycle total costs, including both economic and user impacts. Results are presented in Fig. 3.6, where a rank value of 1 means that the alternative results in the lowest life cycle discounted costs.



	AC35	HIDRO	HS10	CV20	HS5	AC40	R45	CV10	R50	SEAL	R35	GALV	INOX	REF.	HMP10	HMP20
d=3%	3	2	1	5	4	6	9	10	7	8	13	12	11	16	15	14
d=4%	1	2	3	5	4	6	7	8	9	10	11	12	13	15	16	14
d=5%	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Figure 3.6. Preventive strategies ranking considering different discount rates

It can be observed that the main conclusions derived above are robust, as they do not significantly depend on the chosen discount rate. There are, however, slight differences in the rankings. In Fig. 3.6, the ranking changes resulting from the analysis scenarios is marked by a dashed line. It is observed that the worst alternatives, regardless of the discount rate assumed in the evaluation, are the reference alternative and the strategies based on polymer modified concrete. On the other hand, the best alternatives vary between measures HS10, AC35 and HIDRO. It is observed that, in general, the lower the chosen discount rate, the more preferrable are those solutions with either less maintenance demand, such as HS10, or those with lower maintenance costs, such as hydrophobic surface treatments. However, it shall be highlighted that the differences between the best and worst of the alternatives HS10, AC35 and HIDRO in terms of total life cycle costs are found to be less than 10%. In consequence, it can be concluded that results presented in this paper are robust.

3.4. Conclusions and future lines of research

LCCA methodology has been used to assess the different preventive measures against chloride corrosion of concrete reinforcement. These measures have been evaluated taking into account both their durability performance against corrosion, and the economic and social costs derived during the life cycle of the structure. The exposed methodology has been applied to a case study, based on the characteristics of the prestressed concrete bridge in the Arosa Isle.

It has been shown that those alternatives with better performance in terms of durability against chloride corrosion, namely the use of stainless steel or polymer modified concrete, are the ones that incur in greater life cycle costs. Those alternatives that perform worst, namely the reference alternative or the increase of the concrete cover up to 35 mm, show similar resulting life cycle costs. In these cases, in contrast to the previously described alternatives, the major part of the resulting costs is derived from maintenance, which can be up to three times greater than the installation costs, as the case of the reference design. From the results presented above, it seems reasonable to state that the optimum in economic terms is derived from a compromise solution between durability performance and material costs. In the case study presented, the alternatives that perform best economically consist in reducing the water/cement ratio of the reference alternative up to w/c=0.35 and treating the concrete surface by means of hydrophobic products. The addition of high amounts of silica fume and fly ash also derive in very cost-efficient solutions throughout the structure's life cycle. In particular, the addition of 10% silica fume has resulted in a very cost-efficient, maintenance free solution.

It shall be highlighted that, although the LCCA methodology presented here is applicable in general terms to concrete bridge decks exposed to severe environments, the conclusions drawn are based on a particular case study. The transferability of the obtained results is therefore dependent to the specific context of the structure to be evaluated. Further research is suggested to evaluate the combined effect of some of the presented preventive measures, and to bring to light both their compatibilities and their cost competitiveness.

Chapter 4

Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks

Authors:	Ignacio J. Navarro; Víctor Yepes; José V. Martí; Fernando González-Vidosa
Status:	Manuscript published
Journal:	*Journal of Cleaner Production,* Volume 196, Pages 698-713, September 2018
DOI:	10.1016/j.jclepro.2018.06.110
JCR IF (2018)	6.395

JCR Category	Ranking	Quartile
Engineering, environmental	8/52	Q1
Environmental Sciences	18/250	Q1
Green & Sustainable Science & Technology	6/35	Q1

Presentation: Post-print (author version)

Abstract

Chloride corrosion of reinforcing steel in concrete structures is a major issue in the construction sector due to economic and environmental reasons. Assuming different prevention strategies in aggressive marine environments results in extending the service life of the exposed structures, reducing the maintenance actions required throughout their operation stage. The aim of the present study is to analyze the environmental implications of several prevention strategies through a life cycle assessment using a prestressed bridge deck as a case study.

The environmental impacts of 15 prevention alternatives have been evaluated when applied to a real case of study, namely a bridge deck exposed to a chloride laden surrounding. The Eco-indicator 99 methodology has been adopted for the evaluation of the impacts. As some of the alternatives involve the use of by-products such as fly ash and silica fume, economic allocation has been assumed to evaluate their environmental impacts.

Results from the life cycle analysis show that the environmental impacts of the chloride exposed structure can be reduced significantly by considering specific preventive designs, such as adding silica fume to concrete, reducing its water to cement ratio or applying hydrophobic or sealant treatments to its surface. In such scenarios, the damage caused to the environment mainly due to maintenance operations and material consumption can be reduced up to a 30 to 40% of the life cycle impacts associated to a conventional design. The study shows how the application of life cycle assessment methodologies can be of interest to reduce the environmental impacts derived from the maintenance operations required by bridge decks subjected to aggressive chloride laden environments.

Keywords Life cycle assessment • Chloride corrosion • Preventive measures • Eco-Indicator 99 • Bridge deck • Sustainable design • Concrete

4.1. Introduction

Great concern has arisen in the last decades on how human activities affect our environment in terms of climate change and depletion of natural resources, among other environmental consequences. This is especially so since the introduction of the sustainable development concept by the Brundtland Commission in 1987. The construction industry is one of the human activities that consumes more materials. It is also a carbon-intensive sector in our society (Ramesh et al., 2010; Shen et al., 2005), since it accounts for about 5% of the carbon emissions. Regarding production, concrete and other cement derivatives are the construction materials which most impact on the environment, since they are the most dominating materials used in this sector. As a result, over the past few years, there has been increasing interest in the environmental consequences associated to the use of such materials throughout the life cycle of different concrete structures, such as earth-retaining walls (Zastrow et al., 2017; Yepes et al., 2012), water storage tanks (Sanjuan-Delmás et al., 2015), utility poles (De Simone Souza et al., 2017) or building elements (Van den Heede & De Belie, 2014), among others. Besides the impact evaluation along the complete life cycle, it is also common to evaluate impacts derived from particular life cycle stages, such as concrete production (Braga et al., 2017; Texeira et al., 2016), both of them focusing either on specific environmental aspects, such as carbon emissions and embodied energy (Wang et al., 2012; Molina-Moreno et al., 2017), or on the use of score-based, standarized methodologies, such as ReCiPe or CML 2001 (Gursel & Ostertag, 2016; Tait & Cheung, 2016; De Schepper et al., 2014).

In the context of sustainable design, special attention is paid to long lasting, concrete consuming structures, such as bridges (Du et al., 2014; Martínez-Martin et al., 2012; Penadés-Plà et al., 2016). Studies have been performed that deal with the bridge design optimization in terms of embodied energy (Martí et al., 2016) and in terms of greenhouse gas emissions derived from construction (García-Segura & Yepes, 2016; Yepes et al., 2015b). However, less attention has been paid to the particular durability conditions of the structure and how the consequent maintenance needs during its life cycle affect the environmental evaluation of the design under a life cycle perspective (Pang et al., 2015; Zhang et al., 2016).

Degradation of reinforced concrete structures has been shown in recent years to be one of the most demanding challenges facing the construction industry (Gjørv, 2013). The poor durability of many concrete structures around the world derives in short structural service lives and this is not sustainable neither in economic nor in environmental terms (Gao & Wang, 2017). In addition, it is presently a common practice to deal with concrete deterioration mechanisms once the problem is detected and not before it arises. Such kind of strategy leads to greater impacts both in the economic and in the environmental field, since it is more material demanding in the long term than a sustainable design. Although there are several mechanisms that may degrade concrete in severe environments, like carbonation or sulphate attack, experience demonstrates that the most critical threat to concrete structures in marine environments is chloride-induced corrosion of the reinforcing steel bars (Costa & Appleton, 2001; Maes et al., 2012; Miyazato & Otsuki, 2010). Research has been carried out on this specific mechanism for many years, trying to understand the causes, reactions, and consequences of chlorides in concrete. This research has significantly improved our knowledge of the long-term behavior of reinforced concrete in chloride-laden environments. It has also led to the development of different preventive measures to increase resistance to corrosion from the very beginning of the structure life cycle, thus leading to less maintenance demanding solutions.

Focusing on the environmental consequences of concrete degradation of bridge structures, although maintenance is the main contributor to environmental degradation (García-Segura et al., 2014b), few studies have been conducted on the environmental impacts that corrosion reducing design alternatives imply themselves. Mistry et al. (2016) compares the environmental performance of stainless steel versus carbon steel reinforcements in marine environments by using the CML 2001 methodology. Van den Heede et al. (2012) and Van den Heede et al. (2017) show how fly ash concrete performs better environmentally than conventional concrete under a life cycle perspective. Petcherdchoo (2015) evaluates the CO_2 emissions derived from bridge maintenance based on cover replacement of the existing concrete and on sealant surface treatments.

However, due to the fact that many contributions focus on the durability performance of single measures versus the performance of the conventional designs, the results existing in the literature do not meet the necessary conditions for comparability between alternatives: results should be based on the same functional unit, the evaluated system should include the same activities and processes, the same impacts should be assessed, and the same methodology for the impact evaluation should be used (Cooper, 2003). In this sense, this paper is devoted to assessing the environmental impacts that the different and most common corrosion preventive measures generate throughout the entire life cycle of a specific bridge deck, evaluating them under conditions of comparability. The different maintenance operations needed by each measure according to durability limitations has been taken into account. A real concrete bridge deck subject to a marine environment is taken for the study. This bridge deck is modelled and assessed by means of a life cycle assessment (LCA henceforth). This LCA is carried out according to the guidelines of the ISO 14040 and ISO 14044 series. Different preventive designs are considered in the analysis. These alternatives include the maintenance operations needed in each case during a considered period. The assessment calculates their respective contribution to the service life expectancy of the structure. The obtained service life estimates are used as LCA input to quantify the environmental impacts generated by each measure in the life cycle analyzed.

4.2. Materials and methods

4.2.1. Preventive designs and problem definition

The present analysis considers the three categories of preventive measures that are commonly used in the design of concrete structures in severe environments. The first category of measures relates to the characteristics of the concrete cover. This first category of measures increases the time needed by chloride ions to reach the embedded steel bars, which extends the service life of the structure. Two prevention subcategories have been considered in this group. The first subcategory implies increasing the concrete cover, thus increasing the distance to be travelled by chloride ions to reach the steel reinforcement bars. The second subcategory consists of increasing the coverage density by reducing the water/cement ratio of the concrete mix, thus decreasing its diffusion coefficient. A lower diffusion coefficient makes it more difficult for chloride ions to move through concrete, which results as well in more time needed for chloride ions to reach the steel bars. This latter subcategory also covers those cases where special additions are added to the concrete mixture in order to reduce the concrete porosity and so, again, its diffusion coefficient. Additions of fly ash, silica fume, and polymers are considered in the present study. The second category of measures modifies the composition of the reinforcing steel. Although both ordinary and prestressing steel bars are exposed to chloride corrosion, it is common practice to modify the ordinary steel composition, as it is usually more exposed to chlorides in bridge decks than the prestressing tendons. This second category of measures aims at extending the service life concrete structures by increasing the critical chloride content needed for the corrosion of the bars to be started. This is achieved by using corrosion resistant steels, such as stainless or galvanised steels. Both cases have been considered in this analysis. Finally, the third category of measures implies the isolation of concrete from the environment, thus preventing the access of chlorides to concrete by means of specific surface treatments. Two types of such treatments have been considered in the present analysis. Firstly, the impregnation of the concrete surface with a hydrophobic material and, secondly, the treatment with a sealant mortar mixture. There are other methods that prevent corrosion of the steel bars in concrete structures, such as the addition of corrosion inhibitors. These methods have not been considered in this study due to the uncertainties associated with the definition of the corrosion parameters needed to describe their performance (Bolzoni et al., 2014; Shi & Sun, 2013).

A unit length of a real concrete bridge deck exposed to marine chlorides is considered here to compare the environmental performance of alternative designs based on the aforementioned measures. The bridge of Illa de Arosa, in Galicia - Spain is considered as a case study. A cross section of the bridge deck is shown in Fig. 4.1. The input data regarding the durability and geometry characterization of this structure has been obtained from the literature (León et al., 2013; Pérez-Fadón, 1985; Pérez-Fadón, 1986). The original concrete mix of the bridge deck has a cement content of 485 kg/m^3, and a water/cement ratio w/c=0.45. The concrete cover of the deck is 30 mm. The steel amount considered in this study is 100 kg/m^3 of concrete, in accordance with Pérez-Fadón (1985). This quantity does not include the steel of the prestressing tendons. The deck has a width of 13 m and a section depth of 2.3 m. The deck is located 9.6 m over the high tide sea water level. It is worth noting that according to the Spanish regulations for marine environments the deck is designed for no cracking of concrete, i.e. concrete remains uncracked.

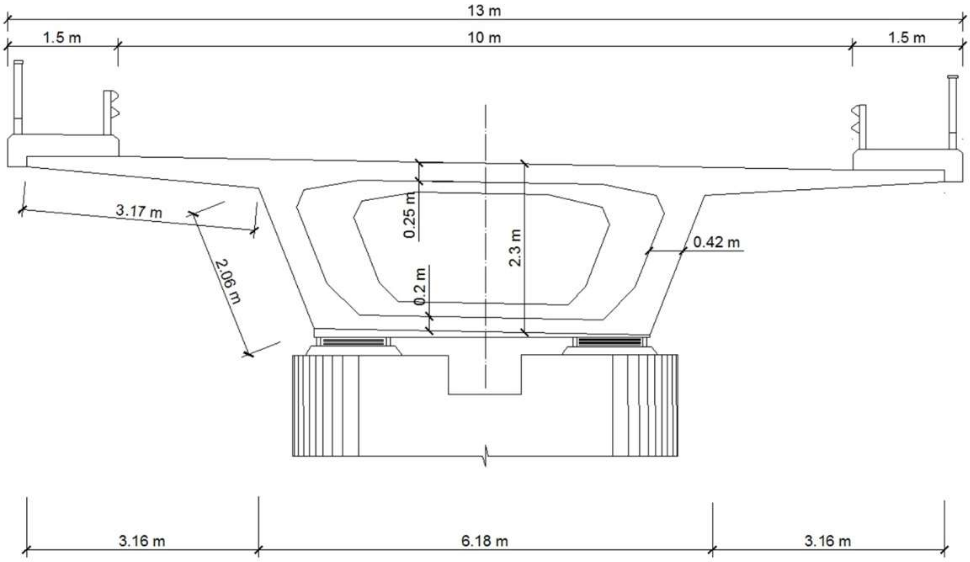


Figure 4.1. Cross section of the Arosa's concrete bridge deck

The present study takes as a starting point the described design (reference design or REF henceforth) to evaluate alternative designs based on the preventive strategies presented above. The particular preventive designs evaluated in the present study are as follows. Firstly, it has been considered an increase in the reinforcement concrete cover to 35 mm, 45 mm, and to 50 mm (measures CC35, CC40 and CC50 respectively henceforth). It shall be noted that, when large concrete covers are used, the cracks width in tensile zones can increase significantly. This can be avoided using fiber-reinforcement (Martí et al., 2015). Fibers will affect the durability performance of this first type of measure and, consequently, the maintenance and the associated environmental impact of the alternative. This study aims to evaluate the impacts derived from single, uncombined solutions. For this reason, fibers have not been considered in the impact evaluation. A second group of measures consists in the addition to the existing concrete mixture of fly ash, silica fume or polymers. The resulting concrete mixes have been assumed to be applied to the whole deck, although only the properties of the cover will affect the durability performance of the design alternative. Additions of 10% and 20% of fly ash (measures FA10 and FA20) have been considered. Regarding silica fume, additions of 5% and 10% (measures SF5 and SF10) have been studied. Regarding polymers, additions of 10% and 20% (measures PMC10 and PMC20) have been assumed. The mentioned percentages are meant to be a percentage of the cement content of the reference concrete mix design. In the cases where fly ash or silica fume are added, the amount of cement is partially substituted by those components, as they contribute to the resistance development of the resulting concrete. On the other hand, it is worth noting that the addition of silica fume shall reduce the critical chloride threshold as a consequence of the reduced chloride binding capacity of the resulting concrete (Manera et al., 2008). This effect has been taken into account in the present study. Thirdly, it has been considered a decrement in the water/cement ratio to w/c=0.40 and to w/c=0.35 (measures W/C40 and W/C35). Again, the resulting concrete mix has been applied to the whole bridge deck. When the water/cement ratio is reduced, it is common practice to add special additives in order to increase concrete workability. As these products may increase the environmental impact of the measure, the addition of superplasticisers has been considered in the definition of measures W/C40 and W/C35. The concrete mixes corresponding to the design alternatives presented above are shown in Table 4.1. It shall be noted that, in order to make alternatives comparable, the resulting strength and deformability of the resulting designs should be at least the same as the ones of the reference design. According to the mix proportions reported by León et al. (2013), the reference design has a mean compressive strength f_{cm} equal to 40 MPa, with a modulus of elasticity E_c equal to 29 GPa. Some alternatives result in greater resistances or modulus of elasticity, as observed in Table 4.1. In order to make the alternatives comparable, in such cases the depth of the deck has been slightly decreased so as to make the resulting designs have the same bending strength and deformability as the original deck. As a consequence, both alternatives W/C35 and those including polymers in the concrete mix have resulted in section depths of 2.1m and 2.23m respectively.

	Cement (kg/m^3)	Water (l/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	Fly Ash (kg/m^3)	Silica Fume (kg/m^3)	Latex (kg/m^3)	SP (kg/m^3)	f_{cm} (Mpa)	E_c (Gpa)
REF*	485.6	218.5	926.7	827.9	-	-	-	-	40	29
W/C40	500	200	948	844.1	-	-	-	7.5	47	30
W/C35	500	175	976.7	882.8	-	-	-	10	55	32
FA10	471	218.5	926.7	798.3	48.6	-	-	-	40	29
FA20	456.4	218.5	926.7	768.7	97.1	-	-	-	40	29
SF5	437	218.5	926.7	849.1	-	24.3	-	-	40	29
SF10	388.4	218.5	926.7	870.2	-	48.6	-	-	40	29
PMC10	485.6	218.5	926.7	827.9	-	-	48.6	-	50	29
PMC20	485.6	218.5	926.7	827.9	-	-	97.1	-	50	29

** Note: This mix is also considered in alternatives CC35, CC45, CC50, INOX, GALV, HYDRO and SEAL*

Table 4.1. Concrete mixes and mechanical properties

At last, it has been considered the replacement of the existing ordinary steel with stainless steel (measure INOX) and with galvanised steel (measure GALV). Finally, it has been considered to treat the exposed deck surface with a hydrophobic product (measure HYDRO) and with sealant product (measure SEAL). A total of 15 preventive designs are considered.

4.2.2. Service life predictions

A criterion is needed to decide when maintenance is required during the service life of the analyzed bridge deck. This varies for the different preventive designs considered. Regarding structures located in chloride laden environments, it is common practice to consider the initiation period in the Tuutti model in Fig. 4.2 (Mosquera-Rey, 2015). The initiation period is the time needed for the chloride ions to travel through the concrete cover and reach the critical chloride content at the embedded reinforcing steel bars. The critical chloride content is the chloride concentration needed to start corrosion. It mainly depends on the chemical composition of the steel. This means that no corrosion is developed during the initiation time. The initiation period is the time after which maintenance operations shall be held. Assuming this criterion, it is guaranteed that the reinforcing steel is not corroded when maintenance operations are held, thus leading to less cost demanding solutions.

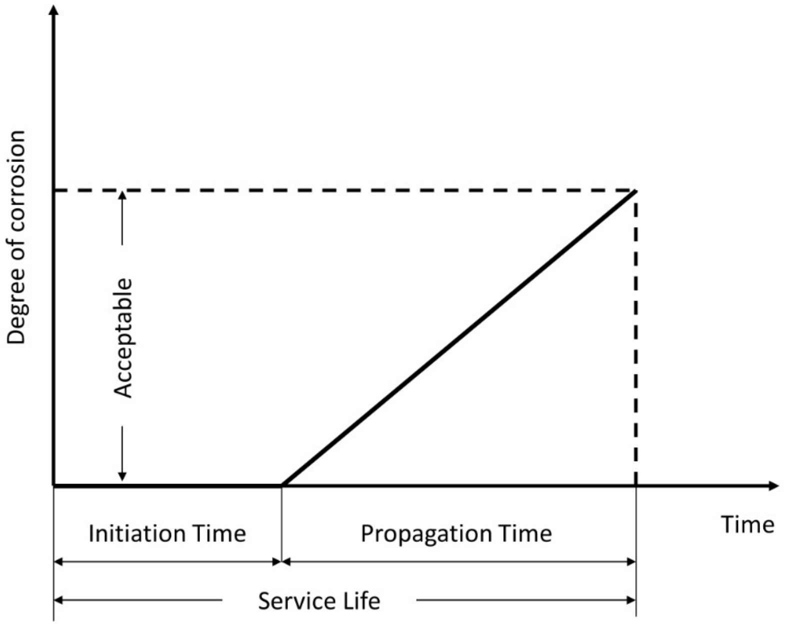


Figure 4.2. Tuutti model for service life prediction of concrete structures exposed to chloride environments

The calculation of the initiation time requires a physical model that describes how chloride ions move through the concrete cover. Existing models for the prediction of the required time to initiate corrosion are mostly based on the assumption of a Fickian process, assuming that the porous concrete cover is a homogeneous material in which ions migrate through a diffusion process in the presence of enough humidity. The development of this diffusive process is based on the chloride concentration gradient between the concrete surface and the cover inside. A deterministic solution of the Fick's equation for the diffusion of chloride along the concrete cover will be used in this analysis, namely the one proposed in Fib Bulletin 34 (Fib, 2006) that assumes a constant, time independent surface chloride concentration. So, the chloride concentration to be expected in the concrete cover at a specific depth x and in a particular time t is expressed as:

$$\boldsymbol{C(x,t) = C_0 + (C_{s,\Delta x} - C_0) \cdot \left(1 - erf\frac{x - \Delta x}{2\sqrt{D_{app,C} \cdot t}}\right)}$$

where $C(x,t)$ is the chloride concentration (wt.%/binder) at concrete depth x (mm) and time t (years); $C_{s,\Delta x}$ is the chloride concentration at depth Δx (wt.%/binder); Δx is the depth of the convection zone (mm), which is the surface layer depth for which the process of chloride penetration differs from Fick's second law of diffusion; *erf(.)* is the Gauss error function; and $D_{app,C}$ is the apparent coefficient of chloride diffusion through concrete (mm^2/years). Note that if Δx is considered to be zero, the term $C_{s,\Delta x}$ is the chloride concentration at the surface of concrete. The apparent diffusion coefficient is obtained from the experimental non-steady state migration coefficient using the equation proposed by Fib (2006):

$$\boldsymbol{D_{app,C} = exp\left(b_e \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T_{real}}\right)\right) \cdot D_{RCM,0} \cdot k_t \cdot \left(\frac{t_0}{t}\right)^{\alpha}}$$

where b_e is a regression variable (constant); T_{ref} is the standard test temperature (ºC); T_{real} is the temperature of the structural element (ºC); $D_{RCM,0}$ is the non-steady state chloride migration coefficient (mm^2/years); k_t is a transfer parameter (constant); t_0 is a reference point of time (years); and α is an age factor. In the present study, T_{ref} and T_{real} are assumed to be the same, and the transfer variable is considered to be $k_t = 1$ as suggested by Fib (2006). The age factor α determines the way the diffusion coefficient varies with the time. A value of 0.5 has been assumed for the age factor, as proposed by the EHE-08 concrete design code (Spanish Ministry of Public Works, 2008). As reference time, $t_0 =$ 0.0767 years (namely 28 days) has been considered. The model suggested by Fib Bulletin 34 (Fib, 2006) is a one-dimensional diffusion model. It shall be noted that two dimensional models provide a more accurate solution to the diffusion problem of chlorides in concrete when predicting the time to initiation of bars exposed simultaneously to two advancing chloride fronts, the so-called corner effect. Therefore, although one dimensional models provide the same accuracy in the solution for surfaces directly exposed to chlorides with no geometry changes (Titi & Biondini, 2016), as is the case of the lateral and bottom surfaces of the analyzed bridge deck, the service life prediction for bars located at the section edges will be overestimated. In order to avoid the corrosion initiation in any of the reinforcement bars exposed to chlorides, the previous model has been modified in order to consider the corner effect:

$$C(x,y,t) = C_0 + (C_s - C_0) \cdot \left(1 - erf\frac{x - \Delta x}{2\sqrt{D_{app,C,x} \cdot t}} \cdot erf\frac{y - \Delta y}{2\sqrt{D_{app,C,y} \cdot t}}\right)$$

In the present study, it has been assumed that the chloride surface concentration is the same in both faces of the corner (C_s), namely the horizontal and the vertical one. Additionally, it has been assumed that the concrete is homogeneous and that the chloride diffusion coefficient is the same in both directions ($D_{app,c,x} = D_{app,c,y}$). The concrete cover in the y-direction (r_y) is assumed to be constant and equal to 50 mm for every alternative analyzed, while the cover in the x-direction (r_x) is assumed to vary between 30 mm and 50 mm depending on the prevention alternative studied.

Table 4.2 presents the values of the reference diffusion coefficient D_o and of the critical chloride C_{crit} content computed for the different preventive measures, as well as the expected durability associated to each of them for the different concrete covers r_x. The values of these parameters for the zero-alternative, i.e. the non-preventive design, are also shown. On the basis of the distance between the structure and the sea water surface, a surface chloride content of $C_{s,0}$=3.34% is assumed for the evaluation of the bridge deck.

Preventive measure	Code	Source	D_0 ($x10^{-12}$ m^2/s)	C_{crit} (%)	r_x (mm)	Expected service life (years)
Case of study, no prevention strategy is followed	REF	Spanish Ministry of Public Works (2008)	10	0.6	30	6.5
Increase the concrete cover of the structure	CC35		10	0.6	35	10.2
	CC45		10	0.6	45	19.7
	CC50		10	0.6	50	23.7
Decrease the water/cement ratio of the concrete mix	W/C40	Cheewaket et al. (2014), Nokken et al. (2006), Vedalakshmi et al. (2009), Xi & Bazant (1999)	6.15	0.6	30	17.2
	W/C35		4.32	0.6	30	34.4
Use of corrosion resistant steels for the reinforcement	INOX	Bertolini et al. (1996)	10	5	30	-
	GALV	Darwin et al. (2009)	10	1.2	30	21.0
Addition of polymers to the concrete mix	PMC10	Ohama (1995), Yang et al. (2009)	7.32	0.6	30	12.2
	PMC20		3.04	0.6	30	73.9
Addition of silica fume to the concrete mix	SF5	Frederiksen (2000), Hooton et al. (1997)	3.31	0.38	30	33.1
	SF10		1.38	0.22	30	101.9
Addition of fly ash to the concrete mix	FA10	Otsuki et al. (2014)	6.16	0.6	30	17.1
	FA20		5.23	0.6	30	23.8
Surface treatment to isolate the concrete from the environment	HYDRO	Zhang & Buenfeld (2000)	7.73	0.6	30	5*
	SEAL	Medeiros et al. (2012)	4.87	0.6	30	5*

* According to manufacturer's specifications

Table 4.2. Durability characterization of the analysed preventive strategies

Considering these parameters, the expected service life for each of the analyzed measures has been calculated taking into account Fick's equation. In Table 4.2, the expected service life of the alternative INOX is not shown, meaning that the service life of this alternative is long enough to meet durability requirements without maintenance needs. This is due to the fact that the assumed surface chloride content is below the chloride threshold value assigned to stainless steel. It shall be noted that, in severe environments, carbonation of the concrete cover may influence the diffusive process of chlorides and reduce the time to corrosion initiation. However, for the present study the influence of the carbonated concrete on the corrosive process of the reinforcement has not been taken into account, as the conditions that favor a rapid carbonation and chloride penetration rarely coexist (Sirivivatnanon et al., 1999).

4.2.3. Life cycle assessment (LCA)

According to ISO 14040, the LCA consists of four main steps, namely the definition of goal and scope, the inventory analysis, the impact analysis and the interpretation.

4.2.3.1 *Definition of goal and scope*

The LCA presented in this paper evaluates and compares the differences between the environmental impacts of the corrosion preventive designs described above in section 2.1. Remember that these measures are applied to a real particular concrete bridge deck exposed to a marine environment. Concepts that are common to all alternatives, such as the excavation operations in the construction phase for example, will not be taken into account in the analysis, since they do not provide useful information for the comparison.

The life cycle of the analyzed bridge deck is divided into five phases. The first phase is the production of the construction materials. The second is their transport from the production facilities to the installation point. The third is the installation. The fourth is the maintenance needed during the structure service life. And the fifth is the end of life phase. The life cycle stages considered in the analysis, together with the different concepts taken into account in the definition of each of them are shown in Fig. 4.3. For this study, the functional unit considered for the LCA is 1 m length of a bridge deck connecting Arosa Isle to the mainland, including the production, transport, installation, and maintenance for a service life of 100 years.

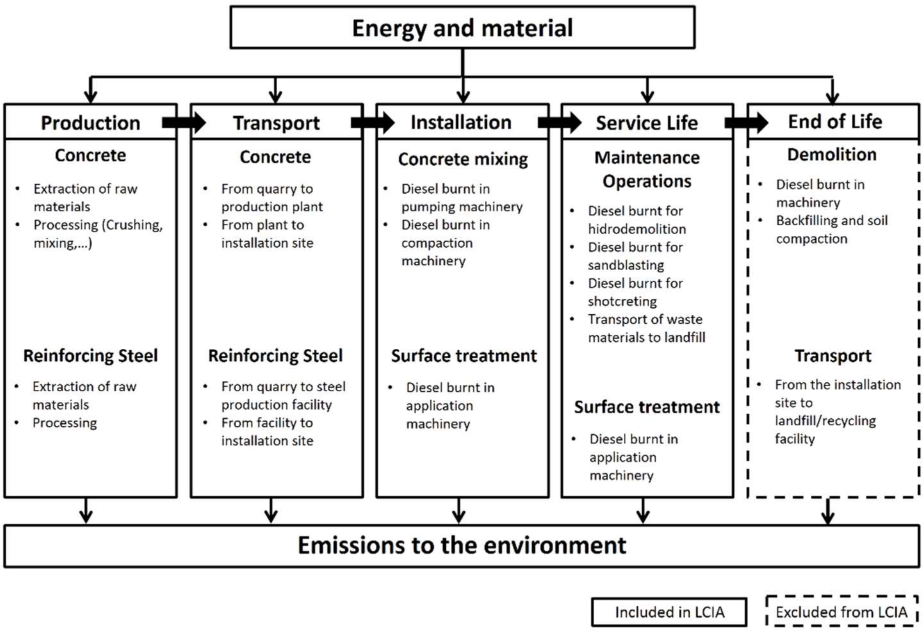


Figure 4.3. Life cycle diagram of the analyzed bridge deck

Note that the current assessment does not include the impacts that might be directly derived from the demolition of the structure and the subsequent transport of the waste materials to landfill. These impacts happening at the end of life of the structure will be very similar regardless of the preventive measure analyzed. As the purpose of this LCA is to compare the impacts between different alternatives, these impacts derived from the end stage would not provide useful information for the comparison. However, concrete, and particularly the calcium hydroxide contained in form of solute within its pores, can react with environmental carbon dioxide in the so-called carbonation process. This results in concrete reabsorbing CO_2 from the atmosphere both during its service life and its secondary life following the demolition, if recycled. This positive impact on the environment has been evaluated. In particular, the present study evaluates the carbon dioxide absorbed by the structure between the different maintenance operations, as well as the CO_2 captured by the recycled concrete.

The CO_2 capture can be evaluated on the basis of predictive models of Fick's first law of diffusion and the study by Lagerblad (2005). Carbon dioxide absorbed by concrete can be calculated as follows (Collins, 2010):

$$\boldsymbol{CO_{2\,(uptake,in\,kg)} = x_c \cdot c \cdot CaO \cdot r \cdot A \cdot M}$$

where x_c is the depth of carbonation (m), c is the cement content within the binder (kg/m^3), *CaO* is the calcium oxide contained in ordinary Portand concrete, which is assumed to be 0.65 (Collins, 2010; García-Segura et al., 2014b), r is the amount of CaO that effectively converts to $CaCO_3$ during the carbonation process (assumed to be 0.75 according to Lagerblad (2005), A is the surface of the concrete exposed to the atmosphere, and M is the dimensionless chemical molar fraction CO_2/CaO (assumed to be 0.79). The carbonation depth has been evaluated with the model proposed by Fib (2006):

$$\boldsymbol{x_c = k \cdot \sqrt{t} \cdot W(t)}$$

where x_c is the carbonation depth (mm), t is the time of evaluation (years), $W(t)$ is a weather function and k is the carbon rate coefficient (mm/year$^{0.5}$). The carbonation rate coefficient depends on the concrete properties. Table 4.3 includes the values of k assumed for each type of concrete analyzed in the present study as obtained from the Fib Bulletin 34 (Fib, 2006). The weather function is defined as:

$$\boldsymbol{W = \left(\frac{t_0}{t}\right)^{w}}$$

where t_0 is the time of reference in years (assumed to be 0.0767), t is the time of evaluation (years), and w is the weather exponent, assumed to be 0.106 for the geographical location of the case study.

It is assumed that both the concrete of the cover demolished in every maintenance activity, as well as the concrete totality resulting from the demolition stage, are crushed into 200 mm boulders to serve as embankment protection. This crushed concrete will expose new surfaces to air for a significant period of time. In the present study, this secondary life has been assumed to be 30 years.

	REF	W/C40	W/C35	SF5	SF10	FA10	FA20
k (mm/year$^{0.5}$)	1.83	1.42	0.8	1.89	1.5	1.52	1.1

Table 4.3. Carbonation rate coefficients for the different types of concrete

It is also important to note that the LCA includes the impacts derived for an analysis period of the first 100 years of bridge life. This is the required service life for bridge structures according to European Committee for Standardization (2002). Taking into account the durability criterion described in Table 4.2, the number of maintenance operations to be held during the analysis period is obtained dividing the 100 year period of analysis of the service life expected for each alternative computed in Table 4.2. Finally, note that unit processes were considered in the definition of the different analyzed concepts in order to make it possible to develop an uncertainty analysis of the resulting environmental indicators. A probabilistic uncertainty analysis of the obtained environmental indicators is performed using Monte Carlo simulations.

4.2.3.2 *Inventory analysis*

Life cycle inventory (LCI) data for the reinforcement steel, cement, aggregate, zinc, and polymer production were collected from the Ecoinvent database 3.2. The data on energy demand for the production of the different concrete alternatives assumed in this study, the energy consumed in the galvanizing process of the reinforcement associated to the alternative GALV and the fuel consumed during the maintenance sandblasting operation were obtained from the existing literature (Blakey & Beck, 2004; Millman & Giancaspro, 2012; Zastrow et al., 2017). LCI data for the rest of the machinery consumptions involved in the maintenance operations, as well as the energy needed for the production of the hydrophobic emulsion, were calculated based on the information about technology processes obtained from the machinery manufacturers. These data are shown in Table 4.4.

Process	Concept	Value	Unit	Source
Concrete production	Concrete Mixer (Power > 75kW, diesel)	7.2	min/m^3	Zastrow et al. (2017)
Reinforcement galvanizing	Specific energy consumption	0.3	kWh/kg	Blakey & Beck (2004)
Emulsifying mixer	Electricity	0.025	kWh/kg	Industry *
Hidrodemolition	Power	750	kW	Industry *
	Capacity	0.6	m^3/h	
Sandblasting	Fuel consumption	2.27	l/h	Millman & Giancaspro (2012)
	Capacity	13.2	m^2/h	
Shotcreting	Power	26.5	kW	Industry *
	Capacity	18	m^3/h	
Hydrophobic treatment	Power	1.3	kW	Industry *
	Capacity	120	l/h	

* According to manufacturer's specifications

Table 4.4. Assumed parameter values in relation to energy consumption

The impacts derived from the addition of fly ash and silica fume to concrete have been assessed by means of economic allocation. The allocation coefficients proposed by Chen (2009) and Chen et al. (2010) have been assumed. For silica fume, this is 4.8% of the environmental impact of the ferrosilicon production associated with the generation of 1kg silica fume. In the case of fly ash, this is 1% of the impact derived from the electricity production needed to generate 1kg fly ash. Mass allocation has not been chosen because, contrary to the economic allocation, it can lead to very high environmental impacts associated to fly ash or silica fume concretes, as reported by Chen et al. (2010), which can set back the industry from using such waste materials (Van den Heede & De Belie, 2012).

It shall be noted that Ecoinvent 3.2 database has some limitations regarding specific construction materials such as the ones analysed in the present study. Consequently, the impacts derived from materials such as polymer modified concrete, stainless steel rebars or hydrophobic surface treatments have been approximated by means of similar concepts to be found in Ecoinvent. Thus, the contribution of the polymers added to alternatives PMC10 and PMC20 has been assimilated to the impacts associated with 'latex production – RER', which represents the impacts associated with the styrene-butadiene dispersion process and includes the contribution of all process from raw material extraction until delivery at plant. Regarding alternative INOX, the reinforcing steel has been approximated by the Ecoinvent concept 'steel production, chromium steel 18/8, hot rolled - RER', which is defined considering a mix of differently produced steels and hot rolling processes, under which the production of reinforcement rebars has been assumed to be included. At last, the hydrophobic treatment has been assimilated to a mix of surfactant (ethoxylated alcohol (AE3) production, petrochemical - GLO) and silicone (silicone product production - RER). According to common hydrophobic surface treatments used in concrete structures, this material has been assumed to consist of 35% silicone, 3.5% surfactant, and 61.5% of water.

The transport distances of the materials from the production facilities to the installation site have been taken from León et al. (2013). These distances take into account the specific geographical locations of the Arosa's bridge and the locations of the nearest construction material providers. The assumed transport distances are summarised in Table 4.5. The distance between the concrete plant and the installation site of the bridge is 17.5 km. All concrete components (aggregates, cement, plasticisers, as well as additives and additions when used) are transported from their respective factories to the concrete plant. Once the concrete is made, it is transported from the concrete plant to the building site. The reinforcing steel and the surface treatment products are transported directly to the construction site of the bridge. If the provider is located more than 100 km away from the site where the structure is built, it is then assumed that 80% of the transport are done by means of freight train and only 20% of the distance is travelled by lorry.

Cement materials - from production facility to concrete plant			
	Lorry (km)	Rail (km)	Total (km)
Aggregates	14		
Portland Cement	12		
Fly Ash	96		
Silica Fume	96		
Polymer	129.8	519.2	649
Plastiziser	129.8	519.2	649
Cement products - from concrete plant to installation site			

	Lorry (km)	Rail (km)	Total (km)
Reference concrete	17.5		17.5
Polymer modified concrete	17.5		17.5
Fly ash concrete	17.5		17.5
Silica fume concrete	17.5		17.5
Steel products - from production facility to installation site			
	Lorry (km)	Rail (km)	Total (km)
Carbon steel reinf.	31	124	155
Stainless steel reinf.	128.4	513.6	642
Galvanised steel reinf.	31	124	155
Surface treatment - from production facility to installation site			
	Lorry (km)	Rail (km)	Total (km)
Hidrophobic	143.4	573.6	717
Sealant	143.4	573.6	717

Table 4.5. Assumed transport distances

4.2.3.3 *Impact analysis and interpretation*

The Eco-Indicator 99 impact method is adopted to evaluate the environmental impacts of the analyzed preventive measures. This method identifies the term environment with three possible types of damage: human health, ecosystem quality, and resources. Under "human health" lays the idea that every human being shall be free from illnesses or premature deaths transmitted environmentally, in present and future. Thus, the effects included under the first concept of damage to human health include climate change (CC), carcinogenic effects (CE), ozone layer depletion (OLD), respiratory effects (RE) and ionizing radiation (IR). On the other hand, the ecosystem quality is considered to be damaged if non-human species suffer changes in terms of population and geographical distribution. Consequently, the effects under this second concept of damage include ecotoxicity (ET), acidification and eutrophication (AE), and land-use (LO). At last, the damage type "resources" tries to identify changes in the availability of non-living goods supplied by the nature to the human society. This third impact group takes into account the additional energy needed in future to extract lower quality natural resources. This group includes fossil fuels extraction (FFE) and mineral extraction (ME).

The damages resulting from the use of Eco-Indicator 99 are obtained differently depending on the type of impact to be evaluated. For the aggregation of the different types of disabilities considered under the category "human health", the DALY (Disability Adjusted Life Years) scale is adopted (Murray & Lopez, 1996). This scale lists different disabilities on a scale from 0 (healthy) to 1 (dead), thus allowing for the direct summation of the different impacts. The aggregation of the different damages to the ecosystem quality is not so straightforward. For the evaluation of the ecotoxicity impact, the Potentially Affected Fraction (PAF) is determined (Meent & Klepper, 1997), which expresses the percentage of species that are exposed to an unbearable concentration of toxic substances. On the other hand, both land use and acidification and eutrophication are evaluated by calculating a Potentially Disappeared Fraction (PDF), which is adapted from the method proposed by Wiertz et al. (1992). In the first case, this indicator is calculated as a function of the species numbers that are not able to survive when their natural habitats are occupied or conversed. In the case of acidification and eutrophication, PDF is the fraction of plants that are not able to survive to a specific increase in the NO_x, SO_x and NH_3 concentrations in water. At last, the impact on resources is measured based on the energy that is required to extract mineral resources and fossil fuels in relation to the concentration (Chapman & Roberts, 1983). This energy is assumed to increase as more resources are extracted. This method measures the "surplus energy", which is defined as the increase of extraction energy per kg of extracted material when mankind has extracted a material amount 5 times the materials extracted until 1990.

Finally, once the three damage scores are obtained, namely the damage to human health, the damage to ecosystem quality and the damage to resources, they are aggregated to a single indicator. The weights proposed by the Eco-indicator 99 methodology are a result from a panel procedure, trying to reflect the preferences of the European society. These default weights are 40% for human health, 40% for ecosystem quality and 20% for resources. This weighting set corresponds to a so called hierarchist perspective, which considers a time perspective balanced between the short and the long term. Other weighting sets are also available, depending on the perspective that is assumed. In the egalitarian (long term) perspective assumes different weights, namely 30% for human health, 50% for ecosystem quality and 20% for resources. The individualist (short time) perspective works with following weights: 55% for human health, 25% for ecosystem quality, and 20% for resources.

All calculations are performed in the LCA software OpenLCA by GreenDelta. The three versions of the methodology are available in the OpenLCA software: the egalitarian, the hierarchic, and the individualist treatment of the impacts. In the present study, the Eco-indicator 99 method is applied from a hierarchist perspective.

4.3. Results of the life cycle assessment

4.3.1. Environmental impact assessment

The environmental impacts for the different preventive designs against chloride corrosion in the Arosa's bridge are shown in Table 4.6, which presents the value of the Eco-indicator 99 for each of the damage groups described in section 2.3.3 above, namely human health, ecosystem quality, and resources. The impact of each measure is shown as a percentage of the impact caused by the zero-alternative. This reference measure, or *zero-alternative*, represents the actual design of the structure, without any further corrosion preventive measures.

It is observed that both the use of hydrophobic surface treatments and the addition of silica fume cause the lowest impacts regarding the acidification and eutrophication potential (AE), which is only 19 to 21% of the impact caused by the zero-alternative. Regarding the ecotoxicity (ET), the stainless steel solution shows a huge impact, over 850% of the reference impact on that field. Considering the damages related to human health, all of the solutions result in lower impact than the zero-alternative. Once again, the surface treatments and the addition of 10% silica fume to the original concrete mix are the prevention alternatives which derive in fewer impacts. Paying attention to the resources impact category, adding polymers in the concrete mix shows the greatest impact on fossil fuel extraction (FFE), approximately 18 to 41% greater than the reference impact. Regarding to mineral extraction (ME), it is again stainless steel the one showing the greatest impact, approximately 1320%. It is worth noting that the measure involving the use of galvanised steel shows also an impact in the ME field over 100%.

Prevention alternatives	Ecosystem quality			Human health					Resources	
	AE	ET	LO	CE	CC	IR	OLD	RE	FFE	ME
REF	100	100	100	100	100	100	100	100	100	100
CC35	72	85	73	83	72	69	71	75	71	96
CC45	55	75	59	72	54	48	54	60	55	94
CC50	48	72	50	69	48	42	46	55	47	93
W/C35	30	60	32	56	30	18	38	39	31	88
W/C40	47	71	49	68	46	38	55	54	48	93
INOX	43	853	62	48	43	12	25	120	35	1318
GALV	58	68	43	64	39	31	38	53	39	103
FA10	46	69	45	66	45	36	42	53	43	92
FA20	41	67	41	63	41	30	36	50	38	91
SF5	36	64	38	62	35	23	31	48	33	91
SF10	21	56	23	53	20	4	15	37	16	88
PMC10	84	79	62	77	82	55	59	82	141	94
PMC20	50	58	24	53	47	11	19	52	118	88
HYDRO	19	54	22	49	17	5	20	29	17	88
SEAL	25	56	24	50	19	5	17	32	23	89

Table 4.6. Eco-indicator 99 values for the analysed preventive measures

Fig. 4.4 shows the LCIA results summarised per damage categories. Regarding the impacts on the ecosystem quality, it is observed that using stainless steel is by far the most hazardous alternative. This high impact derives from its impact on ecotoxicity associated with the stainless steel production. The rest of the alternatives show impacts on this field at least 4 times lower than that of the measure INOX. Similar results have also been reported previously in the literature (Mistry et al., 2016). However, this high impact of stainless steel is not to be seen in the rest of impact categories. Regarding the impacts on human health, the reference alternative shows the greatest impacts, mainly derived from the energy consumed during the maintenance activities in terms of fuel and electricity.

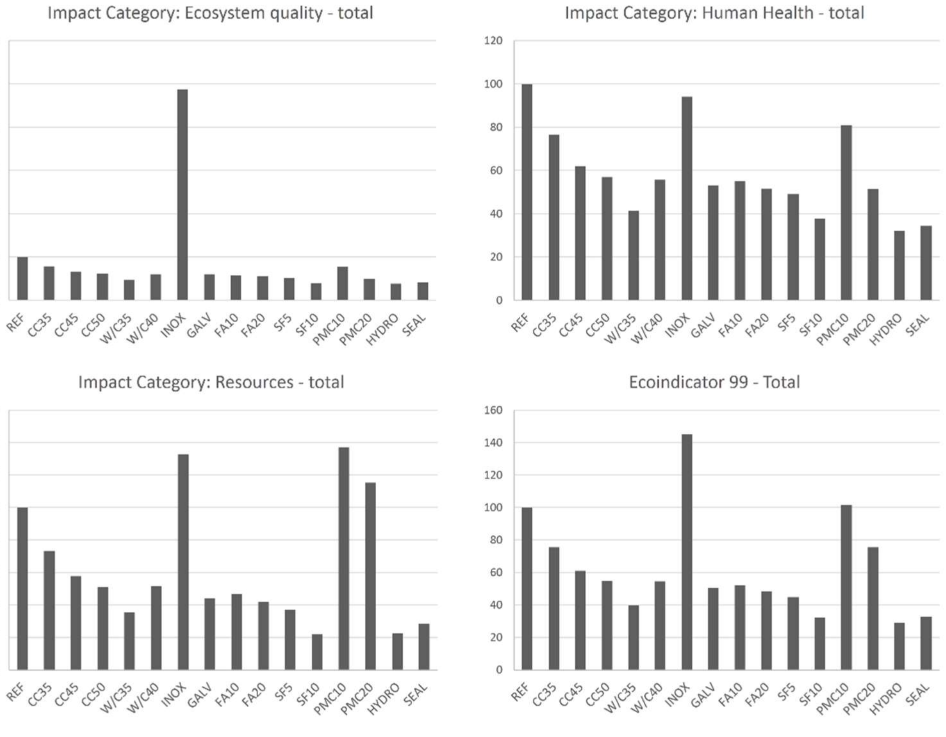


Figure 4.4. Eco-Indicator 99 results for the analysed preventive designs, shown as a percentage of the reference alternative

The main impacts on human health of the maintenance related to the alternative REF are associated with the emission of carcinogenic and its negative contribution to climate change. On the other hand, the alternatives which are more durable and less maintenance demanding, such as reducing the water/cement ratio (W/C35), adding silica fume to the concrete mix (SF10) or treating the deck surface (HYDRO, SEAL) show the lowest impacts on human health, approximately only a 30 - 40% of the impact of the reference design. It has been observed that the impacts derived from the addition of fly ash or silica fume to the concrete mix decrease the greater the addition ratio considered. This impact decrease is mainly due to its better performance against corrosion and its less need for repair. Additionally, it is worth noting that cement production is a main contributor to climate change. Consequently, those alternatives where cement is partially replaced by additions, such as fly ash or silica fume, allow to decrease the global warming potential of the considered preventive strategy and consequently its impact on human health (Van den Heede et al., 2017). However, in this case study, this negative impact of the cement industry is partially masked by the also great impacts on climate change of the steel production and the machinery involved in maintenance. Consequently, alternatives such as FA10 or FA20 find such positive contribution burdened with the damage caused by the activities mentioned above, due to the high requirement of maintenance if exposed to chlorides.

Paying attention to the impacts generated on the extraction of resources, it shall be noted that the alternatives based on the addition of latex (PMC10 and PMC20) show a great impact. This impact is even greater than the one derived from the reference or the stainless steel based design. This is mainly due to the extraction of resources for the production of latex from fossil fuels (FFE). Additionally, this impact is increased by the amount of latex needed in the numerous maintenance activities associated with the alternative PMC10. As observed above, increasing the addition of polymers to the concrete mix (PMC20) reduces the impacts on this damage category as a consequence of increasing exponentially the time to corrosion initiation against chlorides.

The results from the Ecoindicator 99 are obtained assuming a hierarchist perspective, thus increasing the relative importance of damages caused to ecosystem and human health against the ones derived from resources extraction. Those alternatives that perform best in chloride laden environments (W/C35 and SF10) show the lowest impacts, together with those that, although requiring intensive maintenance (HYDRO and SEAL), are less energy demanding. However, it is worth noting that the analysed alternatives allow to reduce the environmental impacts throughout the service life of the bridge deck if compared to the reference design, except for PMC10 and INOX, whose impacts on the environment have been quantified to be 1% and 45% greater than the reference alternative respectively. Regarding the alternatives consisting in increasing the concrete cover, it shall be observed that great cover increases (CC50) act similarly than substituting ordinary carbon steel reinforcement by galvanized steel.

Of particular interest are the contribution of the CO_2 fixation in the climate change impact subcategory. Table 4.7 shows the total score derived from the evaluation of the climate change impact subcategory according to the Eco-indicator 99 methodology, as well as the contribution, both in total and in relative terms, of the CO_2 uptake derived from the maintenance life cycle stage, and from the End of Life stage. As can be seen, the contribution is negative in every case, meaning that CO_2 uptake reduces the resulting environmental impact on climate change.

As can be observed, the alternatives that contribute most positively on climate change in terms of total CO_2 absorbed are those with worse durability, i.e. those solutions that are most likely to be carbonated. However, in relative terms this contribution on the LCA climate change impact is less important, as the total impact for those solutions is greater than in other cases. This is a direct consecuence of the greater maintenance needs and the construction processes involved in these activities. Where conventional concrete with no special additions is used, the contribution of the CO_2 fixed during the End of Life phase ranges between 2.5% and 6%, which is in good accordance with previously published studies (Penadés-Plà et al., 2017).

Prevention alternatives	Climate change EI99 score	Maintenance		EOL		Maintenance + EOL	
		EI99 Score	Contribution (%)	EI99 Score	Contribution (%)	EI99 Score	Contribution (%)
REF	34.92	-1.85	-5.29	-0.99	-2.83	-2.83	-8.12
CC35	25.08	-1.30	-5.20	-0.99	-3.94	-2.29	-9.14
CC45	19.01	-0.93	-4.91	-0.99	-5.20	-1.92	-10.11
CC50	16.78	-0.82	-4.89	-0.99	-5.89	-1.81	-10.77
W/C35	10.38	-0.14	-1.39	-0.42	-4.06	-0.57	-5.45
W/C40	16.05	-0.57	-3.53	-0.76	-4.75	-1.33	-8.28
INOX	15.02	0.00	0.00	-0.99	-6.58	-0.99	-6.58
GALV	13.78	-0.60	-4.37	-0.99	-7.17	-1.59	-11.54
FA10	15.71	-1.08	-3.78	-0.98	-3.43	-2.06	-13.11
FA20	14.42	-0.20	-1.19	-0.98	-5.94	-1.17	-8.14
SF5	12.15	-0.48	-3.96	-1.02	-8.36	-1.50	-12.33
SF10	7.12	0.00	0.00	-0.81	-11.39	-0.81	-11.39
PMC10	28.55	-0.59	-3.75	-0.82	-5.20	-1.41	-4.92
PMC20	16.46	-0.36	-2.51	-0.60	-4.14	-0.96	-5.82
HYDRO	5.90	0.00	0.00	-0.99	-16.76	-0.99	-16.76
SEAL	6.77	0.00	0.00	-0.99	-14.59	-0.99	-14.59

Table 4.7. Contribution of CO2 uptake on climate change impact

If we pay attention to the contribution of the CO_2 absorbed during both maintenance and after recycling, the greatest relative contribution to climate change impact reduction results from surface treatments (16.76% and 14.59% reduction). This reduction is associated to the carbonation of the concrete once it is recycled, as during the service stage the structure does not absorb carbon dioxide. Alternatives with additions, such as FA10 and SF5 also show great reductions in the climate change LCA impacts, namely 13.11% and 12.33% respectively. In any case, it is shown that CO_2 fixation during the life cycle of the structure reduces the climate change impact from 5% to 17%, thus showing the importance of considering CO_2 absorption in environmental life cycle assessments.

System expansion has not been considered in the present study as it can lead to LCA inconsistencies derived from double counting of the avoided burdens and it does not guarantee global coherency between LCA studies (Chen et al., 2010; Pelletier et al., 2015). It also may lead to contradictory results when evaluating waste management systems (Heijungs & Guinée, 2007). However, and for the sake of transparency, the obtained results assuming economic allocation of co-products, namely fly ash and silica fume, are compared with the impacts resulting from adopting a system expansion approach. In this case, system expansion credits for the burdens avoided when using such products in concrete mixes by substracting the impacts derived from transport of these industry co-products to landfills (Margallo et al., 2014; Babbitt & Lindner, 2008). For the particular context of the case study, the landfill lies 8.6 km away from the thermoelectric plant where fly ash is obtained, and 35.7 km away from the ferro-silicon production plant responsible for the silica fume. Fig. 4.5 shows a comparison of the Eco-Indicator 99 results obtained adopting the economic allocation and the system expansion approach. Results show that, under a system expansion perspective, alternatives related to the use of these additions have lower impacts if compared to the ones presented here resulting from economic allocation. It is important to note that these results are highly dependent on the particular geographical context studied. In this case, the resulting impact reduction is greater for the solutions based on silica fume additions due to the really short distances to landfill in the case of fly ash. Under this new modeling hypothesis, the greatest impact difference is that of SF10, which turns to be the most preferable alternative in environmental terms, incurring in even lower impacts than the hydrophobic treatments.

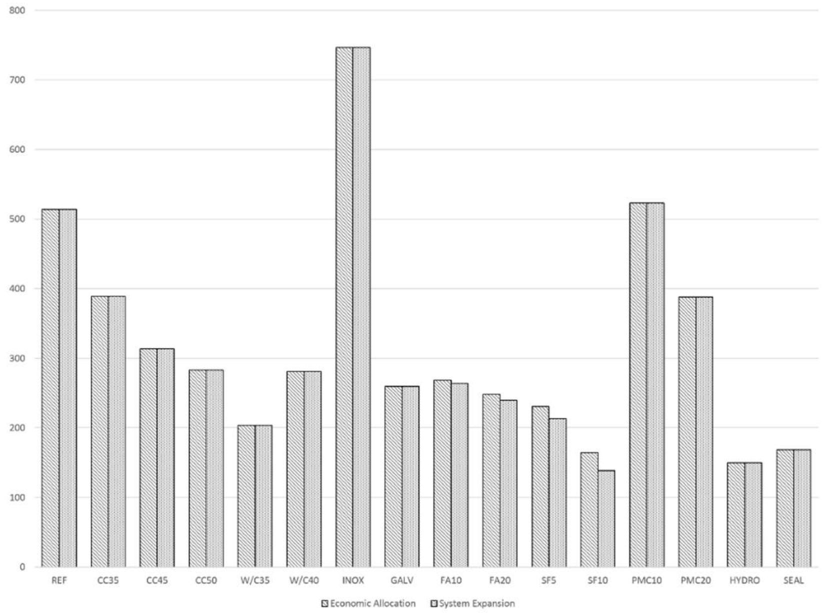


Figure 4.5. System expansion versus economic allocation of co-products

4.3.2. Element contribution to the overall impacts

The elements considered are the different types of concrete and reinforcing steel used, the transport activities, and the maintenance operations needed for each alternative. Fig. 4.6 shows the contribution of each life cycle element to the environmental effects for the different preventive measures. The environmental effects are the ecosystem quality, human health, and resources, together with the overall environmental effect. Maintenance operations include the activities of hydrodemolition of the concrete cover, cleaning of the outermost reinforcement and shotcreting with the corresponding concrete mixture to restore the original cover. The impact of the concrete used for the replacement is evaluated under the corresponding concrete concept in the mentioned tables. In the case of surface treatment, maintenance operations only involve the reapplication of the treatment.

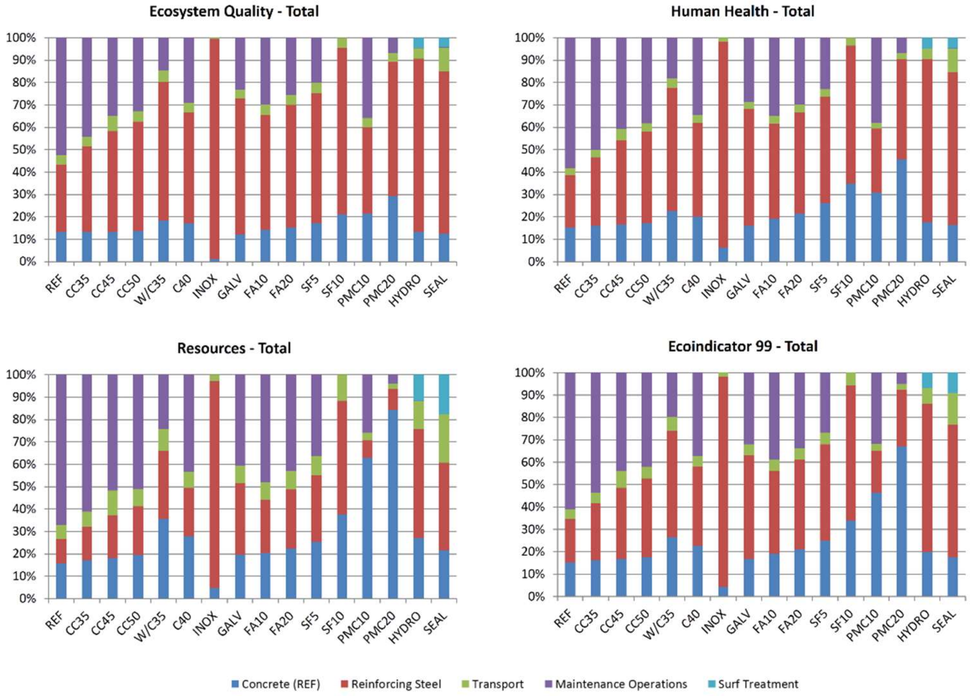


Figure 4.6. Contribution (in percentage) of each element for every impact category

The contribution of concrete and steel depend on the number of maintenance activities performed throughout the service life of the structure. Therefore, for those alternatives where great maintenance efforts are needed, the impact derived from the maintenance operations can reach a 62% of the total impact. This is the case of the zero alternative, but can also be observed for those strategies that are very demanding of maintenance, such as CC35 (53.7%). It shall be noted that the impact resulting from maintenance activities, as explained above, is a consequence of the machinery involved in the operations. Therefore, their contribution depends on the repair strategy assumed. So, it can be observed that the strategies that imply surface treatments (HYDRO and SEAL) generate very low impacts during the operation stage of the bridge, in spite of the fact that they require 20 interventions throughout the 100 years analyzed. This is a consequence of the lower energy consumed in the reapplication of the treatments, if compared to the greater consumptions involved in the hydrodemolition and shotcreting activities.

It shall be observed that the contribution of steel to the total impact increases with the concrete cover, from 19.4% in the case of 30 mm cover to 35.2% in the case of 50 mm cover. This increase shall be explained by the lower number of maintenance activities needed for alternatives with greater cover depths. Taking into account that steel impacts only during the construction stage (no steel is consumed during maintenance operations), it is clear that the relative contribution of the construction stage, and consequently of steel, to the total impact increases the less maintenance is needed.

The transport concept includes both, the transport needed for the materials production and the transport from the transport phase as well as the transport activities involved in the maintenance operations. It is shown that transport is a significant contributor to environmental impacts of each prevention alternative, representing between 3% and 15% of the total impact in those cases where maintenance is needed. When no maintenance is performed, this value decreases up to levels below 2%, as is the case with stainless steel (INOX). Although transport impacts are highly related to the quantity of interventions needed throughout the analysis period, their contribution is less than the one derived from the energy consumed by the machinery involved in maintenance operations.

4.3.3. Uncertainty analysis

An uncertainty analysis of the obtained environmental results is performed using Monte Carlo simulations. The model converges after 1000 Monte Carlo iteratons. In this study, convergence is said to be achieved when the relative error associated to the mean value of the estimation of the total environmental impact falls below 0.25% with a confidence level of 99% for every alternative evaluated. The uncertainty associated with each unit is defined according to the Ecoinvent database, which assigns particular log-normal probability distributions to every unit process so as to take into consideration the geographic representativeness of the data, as well as the inaccuracies associated to data and measurement quality at the production locations (Frischknecht et al., 2005). Table 4.8 shows the uncertainty range for the impact results by applying a 95% confidence interval. Results are shown for the ecosystem, human health, and resources categories, as well as for the resulting final value of the eco-indicator. The uncertainty range in all the studied measures is less than 15% of their corresponding impact indicator results for the Eco-indicator resulting value. Slightly higher ranges can be seen in the subcategory human health, where for the reference measure the difference reaches 15.8%. The uncertainty associated to the considered Ecoinvent processes is, indeed, reduced. The coefficients of variation derived from the obtained results, which result from dividing the standard deviation by the mean, are below 5% for every of the results presented. The greatest variation is associated to impact categories Ecosystem Quality and Human Health.

	Ecosystem Quality - total			Human Health - total			Resources - total			Total - total		
	Mean	CV	5 - 95 Perc. range	Mean	CV	5 - 95 Perc. range	Mean	CV	5 - 95 Perc. range	Mean	CV	5 - 95 Perc. range
REF	47,9	4,4	6,9	274,1	4,8	43,4	194,8	2,1	13,2	516,8	3,2	52,7
CC35	37,9	4,2	5,3	210,4	4,1	27,2	143,2	1,8	8,7	391,4	2,7	34,3
CC45	32,1	4,4	4,8	171,4	3,2	18,1	113,1	1,7	6,3	316,5	2,3	23,5
CC50	29,5	4,1	4,1	156,6	3,1	15,7	99,3	1,6	5,3	285,4	2,2	20,7
W/C35	22,7	4,4	3,2	113,4	2,0	7,4	70,0	3,9	8,9	206,0	2,3	15,3
W/C40	29,0	4,1	4,0	153,8	3,0	14,8	101,5	2,8	8,7	284,3	2,3	20,9
INOX	232,3	0,3	2,4	257,3	0,4	3,1	259,1	0,2	1,6	748,8	0,3	6,0
GALV	29,1	4,5	4,3	147,3	2,8	12,7	86,6	1,5	4,4	263,1	2,1	17,4
FA10	28,0	3,9	3,6	151,4	2,9	14,7	91,4	1,5	4,4	270,9	2,1	18,6
FA20	26,4	3,8	3,3	142,0	2,5	11,9	81,8	1,5	3,7	250,2	1,9	15,2
SF5	24,9	4,0	3,2	135,6	1,9	8,3	72,8	1,2	3,0	233,2	1,5	11,8
SF10	19,3	3,9	2,5	104,6	0,8	2,5	43,0	0,9	1,3	166,9	1,0	5,4
PMC10	37,0	3,8	4,7	221,8	3,3	22,9	266,8	0,8	7,2	525,6	1,7	29,1
PMC20	23,8	3,4	2,7	141,8	0,9	4,1	224,9	0,2	1,6	390,5	0,5	6,7
HYDRO	18,7	4,3	2,5	89,0	1,1	3,0	44,7	0,9	1,5	152,4	1,2	5,7
SEAL	20,1	4,5	2,9	95,4	1,4	4,0	55,8	2,0	3,4	171,3	1,6	8,4

Table 4.8. Results of the uncertainty analysis

Additionally, the differences between various LCIA methods can mean a great source of uncertainty. According to Hung and Ma (2009), the application of different LCIA methodologies can produce different rankings of the analyzed alternatives, thus leading to different decisions. Taking this into account, two other methods, namely EPS (acronym for Environmental Priority Strategies) and ReCiPe, are considered. These methods have been chosen due to the fact that they can estimate the environmental performance of an alternative in one single indicator, as Ecoindicator 99 does. In particular, the results of the EPS assessment method are damage costs derived from emissions and use of natural resources and are expressed as Environmental Load Units (ELU), each ELU representing the externalities corresponding to one Euro enviromental damage cost. On the other hand, the ReCiPe assessment integrates eighteen midpoint indicators into three impact categories in the endpoint level, related to environmental effects on human health, on biodivesrity and on resource scarcity. The ranking resulting from the evaluation of the alternatives based on these three methods is shown in Table 4.9. It can be observed that the considered methods offer very slight differences for the case study considered.

	Eco-99	EPS	ReCiPe
REF	14	15	16
CC35	13	13	13
CC45	11	11	11
CC50	10	10	10
W/C35	4	4	4
W/C40	9	9	9
INOX	16	16	15
GALV	7	7	7
FA10	8	8	8
FA20	6	6	6
SF5	5	5	5
SF10	2	3	3
PMC10	15	14	14
PMC20	12	12	12
HYDRO	1	1	1
SEAL	3	2	2

Table 4.9. Ranking results under different LCIA methods

In view of the presented uncertainty analysis, the variations in terms of elementary data are not considered to affect the results and they shall be considered robust.

4.3.4. Design-oriented approach versus maintenance-oriented approach

The results of this study focus on the impacts derived from alternative deck designs with different durability and maintenance needs. However, it is interesting to compare such a design-based approach with the usual maintenance-oriented approach, i.e. an existing, unsistainable design with poor durability in which different maintenance strategies are held when needed. The question arises wether such an approach is preferable in environmental terms to a design in which sustainability is already considered at the project phase. The new scenario now considers that the reference design (REF) is maintained for the first time after 6.5 years, according to the expected service life of this design presented in Table 4.2. The concrete cover is then replaced by a new cover with alternative durability properties, namely those associated to the alternative designs evaluated in the present study. Assuming that the geometry of the deck remains unchanged along the time, and given that reinforcement is not to be substituted during maintenance activities, alternatives INOX, GALV, CC35, CC45 and CC50 are not considered in the current comparative analysis.

Fig. 4.7 shows the Eco-indicator 99 results associated to both the design- and the just described maintenance-oriented approach. It can be observed that, considering this new scenario, the most preferable maintenance alternative consists in replacing the reference concrete cover by concrete with 10% silica fume addition (SF10). It is observed as well that some alternatives incur in lesser impacts than in the original approach. This is the case, for example, of alternatives based on polymer modified concrete. In the design-based approach, it is considered that the complete bridge deck is made of this material, while now, as the deck is constructed with the reference concrete, the impacts at the construction stage are lower for these alternatives and the LCA results are consequently reduced. Maintenance based on SF5 and FA20 concretes, although almost the same as in the design approach, show lower impacts. This is due to the fact that design alternatives based on silica fume and fly ash have slighly greater impacts at the construction stage derived from the transport processes associated to these additions. From the results presented in Fig. 4.7, it is derived that the design-based approach is preferable in environmental terms than the maintenance-based one. The former perspective allows the designer to reduce the life cycle environmental impacts up to 10.8% when compared to the most preferable of the alternatives in the new maintenance-oriented scenario.

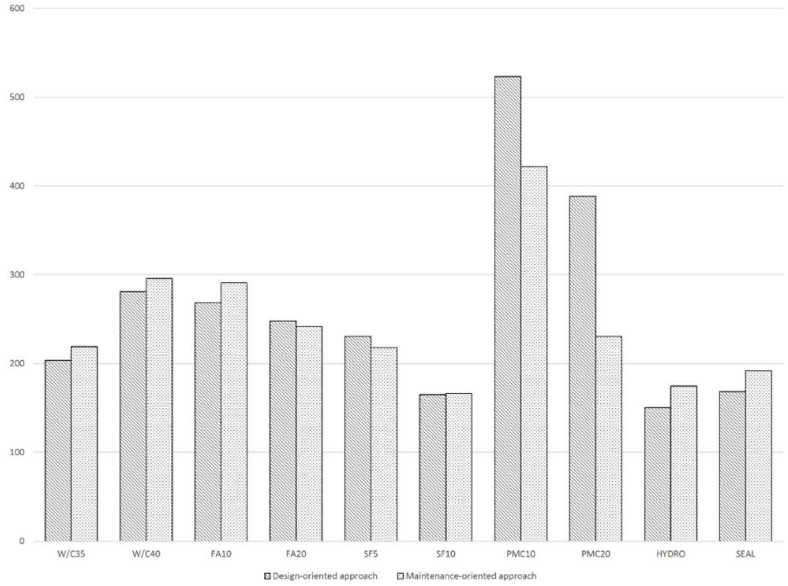


Figure 4.7. Eco-Indicator 99 results for the design- and the maintenance-based approaches

4.4. Discussion

Sustainable design of long-lasting, maintenance demanding structures, such as concrete bridges in marine environments, is a key issue for the construction industry. Over the past years, environmental impacts of different preventive designs have been assessed under a life cycle perspective. The results published, however, do not meet the conditions for the comparability between them. An evaluation of the different designs considering the same functional unit, assessment methodology and boundary conditions may improve the knowledge on the environmental performance of the existing measures and provide useful information for the sustainable design of concrete structures.

Preventive designs based on hydrophobic and sealant surface treatments have proven to perform best from an environmental point of view. Although they require the greatest amount of maintenance interventions along the service life of the structure, they result in almost 70% lower impacts than the reference, non-preventive design. Similar results were already reported by Årskog et al. (2004) and Petcherdchoo (2015), where it is shown that such measures are fair more preferable from an ecological perspective than designs where concrete cover has to be replaced periodically. These results result from the lower impacts associated to maintenance operations, as shown in Fig. 4.6, in comparison to those associated to conventional repairs.

However, the present study also shows that there are designs based on special concrete mixes that are highly competitive in environmental terms. So, concrete with silica fume (SF10) has been shown to perform almost as well as surface treatments, due to its high durability and to the low impacts related to the material production. Such environmental benefits of concretes with high percentages of additions on human health, as well as on the ecosystem quality, have already been reported (Tait & Cheung, 2016), although not applied to a chloride exposed structure. On the contrary, other solutions with also great durability, such as those based on polymer modified concrete (expected service life of 73.9 years for PMC20), have shown to reduce environmental impacts only a 20% when compared to the reference design. The findings above assume that the alternative concrete mixes are applied to the complete concrete volume. In these cases, the high impacts related to material production burden their good durability performance, taking from 40% to 60% of the total environmental impact, as derived from Fig. 4.6. From a maintenance-oriented perspective, replacing the original concrete cover with polymer modified concrete (PMC20) has shown to perform quite better, reducing the impacts of the design-based approach by approximately one half.

Although steel production has been identified as one of the main contributors to environmental impacts, for those alternatives that are very maintenance demanding, such as the reference design or those based on increased concrete cover, the greatest impacts result from maintenance activities and the associated energy and diesel consumption. Transport has proven to be the process that causes the least affection to the environment, contributing by less than 10% of the resulting total impact. It is important to note that the material production facilities considered in this study are in the same region of Spain, except for those related to stainless steel and polymer-derived materials production, which are still located within the national territory, thus explaining the minor influence of transport on the assessment results.

4.5. Concluding remarks

This study presents the LCA of 15 different preventive designs applied to the Arosa's concrete bridge deck exposed to a chloride laden environment. The environmental impacts are analyzed during the life cycle of the bridge resulting from the different preventive designs. A service life of 100 years has been considered and, once this point in time is reached, the structure is assumed to be demolished and used as embankment protection. Under the assumptions adopted in this specific case study, following may be concluded:

- Prevention strategies based on the application of surface treatments to prevent the chloride ingress on concrete show the lowest environmental impacts. This is mainly due to the use of less energy demanding machinery for the maintenance operations.
- Alternatives focused on reducing the density of the concrete cover, such as the reduction of water/cement ratios or the partial replacement of cement by silica fume, have also shown to be very competitive against surface treatments in terms of environmental impacts. These alternatives perform better from the point of view of durability, and are less intensive in maintenance, reducing consequently the damage to the environment associated with these activities.
- Other additions, such as fly ash, although performing more than acceptably from the environmental point of view, have shown average impacts if compared to the rest of the considered strategies. Other additions, such as silica fume, have shown to perform better, thus leading to less maintenance demanding solutions.
- The use of polymeric additives in concrete mixes has great impacts on human health and resources depletion throughout the life cycle of the analysed bridge deck. Although this may seem contradictory, these negative impacts can be lessened by increasing the amount of addition used, as the durability performance of polymer modified concretes increases exponentially with the addition percentage.
- The environmental impacts of stainless steel rebars are greater than those alternatives with carbon steel rebars regarding the ecosystem quality and the resource depletion. Thus, despite the unnecessary maintenance for this alternative, the global environmental impact of such design results in the less environmentally friendly alternative, leading to impacts almost 50% greater than the reference design.
- Increasing the concrete cover can reduce the environmental life cycle impacts of the deck if compared to the reference alternative up to 45%, performing similarly than using of galvanized reinforcement.

Chapter 5

Reliability-based maintenance optimization of corrosion preventive designs under a life cycle perspective

Authors: Ignacio J. Navarro; José V. Martí; Víctor Yepes

Status: Manuscript published

Journal: *Environmental Impact Assessment Review,* Volume 74, Pages 23-34, January 2019

DOI: 10.1016/j.eiar.2018.10.001

JCR IF (2018) 3.749

JCR Category	Ranking	Quartile
Environmental Studies	24/116	Q1

Presentation: Post-print (author version)

Abstract

Sustainability is of paramount importance when facing the design of long lasting, maintenance demanding structures. In particular, a sustainable life cycle design for concrete structrues exposed to aggressive environments may lead to significant economic savings, and to reduced environmental consequences. The present study evaluates 18 different design alternatives for an existing concrete bridge deck exposed to chlorides, analyzing the economic and environmental impacts associated with each design as a function of the maintenance interval chosen. Results are illustrated in the context of a reliability-based maintenance optimization on both life cycle costs and life cycle environmental impacts. Maintenance optimization results in significant reductions of life cycle impacts if compared to the damage resulting from performing the maintenance actions when the end of the service life of the structure is reached. The use of concrete with 10% silica fume has been shown to be the most effective prevention strategy against corrosion of reinforcement steel in economic terms, reducing the life cycle costs of the original deck design by 76%. From an environmental perspective, maintenance based on the hydrophobic treatment of the concrete deck surface results in the best performance, allowing for a reduction of the impacts associated with the original design by 82.8%.

Keywords Life Cycle Assessment, Life Cycle Cost Analysis, Chloride corrosion, Sustainable design, Maintenance Optimization, Reliability

5.1. Introduction

Sustainability seeks to ensure on-going development without compromising the capacity of future generations to meet their own needs. In this context, the construction sector is one of the main environmental and economical stressors (Worrell et al., 2001); as such, special attention has been paid in recent years to sustainable design of structures. In particular, concrete bridges are the subject of particular interest in regard to the design approach, due to the existing long service life requirements and to the extensive material consumption associated with their construction and maintenance. Along the lines of sustainable structural design, research has been conducted on the cost optimization of concrete bridge design (García-Segura et al., 2014a; Martí et al., 2013; Yepes et al., 2017), and also on the minimization of CO_2 emissions and energy consumption (García-Segura et al., 2015; García-Segura & Yepes, 2016; Martí et al., 2016) resulting from bridge construction activities.

According to the long-term perspective on which the sustainability concept is based, life cycle assessment has become an internationally recognized method when dealing with the sustainable design of concrete bridges. Within this framework, the three pillars on which sustainability is based, namely society, environment and economy, have been covered to a greater or lesser extent. Hammervold et al. (2013) compare the life cycle environmental impacts of three bridges built in Norway, assuming routine repairs during the use phase. Zhang et al. (2016) include uncertainty in the evaluation of the environmental impacts. Du et al. (2014) and Penadés-Plà et al. (2017) compare alternative bridge designs from an environmental point of view. On the other hand, Eamon et al. (2012) compare the life cycle costs of reinforcement alternatives for concrete bridges. Navarro et al. (2018a) evaluate the costs associated with alternative bridge designs in coastal environments. A general conclusion is that the maintenance and use phase of a concrete bridge is the main source of impacts during its life cycle, both environmentally and economically. An adequate maintenance strategy is essential in order to reduce the life cycle impacts of the structure (Frangopol & Soliman, 2016). Studies have been carried out that optimize the maintenance costs of concrete bridges (Kendall et al., 2008; Safi et al., 2015; Frangopol, 2011). García-Segura et al. (2017) include environmental criteria in the maintenance optimization of bridge decks.

Maintenance and its impact are crucial for concrete structures in aggressive environments, where deterioration plays a major role over the term of their service life. Although there are several ways that concrete bridges may deteriorate in severe environments, experience shows that the most important threat to concrete structures is chloride-induced corrosion of the reinforcement (Valipour et al., 2017). Over the last few decades, different preventive measures have been developed to increase the corrosion resistance of concrete structures exposed to chlorides, thus leading to extended service lives and consequently to lower maintenance needs. However, lower maintenance needs do not always lead to the minimum of environmental and economic (Navarro et al., 2018a) impacts. A sustainable design of a concrete bridge in a coastal environment involves selecting the most suitable prevention alternative in terms of life cycle impacts, attending to the optimal maintenance strategy associated with it.

In this sense, this paper is devoted to shedding light on the way that different corrosion prevention measures may influence the results of optimum maintenance strategies from both the economic and the environmental points of view. To do so, a real concrete bridge deck subject to a marine environment is considered for the study. This bridge deck is modelled and assessed by means of both a life cycle cost analysis (LCCA henceforth) and an environmental life cycle impact analysis (LCA henceforth) with respect to a design service life of 100 years. Reliability-based maintenance optimization is performed for each of the analyzed preventive measures. Results will be presented and discussed for the optimal environmental and economic maintenance strategies.

5.2. Materials and methods

LCA is a widespread methodology that in recent years has taken firm root and been standarized (ISO, 2006a, 2006b) in the international context. LCCA, on the contrary, although in a fairly advanced stage of development (Hunkeler et al., 2008), still lacks an ISO standard that helps the integration of both assessment methodologies. In order to provide a comparative analysis on a consistent basis, the present study applies the ISO

14040 methodological framework for the LCC assessment (Swarr et al., 2011). According to ISO 14040, the assessment should be carried out in four phases: the definition of goal and scope, the inventory analysis, the impact assessment and the interpretation of the results.

5.2.1. Goal and scope definition

The present study focuses on particular preventive design alternatives applied to a real concrete bridge deck in a coastal environment. The bridge of Ensenada do Engano in Spain is analyzed. A cross-section of the bridge deck is shown in Fig. 5.1. The bridge, which is 721 m long and has a span distribution of 41 m + 9 x 70 m + 50 m, crosses over an estuary, with the deck less than 9 m above the mean sea level. The bridge consists of a box girder deck, with a section height of 3.2 m and a total width of 11 m. The concrete cover of the deck is 30 mm. The concrete mix of the deck is assumed to consist of a cement content of 400 kg/m^3, and a water/cement ratio of 0.45. A passive reinforcing steel in the amount of 100 kg/m^3 of concrete is considered. It shall be noted that, according to the Spanish design codes for marine environments, the bridge is designed to remain uncracked. This will be assumed for the rest of the study.

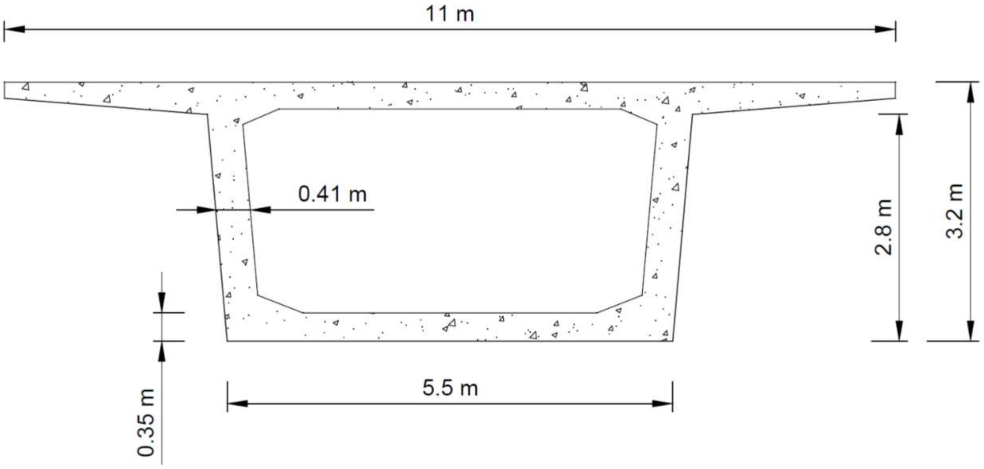


Figure 5.1. Cross-section of the concrete bridge deck at Ensenada do Engano (dimensions in m)

This study considers alternative designs for the described case study (called reference design or REF hereafter) based on the prevention strategies that are usually assumed for concrete structures exposed to marine environments. Firstly, increasing the original concrete cover of the steel reinforcement from 30 mm to 45 mm and to 55 mm (named here CC45 and CC55) has been considered. Secondly, a reduction in the water to cement ratio from the existing w/c=0.45 to w/c=0.40 and to w/c=0.35 (alternatives W/C40 and W/C35 respectively) has also been considered. Reducing the water/cement ratio results in concretes with lower porosity, thus reducing the chloride diffusivity throughout the cover. The third type of preventive measure evaluated consists in the partial substitution of the concrete by fly ash or silica fume in the original concrete mixture. Additions of 10% and 20% fly ash (called here FA10 and FA20), and 5% and 10% silica fume (alternatives SF5 and SF10) have been considered. As with fly ash and silica fume additions, polymer-modified concretes also result in denser concretes, thus contributing to an increase in the durability of concrete by hindering chloride diffusion. Consequentlly, additions 10% and 20% styrene butadiene rubber latex (designs PMC10 and PMC20) have been considered. The aforementioned percentages are expressed as a fraction of the cement content in the original mix. It shall be noted that the presented concrete mixes are assumed to replace completely the reference design mix.

The use of corrosion inhibitors is a usual way to extend the service lives of concrete structures in agressive environments. The present study considers two types of inhibitor, namely an organic inhibitor used as an additive to the original concrete mix (design OCI hereafter), and a migratory inhibitor, which is applied to the concrete surface and penetrates the concrete cover, thus reacting with the concrete and increasing its resistivity (alternaive MIG). The study also evaluates the use of galvanized steel (design GALV) and stainless steel (design INOX) instead of the ordinary steel of the reference design in the bridge structure. The use of durable steels increases the amount of chlorides needed to start the corrosion process, thus extending the service life of the design. In addition, the application of a hydrophobic product to the exposed deck surface (alternative HYDRO) and the application of a sealant product (alternative SEAL) in order to prevent chloride ingress in the concrete cover have been considered. Finally, large structures in marine environments are also protected by means of impressed current cathodic protection (ICCP), where the reinforcing steel is forced to act as a cathode, thus preventing its oxidation. In summary, a total of 18 design alternatives, including the reference design, are taken into account in the performance evaluation. The resulting concrete mixes are shown in Table 5.1.

Concrete mix components	REF[a]	W/C40	W/C35	SF5	SF10	FA10	FA20	PMC10	PMC20	OCI
Cement (kg/m^3)	400	400	400	342.2	302.2	370.2	358.2	400	400	400
Water (l/m^3)	172	160	140	172	172	172	172	172	172	172
Gravel (kg/m^3)	926.7	993.9	1016.9	980.1	980.1	980.1	980.1	926.7	926.7	926.7
Sand (kg/m^3)	827.9	993.2	1024.2	1007.5	1024.9	965.7	941.3	827.9	827.9	827.9
Fly Ash (kg/m^3)	-	-	-	-	-	40	80	-	-	-
Silica Fume (kg/m^3)	-	-	-	20	40	-	-	-	-	-
Styrene Butadiene Latex (kg/m^3)	-	-	-	-	-	-	-	40	80	-
Organic Inhibitor (kg/m^3)	-	-	-	-	-	-	-	-	-	12
Plasticiser (kg/m^3)	-	6	8	-	-	-	-	-	-	-

f_{ck} (MPa)	32	39	47	32	32	32	32	42	42	32
E_c (GPa)	29	31	32	29	29	29	29	31	31	29

Notes:

[a] Concrete in alternatives CC45, CC55, INOX, GALV, MIG, HYDRO, SEAL, and ICCP are based on this reference mix

Table 5.1. Alternative concrete mixes assumed in the preventive designs

5.2.1.1 *Goal and scope of the study*

The goal of the present study is to evaluate and compare both the economic and environmental performance of the presented design alternatives for the concrete bridge deck in a coastal environment. The assessment is based on the impacts derived from a reliability-based maintenance approach, optimized for each design to minimize either the environmental or the economic life cycle impacts. This research aims at helping gain better insight into the impacts resulting from corrosion prevention designs of concrete structures, thus leading to better decisions in the early design stage.

5.2.1.2 *Functional unit*

Both assessments, LCCA and LCA, should be based on the same functional unit. The functional unit considered in this assessment is a 1 m length section of a 11 m wide concrete bridge deck serving to provide continuity to the existing coastal roadway at Ensenada do Engano, including the construction and maintenance activities for a service life of 100 years, as required by the Spanish Ministry of Public Works (2008). The deck that currently exists, the reference design as defined above, is assumed to provide the described functionality if an adequate level of maintenance is guaranteed. In order to make the assessments of the alternatives consistent and comparable, the functionality of every design is the same: an alternative-specific maintenance strategy is evaluated here to achieve the required service life, making the assessed designs equivalent in terms of durability. Maintenance consists in replacing the deteriorated concrete cover depth by a concrete with the same properties as the base concrete, thus not affecting the functionality of the system. Where hydrophobic and sealant surface treatments are considered, the maintenance consists in the periodical reapplication of these to the system, leaving the concrete cover unaffected.

However, the analyzed solutions shall provide not only the same service life but the same structural behavior as well. The reference design has a modulus of elasticity E_c equal to 29 GPa, and a characteristic compressive strength f_{ck} equal to 32 Mpa. Some of the evaluated alternatives are based on concrete mixes that result in different structural properties, as observed in Table 5.1. In order to make the resulting alternative concrete decks display the same deformability and strength than the reference design, the depth of some of the alternatives has been modified. Assuming the vertical deflection of the bridge mid-span section under service loads to be a measure of the deformability, section depths of the stiffer designs have been reduced. In particular, the designs W/C40, PMC10 and PMC20 have resulted in 3.04 m deep box girder sections, while the alternative

W/C35 has a depth of 2.89 m to make these designs equally deformable as the reference design. The reference bending strength is achieved in these modified sections by slightly increasing the pre-stress force.

5.2.1.3 *System boundaries*

The system boundary definition can substantially affect the results of LCCA and LCA. The same system has been considered for both assessments, covering from the production of the construction materials needed both for the construction and for the maintenance and use phase of the deck, to the end of the required service life, following a "gate-to-grave" approach. As usual for a comparison-oriented assessment, and according to the cut-off criteria established in ISO (2006b), processes that are considered as identical between alternatives are excluded from the analysis (Martínez-Blanco et al., 2014, Navarro et al., 2018b). Processes conisdered to be identical between alternatives include the execution of the road pavement, the wall parapets of the deck, the prestressing tendons, the installation of the adequate lighting spots or the painting works, as well as their respective maintenance needs throughout the required 100 years service life. The present study only takes into consideration those activities that are different between the alternatives, which are those related to both the different materials consumed in the construction and repair processes of the reinforced concrete deck shown in Fig. 5.1 and the number of maintenance activities resulting from the optimized strategy selected. Environmental impacts related to the demolition stage have also been considered, derived from the recycling treatments of waste concrete and steel, as well as from the secondary life of crushed concrete. Fig. 5.2 shows the system boundaries considered in both the LCCA and LCA.

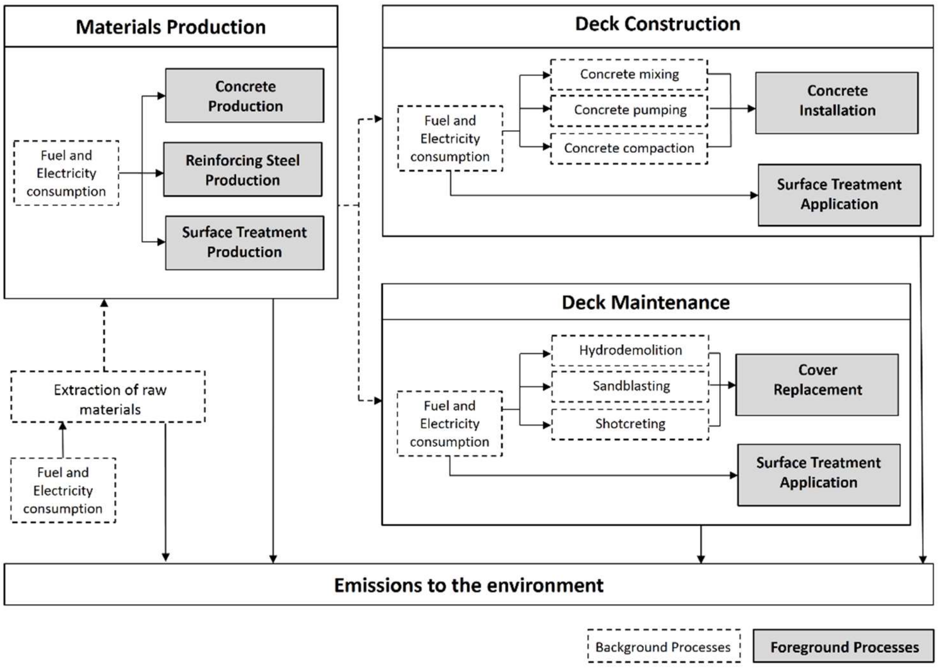


Figure 5.2. System boundaries considered in the assessment

5.2.2. Inventory analysis

The inventory data assumed in the environmental characterization of the production activities of the different construction materials, such as cement, aggregates, reinforcement steel or polymers, have been gathered from the environmental database Ecoinvent 3.2. Table 5.2 presents the Ecoinvent datasets to which the different construction materials related to the different alternative designs have been assimilated. This information has been complemented with data on specific concepts, such as machinery performance and fuel demand values.

Inventory data concept	Ecoinvent dataset
Cement	Cement production, Portland [kg]
Gravel	Gravel production, crushed [kg]
Sand	Silica sand production [kg]
Plasticiser	Plasticiser production, for concrete, based on sulfonated melamine formaldehyde [kg]
Inhibitor	EDTA production [kg][a]
Styrene Butadiene Latex	Latex production [kg]

Hydrophobic treatment[b]	Ethoxylated alcohol (AE3) production, petrochemical [kg]; Silicone product production [kg]
Sealant treatment[c]	Cement production, Portland [kg]; Silica sand production [kg]; Butyl acrylate production [kg]
Reinforcing steel	Reinforcing steel production [kg]
Stainless reinforcement	Steel production, chromium steel 18/8, hot rolled [kg]
Galvanized reinforcement	Reinforcing steel production [kg]; Zinc coating, coils [m^2]

Notes:

[a] Used for both design alternative MIG and design alternative OCI

[b] Acc. to manufacturer's specifications: 0.65 kg water + 0.35 kg silicone + 0.035 kg surfactant per kg of treatment

[c] Acc. to manufacturer's specifications: 300 l water + 460 kg cement + 690 kg sand + 31 kg butyl acrylate per m^3 of treatment

Table 5.2. Ecoinvent datasets considered for modelling inventory data related to the assumed construction materials

Table 5.3 shows the assumed values, which have been obtained from the existing literature and from machinery manufacturers. The impacts derived from the use of silica fume and fly ash additions, as by-products of industry, have been economically allocated as suggested by Chen (2009) and Chen et al. (2010). Consequently, the impact derived from the use of fly ash is 1% of the impact resulting from the electricity production that results in the generation of 1 kg fly ash, while for silica fume, an allocation of 4.8% of the impact derived from the production of the ferrosilicon needed to generate 1 kg silica fume is considered.

Process	Concept	Value	Sources
Concrete mixing[a]	Performance	7.2 min/m^3	Zastrow et al. (2017)
Galvanization[b]	Electricity consumption	0.3 kWh/kg	Blakey & Beck (2004)
Emulsifying mixer[b]	Electricity consumption	0.025 kWh/kg	Acc. to manufacturer's specifications
Hydrophobic treatment[b]	Power	1.3 kW	Acc. to manufacturer's specifications
	Performance	120 l/h	
Cathodic Protection[b]	Electricity consumption	0.41 kWh/ m^2/year	Bertolini et al. (2009)
Hidrodemolition[b]	Power	0.750 kW	Acc. to manufacturer's specifications
	Performance	0.6 m^3/h	
Sandblasting[a]	Fuel consumption	2.27 l/h	Millman & Giancaspro (2012)
	Performance	13.2 m^2/h	
Shotcreting[a]	Power	26.5 kW	Acc. to manufacturer's specifications
	Performance	18 m^3/h	

Notes:

[a] Fuel consumption has been assimilated to Ecoinvent concept "Machine operation, diesel, >= 74.57 kW, generators [hours]"

[b] Electricity consumption has been assimilated to Ecoinvent concept "Electricity, medium voltage [kWh]"

Table 5.3. Life cycle inventory data on process performances and energy consumptions

Transport distances between the different production facilities and the installation site have been estimated taking into consideration the location of the nearest material providers to the Engano bridge. Table 5.4 shows the assumed transport distances. Materials are assumed to be transported between locations by lorry. However, when the production center is located more than 100 km away from the construction site, it is assumed that only 20% of the distance is travelled by lorry, while the rest of the transport is done by freight train.

Activity or production process	Lorry (km)	Rail (km)	Total (km)
Aggregates[a]	10.6	-	10.6
Portland Cement[a]	16.2	-	16.2
Fly Ash[a]	34.8	-	34.8
Silica Fume[a]	71.2	-	71.2
Polymer[a]	133	532	665
Plastiziser[a]	133	532	665
Corrosion inhibitor aditive[a]	122	488	610
Reference concrete[b]	43.9	-	43.9
Polymer modified concrete[b]	43.9	-	43.9
Fly ash concrete[b]	43.9	-	43.9
Silica fume concrete[b]	43.9	-	43.9
Carbon steel reinforcement[c]	28.6	114.4	143
Stainless steel reinforcement[c]	124	496	620
Galvanized steel reinforcement[c]	28.6	114.4	143
Hydrophobic product[c]	138.6	554.4	693
Sealant product[c]	138.6	554.4	693
Corrosion inhibitor aditive[c]	127.4	509.6	637
Cathodic Protection System[c]	126.8	507.2	634

Notes:
[a] Distance from production facility to concrete plant
[b] Distance from concrete plant to installation site
[c] Distance from production facility to installation site

Table 5.4. Assumed transport distances and transport modes

In the environmental assessment, it is assumed that the concrete of the cover demolished after each maintenance activity, and the waste concrete resulting from the structure demolition at the end of life stage, are crushed into 200 mm boulders and recycled to serve as embankment protection. The environmental impacts derived from the end-of-life treatment of the concrete cover removed during the maintenance activities, as well as for the waste concrete and reinforcing steel after the demolition of the deck after the 100 years service life has been considered in the present study. Ecoinvent concepts "treatment of waste concrete, not reinforced, sorting plant" and "treatment of waste reinforcing steel, sorting plant" have been considered in the present study fur such purpose.

The surface of the concrete disposed as embankment protection tends to absorb atmospheric CO_2 from the atmosphere as a result of the so-called carbonation process, thus resulting in positive environmental impacts during the concretes secondary life following each deck cover removal or the final bridge demolition. This CO_2 uptake can be calculated as follows (Collins, 2010):

$$\boldsymbol{CO_{2\,(uptake,in\;kg)} = c \cdot CaO \cdot r \cdot A \cdot M \cdot k \cdot \sqrt{t} \cdot \left(\frac{t_0}{t}\right)^{0.106}} \tag{1}$$

where c is the cement content (kg/ m^3), CaO is a parameter assumed to be 0.65 (García-Segura et al., 2014a), which represents the calcium oxide contained in Portland concrete, r is the amount of CaO that absorbs CO_2 and is assumed to be 0.75 according to Lagerblad (2005), A is the concrete surface exposed to air, M is the molar fraction CO_2/CaO (assumed to be 0.79), t is the exposure time (years), t_0 is the time of reference in years (assumed to be 0.0767 years) and k is the carbon rate coefficient, which is material dependent. The assumed values for the carbon rate coefficients are shown in Table 5.5. In the present study, the duration of the secondary life of the recycled concrete is assumed to be 30 years.

Design alternative	REF	W/C40	W/C35	FA10	FA20	SF5	SF10	OCI
k (x 10^{-3} m/$\text{year}^{0.5}$)	1.83	1.42	0.8	1.52	1.1	1.89	1.5	1.83

Table 5.5. Assumed carbonation rate coefficient k depending on the concrete type considered, according to Fib Bulletin 34 (Fib, 2006)

Regarding the inventory data considered in the LCCA, the cost data have been gathered from the construction cost database developed by CYPE (CYPE Ingenieros S.L., Alicante, Spain). This database is constantly updated and considers the costs of materials, machinery and labour, as well as indirect costs for the different construction and maintenance activities that are usual in the Spanish construction sector. The present LCCA assumes the performance values adopted for machinery in the LCA. The assumed unit costs for each concept are shown in Table 5.6. As the analyzed system is located in Spain, the currency chosen for the assessment is the Euro (€).

m^3 of conctrete HA30	83.62
m^3 of conctrete HA30 (w/c=0,4)	97.99
m^3 of conctrete HA30 (w/c=0,35)	104.26

m^3 of conctrete HA30+10%FA	101.63
m^3 of conctrete HA30+20%FA	101.23
m^3 of conctrete HA30+5%SF	131.40
m^3 of conctrete HA30+10%SF	137.58
m^3 of conctrete HA30+Organic corrosion inhibitor	164.30
l of styrene butadiene rubber latex	4.70
kg of steel (B 500 S)	1.24
kg of stainless steel	5.24
kg of galvanized steel	3.62
m^2 of hydrophobic treatment	17.78
m^2 of sealant treatment	29.04
m^2 of inhibitor surface treatment	19.76
m^2 of cathodic protection	63.54
m^2 of hydrodemolished cover[a]	27.68
m^2 of sandblasting	4.29
m^2 of reinforcement priming	11.73

Notes:

[a] The cost of cover demolition depends on the depth to be demolished. The value shown here corresponds to a 30 mm deep cover completely demolished

Table 5.6. Unit costs (€) considered in the LCCA

It shall be noted that, although sharing the same system boundaries with LCA, the background processes are assumed to be indirectly reflected in the considered element prices (Martínez-Blanco et al., 2014). Thus, although costs are provided for foreground processes, namely production activities and construction and maintenance operations, it is assumed that producers and material providers include in these concepts all of the costs of the chain processes along the product's life cycle, such as energy consumption or raw materials extraction.

The costs considered are up to date as of year 2018. The different design alternatives, according to the expected durability performance, will incurr in future costs at different times. In order to make these impacts comparable with each other, the future costs are discounted and converted into present (2018) values. It is important to note here that there is no consensus on which discount rate is more appropiate for each particular project under study. High discount rates will emphasize the near future, thus resulting in assessments in which the future effects are almost negligible from an economic point of view. This perspective is not coherent with assessments focused on sustainable designs. Therefore, preference is usually given to the use social discount rates, which are lower than private rates (Allacker, 2012). A discount rate of 2% is chosen for the present LCCA.

5.2.3. Life cycle impact assessment

The assessment of the life cycle environmental impacts associated with the alternative deck designs under evaluation is conducted considering the ReCiPe 2008 assessment methodology (Goedkoop et al., 2009), which combines the midpoint approach of CML method and the endpoint approach of Eco-Indicator 99. ReCiPe is applied here from a hierarchist perspective, a consensus model between the short-term focused individualist and the long-term focused egalitarian perspectives. The impacts are weighted and normalized using the ReCiPe Europe Endpoint H/A set so as to integrate the different impact categories into a single score.

With regard to the LCCA, and according to Swarr et al. (2011), as all inventory data in an LCCA are expressed by a single unit of measure, namely the adopted currency, there is no assessment phase as such, where a particular characterization or normalization of the inventory data is needed. For the same reason, weighting between cost categories has not been considered either (Özkan et al., 2016).

5.3. Reliability-based maintenance optimization

5.3.1. Service life prediction

Concrete deterioration in marine environments occurs when chloride ions reach the reinforcing bars in sufficient concentration to trigger steel corrosion. This critical threshold is known as the critical chloride content (*C_{cr}*) and depends mainly on the properties of the rebars. To evaluate the chloride concentrations at the reinforcements over time, the Fickean model proposed in Fib Bulletin 34 (Fib, 2006) is considered. This model assumes chlorides to ingress the concrete cover as a result of a diffussive process, and allows the evolution of the chloride concentration at the reinforcing bars at any time to be evaluated. As shown by Titi and Biondini (2016), reinforcing bars at the section corners are more prone to corrosion than the rest of the rebars, due to the so-called corner effect. Consequently, the one-dimensional model suggested in Fib (2006) has been adapted to consider the case where a reinforcing steel bar is exposed to two chloride fronts advancing simultaneously. The chloride concentration *C* at a particular time *t* and at any depth in both *x* and *y* directions of the evaluated cross-section shall then be expressed as:

$$\boldsymbol{C(x,y,t) = C_s \cdot \left(1 - erf\,\frac{x}{2\sqrt{D_{0,x}\cdot\left(\frac{t_0}{t}\right)^{\alpha}\cdot t}} \cdot erf\,\frac{y}{2\sqrt{D_{0,y}\cdot\left(\frac{t_0}{t}\right)^{\alpha}\cdot t}}\right)} \tag{2}$$

where *C(x,y,t)* is the chloride concentration (wt.%/binder) at a particular position in the concrete depth [x, y] (mm) at time *t* (years); *C_s* is the surface chloride concentration (wt.%/binder); *erf(.)* is the Gauss error function; D_0 is the chloride diffusion coefficient (mm^2/years). It has been assumed that the concrete is homogeneous and that the chloride diffusivity in both directions is the same ($D_{0,x} = D_{0,y}$). The age factor α has been assumed to be 0.5, as proposed in the Spanish concrete design code (Spanish Ministry of Public Works, 2008). The reference time t_0, expressed in years, is considered to be 28 days (t_0 = 0.0767 years). The concrete cover in the y-direction (r_y) for the most exposed corner rebar is assumed constant and equal to 50 mm for each of the analyzed designs, while the cover in the x-direction (r_x) varies depending on the prevention design considered. Considering the distance existing between the sea water surface and the deck, a surface chloride content of $C_{s,0}$=2.88% is assumed for the case study (Spanish Ministry of Public Works, 2008).

The parameter values for the durability characterization of each design alternative have been obtained from the literature. Table 5.7 shows the mean and the standard deviation values assumed for both the critical chloride content and the diffusion coefficients considered for the different materials, as well as the resulting mean time to failure for each of the alternatives, in years. Parameters are assumed to follow a Gaussian distribution.

Design alternative	D_0	(x10^{-12} m^2/s)	C_{crit}	(%)	r_x	(mm)	Mean service life (years)	Sources
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.		
REF	9.56	1.02	0.6	0.1	35	1.75	4	Spanish Ministry of Public Works (2008)
CC45	9.56	1.02	0.6	0.1	45	2.25	10	
CC55	9.56	1.02	0.6	0.1	55	2.75	15	
W/C40	5.90	0.48	0.6	0.1	30	1.75	9	Vedalakshmi et al. (2009), Cheewaket et al. (2014)
W/C35	3.84	0.29	0.6	0.1	30	1.75	20	
INOX	9.56	1.02	5	0.94	30	1.75	-	Bertolini et al. (1996)
GALV	9.56	1.02	1.2	0.21	30	1.75	12	Darwin et al. (2009)
OCI	3.81	0.29	0.71	0.1	35	1.75	26	Bolzoni et al. (2014)
MIG	2.72	0.22	0.6	0.1	35	1.75	36	
SF5	3.16	0.25	0.38	0.06	35	1.75	16	Frederiksen (2000), Manera et al. (2008)
SF10	1.32	0.17	0.22	0.03	35	1.75	42	
FA10	5.89	0.48	0.6	0.1	35	1.75	10	Otsuki et al. (2014)
FA20	5.00	0.39	0.6	0.1	35	1.75	12	
PMC10	7.00	0.61	0.6	0.1	35	1.75	7	Ohama (1995), Yang et al. (2009)
PMC20	2.91	0.23	0.6	0.1	35	1.75	32	
ICCP	9.56	1.02	2.49	0.1	35	1.75	53[a]	Bertolini et al. (2009)

HYDRO	7.39	0.67	0.6	0.1	35	1.75	5[b]	Zhang and Buenfeld (2000)
SEAL	4.66	0.35	0.6	0.1	35	1.75	11[b]	Medeiros et al. (2012)

Notes:

[a] According to manufacturer specifications, service life of the titanium anode is 20 years

[b] According to manufacturer specifications, surface treatments shall be reapplied every 5 years to ensure durability

Table 5.7. Durability parameters assumed for the alternative designs

5.3.2. Maintenance optimization problem

The adoption of an adequate maintenance strategy is essential to reduce the economic and environmental impacts resulting from an excessive level of deterioration of the structure. To prevent steel rebars becoming corroded, it is common practice to undertake maintenance operations before the critical chloride content is reached at the position of the rebars. From such a preventive perspective, maintenance is reduced to simply demolishing and regenerating the concrete cover only to the depth where the critical chloride threshold has been exceeded, thus it is not necessary to replace the embedded steel and incur in unnecessary economic and environmental impacts.

Maintenance optimization consists in finding the specific maintenance interval that minimizes the economic or environmental impacts at the end of the service life of the structure, while ensuring an adequate level of reliability. Here, maintenance is assumed to be carried out at a fixed regular interval T_{opt}, different for each alternative under study. The magnitude of the impacts derived from a particular maintenance operation is then proportional to the depth reached by the chlorides at the time when maintenance is performed.

The reliability index β of the structure at a specific time depends on the advance of the chloride front at that time and on the associated probability of failure (p_f). In the context of preventive maintenance, failure is assumed to occur when the chloride concentration at the rebars exceeds the critical threshold C_{cr}. The optimization problem for new bridges consists in finding, for each of the alternative designs under evaluation, the maintenance interval T_{opt} that minimizes the total expected impacts under reliability constraints. Thus the optimization problem is formulated as follows:

Given

The durability characterization of the alternative under study, provided by the critical chloride content C_{cr}, the surface chloride concentration C_s, the chloride diffusion coefficient D_0 and the concrete cover r_x.

Goal

Find the optimal maintenance interval T_{opt} so that the impacts derived from the life cycle phases of construction, maintenance and demolition are minimal.

Subject to

The reliability at the time of maintenance shall not exceed the minimum annual target reliability index:

$$\boldsymbol{\beta}(\boldsymbol{T}_{opt}) = -\boldsymbol{\phi}^{-1}[\boldsymbol{p}_f\ (\boldsymbol{T}_{opt})] \leq \boldsymbol{\beta}_{lim} \tag{3}$$

where Φ^{-1} is the inverse of the Gaussian cumulative distribution function of the probability of failure at time T_{opt}, and β_{lim} is the minimum annual reliability index required to guarantee a proper condition of the bridge during its entire service life. Following Nogueira et al. (2012), a value of 1.30 is assumed in the present study for the target reliability. The present study assumes that maintenance restores the durability performance of the deck to its original state. Consequently, once maintenance is carried out, the reliability of the deck returns to its initial value. Monte Carlo simulation is used to obtain the probability of failure needed to evaluate the reliability index for each of the analyzed measures at any time.

5.4. Results and discussion

Results are analyzed under two different scenarios. The first evaluates both the economic and the environmental life cycle impacts assuming a maintenance strategy that minimizes the LCCA results of every alternative. The second scenario assumes, for the different designs, maintenance strategies focused on minimizing the environmental life cycle impacts. In both cases, and considering the uncertainty associated with each of the durability parameters, 20000 Monte Carlo simulations have been performed to ensure that the results converge, resulting in a relative error of the estimation of 0.5%.

5.4.1. Assessment results under economically optimized maintenance

Fig. 5.3 shows the assessment results of both LCCA and LCA considering the maintenance intervals for each alternative associated with minimum life cycle costs. The results presented are sorted from the most to the least expensive design, considering a period of analysis of 100 years. In accordance with the definition of the functional unit of the present assessment, the results are presented as mean impacts per longitudinal meter of deck.

It is observed that the most expensive prevention alternative is the reference measure (REF), namely the original deck design, followed by the alternatives PMC10 and GALV. It can be seen that, for the particular case evaluated, any of the analyzed preventive designs would allow us to reduce the life cycle costs significantly. The addition of 10% polymer to the original concrete mix (PMC10) or the substitution of ordinary steel reinforcement by galvanized bars (GALV) leads to designs which are between 16% and 36% lower in cost than the original design, respectively. From the results obtained, it is clear that, among the alternatives evaluated in this study, the optimal prevention alternative in terms of life cycle costs is SF10, which consists in the addition of 10% silica fume to the original concrete mix and the partial substitution of the cement content.

The cost of this solution is 24% of the life cycle cost of the original design. This design is followed by the use of migrating inhibitors, which results, via LCCA, in 27% of the costs associated with the reference solution. The surface treatments (alternatives HYDRO and SEAL) are also very cost-efficient measures in the long term, generating life cycle costs of approximately 31 to 33% of the costs associated with the reference measure.

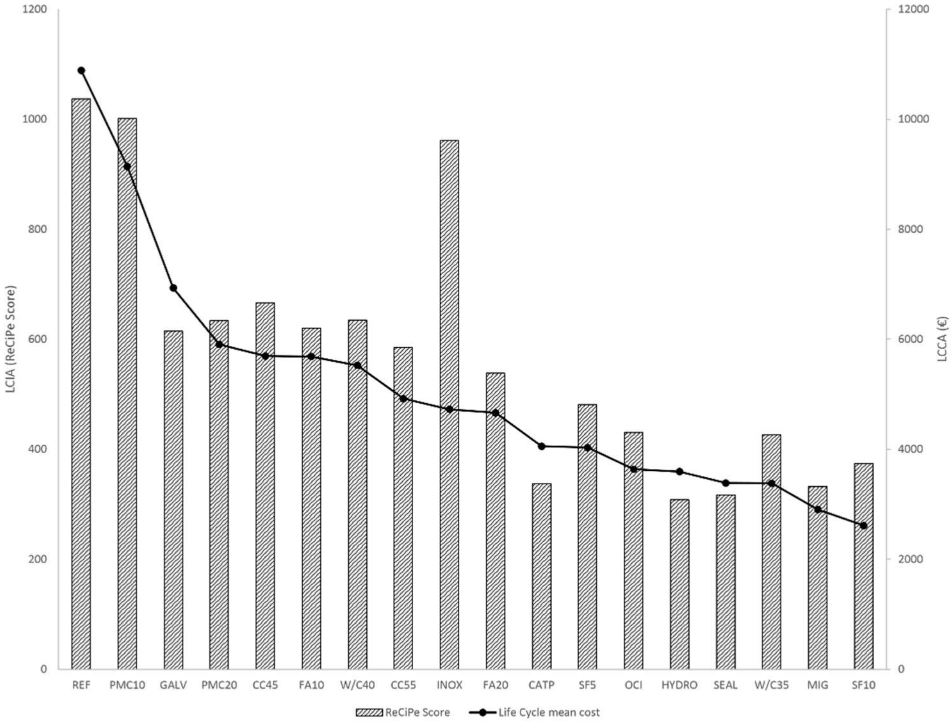


Figure 5.3. Assessment results assuming cost optimized maintenance strategies

Table 5.8 shows the intermediate results related to the cost optimization calculation. It is common to undertake maintenance actions only when the end of the service life of the structure has been reached and not before, under the false assumption that less maintenance will lead to lower costs at the end of the life cycle. It is observed that, in general, it cannot be said that alternatives with shorter maintenance intervals show greater life cycle costs. Indeed, it is observed that surface treatments with hydrophobic products (HYDRO) and designs with polymers (PMC10), which have the same maintenance optimum interval, have completely different LCCA costs. So, although this statement is true for alternatives belonging to the same design family (CC45 and CC55, or W/C40 and W/C35), when comparing alternatives of a different nature, the costs associated with the different materials and repair processes play a major role. Table 5.8 presents the economic impacts due to installation and maintenance for the diferent designs. The economic impacts derived from demolition have not been included due to the reason that, when discounted, its effect can be neglected when compared to the impacts across the rest of the life cycle. It can be concluded that, in general, the economic impact of the maintenance and use phase is essential in the LCC assessment, taking up to 85% of the total life cycle costs in some cases. Similar results have been reported by Navarro et al. (2018a).

Design alternative	Optimum maint. interval (years)	Installation phase impact (euro)	Maint. phase impact (euro)	LCCA results (euro)	5% conf. interval for LCCA	95% conf. interval for LCCA	Associated LCA results (ReCiPe)	Impact reduction after optimization
REF	2	1617	9270	10887	8293	13481	1037	10.5%
PMC10	4	3246	5894	9140	6922	11359	1001	7.2%
GALV	11	3466	3466	6932	5271	8592	615	0.0%
PMC20	26	4766	1139	5905	4499	7311	634	6.7%
CC45	6	1617	4077	5694	4362	7026	666	11.4%
FA10	6	1758	3926	5684	4307	7061	620	8.3%
W/C40	6	1702	3822	5524	4215	6833	635	6.6%
CC55	8	1617	3300	4917	3770	6065	586	8.9%
INOX	0	4726	0	4726	0	0	961	0.0%
FA20	8	1754	2909	4663	3542	5784	538	5.3%
ICCP	20	2685	1370	4055	3058	5051	337	0.0%
SF5	8	1989	2040	4029	3092	4967	481	10.4%
OCI	21	2245	1392	3637	2772	4503	431	6.8%
HYDRO	4	1905	1686	3591	2711	4471	308	4.1%
SEAL	5	2086	1300	3386	2571	4200	317	0.0%
W/C35	17	1725	1656	3381	2572	4189	426	4.8%
MIG	34	1937	965	2902	2173	3632	332	1.1%
SF10	34	2037	573	2610	1979	3240	374	8.2%

Table 5.8. Assessment results considering LCC optimized maintenance intervals

Table 5.8 shows for each alternative how much the resulting life cycle impact has been reduced by selecting the optimum interval for maintenance with respect to the impact resulting from performing maintenance only at the end of the service life for each design. It is observed that the optimization leads to a reduction of the life cycle costs that reaches up to 10 to 11% in some cases.

5.4.2. Assessment results under environmentally optimized maintenance

Fig. 5.4 shows the environmental and economic assessment results when the maintenance strategy is selected in order to minimize life cycle environmental impacts. Again, the results presented in Fig. 5.4 are sorted in descending order according to the resulting environmental impacts of each design throughout a period of analysis of 100 years. All the results are presented as mean impacts per longitudinal meter of deck.

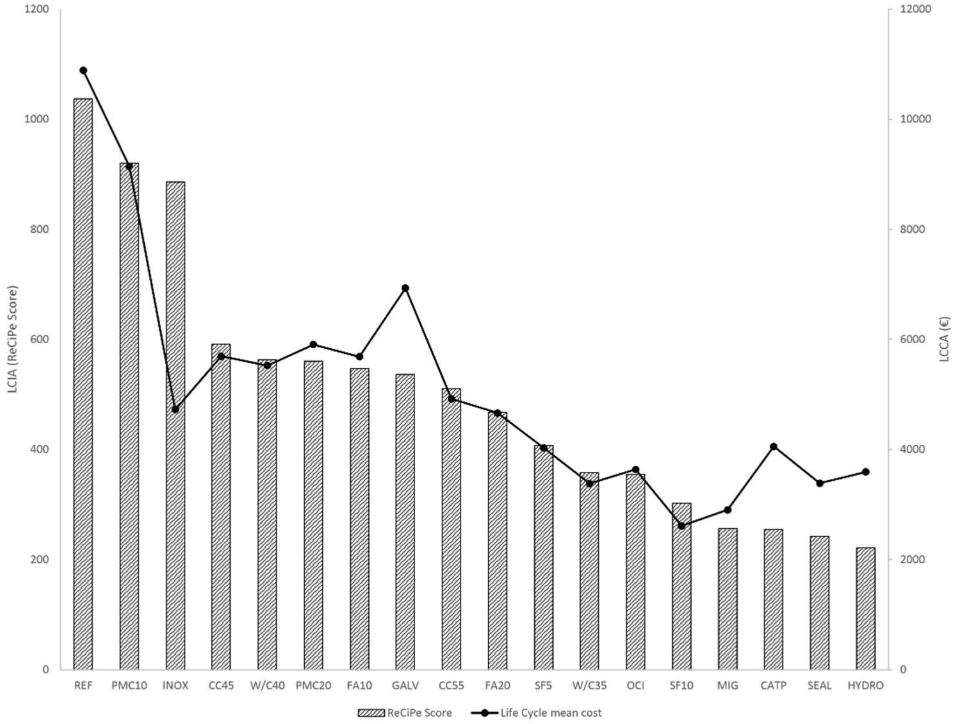


Figure 5.4. Assessment results assuming environmentally optimized maintenance strategies

The greatest life cycle environmental impacts are associated with the reference design (REF), followed by alternatives PMC10 and INOX. It is interesting how alternatives with great durability such as show such life cycle results. According to Mistry et al. (2016), the high impacts resuling from the use of stainless steel are mainly derived from the affection of the manufacturing process to the quality of the ecosystem. On the other hand, the impacts associated with alternative PMC result from the extraction process associated to the production of styrene butadiene latex. On the other hand, the most environmentally friendly alternative among those evaluated in the present study is HYDRO, whose life cycle environmental impact is 21.3% of the impact of the reference alternative. This measure is followed by a number of designs that result in very similar LCA results, namely those based on sealant surface treatments (SEAL), cathodic protection (ICCP), migrating inhibitors (MIG), and silica fume additions (SF10), whose impacts range between 23.3% and 29.1% of the original design impact, respectively. It should be noted that, similar to what is observed for the cost optimization results, the application of any of the analyzed preventive measures allows us to reduce the life cycle environmental impacts.

Table 5.9 shows the intermediate results associated with the environmental maintenance optimization. It is observed that optimization in environmental terms leads to greater impact reductions, reaching a reduction of up to 23% of the impacts derived from performing maintenance actions only at the end of the service life of the design. As with LCC assessment results, it is observed that the relative importance of maintenance is essential for the minimization of the total impact of any preventive solution, as this impact is shown to be proportional to the number of maintenance operations required for the alternative evaluated. Exceptions to this are alternatives HYDRO and SEAL, which in fact require very intensive maintenance and generate very low environmental impacts. This result is based on the fact that the assumed maintenance operations for surface treatments imply less damage to the environment than the replacement of the concrete cover needed in the maintenance of the other alternatives. The impacts derived from demolition are also presented. Only those impacts derived from transport and recycling of waste materials are considered, neglecting those associated to machinery and energy consumption, which are considered identical between alternatives.

Design alternative	Optimum maint. interval (years)	Installation phase impact (ReCiPe)	Maint. phase impact (ReCiPe)	Demolition phase impact (ReCiPe)	LCA results (ReCiPe)	5% conf. interval for LCA	95% conf. interval for LCA	Associated LCCA results (euro)	Impact reduction after optimization
REF	2	245	867	-75	1037	993	1082	10887	12.6%
PMC10	4	368	626	-74	920	929	993	9140	8.8%
INOX	0	961	0	-75	886	900	964	4726	0.0%
CC45	6	245	421	-75	591	605	638	5694	17.6%
W/C40	6	258	377	-72	563	546	591	5524	10.3%
PMC20	26	494	140	-74	560	591	628	5905	23.2%
FA10	6	253	367	-73	547	542	566	5684	12.7%
GALV	8	275	337	-75	537	519	556	6932	0.9%
CC55	8	245	340	-75	511	557	584	4917	11.9%
FA20	8	256	282	-71	467	513	526	4663	8.6%
SF5	8	277	204	-74	407	455	485	4029	17.4%
W/C35	17	259	167	-68	358	387	422	3381	12.9%
OCI	17	289	141	-75	355	345	357	3637	20.6%
SF10	34	307	68	-72	302	432	460	2610	23.3%
MIG	34	249	83	-75	257	249	258	2902	5.9%
ICCP	17	246	83	-75	254	247	255	4055	9.0%
SEAL	5	247	70	-75	242	235	243	3386	0.0%
HYDRO	5	246	50	-75	221	217	229	3591	0.0%

Table 5.9. Assessment results considering LCA optimized maintenance intervals

5.4.3. Analysis of the Pareto Front

Results have been presented considering those maintenance intervals that minimize either the environmental or the economic life cycle impacts of each alternative under study. However, it is possible to find other solutions that, not being the absolute optimum in either of the two impact areas considered, may provide an optimum in overall terms. Taking into consideration every feasible combination between alternatives and maintenance intervals, the Pareto principle is used to identify those optimal solutions. Fig. 5.5 shows the Pareto front of the alternatives under study. It is observed that the results present, in general, an almost linear behavior, which means that economic and environmental impacts are proportional. This can also be appreciated in Tables 4.8 and 4.9, where it is observed that the maintenance intervals that minimize impacts from an LCCA and LCA perspective are very close.

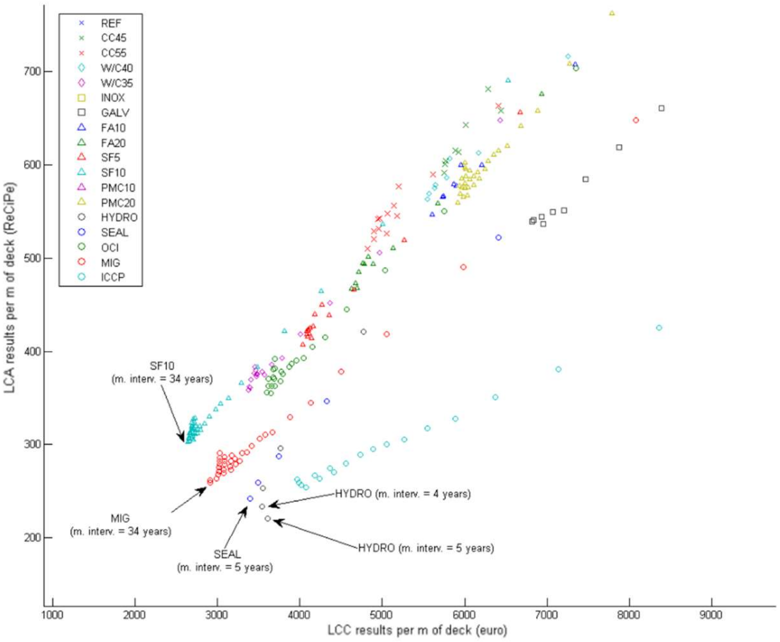


Figure 5.5. Representative solutions of the Pareto optimal set

The Pareto optimal set consists of five alternatives. Two of the alternatives are the optima described above for environmental and economic terms, namely designs HYDRO and SF10 with maintenance intervals of 5 and 34 years respectively. The optimal set is completed with alternatives MIG (with a maintenance interval of 34 years), SEAL (reapplied every 5 years) and HYDRO (with a maintenance interval of 4 years). From the analysis of the optimal set, it is shown that designs based on surface treatments are very competitive in environmental terms, which is a consequence of the low emmisions and energy consumption derived from the machinery involved in the reapplication of the treatments in contrast to the impacts resulting from concrete replacement. Similar results have been previously reported in the existing literature (Petcherdchoo, 2012; Petcherdchoo, 2015). On the other hand, the advantage of solutions based on concrete with silica fume (SF10) and corrosion inhibitors (MIG) relies on their high durability.

5.4.4. Uncertainty analysis of the results

Due to the complexity and long-life spans of concrete bridge structures, the assessment of their life cycle impacts is subject to high levels of uncertainty. Analyzing the sensitivity of the assessment results with regard to variations in particular key factors is therefor of great importance to validate the conclusions derived from such studies. Tables 8 and 9 show, for the economic and the environmental assessment respectively, the confidence intervals of the life cycle results obtained for each alternative.

With respect to the environmental results, the uncertainty associated to each of the considered datasets is defined in accordance with Ecoinvent database, which takes into consideration different aspects that might influence the input values, such as geographic representativeness or measurement inaccuracies at production locations. From the results presented in Table 5.9 it is derived that the estimations of the environmental impacts have coefficients of variation (COV) that fall below 5% for every alternative under evaluation. Regarding the economic assessment, the considered costs have been assigned a normal probability distribution with a variance of 0.15. As a consequence, economic results have slightly greater uncertainty, as their COV reach up to 12% for the worst case (REF), due to the reduced maintenance interval and the consequently great number of repair activities to be considered in the evaluation.

In addition, two main sources of uncertainty are evaluated here: the considered LCA methodology chosen for the environmental assessment and the discount rate assumed for the LCCA. The discount rate chosen for LCCA is one of the main contributors on the assessment results, and therefore a critical source of uncertainty (Lee et al., 2011; Harvey et al., 2012). A sensitivity analysis on this parameter is performed to evaluate its effect on the Pareto set of optimal solutions obtained for the assumed discount rate of 2%. Two new discount rates are chosen within the usual range for European infrastructures, namely 3% and 4%. For these two new scenarios, the Pareto sets have been recalculated and are shown in Table 5.10. Results show that, regardless of the discount rate considered, the set of optimal solutions consists of the same alternative designs, namely SF10, MIG, SEAL and HYDRO. Slight differences are to be found, however, in the optimal maintenance interval: it can be observed that for a discount rate of 4%, the Pareto set consists of 7 solutions, with maintenance intervals that tend to be longer than when considering reduced discount rates. This is due to the fact that the greater the chosen discount rate, the less importance is given to future costs, thus promoting solutions with costs distant in time.

Discount rate	Set of Pareto optimal solutions						
2%	SF10 (34 years)[a]	MIG (34 years)	SEAL (5 years)	HYDRO (4 years)	HYDRO (5 years)		
3%	SF10 (35 years)	MIG (34 years)	SEAL (4 years)	HYDRO (4 years)			
4%	SF10 (41 years)	SF10 (37 years)	MIG (36 years)	MIG (35 years)	SEAL (5 years)	HYDRO (4 years)	HYDRO (5 years)

Notes:
[a] The resulting optimal maintenance interval is given in brackets

Table 5.10. Uncertainty derived from the chosen discount rate

The LCA methodology chosen in the impact assessment is considered to be a great source of uncertainty as well (Cellura et al., 2011; Hung & Ma, 2009). Taking this into consideration, two different impact assessment methods are evaluated, namely EPS (which stands for Environmental Priority Strategies) and the Eco-Indicator 99. These methods have been chosen in this sensitivity study due to the fact that they allow the estimation of the environmental performance of a system in one single endpoint indicator. The Pareto sets resulting from the use of these methodologies are shown in Table 5.11. From the results it is concluded that the solutions conforming the Pareto set are not significantly sensitive to the environmental impact assessment methodology chosen. It shall be observed, however, that the sealant surface treatment is discarded from the Pareto set when using Eco-Indicator 99 method.

Impact Assessment Methodology	Set of Pareto optimal solutions				
ReCiPe	SF10 (34 years)[a]	MIG (34 years)	SEAL (5 years)	HYDRO (4 years)	HYDRO (5 years)
Eco-Indicator 99	SF10 (34 years)	MIG (34 years)	HYDRO (4 years)	HYDRO (5 years)	
EPS	SF10 (34 years)	MIG (34 years)	SEAL (5 years)	HYDRO (4 years)	HYDRO (5 years)

Notes:
[a] The resulting optimal maintenance interval is given in brackets

Table 5.11. Uncertainty derived from the chosen impact assessment methodology

In view of the presented results, the conclusions of the present comparative study shall be considered robust and not sensitive to the analyzed sources of uncertainty.

5.5. Conclusions

The present study assesses the life cycle environmental and economic impacts derived from the different design alternatives that are usual for concrete structures in marine environments. In particular, the performance of 17 corrosion preventive designs are evaluated as alternatives to the current design of the bridge deck at Ensenada do Engano in Spain. The study focuses on the particular maintenance intervals that minimize the impacts along the life cycle of the structure under evaluation, assuming a reliability-based maintenance optimization. From the obtained results it is concluded that the impacts derived from the maintenance phase of a structure can be critical with respect to the resulting life cycle impacts, as was the case here. It has been observed that the optimization of the maintenance intervals reduces the economic and environmental life cycle impacts up to 13 and 19%, respectively, if compared to the usual strategy where maintenance is performed only when the end of the service life of the structure is reached.

However, excepting the case using stainless steel rebars, and irrespective of the material and installation costs and impacts, every prevention design considered in this study reduces both the economic and the environmental impacts throughout the service life of the bridge deck when compared to the impacts associated with the durability design of the actual bridge. It has been shown that, among the options considered, designs based on silica fume additions (SF10), hydrophobic surface treatment (HYDRO) and the use of migrating inhibitors (MIG) comprise the optimal set. In relation to the reference design, the use of concretes with the addition of 10% silica fume allows for a reduction of the economic and environmental impacts of 74% and 78% respectively. On the other hand, designs based on the periodic application of hydrophobic surface treatment result in reductions of the life cycle impacts of up to 67% from an economic perspective, and 82% in the environmental field.

The present study evaluates the sustainability of alternative corrosion preventive designs considering both an environmental and an economic approach, taking into consideration the impacts derived from the construction, the maintenance and the end of life phases. Further research is required to effectively incorporate the third pillar of sustainable design, namely the social dimension, in the evaluation of prevention strategies for concrete bridge decks. In addition, the present work is limited to the sustainability assessment of a single bridge, not considering the rest of the elements of the infrastructure network in which it is included. Future works shall therefore be oriented to consider the assessment of sustainable maintenance strategies for a particular bridge within the framework of a bridge management system.

Chapter 6

Social life cycle assessment of concrete bridge decks exposed to aggressive environments

Authors: Ignacio J. Navarro; Víctor Yepes; José V. Martí;

Status: Manuscript published

Journal: *Environmental Impact Assessment Review,* Volume 72, Pages 50-63, September 2018

DOI: 10.1016/j.eiar.2018.05.003

JCR IF (2018) 3.749

JCR Category	Ranking	Quartile
Environmental Studies	24/116	Q1

Presentation: Post-print (author version)

Abstract

Sustainable design of structures includes environmental and economic aspects; social aspects throughout the life cycle of the structure, however, are not always adequately assessed. This study evaluates the social contribution of a concrete bridge deck. The social performance of the different design alternatives is estimated taking into account the impacts derived from both the construction and the maintenance phases of the infrastructure under conditions of uncertainty. Uncertain inputs related to social context are treated through Beta-PERT distributions. Maintenance needs for the different materials are estimated by means of a reliability-based durability evaluation. Results show that social impacts resulting from the service life of bridges are not to be neglected in sustainability assessments of such structures. Designs that minimize maintenance operations throughout the service life, such as using stainless steel rebars or silica fume containing concretes, are socially preferable to conventional designs. The results can complement economic and environmental sustainability assessments of bridge structures.

Keywords Social Life Cycle Assessment; • Chloride corrosion; • Preventive measures; • Guidelines; • Concrete bridge; • Sustainable design

6.1. Introduction

The World Commission on Environment and Development (WCED) defined in 1987 sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their needs" (WCED, 1987). Since then, sustainability has attracted an increasing attention in many sectors of the society as a response to the negative side effects of the predominant focus put on economic expansion. By definition, sustainability has to be understood as maximizing the benefits, or minimizing the burdens, for the society, not only in the short but in the long term as well. Sustainable design of a specific product shall therefore be based on the economic, social and environmental implications of its production and use over time. According to the definition of sustainable design, long lasting products are very prone to interfere in sustainable development, as their impacts will be long lasting as well, thus affecting future generations. This is the reason why essential structures, such as dams or bridges, which are designed to last for over 100 years in most of the cases, are in the spotlight of many researchers. In particular, bridges are critical elements of the transport system of a region, due to the economic and social consequences that may derive from their failure. In recent years, research has been conducted on both the environmental (Du et al., 2014; Pang et al., 2015) and the economic impacts of concrete bridges (Safi et al., 2015; Yepes et al., 2017; Navarro et al., 2018a). Additionally, the simultaneous impacts in the environmental and economic field derived from the design have also been analyzed (Yepes et al., 2015b; García-Segura & Yepes, 2016; Martí et al., 2016). However, to the best of our knowledge, very little has been published regarding the social assessment of bridge structures throughout their life cycle (Gervásio & Da Silva, 2013; Lounis & Daigle, 2010).

This is a natural consequence of the maturity level of the different methodologies existing for the assessment of the environmental, economic and social impacts under a life cycle framework. The environmental life cycle assessment (E-LCA) has become highly standardized both methodologically and in terms of implementation (ISO, 2006a, 2006b). The methodology existing for the assessment from an economic perspective, namely the life cycle costing (LCC), also shows a relatively mature state (Hunkeler et al., 2008), although an ISO standard does not yet exist. However, social life cycle assessment (SLCA) is a quite new technique for estimating social impacts throughout a product's life cycle. Considerable efforts have been made in SLCA for developing a strong and coherent methodology, resulting in 2009 in the 'Guidelines for social life cycle assessment of products' (UNEP/SETAC, 2009), referred herein simply as the 'Guidelines'. Nonetheless, according to Jørgensen (2013), the SLCA still requires showing its validity before it can be considered to be out of its infancy. Even the Guidelines state that 'there is an urgent need for the application of SLCA' by means of case studies that help to further develop this recently arisen methodology.

Since the publication of the Guidelines, several studies have been carried out under the life cycle framework focusing on different types of products, such as electronics (Umair et al., 2015; Wilhelm et al., 2015), food industry (De Luca et al., 2015; Bouzid & Padilla, 2014) or fertilizers (Martínez-Blanco et al., 2014). Regarding the construction sector, social impacts related to different building materials (Hosseinijou et al., 2014; Hossain et al., 2018), to concrete recycling (Hu et al., 2013) and to building construction (Dong & Ng, 2015) has been assessed so far. These latter studies exclude the maintenance and use stage from the analysis, due to the complexity of the evaluation required for this phase. This analysis perspective may lead to erroneous conclusions, as the maintenance stage is a main source of impacts throughout the life cycle of a structure. Consequently, the comparison of different building materials under a life cycle perspective should not only take into account their different maintenance needs, but it should integrate them as well in an assessment, which considers every relevant life cycle phase of the product.

Considering the above, the application of SLCA to concrete structures taking into consideration the different life cycle stages cannot be found. In particular, no SLCA has been performed to date on bridge structures, thus evidencing a lack of information towards the sustainable design of such infrastructures. To overcome the above-mentioned limitations, this study aims to apply the methodological framework proposed in the Guidelines to assess the social performance associated to different construction materials applied to a reinforced concrete bridge deck.

6.2. Social performance evaluation of deck designs

Deterioration and maintenance of reinforced concrete structures are some of the most demanding challenges that the construction industry is confronted with. In particular, concrete structures are subjected to particularly aggressive degradation processes when exposed to marine environments. Although there are several mechanisms that may degrade concrete in such environments, experience demonstrates that the most critical threat in concrete structures in marine environments is chloride-induced corrosion in the reinforcing steel. Different alternatives have been developed throughout the last years to prevent reinforcing steel from being corroded. The present research focuses on specific prevention strategies applied to a real concrete bridge deck exposed to a marine environment. The bridge of Illa de Arosa, in Galicia - Spain is analyzed. Fig. 6.1 shows a cross section of the bridge deck. The input data regarding both the geometry and the durability characterization of this structure has been obtained from the literature (León et al., 2013; Pérez-Fadón, 1985; Pérez-Fadón, 1986). Located 9.6 m over the high tide sea water level, the deck has a width of 13 m and a section depth of 2.3 m. The original concrete mix of the bridge deck has a cement content of 485 kg/m^3, and a water/cement ratio w/c=0.45. According to Pérez-Fadón (1985), the reinforcing steel amount is 100 kg/m^3 of concrete, with a concrete cover of 30 mm. This quantity does not include the steel of the prestressing tendons. It is worth noting that according to the Spanish regulations for marine environments, the deck is designed for no cracking of concrete, i.e. the concrete remains uncracked.

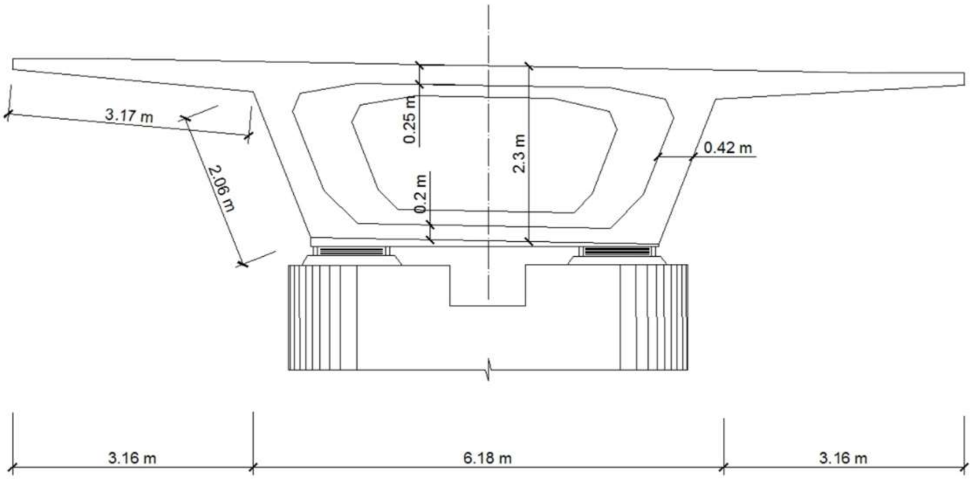


Figure 6.1. Cross section of the Arosa's concrete bridge deck

This study evaluates the social performance of alternative deck designs for the case study considered based on prevention strategies that are usually assumed when designing structures in marine environment. On one hand, the original concrete cover is increased to 35 mm, 45 mm and to 50 mm (measures CC35, CC45 and CC50 respectively henceforth). On the other hand, the original concrete mix is modified by adding fly ash, silica fume and polymers. Specifically, additions of 10% and 20% of fly ash (measures FA10 and FA20), 5% and 10% of silica fume (measures SF5 and SF10) and 10% and 20% of polymers (measures PMC10 and PMC20) are assumed. The mentioned percentages are expressed as a percentage of the cement content of the reference concrete mix design. The polymer assumed in the present study in the definition of PMC alternatives is styrene-butadiene rubber (SBR) latex, which has been widely used for such purposes (Yang et al., 2009). Both polymers, silica fume and fly ash, improve concrete durability by densification of concrete, thus hindering chloride diffusion. Another way to reduce concrete porosity is by reducing the water/cement ratio. In this study, a decrement in the water/cement ratio to w/c=0.40 and to w/c=0.35 (measures W/C40 and W/C35) has been considered. The concrete mixes corresponding to the design alternatives presented above are shown in Table 6.1. Additionally, it has been considered to treat the exposed deck surface with hydrophobic (measure HYDRO) and with sealant (measure SEAL) surface treatments. The replacement of the existing ordinary steel with galvanized steel (measure GALV) and with stainless steel (measure INOX) has also been considered. In summary, 15 preventive designs are evaluated as alternatives to the design of the existing bridge deck. This study compares the social performance of each of the presented preventive designs, taking into consideration the social impacts derived from the different stages of the life cycle for the described deck.

	Cement (kg/m^3)	Water (l/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Fly Ash (kg/m^3)	Silica Fume (kg/m^3)	SBR Latex (kg/m^3)	Superplastiziser (kg/m^3)	E_c (Gpa)	f_{cm} (Mpa)
REF[a]	485.6	218.5	827.9	926.7	-	-	-	-	29	40
W/C40	500	200	844.1	948.0	-	-	-	7.5	30	47
W/C35	500	175	882.8	976.7	-	-	-	10	32	55
FA10	471	218.5	798.3	926.7	48.6	-	-	-	29	40
FA20	456.4	218.5	768.7	926.7	97.1	-	-	-	29	40
SF5	437	218.5	849.1	926.7	-	24.3	-	-	29	40
SF10	388.4	218.5	870.2	926.7	-	48.6	-	-	29	40
PMC10	485.6	218.5	827.9	926.7	-	-	48.6	-	29	50
PMC20	485.6	218.5	827.9	926.7	-	-	97.1	-	29	50

Notes:
[a] This mix is also considered in alternatives CC35, CC45, CC50, INOX, GALV, HYDRO and SEAL

Table 6.1. Concrete mixes and mechanical properties considered in the alternative designs

6.3. Social Life Cycle Assessment

The framework for SLCA presented in the Guidelines relies on the standardized E-LCA methodology as presented in ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b).

Therefore, the SLCA involves four steps, namely the goal and scope definition, inventory analysis, impact assessment, and interpretation.

6.3.1. Definition of goal and scope

6.3.1.1 *Goal of the study*

The main goal of the present study is to evaluate the social performance of the different design alternatives of the bridge deck exposed to a marine environment. The comparison of the results shall provide information to determine which of the analyzed alternatives is preferable in social terms. The research also aims to apply the SLCA methodology exposed in the Guidelines on a concrete structure, thus contributing with an unprecedented case study to the existing knowledge on SLCA and to the sustainable design of bridges.

6.3.1.2 *Functional unit*

The functional unit considered for the LCA is 1 m length of a bridge deck providing a terrestrial connection between the Arosa Isle and the mainland. The functional unit includes the production, installation and maintenance for a service life of 100 years as required by the Spanish Ministry of Public Works (2008). This functionality is assumed to be guaranteed by the currently existing bridge deck (reference design, called 'REF' hereafter) if a proper maintenance is carried out. Consequently, in order to make the analysis results comparable, the alternative designs shall provide the same solution not only in terms of durability, but also in terms of structural behavior. According to the mix proportions reported by León et al. (2013), the reference design has a mean compressive strength f_{cm} equal to 40 MPa, and a modulus of elasticity E_c equal to 29 GPa. As observed in Table 6.1, the concrete mixes considered in some of the designs evaluated here, result in greater elasticity moduli or compressive strengths. In order to make the resulting designs have the same bending strength and deformability as the reference design, the depth of the deck has been slightly modified in some of the alternatives. Considering the vertical deflection at the midspan section of the bridge as a control parameter to measure deformability, the designs presenting a stiffness greater than the one of the reference design has been modified, in particular alternatives W/C35 and those including polymers in the concrete mix, namely PMC10 and PMC20. Their stiffness has been adjusted and reduced by modifying the depth of the bridge section, thus resulting in depths of 2.1 m and 2.23 m respectively. These modified sections show the same deflection than the reference design under service loads at the midspan section of the bridge. The bending strength of the reference design is guaranteed in the aforementioned modified alternatives by increasing the applied prestressing force.

6.3.1.3 *System boundaries*

Whereas one of the goals of the present study is to serve for the sustainability assessment of bridge structures, and considering that the system boundaries in environmental and economic LCA are usually modelled on an attributable basis, the boundaries of the present SLCA will be established based on technical processes and life cycle stages.

The system boundary is defined from the point when the construction materials are produced in their respective production centers up to the end of the required service life. The extraction of raw materials has been excluded from the analysis, following a "gate-to-grave" approach. An exception is made for the aggregates extraction for the production of concrete. This process has been considered in the study, as it takes place at the very production site, and the social impacts derived from it are directly allocatable to this center. As a comparative SLCA, processes that are considered to be identical are cut-off (ISO, 2006b). Consequently, this study considers only those processes and stages of the life cycle that are different between alternatives are considered (Martínez-Blanco et al., 2014). The differences between designs are to be found in the materials used for the construction and repair of the structure, as well as in the number of maintenance operations required during the life cycle of the bridge. The demolition stage is assumed to have very similar social impacts between the alternatives and shall therefore be excluded from the present analysis.

The social influence of an infrastructure shall be evaluated within its particular geographical context (Sierra et al., 2017b). The present study assumes that every process in the life cycle of the analyzed design options happens in Spain, but different production locations are involved. Fig. 6.2 summarizes the social system and the activity locations considered in the present SLCA. It shall be noted that the social impacts derived from energy generation, as well as those related to transportation processes between the different production facilities, have been excluded from the present study due to the lack of available data. In the future, when more information becomes accessible, social impacts of background processes will be possible.

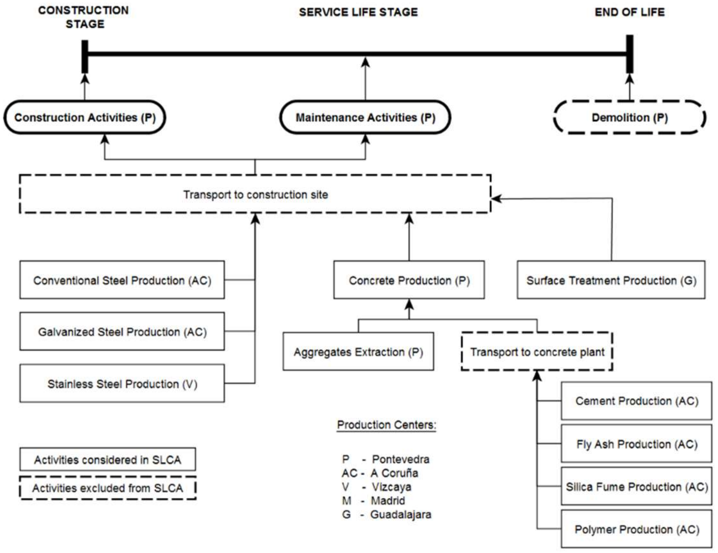


Figure 6.2. System boundaries considered in the assessment

6.3.2. Inventory

In the inventory phase of a SLCA, it is essential to identify those stakeholders affected along the life cycle of the product that is being analyzed. The selection of the different stakeholder categories and subcategories follows a top-down approach based on the methodological sheets proposed by UNEP/SETAC (2013). A hot spot analysis has been carried out to identify the relevant social concerns for the specific case study analyzed (Hosseinijou et al., 2014). This analysis is based on the evaluation of the regional development plan designed for the region of Pontevedra, as this region concentrates the greatest input to the bridge deck's life cycle (UNEP/SETAC, 2009). In particular, the SWOT (strengths, weaknesses, opportunities and threats) analysis presented in the aforementioned plan gives an overall picture of the social problems in the area, thus allowing to select the categories and subcategories of the present SLCA. Additionally, focusing on Pontevedra to detect the hot spots seems reasonable in this particular case since both Pontevedra and A Coruña shares a similar social context, and this context is more disadvantageous than the ones for the rest of the regions involved in the analysis.

Four main stakeholders are identified based on the development plan for Pontevedra. The first category considered in the present analysis includes the workers from the different production sites. Special emphasis is put on the problems related to gender discrimination, as well as on the high unemployment and the low salaries in the region. Additionally, due to the nature of the activities of the construction sector, the safety of the workers is also a major concern to be considered. The second category is the society and local economy, which will benefit from the economic inflows due to the production, construction and maintenance activities held in the region. The third category is the local community and the particular aesthetics of the construction site. Since tourism is a key contributor to the economy of the area, the consequences of affecting the visual perception of the area due to maintenance works are also being taken into account. At last, the fourth category is the consumers of the structure, i.e. its users. How maintenance affects the accessibility and their safety is reflected in the present SLCA. In this light, subcategories have been selected from the ones proposed by UNEP/SETAC (2013) and adapted to fit the specific social context of the region.

Based on the categories and subcategories identified above as relevant for the present study, inventory data are gathered through web research and from national statistical databases (Spanish National Statistics Institute and Spanish Tax Office database). To understand the meaning of the social context of the regions involved in the present study in relation to the rest of the regions in the Spanish territory, information has been collected as well on the minima and maxima values to be found in the Spanish regions for each of the social indicators. Table 6.2 shows the inventory data considered for the social assessment of the alternative bridge deck designs. It shall be highlighted that this information does not allow to evaluate the social impact of a specific activity per se, but to contextualize it, as will be explained in Section 3.3.1 of the present paper.

	Pontevedra	A Coruña	Vizcaya	Madrid	Guadalajara
Background data on Unemployment and gender discrimination:					
Unemployment rate (%)	19	14.4	12.5	13	15.4
Maximum and minimum national unemployment (%)	[8.2 - 30.8]	[8.2 - 30.8]	[8.2 - 30.8]	[8.2 - 30.8]	[8.2 - 30.8]
Men unemployment (%)	18.5	13.6	12.3	12.8	13.1
Women unemployment (%)	19.5	18.2	12.9	13.3	18.2
Mean region unemployment (%)	18.99	14.42	12.54	13.04	15.43
Background data on Fair Salary and gender discrimination:					
Salary (x10^3€/year)	14.63[a] 20.61[b]	20.61[a]	29.06[a]	27.91[a]	25.06[a]
Maximum national salary (x10^3€/year)	21.61[b]	29.065[a]			
National living wage (x10^3€/year)	9.90				
Men salary (x10^3€/year)	19.64	21.78	29.34	27.66	22.19
Women salary (x10^3€/year)	14.87	16.59	20.88	20.88	16.33
Mean region salary (x10^3€/year)	17.37	19.23	25.50	25.50	19.64
Background data on Health and Safety:					

Accident rate (accidents/1.000 employees)	73[b] 55[c]	72[d] 57[c]	75[d]	27[e]	50[e]
Maximum and minimum national accident rates (accidents/1.000 employees)	[69 - 126][b] [47 - 86][c]	[59 - 109][d] [47 - 86][c]	[59- 109][d]	[27 - 50][e]	[27 - 50][e]
Background data on Regional economy:					
Gross Domestic Product (x10^6 €)	3157[a] 1142[b]	2588[a]	5030[a]	13571[a]	934[a]
Maximum and minimum national GDP (x10^6 €)	[14 - 24490][a] [64 - 7901][b]	[14 - 24490][a]	[14 - 24490][a]	[14 - 24490][a]	[14 - 24490][a]

Notes:
Data in the present table has been collected from Spanish National Statistics Institute and Spanish Tax Office databases
[a] Industry sector; [b] Construction sector; [c] Extraction industry; [d] Metallurgic industry; [e] Chemical industry

Table 6.2. Inventory data on the social context of the different production locations

Additional information is required to properly characterize the activities happening throughout the life cycle of the structure. From the existing literature and from conversations with specific material manufacturers, production performance values have been obtained for the different materials evaluated in terms of working hours per production output. Furthermore, information has been obtained regarding workers' performance. It is noted that the specific activities of the maintenance operations depend on the design considered. So, while the maintenance of the designs based on surface treatments simply consists on the periodic reapplication of this product over the surface, in the rest of the cases the concrete cover is demolished, reinforcing bars are cleaned and primed, and the cover is then regenerated with the same material as the one considered in the design evaluated. Both, the performance values regarding materials production and those related to worker activities, are shown in Table 6.3. The performance values assumed in the present study, expressed as working hours per output unit (Hunkeler et al., 2008), have been gathered from both local companies involved in the production of the construction materials considered, and from official construction databases provided in Spain by regional governments. It shall be noted that data related to demolition and repair activities depend on the depth of the cover to be repaired. Table 6.3 shows demolition and repair performance values associated with 30 mm and 50 mm cover.

Material Production		
Carbon steel	0.4136	h/tn
Galvanized steel	0.4136	h/tn
Stainless steel	4.9	h/tn
Cement	0.165	h/tn

Aggregate extraction	0.1925	h/tn
Concrete production	0.18	h/tn
Hydrophobic treatment production	0.045	h/m^3
Sealant treatment production	0.069	h/m^3
Polymer production	0.0286	h/l
Construction activities		
Concreting	0.35	h/m^3
Steel disposal	0.024	h/kg
Surface treatment	0.11	h/m^2
Concrete cover demolition[a]	0.27 - 0.405	h/m^2
Steel surface treatment	0.12	h/m^2
Cover repair[a]	0.84 - 1.4	h/m^2

Notes:

[a] For 30mm and 50 mm cover, respectively. Intermediate results are obtained by linear interpolation.

Table 6.3. Performance values considered for the different processes

Information is gathered as well on unitary costs associated with the raw materials involved in the alternative designs (Navarro et al., 2018a). These costs have been obtained from national construction specific price databases. Table 6.4 shows the unitary economic flows associated with the activities that are necessary to install a unit of the specific construction material in the bridge construction site. These economic flows are derived from the payment for the specific materials or activities. Depending on the inputs needed for the production and installation of a particular material, and considering the unitary costs associated to each of them, the economic flows can be allocated to each of the involved activities. The unitary costs associated to the inputs considered within the construction units have been obtained from national construction specific price databases. The material proportions assumed are derived from the concrete mixes presented in Table 6.1.

	Steel Prod.	Cement Prod.	Concrete Prod.	Addition Prod.	Surface Treatment Prod.	Construction and installation	TOTAL	
HA-30 (reference concrete)	0.00	42.62	26.93	0.00	0.00	21.62	91.18	€/m^3
HA-30 (w/c=0.4)	0.00	43.89	37.81	0.00	0.00	24.33	106.03	€/m^3
HA-30 (w/c=0.35)	0.00	43.89	42.24	0.00	0.00	27.04	113.17	€/m^3
HA-30 +10% fly ash	0.00	62.09	28.37	0.00	0.00	21.62	112.08	€/m^3
HA-30 +20% fly ash	0.00	60.16	29.80	0.00	0.00	21.62	111.58	€/m^3
HA-30 +5% silica fume	0.00	57.61	60.95	0.00	0.00	21.62	140.17	€/m^3

HA-30 +10% silica fume	0.00	51.20	88.94	0.00	0.00	21.62	161.76	€/m^3
HA-30 +10% polymers	0.00	64.01	26.93	240.98	0.00	21.62	353.55	€/m^3
HA-30 +20% polymers	0.00	64.01	26.93	481.47	0.00	21.62	594.04	€/m^3
Carbon steel	0.86	0.00	0.00	0.00	0.00	0.38	1.24	€/kg
Stainless steel	4.86	0.00	0.00	0.00	0.00	0.38	5.24	€/kg
Galvanized steel	3.24	0.00	0.00	0.00	0.00	0.38	3.62	€/kg
Hydrophobic treatment	0.00	0.00	0.00	0.00	4.10	1.62	5.72	€/m^2
Sealant treatment	0.00	0.00	0.00	0.00	14.13	1.62	15.75	€/m^2

Table 6.4. Economic flows per output unit

6.3.3. Impact assessment

6.3.3.1 *Methodology*

The SLCA performed to compare the described design alternatives is based on the principles and the impact categories exposed in the Guidelines. As the present study aims to compare the social performance of different designs, the interest lies in the relative social effect of each of them rather than in the social impact itself. For such cases, the Guidelines present a methodology based on the use of Performance Reference Points, which are derived from internationally set thresholds or objectives according to best practices or particular consensus. These reference points allow the evaluation not of social impacts per se, but of social performance, namely the effect that a specific activity or product has on the social system defined in the analysis in relation to its present state. Given that every activity considered in the study takes place in Spain, the social performance of a specific activity is here estimated in relation to the Spanish average, maximum and minimum values registered in Spanish regions for specific social aspects. Based on the mentioned reference values, inventory data is normalized and transformed into subcategory indicators that range between 0 and 1, being 1 the most desirable situation for the Spanish context.

In order to get the social performance of the alternatives for each of the considered categories, the resulting indicator values for each subcategory is aggregated, assigning a relative importance to each subcategory p_i as shown in Eq. (1). According to Hagerty and Land (2007) where no information is available regarding the importance that people place on each subcategory, and in order to avoid biased results, equal weighting shall be considered, assuming equal importance for every category considered in the study. Assuming this criterion results in the lowest level of disagreement among large variance in individuals' weightings (Hagerty & Land, 2007).

$$\boldsymbol{X_j^k = \sum_{subcat} x_i^k \cdot p_i} \qquad (1)$$

where X_j^k is the unitary social performance related to impact category *j* and activity *k*, and x_{ik} is the social performance associated to activity *k* in relation to subcategory *i* defined in Table 6.5.

The aforementioned indicators serve to characterize the social context of each of the activities held within each of the life cycle stages for each of the evaluated design alternatives, but the indicator results so as defined here are not related to the functional unit. Therefore, an activity variable is used to allocate a specific weight to the different activities assumed. The considered values of the selected activity variables are proportional to the functional unit and represent the relative importance of each of them within the analyzed system. The activity variable considered for the category Workers is the number of working hours required for each activity, and are derived from the performance values presented in Table 6.3. The working time, which represents the jobs created by a particular process, has been extensively used to assess social life cycle impacts in relation to stakeholder category Workers (Andrews et al., 2009; Benoît et al., 2011; Martínez-Blanco et al., 2014). The activity variable assumed for the Society category is the economic flow resulting from each activity, taking into account the values shown in Table 5. Categories Local Community and Consumer do not require such a weighting method, as the impacts affecting them happen in the same location, namely the construction site, and affect the same number of persons. However, these impacts are, so as defined in the present study, proportional to the functional unit, to the extent that they are a function of the required maintenance operations and the consequent time Σt_m that the structure is affected by them.

Category	Subcategory	Transference Function	Reference
Workers	Local Employment	$X_{local\ empl.}^{activity} = \frac{ur - Ur_{min}}{Ur_{max} - Ur_{min}}$ ur = unemployment rate at the activity location Ur_{min} = minimum national unemployment rate Ur_{max} = maximum national unemployment rate	OECD (2008), Sierra et al. (2017[a])
	Gender Discrimination	$X_{gender\ disc.}^{activity} = 0.5 \cdot min\left\{1 - \left\lvert\frac{Ur_m}{Ur_{mean}} - 1\right\rvert ; 1 - \left\lvert\frac{Ur_w}{Ur_{mean}} - 1\right\rvert\right\} + 0.5 \cdot min\left\{1 - \left\lvert\frac{S_m}{S_{mean}} - 1\right\rvert ; 1 - \left\lvert\frac{S_w}{S_{mean}} - 1\right\rvert\right\}$ Ur_m = men's unemployment rate at the activity location Ur_w = women's unemployment rate at the activity location Ur_{mean} = mean unemployment rate at the activity location S_m = men's mean salary for the specific activity at the activity location S_w = women's mean salary for the specific activity at the activity location S_{mean} = mean salary for the specific activity at the activity location	European Institute for Gender Equality (2015)
	Workers Safety	$X_{safety}^{activity} = 1 - \frac{ar - Ar_{min}}{Ar_{max} - Ar_{min}}$	OECD (2008);

		ar = accident rate for the specific activity at the activity location Ar_{min} = minimum national accident rate for the specific activity Ar_{max} = maximum national accident rate for the specific activity	Sierra et al. (2017^{a})
	Fair Salary	$X_{salary}^{ctivity} = \frac{s - S_{min}}{S_{max} - S_{min}}$ s = mean salary for the specific activity at the activity location S_{min} = Lnational living wage S_{max} = maximum national salary for the specific activity	OECD (2008)
Society	Economic Development	$X_{local\ economy}^{activity} = (1 - \frac{gdp-GDP_{min}}{GDP_{max}-GDP_{min}})$ gdp = Gross Domestic Product at the activity location GDP_{min} = Minimum national Gross Domestic Product GDP_{max} = Maximum national Gross Domestic Product	OECD (2008)
Consumer	Accesibility	$X_{accesibility}^{maintenance} = \frac{(T_{SL} - \sum t_m) \cdot 1 + \sum t_m \cdot a}{T_{SL}}$ T_{SL} = bridge service life Σt_m = total time that the bridge is under maintenance a = bridge availability, which is the ratio between traffic speed under maintenance and normal operation circumstances	Dette & Sigrist (2011)
	User's Safety	$X_{user's\ safety}^{maintenance} = 1 - \frac{l}{L_{tot}} \cdot \frac{\sum t_m}{T_{SL}} \cdot \frac{v}{V_{norm}}$ l = length of the maintenance work zone L_{tot} = bridge total length T_{SL} = bridge service life Σt_m = total time that the bridge is under maintenance v = traffic speed under maintenance operations along the work zone V_{norm} = traffic speed under normal operation conditions	Ozturk et al. (2013)
Local Community	Public Opinion	$X_{public\ opinion}^{maintenance} = 1 - RTUA = 1 - \frac{\sum t_m}{T_{SL}}$ RTUA = relative time of unsatisfactory appearance T_{SL} = bridge service life Σt_m = total time that the bridge is under maintenance	Dette and Sigrist (2011)

Table 6.5. Social indicators for the subcategories considered in the study

Once the category indicators X_j^k for each of the involved production centers are calculated, the indicators are aggregated considering the described weighting system, thus resulting in a weighted category indicator $\overline{X_j}$ for each of the considered categories as shown in Eq. (2).

$$\overline{\boldsymbol{X_j}} = \sum\nolimits_{\boldsymbol{activities}} \boldsymbol{X_j^k} \cdot \frac{\boldsymbol{n_{k,j}}}{\sum \boldsymbol{n_{k,j}}} \tag{2}$$

where $n_{k,j}$ is the value of the activity variable associated to impact category j which is involved in activity k.

Equal weighting is assumed to aggregate the indicators obtained for each category, namely p_j. The weighting defined for the calculation of the category indicator $\overline{X_j}$ allows the designer to know the relative importance that each activity has on the social impact of an alternative, thus providing an intermediate result to help in the decision assessment. However, this does not allow the designer to compare between alternatives, as weights have been defined in relation to each of the alternatives, and not in relation to the collection of alternatives to be compared. In order to make comparison feasible, a comparison factor ϕ_j is defined for each category as shown in Eq. (3) and Eq. (4). The comparison factors are here used to reward those alternatives that contribute to better social performances in the particular category under evaluation by either creating more jobs (category Workers), creating more wealth (category Society) or reducing the time that the bridge is affected by maintenance (categories Local Community and Consumer) when compared to the rest of the alternatives. The activity variables chosen here are meant to measure the different stakeholders' interests. Consequently, these factors are obtained for a specific alternative as the ratio between the total amount of the activity variable resulting from the life cycle stage evaluated and the maximum of those amounts taking into consideration all the alternatives. The maximum value of a comparison factor is 1, being this the case of the most desirable alternative in terms of the specific activity variable considered.

$$\phi_j = \frac{\sum n_{k,j}}{(\sum n_{k,j})_{max}} \tag{3}$$

Where the most desirable alternative is the one that minimizes the value of the activity variable, as in the case of the categories Local Community and Consumer, the comparison factor is defined as:

$$\phi_j = \frac{(\sum n_{k,j})_{min}}{\sum n_{k,j}} \tag{4}$$

Considering the above, social performance I_m is obtained for each of the defined life cycle stages m as shown in Eq. (5). As mentioned in the inventory phase, two main stages have been considered in the comparison of design, namely the construction and the maintenance stage, assuming that each of these includes every extraction and material production activity described in the inventory.

$$\boldsymbol{I_m} = \sum_{cat} \overline{\boldsymbol{X}}_{\boldsymbol{j}} \cdot \boldsymbol{p_j} \cdot \phi_j \tag{5}$$

A simple addition is performed between the impacts resulting from each life cycle stage to get the social performance score I_{LCA} of an alternative throughout its entire life cycle, as shown in Eq. (6). It shall be noted that categories Local Community and Consumer are only considered in the evaluation of the social performance during the maintenance stage of the life cycle. This is because the impacts on these stakeholders are the same during the construction stage and have been therefore excluded (Section 3.1.3).

$$\boldsymbol{I_{LCA}} = \sum \boldsymbol{I_m} \tag{6}$$

6.3.3.2 *Service Life prediction and maintenance strategies*

A reliability-based service life prediction is assumed to evaluate when maintenance operations shall be held. In the present study, the chloride-induced corrosion of the deck steel reinforcement is considered to affect reliability, so that the bridge condition is guaranteed if the chloride concentration at the reinforcing bars is below the critical content. The critical chloride content C_{crit} is the concentration of chlorides needed to start the corrosion and depends on the properties of steel. Here, it is accepted that maintenance operations take place before the critical chloride content is reached, so that the steel rebars are not affected by corrosion when maintenance is carried out.

The chloride concentration at the reinforcement *C(r,t)* is predicted on the basis of the fickean model suggested in Fib Bulletin 34 (Fib, 2006). This model has been modified to take into account the scenario where a reinforcing bar is simultaneously exposed to two advancing chloride fronts, the so-called corner effect (Titi & Biondini, 2016). So, the chloride concentration to be expected in the concrete cover at a specific depth in both *x* and *y* directions, and in a particular time *t* is expressed as:

$$\boldsymbol{C(x,y,t) = C_0 + (C_s - C_0) \cdot \left(1 - erf\frac{x}{2\sqrt{D_{0,x}\cdot\left(\frac{t_0}{t}\right)^{\alpha}\cdot t}} \cdot erf\frac{y}{2\sqrt{D_{0,y}\cdot\left(\frac{t_0}{t}\right)^{\alpha}\cdot t}}\right)} \tag{7}$$

where $C(x,y,t)$ is the chloride concentration (wt.%/binder) at concrete depth $[x, y]$ (mm) and time t (years); C_s is the chloride concentration at the surface of the concrete (wt.%/binder); C_0 is the initial chloride content of the concrete (wt.%/binder), assumed here to be zero; *erf(.)* is the Gauss error function; D_0 is the non-steady state chloride migration coefficient (mm^2/years). It has been assumed that the concrete is homogeneous and that the chloride diffusion coefficient is the same in both directions ($D_{0,x} = D_{0,y}$). A value of 0.5 has been assumed for the age factor α, as proposed in the Spanish concrete design code (Spanish Ministry of Public Works, 2008). As reference time, $t_0 = 0.0767$ years (namely 28 days) has been considered. The concrete cover in the y-direction (r_y) is assumed constant and equal to 50 mm for every design analyzed, while the cover in the x-direction (r_x) is assumed to vary depending on the prevention alternative studied.

The service life of the concrete bridge deck is then evaluated taking into account a reliability index β, which results from evaluating the inverse of the Gaussian cumulated distribution function of the probability of failure p_f. The reliability-based maintenance has been optimized by finding the specific maintenance interval T_{opt} that maximizes the life cycle social performance of the structure, while ensuring that the minimum required reliability index β_{lim} is not exceeded. According to Nogueira et al. (2012), a target reliability index β_{lim} of 1.30 is assumed. It shall be noted that the reliability index $\beta(t)$ of the structure at a specific time depends on the advance of the deterioration process at this time. This study assumes that those maintenance operations where concrete cover is demolished and regenerated only affect the depth where the chloride concentration exceeds the critical chloride content, so that the social impacts associated to maintenance activities depend on the maintenance interval evaluated.

In the present study, durability characterization parameters for each material have been obtained from the existing literature. Table 6.6 shows the statistical values of the diffusion coefficient D_o and of the critical chloride C_{crit} content assumed for the different designs, as well as the resulting mean time to failure for each of them in years. Considering the existing distance between the structure and the sea water surface, a surface chloride content of $C_{s,0}$=3.34% is assumed for the evaluation of the bridge.

Design alternative	Reference	D_0 ($x10^{-12}$ m^2/s)		C_{crit} (%)		r_x (mm)		Mean time to failure (years)
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	
REF	Spanish Ministry of Public Works (2008)	10	1.1	0.6	0.1	30	1.5	4
CC35		10	1.1	0.6	0.1	35	1.75	5
CC45		10	1.1	0.6	0.1	45	2.25	9
CC50		10	1.1	0.6	0.1	50	2.5	11
W/C40	Cheewaket et al. (2014), Vedalakshmi et al. (2009)	6.15	0.51	0.6	0.1	30	1.5	8
W/C35		4.32	0.33	0.6	0.1	30	1.5	14
INOX	Bertolini et al. (1996)	10	1.1	5	0.94	30	1.5	-
GALV	Darwin et al. (2009)	10	1.1	1.2	0.21	30	1.5	9
PMC10	Ohama (1995), Yang et al. (2009)	7.32	0.66	0.6	0.1	30	1.5	8
PMC20		3.04	0.24	0.6	0.1	30	1.5	10
SF5	Frederiksen (2000), Manera et al. (2008)	3.31	0.25	0.38	0.06	30	1.5	14
SF10		1.38	0.17	0.22	0.03	30	1.5	34
FA10	Otsuki et al. (2014)	6.16	0.51	0.6	0.1	30	1.5	6
FA20		5.23	0.41	0.6	0.1	30	1.5	25
HYDRO	Zhang & Buenfeld (2000)	7.73	0.72	0.6	0.1	30	1.5	5[a]
SEAL	Medeiros et al. (2012)	4.87	0.37	0.6	0.1	30	1.5	5[a]

Notes:

[a] In the present study, the service life of surface treatments (HYDRO and SEAL) is limited to 5 years according to manufacturer specifications

Table 6.6. Durability characterization parameters of the analyzed designs

6.3.3.3 *Uncertainties*

In order to deal with the uncertainty associated to the social context during the maintenance phase, a distribution function is chosen based on the most likely value, as well as the minimum and maximum values that the considered social parameters might adopt in the future (Sierra et al., 2017a). Consequently, a Beta distribution is assigned in the present study to the inventory data. The distribution used is based on the PERT technique, also known as Beta-PERT distribution. Let x_{max}, x_{mod} and x_{min} be the three values defining the maximum, the most probable and the minimum values of each uncertain variable. These values are derived from the analysis of the historical series consulted in the National Statistics Institute in Spain and are shown in Table 6.7.

	Pontevedra	A Coruña	Vizcaya	Madrid	Guadalajara
Background data on Unemployment and gender discrimination:					
Unemployment rate (%)	$x_{mod}=16.8$, $x_{min}=7.5$, $x_{max}=25.8$	$x_{mod}=13.9$, $x_{min}=6.8$, $x_{max}=21.7$	$x_{mod}=12.5$, $x_{min}=6.6$, $x_{max}=18.9$	$x_{mod}=12.4$, $x_{min}=5.9$, $x_{max}=20.5$	$x_{mod}=14$, $x_{min}=3.3$, $x_{max}=24.9$
Maximum national unemployment (%)	$x_{mod}=28.98$, $x_{min}=13.53$, $x_{max}=43.23$				
Minimum national unemployment (%)	$x_{mod}=7.74$, $x_{min}=2.1$, $x_{max}=14.31$				
Men unemployment (%)	$x_{mod}=15$, $x_{min}=5.7$, $x_{max}=26.1$	$x_{mod}=12.5$, $x_{min}=4.7$, $x_{max}=22.8$	$x_{mod}=11.8$, $x_{min}=4.9$, $x_{max}=19.8$	$x_{mod}=11.6$, $x_{min}=3.9$, $x_{max}=20$	$x_{mod}=12.2$, $x_{min}=2.2$, $x_{max}=24.2$
Women unemployment (%)	$x_{mod}=19.1$, $x_{min}=8.3$, $x_{max}=26.4$	$x_{mod}=15.8$, $x_{min}=8.5$, $x_{max}=22.2$	$x_{mod}=13.4$, $x_{min}=7.7$, $x_{max}=18.7$	$x_{mod}=13.3$, $x_{min}=6.8$, $x_{max}=21.9$	$x_{mod}=16.7$, $x_{min}=3.7$, $x_{max}=29.1$
Mean region unemployment (%)	$x_{mod}=16.8$, $x_{min}=7.5$, $x_{max}=25.8$	$x_{mod}=13.9$, $x_{min}=6.7$, $x_{max}=21.7$	$x_{mod}=12.5$, $x_{min}=6.6$, $x_{max}=18.9$	$x_{mod}=12.4$, $x_{min}=5.9$, $x_{max}=20.5$	$x_{mod}=14$, $x_{min}=3.3$, $x_{max}=24.9$
Background data on Fair Salary and gender discrimination					
Salary ($x10^3$ €/year)	$x_{mod}=19.6$, $x_{min}=18$, $x_{max}=20.6^a$ $x_{mod}=14.3$, $x_{min}=13.1$, $x_{max}=14.9^b$	$x_{mod}=19.6$, $x_{min}=18$, $x_{max}=20.6$	$x_{mod}=20.3$, $x_{min}=19.7$, $x_{max}=21.6$	$x_{mod}=32$, $x_{min}=27.9$, $x_{max}=34.6$	$x_{mod}=23.6$, $x_{min}=21.4$, $x_{max}=25$
Maximum national salary ($x10^3$ €/year)	$x_{mod}=32$, $x_{min}=27.9$, $x_{max}=34.6^a$ $x_{mod}=20$, $x_{min}=19.1$, $x_{max}=21^b$				
National living wage ($x10^3$ €/year)	9.90				
Men salary ($x10^3$€/year)	$x_{mod}=18.8$, $x_{min}=17.8$, $x_{max}=19.6$	$x_{mod}=20.9$, $x_{min}=19.8$, $x_{max}=21.7$	$x_{mod}=28.2$, $x_{min}=26.6$, $x_{max}=29.5$	$x_{mod}=27.4$, $x_{min}=26.6$, $x_{max}=28$	$x_{mod}=21.9$, $x_{min}=20.6$, $x_{max}=22.7$
Women salary ($x10^3$€/year)	$x_{mod}=14.2$, $x_{min}=13.6$, $x_{max}=14.8$	$x_{mod}=15.9$, $x_{min}=15.2$, $x_{max}=16.5$	$x_{mod}=20.1$, $x_{min}=19.3$, $x_{max}=21.1$	$x_{mod}=20.1$, $x_{min}=19.3$, $x_{max}=20.8$	$x_{mod}=16$, $x_{min}=15.7$, $x_{max}=16.3$

Mean region salary ($x10^3$€/year)	$x_{mod}=16.7$, $x_{min}=16.1$, $x_{max}=17.3$	$x_{mod}=18.6$, $x_{min}=17.9$, $x_{max}=19.2$	$x_{mod}=24.6$, $x_{min}=23.6$, $x_{max}=25.7$	$x_{mod}=24$, $x_{min}=23.3$, $x_{max}=24.5$	$x_{mod}=19.4$, $x_{min}=18.7$, $x_{max}=19.6$
Background data on Health and Safety:					
Accident rate (accidents/1.000 employees)	$x_{mod}=84$, $x_{min}=55$, $x_{max}=116^b$ $x_{mod}=76$, $x_{min}=44$, $x_{max}=133^c$	$x_{mod}=95$, $x_{min}=65$, $x_{max}=142^d$ $x_{mod}=73$, $x_{min}=47$, $x_{max}=114^c$	$x_{mod}=94$, $x_{min}=67$, $x_{max}=156^d$	$x_{mod}=33$, $x_{min}=23$, $x_{max}=50^e$	$x_{mod}=54$, $x_{min}=39$, $x_{max}=84^e$
Maximum national accident rate (accidents/1.000 employees)	$x_{mod}=111$, $x_{min}=84$, $x_{max}=156^b$ $x_{mod}=100$, $x_{min}=67$, $x_{max}=180^c$	$x_{mod}=129$, $x_{min}=92$, $x_{max}=220^d$ $x_{mod}=100$, $x_{min}=67$, $x_{max}=180^c$	$x_{mod}=129$, $x_{min}=92$, $x_{max}=220^d$	$x_{mod}=55$, $x_{min}=40$, $x_{max}=85^e$	$x_{mod}=55$, $x_{min}=40$, $x_{max}=85^e$
Minimum national accident rate (accidents/1.000 employees)	$x_{mod}=60$, $x_{min}=43$, $x_{max}=81^b$ $x_{mod}=54$, $x_{min}=34$, $x_{max}=90^c$	$x_{mod}=70$, $x_{min}=47$, $x_{max}=112^d$ $x_{mod}=54$, $x_{min}=34$, $x_{max}=90^c$	$x_{mod}=70$, $x_{min}=47$, $x_{max}=112^d$	$x_{mod}=29$, $x_{min}=20$, $x_{max}=45^e$	$x_{mod}=29$, $x_{min}=20$, $x_{max}=45^e$
Background data on Regional economy:					
Gross Domestic Product ($x10^6$ €)	$x_{mod}=3210$, $x_{min}=2429$, $x_{max}=4316^a$ $x_{mod}=1562$, $x_{min}=1136$, $x_{max}=2126^b$	$x_{mod}=2695$, $x_{min}=1773$, $x_{max}=3351^a$	$x_{mod}=4908$, $x_{min}=3986$, $x_{max}=5603^a$	$x_{mod}=14030$, $x_{min}=13121$, $x_{max}=15082^a$	$x_{mod}=872$, $x_{min}=529$, $x_{max}=1071^a$
Maximum national GDP ($x10^6$ €)	$x_{mod}=25041$, $x_{min}=22695$, $x_{max}=28376^a$ $x_{mod}=12515$, $x_{min}=7871$, $x_{max}=16489^b$	$x_{mod}=25041$, $x_{min}=22695$, $x_{max}=28376^a$			
Minimum national GDP ($x10^6$ €)	$x_{mod}=16$, $x_{min}=14$, $x_{max}=19^a$ $x_{mod}=92$, $x_{min}=58$, $x_{max}=124^b$	$x_{mod}=16$, $x_{min}=14$, $x_{max}=19^a$			

Notes:

Data in the present table has been collected from Spanish National Statistics Institute and Spanish Tax Office databases

[a] Industry sector; [b] Construction sector; [c] Extraction industry; [d] Metallurgic industry; [e] Chemical industry

Table 6.7. Inventory data expected values on the social context of the different production locations

So, the parameters α and β of the Beta-Pert distribution are obtained as:

$$\boldsymbol{\alpha} = \frac{2\cdot(x_{max}+4\cdot x_{mod}-5\cdot x_{min})}{3\cdot(x_{max}-x_{min})}\cdot\left[1+4\cdot\frac{(x_{mod}-x_{min})\cdot(x_{max}-x_{mod})}{(x_{max}-x_{min})^2}\right] \quad (8)$$

$$\boldsymbol{\beta} = \frac{2\cdot(5\cdot x_{max}-4\cdot x_{mod}-x_{min})}{3\cdot(x_{max}-x_{min})}\cdot\left[1+4\cdot\frac{(x_{mod}-x_{min})\cdot(x_{max}-x_{mod})}{(x_{max}-x_{min})^2}\right] \tag{9}$$

It has been shown that results converge with 6000 iterations.

6.3.4. Results and interpretation

The SLCA based on the methodology presented above results in the use of stainless steel being the most socially preferable design alternative for the case study evaluated, followed by the designs based on the addition of silica fume and polymers. Table 6.8 shows the social life cycle performance results I_{LCA} for the alternative designs considered, including as well the partial impact scores I_m derived from the construction and the maintenance life cycle phases. It shall be derived that the social impacts resulting from the construction stage and those derived from the maintenance phase are both equally contributing to the final score, which is in line with the results of previous studies in the field of SLCA applied to bridges (Gervásio & Da Silva, 2013; Soliman & Frangopol, 2014). Although in some cases the impacts of maintenance are even higher than those of construction, it is concluded that, in general, impacts arising from construction are 5 to 15% higher.

	Construction Stage	Service Stage	Life Cycle Performance	Confidence Intervals [5% - 95%]	
REF	0.368	0.351	0.360	0.347	0.372
CC35	0.368	0.261	0.314	0.305	0.323
CC45	0.368	0.228	0.298	0.292	0.304
CC50	0.368	0.238	0.303	0.297	0.309
W/C40	0.377	0.197	0.287	0.282	0.292
W/C35	0.371	0.206	0.288	0.286	0.291
INOX	0.618	0.500	0.559	0.559	0.559
GALV	0.517	0.204	0.360	0.356	0.365
FA10	0.381	0.208	0.294	0.289	0.300
FA20	0.380	0.193	0.287	0.283	0.291
SF5	0.397	0.211	0.304	0.301	0.307
SF10	0.410	0.517	0.464	0.463	0.464
PMC10	0.491	0.241	0.366	0.359	0.373
PMC20	0.605	0.295	0.450	0.449	0.451
HYDRO	0.402	0.179	0.291	0.290	0.291
SEAL	0.423	0.236	0.329	0.329	0.330

Table 6.8. Life cycle social performance of the analyzed designs

As mentioned above, construction stage is considered here to affect only two main stakeholders, namely the workers and the local economies involved in the production and construction processes. Fig. 6.3 shows the performance results during this stage for the evaluated alternatives, as well as the percentage that each concept represents of the total. Regarding the impact category Workers, it is observed that the social performance is very similar between alternatives. This is mainly because the activity that comprises the most of the workers' activity variable is the construction itself, being this process very similar between the different designs. The slight differences observed are due to the material production processes. It is worth noting that the alternatives with a greater affection to this category are those involving very specialized materials, such as stainless steel and polymer-modified concrete, as those processes require greater work force. This positive impact is partially diminished because the production centers associated with these materials are located in very desirable social contexts as derived from Table 6.2, thus not contributing to regional equity. In general, it is shown that the relevance of the category Workers in this stage takes up to 60-65% of the performance result of every alternative. However, it is observed that those alternatives based on specialized and consequently more expensive materials result in greater social impact. This is a consequence of the greater impact of these alternatives on the local economies derived from greater economic flows to the production centers. In those cases, the relative importance of the category Society takes up to 54-57% of the total performance result. Consequently, the alternatives that show a better social performance during the construction stage are based on the use of those materials, namely stainless and galvanized steel, as well as polymer-modified concrete.

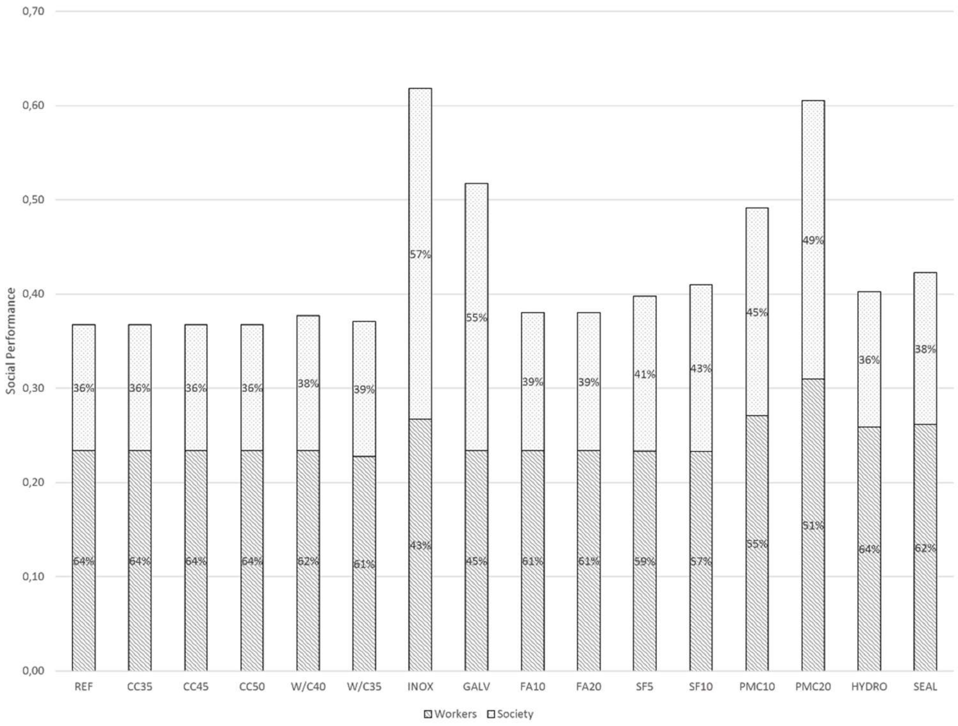


Figure 6.3. Assessment results assuming cost optimized maintenance strategies

During the maintenance stage, the most desirable designs in social terms are by far those based on the use of stainless steel and the addition of silica fume. Both of them are alternatives with a high durability that require no or very little maintenance. Therefore, the accessibility and the safety conditions for the users, as well as the site aesthetics, remain almost unaffected by maintenance operations. Additionally, local people are not affected by noise or pollutants emitted during those activities. This fact results in very high-performance results associated to Consumers and Local Community categories. The social performance on workers and local economies are, however, almost nil. Fig. 6.4 shows the results associated to the maintenance stage of the bridge, as well as the percentage that each concept represents of the total.

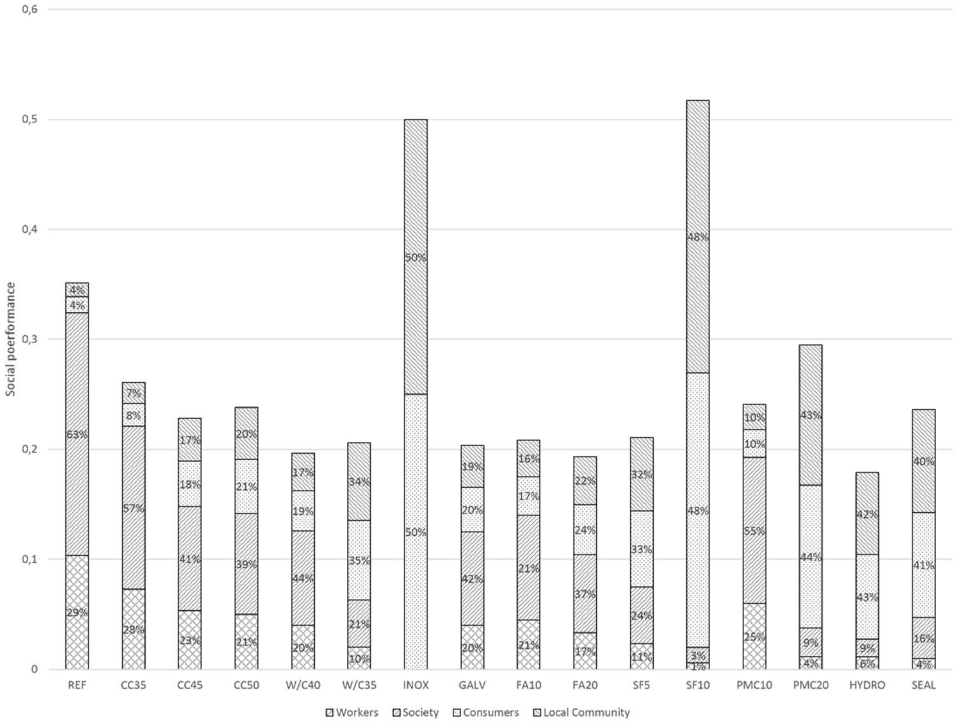


Figure 6.4. Assessment results assuming environmentally optimized maintenance strategies

In the rest of the alternatives, two clear trends can be observed. On the one hand, alternatives that are less durable and consequently demand more maintenance have a great impact on categories Workers and Society, derived from the production of materials and the repair activities to be held. In those cases, social performance on Consumers and Local Community is almost non-existent. This is the case of alternatives such as the reference design (REF) or those based on the increase of the concrete cover. On the other hand, alternatives with a greater durability, such as W/C35 or PMC20, show exactly an opposite composition of the resulting social performance, mainly based on the positive affection to the local community and infrastructure users. Alternatives based on surface treatments, which are very maintenance demanding, show the same performance behavior, as these maintenance activities are carried out particularly fast.

Fig. 6.5 shows the life cycle performance scores I_{LCA} of each alternative, as well as the contribution of the construction and the service stage on the final score. On the basis of the assumptions considered in this study, the use of stainless steel reinforcement (INOX) has resulted in the greatest social impact, followed by the alternatives based on the addition of silica fume SF10 and the use of polymer modified concrete PMC20. All of them are alternatives with high durability which result in low maintenance. In Fig. 6.5 it can be observed that two alternatives, such as the reference design and PMC10, which are opposite in durability and service life performance, result in very similar social results. This is due to the fact that in the present study the same weight is assigned to every stakeholder, and they benefit from either the presence (Workers, Society) or the absence of maintenance (Consumers, Local Community).

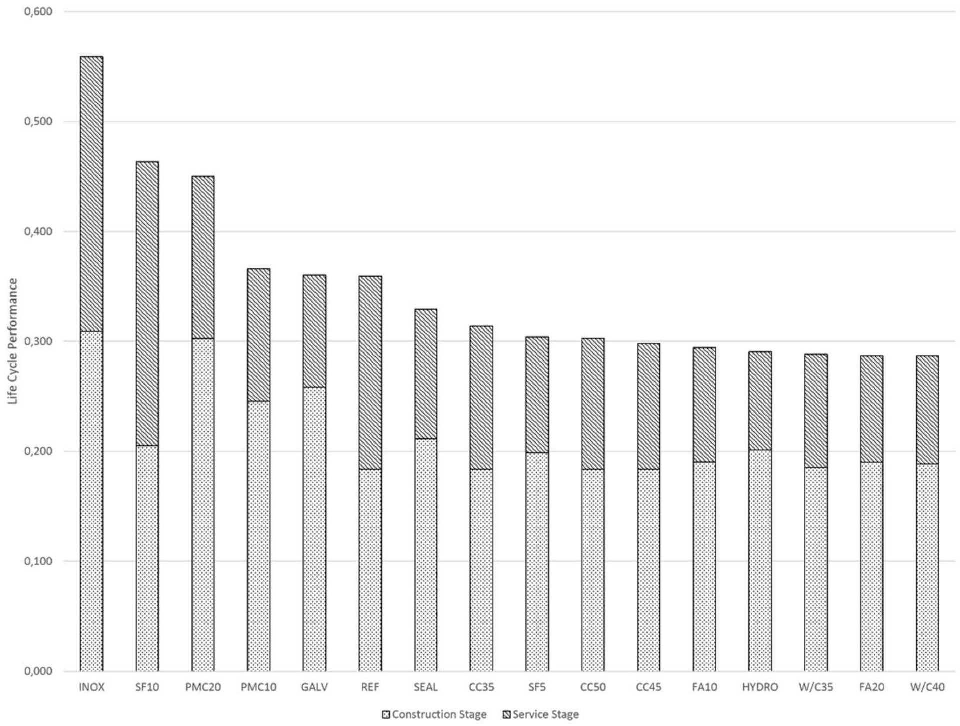


Figure 6.5. Representative solutions of the Pareto optimal set

In order to understand the effect of considering different weighting factors, two alternative weighting scenarios are tested to evaluate the sensitivity of the results, where greater importance (30%) is assigned either to stakeholders Workers and Society or to Consumers and Local Community. Table 6.9 shows the social performance results for the different scenarios assumed. According to the sensitivity analysis, it is found that the results of the assessment do not vary significantly with smaller changes in the assumed weighting factors. Consequently, the equal weighting of the categories is shown to be an appropriate and reliable method for the present case study.

	Scenario 1[a]	Scenario 2[b]	Scenario 3[c]
REF	0.360	0.329	0.383
CC35	0.314	0.301	0.343
CC45	0.298	0.296	0.309
CC50	0.303	0.301	0.312

W/C40	0.287	0.284	0.300
W/C35	0.288	0.297	0.283
INOX	0.559	0.609	0.509
GALV	0.360	0.356	0.370
FA10	0.294	0.287	0.304
FA20	0.287	0.287	0.286
SF5	0.304	0.311	0.298
SF10	0.464	0.512	0.416
PMC10	0.366	0.351	0.390
PMC20	0.450	0.510	0.453
HYDRO	0.291	0.325	0.291
SEAL	0.329	0.345	0.317

Notes:

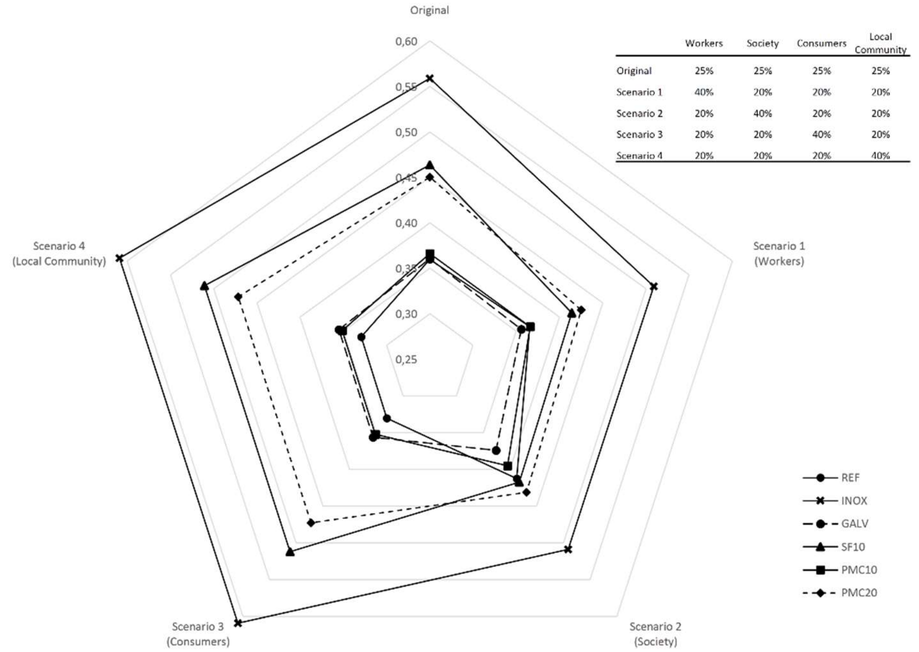
[a] Scenario 1 is based on equal weighting of the different stakeholder categories (25%). It is the scenario considered in the present study.

[b] Scenario 2 assigned weights: Workers (20%), Society (20%), Consumers (30%), Local Community (30%)

[c] Scenario 3 assigned weights: Workers (30%), Society (30%), Consumers (20%), Local Community (20%)

Table 6.9. Sensitivity analysis on weighting factors

An additional sensitivity analysis is performed in order to show how giving preference to each of the stakeholders affects the results of the assessment. Four additional scenarios are considered, each of them gives a significant importance to one of the stakeholder groups (40%), while leaving the weights of the rest of the group to 20%. Fig. 6.6 shows the obtained social scores I_{LCA} under the different scenarios for the six alternatives that reached the highest social scores in the egalitarian scenario, namely alternatives INOX, SF10, PMC10, PMC20, GALV and REF. It shall be noted that these are the six alternatives with the highest scores in the 4 new scenarios evaluated as well. Fig. 6.6 also shows the weights assumed for each of the evaluated scenarios.



	Workers	Society	Consumers	Local Community
Original	25%	25%	25%	25%
Scenario 1	40%	20%	20%	20%
Scenario 2	20%	40%	20%	20%
Scenario 3	20%	20%	40%	20%
Scenario 4	20%	20%	20%	40%

Figure 6.6. Sensitivity of the results under different weighting scenarios

It is observed that the alternative INOX is socially preferable under every scenario, and with a wide margin compared to the other alternatives. Regarding the second alternative, SF10, it is preferable both in the egalitarian scenario and in those that give more importance to the users and the local community. When greater weight is associated to either workers or society categories, PMC20 alternative is preferable over SF10. This is mainly due to the fact that SF10 alternative generates lesser economic flow towards the involved production centers and demands lesser working hours for the production of the construction materials when compared to PMC20 alternative.

6.4. Conclusions

Social Life Cycle Assessment is a new technique still under development in order to serve for the sustainability assessment. As there is no commonly agreed methodology available thus far, the application of SLCA to real case studies is highly recommended according to the Guidelines to further develop this tool. In this study, 15 different preventive designs for a concrete bridge deck is carried out in accordance with the four-step assessment structure proposed in the Guidelines. As one of the first attempts of social assessment of a bridge structure under a life cycle perspective, the developed model provides a comprehensive framework to be used by designers in order to evaluate the social performance of different construction materials. The methodology developed allows for the evaluation of a single life cycle indicator, taking into account the uncertainties associated both to maintenance activities as well as on the social context expected throughout the life cycle of the structure.

A reliability-based maintenance optimization is performed for the designs under evaluation. Considering an equally weighting system, it has been shown that the social benefits resulting from maintenance-free solutions are considerably greater than those derived from maintenance demanding designs. A sensitivity analysis on the weighting system has served to confirm this conclusion when small changes in the assigned weights are assumed.

The analysis has shown that the use of stainless steel reinforcement performs socially the best for the case study evaluated, as well as those designs based on silica fume and polymer additions to concrete. The results obtained in the present study have brought to light that social impacts derived from maintenance play a major role in the sustainability performance of a structure. As for future lines of research, it would be interesting to integrate the social assessment methodology presented into the environmental and economic life cycle assessment of bridges, in order to produce a comprehensive sustainability analysis of such long lasting structures.

Chapter 7

Sustainability assessment of concrete bridge deck designs in coastal environments using neutrosophic criteria weights

Authors: Ignacio J. Navarro; Víctor Yepes; José V. Martí;
Status: Manuscript accepted, in press
Journal: *Structure and Infrastructure Engineering*
JCR IF (2018) 2.43

JCR Category	Ranking	Quartile
Engineering, Civil	44/132	Q2
Engineering, Mechanical	45/129	Q2

Presentation: Pre-print version

Abstract

Essential infrastructures such as bridges are designed to provide a long-lasting and intergenerational functionality. In those cases, sustainability becomes of paramount importance when the infrastructure is exposed to aggressive environments which can jeopardize their durability and lead to significant maintenance demands. The assessment of sustainability is however often complex and uncertain. The present study assesses the sustainability performance of 16 alternative designs of a concrete bridge deck in a coastal environment on the basis of a neutrosophic group Analytic Hierarchy Process (AHP). The use of neutrosophic logic in the field of multi-criteria decision-making, as a generalisation of the widely used fuzzy logic, allows for a proper capture of the vagueness and uncertainties of the judgements emitted by the decision makers. TOPSIS technique is then used to aggregate the different sustainability criteria. From the results, it is derived that only the simultaneous consideration of the economic, environmental and social life cycle impacts of a design shall lead to adequate sustainable designs. Choices made on the basis of the optimality of a design in only some of the sustainability pillars will lead to erroneous conclusions. The use of concrete with silica fume has resulted in a sustainability performance 46.3% better than conventional concrete designs.

Keywords Sustainable Design; Chloride Corrosion; Neutrosophic AHP; Preventive Maintenance; Multi-Criteria Decision-Making; Life Cycle Assessment

7.1. Introduction

As developed countries have been placing greater emphasis on the conservation of infrastructures, durability has become a key issue in structural design. During the last decades, significant efforts have been made to optimise the maintenance strategies of structures in terms of their life cycle costs, paying special attention to bridge structures (Sabatino et al., 2016; Barone & Frangopol, 2014). Eamon et al., (2012) compare the life cycle costs of different reinforcement materials used in bridge deck designs. Safi et al. (2015) introduce a life cycle cost assessment technique to help agencies in the exploitation of their Bridge Management Systems through fair tendering processes. Efforts have also been conducted on the optimisation of maintenance strategies and on the selection of the most cost-efficient corrosion preventive design of concrete (Navarro et al., 2018a; Sajedi & Huang, 2019) and steel bridges (Cope et al., 2013; Kere & Huang, 2019). In general terms, studies conclude that the maintenance phase of bridges is an essential source of impacts during their life cycle, and that the optimisation of maintenance is therefore crucial to reduce such impacts.

However, the life cycle cost optimisation of structures is currently not enough to meet the increasing environmental and social demands of the 21st century world. Since its definition in 1987, sustainability has called for a paradigmatic shift in the way structural design and maintenance are optimised: it is now expected that from the design stage, infrastructure designers will simultaneously take into account the effects of economic, social and environmental decisions. Consequently, research has been conducted to include environmental and social considerations in the design of infrastructures, taking into account different aspects such as embodied energy (Martí et al., 2016), greenhouse gas emissions (García-Segura et al., 2017; García-Segura & Yepes, 2016), or social impacts (Navarro et al., 2018b; Sierra et al., 2018b) derived from construction activities.

Sustainable design and management of infrastructures are complex problems involving multiple and conflicting criteria. During the last few years, Multi-Criteria Decision-Making (MCDM) techniques have been used to assess the sustainability of infrastructures, such as bridges (Gervásio & Da Silva, 2012; Yepes et al., 2015a), buildings (Mosalam et al., 2018; Invidiata et al., 2018), or hydraulic infrastructures (De la Fuente et al., 2016b; Tahmasebi & Yazdandoost, 2018), among others.

Different MCDM methodologies have been used in the existing literature for such sustainability-oriented infrastructure assessments, being the Simple Additive Weighting (SAW) technique the most widely used one (Rashidi et al., 2016; Jakiel & Fabianowsky, 2015). The popularity of such technique is based on its ease of use. However, as it can only handle with maximizing, positive defined criteria, during the past years other MCDM methods have been preferred for sustainability assessments, such as TOPSIS (Guzmán-Sánchez et al., 2018) or ELECTRE (Heravi et al., 2017).

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is an MCDM method that allows to rank different alternatives taking into account the fact that the most desirable solution should have the shortest Euclidean distance to the positive ideal solution, and the longest distance to the less preferred one (Penadés-Plà et al., 2016). The ideal point is constructed from the best performance scores exhibited for each criterion by any alternative, while the less preferred point is derived from the worst performances. This technique is meant to allow for the simultaneous consideration of qualitative and quantitative criteria in the assessment. After SAW, TOPSIS method is the second most popular technique used to deal with MCDM problems (Zavadskas et al., 2016).

The resolution of such MCDM problems in the field of sustainability is usually based on the subjective judgments of several decision makers (DM). To derive the relative relevance of each criterion involved in MCDM assessments related to infrastructure projects based on individual preferences of DMs, Analytic Hierarchy Process (AHP) has been widely used (Ali et al., 2016; Pryn et al., 2015). AHP technique presumes the judgements to be both precise and certain. However, as the complexity of an assessment increases, the ability of individuals to make meaningful and accurate judgments diminishes to the point where both attributes become almost exclusive (Zadeh, 1973). Therefore, traditional AHP, as originally defined by Saaty (Saaty, 1980), has been the subject of strong criticism for not being able to reflect the complex and diffuse nature of human thought (Radwan et al., 2016).

In an attempt to handle the non-probabilistic uncertainties associated with human cognitive information in decision-making problems, the fuzzy sets theory (Zadeh, 1965) has been applied to derive criteria weights using an AHP approach in the field of construction industry (Penadés-Plà et al., 2016), assessing different aspects ranging from pavement maintenance (Moazami et al., 2011) or bridges design (García-Segura et al., 2018) to the selection of construction projects (Prascevic & Prascevic, 2017). MCDM based on fuzzy logic assigns to the emitted judgements a so-called membership grade, which represents to what extent the information provided by the DM is certain or not. Such grade lies between 0 and 1. Fuzzy sets theory successfully incorporates the vagueness of human thinking into mathematical modelling, although only to a certain extent, as it cannot deal with more complex contexts involving incomplete information.

Fuzzy sets theory was further generalized by Atanassov (1986), who introduced the Intuitionistic fuzzy sets (IFSs). IFSs complement the membership grade of fuzzy elements with a non-membership grade. Both grades are dependent on each other, and their sum cannot be greater than 1. Fuzzy sets are considered as a particular case of IFSs where the non-membership grade is equal to zero. IFSs have been applied in a variety of fields, such as the sustainability evaluation of energy technologies (Abdullah & Najib, 2016), supplier selection (Büyüközkan & Ger, 2017), or landfill site selection (Kahraman et al., 2018), among others. However, the dependency between grades associated to IFSs does not allow to mathematically model more complex aspects related to nonprobabilistic uncertainties, such as information inconsistencies or paradoxes.

Neutrosophic sets (NSs) theory has been recently introduced by Smarandache (1999) as a means to fill the modeling gaps still left with the IFSs by further generalizing the IFSs theory. In neutrosophic logic, elements are described by means of three independent properties, namely, indeterminacy, truth and falsity, thus allowing dealing with most cases of linguistic vagueness, inconsistencies and even with paradoxical statements. Although introduced in 1999, it has been only in very recent years that NSs theory has been developed from a practical point of view to deal with real scientific and engineering applications. Consequently, during the last few years, NSs theory has been applied to assess decision making problems, dealing with aspects such as supplier selection (Abdel-Basset et al., 2018; Peng et al., 2017), company investment strategies (Liu & Liu, 2018) or power technology selection (Pamucar et al., 2018).

The construction sector is considered to be one of the main stressors of the economy and environment of a region, but it can contribute in a similar way to its social and economic development. Therefore, proper design and management of infrastructures becomes essential to ensure the sustainability of a country. Given the significant impact that the weightings of the criteria can have on the outcome of MCDM processes, it is essential to capture the maximum information underlying the subjective judgments of DMs in the evaluation of the infrastructures. Although NSs provide a powerful tool for this purpose (Bolturk & Kahraman, 2018), to the best knowledge of the authors, it has not yet been applied to the sustainability assessment of infrastructures. The present paper provides a neutrosophic-based MCDM methodology to be integrated with the ISO-standarised life cycle assessment procedure (ISO, 2006a) applied to the evaluation of the sustainability of structures. In particular, such methodology is applied to assess the sustainability of different design alternatives and maintenance strategies of a concrete bridge in an aggressive environment using TOPSIS technique.

7.2. Materials and methods

7.2.1. Preliminaries on Neutrosophic sets

In this section, some important definitions pertaining to neutrosophic sets theory are introduced, which are required for an adequate understanding of the subsequent sections of the present paper.

Definition 1. (Smarandache, 1999; Ye, 2013) Let X be a non-empty space of points, where $x \in X$. A single-valued neutrosophic set A in X is defined as:

$$\boldsymbol{A} = \{\langle \boldsymbol{x}, \boldsymbol{T_A}(\boldsymbol{x}), \boldsymbol{I_A}(\boldsymbol{x}), \boldsymbol{F_A}(\boldsymbol{x})\rangle | \boldsymbol{x} \in \boldsymbol{X}\} \tag{1}$$

where $T_A(x)$, $F_A(x)$, $I_A(x)$ ∈ [0,1] denote the truth, falsity and the indeterminacy membership degree of the element $x \in X$, respectively. The membership functions are independent and satisfy that:

$$\mathbf{0} < \boldsymbol{T_A}(\boldsymbol{x}) + \boldsymbol{I_A}(\boldsymbol{x}) + \boldsymbol{F_A}(\boldsymbol{x}) < \mathbf{3} \tag{2}$$

Definition 2. (Deli & Şubaş, 2017) A single-valued triangular neutrosophic number $\bar{a}=\langle(a_1,a_2,a_3); t_{\bar{a}}, i_{\bar{a}}, f_{\bar{a}}\rangle$ is defined as a neutrosophic number on the real number set, whose truth, indeterminacy and falsity membership functions are respectively defined as follows:

$$\boldsymbol{\mu_{\bar{a}}}(\boldsymbol{x}) = \begin{cases} \frac{(\boldsymbol{x}-\boldsymbol{a})}{(\boldsymbol{b}-\boldsymbol{a})} \cdot \boldsymbol{t_{\bar{a}}}, \boldsymbol{for}\ \boldsymbol{a} \le \boldsymbol{x} < \boldsymbol{b} \\ \frac{(\boldsymbol{c}-\boldsymbol{x})}{(\boldsymbol{c}-\boldsymbol{b})} \cdot \boldsymbol{t_{\bar{a}}}, \boldsymbol{for}\ \boldsymbol{b} \le \boldsymbol{x} \le \boldsymbol{c} \\ \mathbf{0}, \boldsymbol{otherwise} \end{cases} \tag{3}$$

$$\boldsymbol{\nu_{\bar{a}}}(\boldsymbol{x}) = \begin{cases} \frac{(\boldsymbol{b}-\boldsymbol{x}+\boldsymbol{i_{\bar{a}}}\cdot(\boldsymbol{x}-\boldsymbol{a}))}{(\boldsymbol{b}-\boldsymbol{a})}, \boldsymbol{for}\ \boldsymbol{a} \le \boldsymbol{x} < \boldsymbol{b} \\ \frac{(\boldsymbol{x}-\boldsymbol{b}+\boldsymbol{i_{\bar{a}}}\cdot(\boldsymbol{c}-\boldsymbol{x}))}{(\boldsymbol{c}-\boldsymbol{b})}, \boldsymbol{for}\ \boldsymbol{b} \le \boldsymbol{x} \le \boldsymbol{c} \\ \mathbf{0}, \boldsymbol{otherwise} \end{cases} \tag{4}$$

$$\boldsymbol{\lambda_{\bar{a}}}(\boldsymbol{x}) = \begin{cases} \frac{(\boldsymbol{b}-\boldsymbol{x}+\boldsymbol{f_{\bar{a}}}\cdot(\boldsymbol{x}-\boldsymbol{a}))}{(\boldsymbol{b}-\boldsymbol{a})}, \boldsymbol{for}\ \boldsymbol{a} \le \boldsymbol{x} < \boldsymbol{b} \\ \frac{(\boldsymbol{x}-\boldsymbol{b}+\boldsymbol{f_{\bar{a}}}\cdot(\boldsymbol{c}-\boldsymbol{x}))}{(\boldsymbol{c}-\boldsymbol{b})}, \boldsymbol{for}\ \boldsymbol{b} \le \boldsymbol{x} \le \boldsymbol{c} \\ \mathbf{0}, \boldsymbol{otherwise} \end{cases} \tag{5}$$

Definition 3. (Liang et al., 2018; Ye, 2017) Let $\bar{a}=\langle(a_1,a_2,a_3);\ t_{\bar{a}},\ i_{\bar{a}},\ f_{\bar{a}}\rangle$ and $\bar{b}=\langle(b_1,b_2,b_3);\ t_{\bar{b}},\ i_{\bar{b}}, f_{\bar{b}}\rangle$ be two single-valued triangular neutrosophic numbers. Let k be a real, positive number. Then, the basic arithmetic operations for neutrosophic numbers, based on Kolmogorov's probability axioms, are defined as:

$$\boldsymbol{k\bar{a} = \langle(ka_1, ka_2, ka_3); 1-(1-t_{\bar{a}})^k, (i_{\bar{a}})^k, (f_{\bar{a}})^k\rangle} \tag{6}$$

$$\boldsymbol{\bar{a}^k = \langle\left({a_1}^k, {a_2}^k, {a_3}^k\right); (t_{\bar{a}})^k, 1-(1-i_{\bar{a}})^k, 1-(1-f_{\bar{a}})^k\rangle} \tag{7}$$

$$\boldsymbol{\bar{a}+\bar{b} = \langle(a_1+b_1, a_2+b_2, a_3+b_3); t_{\bar{a}}+t_{\bar{b}}-t_{\bar{a}}t_{\bar{b}}, i_{\bar{a}}i_{\bar{b}}, f_{\bar{a}}f_{\bar{b}}\rangle} \tag{8}$$

$$\boldsymbol{\bar{a}\times\bar{b} = \langle(a_1b_1, a_2b_2, a_3b_3); t_{\bar{a}}t_{\bar{b}}, i_{\bar{a}}+i_{\bar{b}}-i_{\bar{a}}i_{\bar{b}}, f_{\bar{a}}+f_{\bar{b}}-f_{\bar{a}}f_{\bar{b}}\rangle} \tag{9}$$

$$\boldsymbol{\bar{a}\div\bar{b} = \langle\left(\frac{a_1}{b_3}, \frac{a_2}{b_2}, \frac{a_3}{b_1}\right); \frac{t_{\bar{a}}}{t_{\bar{b}}}, \frac{i_{\bar{a}}-i_{\bar{b}}}{1-i_{\bar{b}}}, \frac{f_{\bar{a}}-f_{\bar{b}}}{1-f_{\bar{b}}}\rangle, valid\ if\ t_{\bar{a}}\leq t_{\bar{b}}, i_{\bar{a}}\geq i_{\bar{b}}, f_{\bar{a}}\geq f_{\bar{b}}, t_{\bar{b}}\neq 0, i_{\bar{b}}, f_{\bar{b}}\neq 1} \tag{10}$$

7.2.2. Neutrosophic extension of the analytical hierarchy process

AHP is a well-known decision assessment technique where DMs are required to compare two elements belonging to the same hierarchy level with each other. Such comparison is based on the Saaty's fundamental scale (Saaty, 1980), that expresses how much more important one element is with respect to another one. Consequently, when n elements are compared, the resulting pairwise comparison matrix $A=\{a_{ij}\}$ is square and reciprocal, i.e. $a_{ij}=1/a_{ji}\ \forall i,j\in\{1,\ldots,n\}$. This section presents a neutrosophic extension of the traditional scalar (crisp) AHP technique. The steps of the methodology are presented in Fig. 7.1.

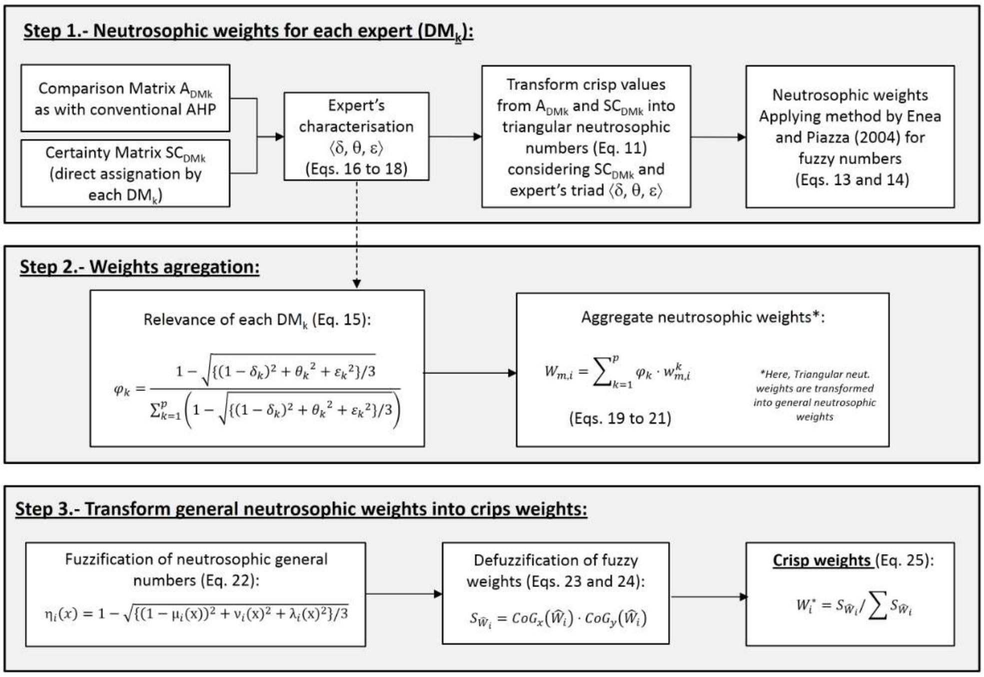


Figure 7.1. Steps of the group neutrosophic AHP methodology

7.2.2.1 *Neutrosophic AHP comparison matrix*

To reflect the vagueness of the judgements emitted by the DMs, triangular neutrosophic numbers (TNN) are considered. Let $\bar{A}=\{\bar{a}_{ij}\}$ represent the neutrosophic pairwise comparison matrix of a DM for n elements with $\bar{a}_{ij}=\langle(l_{ij},m_{ij},u_{ij});\ t_{ij},\ i_{ij},f_{ij}\rangle\ \forall i,j\in\{1,...,n\}$. The reciprocal elements are defined as $\bar{a}_{ji}=1/\bar{a}_{ij}=\langle(1/u_{ij},1/m_{ij},1/l_{ij});\ t_{ij},\ i_{ij},f_{ij}\rangle\ \forall i,j\in\{1,...,n\}$ (Abdel-Basset et al., 2018). For the diagonal elements of Ā it is valid that $\bar{a}_{ii}=\langle(1,1,1);\ 0,0,0\rangle\ \forall i\in\{1,...,n\}$.

The values (l_{ij},m_{ij},u_{ij}) of every judgement are defined according to Saaty's fundamental scale, and range therefore from 1/9 to 9. The center values m_{ij} correspond to the judgments emitted by the DM. These are the values that the conventional crisp AHP technique would consider deriving the weights of each element. Here, the center values m_{ij} are also required to satisfy the consistency check so as defined by Saaty (1980). The lower and upper bounds (l_{ij},u_{ij}) are dependent on the certainty SC_{ij} that the DM has declared in relation to his/her statement a_{ij}, and are calculated as:

$$\boldsymbol{l_{ij}=m_{ij}-\Delta V_{ij};\ u_{ij}=m_{ij}+\Delta V_{ij}} \tag{11}$$

where ΔV_{ij} is the number of steps in the Saaty's scale between the center value m_{ij} and the corresponding extremes (García-Segura et al., 2018). Table 7.1 shows how ΔV_{ij} is defined here, depending on the certainty SC_{ij} verbally expressed by the DM, which can range from 0 to 100%.

Uncertainty in judgement a_{ij} (SC_{ij})	Steps in Saaty's scale (ΔV_{ij})
$SC_{ij} = 1$	0
$0.8 \leq SC_{ij} < 1$	1
$0.6 \leq SC_{ij} < 0.8$	2
$0.4 \leq SC_{ij} < 0.6$	3
$0.2 \leq SC_{ij} < 0.4$	4
$0 < SC_{ij} < 0.2$	5
$SC_{ij} = 0$	6

Table 7.1. Range of triangular numbers in relation to expressed uncertainty

7.2.2.2 *Neutrosophic weights*

According to the conventional AHP technique, the weights of each element are calculated using the eigenvalue method. The weights are then obtained as the normalised components of the eigenvector associated to the largest eigenvalue of the comparison matrix. A rigorous calculation of eigenvalues and eigenvectors in a fuzzy and, by extension, neutrosophic environment is neither evident nor practical (Dubois, 2011). Buckley (1985) introduced an alternative weight evaluation procedure for fuzzy comparison matrices based on the geometric mean method, which has been widely used for fuzzy AHP ever since (Tesfamariam & Sadiq, 2006; Cebeci, 2009). On the basis of the neutrosophic arithmetic, the establishment of which has been recently completed with the introduction of the division operation for neutrosophic sets by Ye (2017), a neutrosophic extension of Buckley's method is proposed here:

$$\bar{\boldsymbol{w}}_{\boldsymbol{i}} = \frac{\left(\prod_{j=1}^{n} \bar{a}_{ij}\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} \bar{a}_{ij}\right)^{1/n}} \tag{12}$$

where $\bar{w}_i$ is the triangular neutrosophic weight of element i, n is the number of elements to be compared, and $\bar{a}_{ij}$ is the neutrosophic comparison value between elements i and j. However, as originally defined, the normalisation procedure of Buckley's method has been shown to be incorrect if the fuzzy AHP matrices are defined according to Saaty's scale, as it results in fuzzy weights with unreasonably high and asymmetrical uncertainty ranges (Wang & Elhag 2006). Enea and Piazza (2004) suggested a method to derive an adequate constrained fuzziness range of weights using a scalar mathematical programming model. The method consists in defining the lower (upper) bound of the fuzzy weight of an element as the lowest (greatest) weight that can be obtained by varying each element of the comparison matrix within its respective bounds. An extension of the fuzzy method by Enea and Piazza (2004) is proposed in the present study to derive constrained truth, falsity and indeterminacy ranges of the resulting neutrosophic weights. So, the upper and lower bounds of the neutrosophic weights are obtained through following scalar mathematical programming models:

$$\boldsymbol{w_{l,i}} = \boldsymbol{min}\left[\frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{kj}\right)^{1/n}}\right] \tag{13}$$

subject to:

$$a_{kj} \in \left[l_{kj}, u_{kj}\right]\ \forall j > k$$

$$a_{jk} = 1/a_{kj}\ \forall j < k$$

$$a_{jj} = 1$$

and

$$\boldsymbol{w_{u,i}} = \boldsymbol{max}\left[\frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{kj}\right)^{1/n}}\right] \tag{14}$$

subject to:

$$a_{kj} \in \left[l_{kj}, u_{kj}\right]\ \forall j > k$$

$$a_{jk} = 1/a_{kj}\ \forall j < k$$

$$a_{jj} = 1$$

where $w_{l,i}$ and $w_{u,i}$ are the lower and upper bound of the weight of the i^{th} element, respectively.

7.2.2.3 *Group N-AHP*

According to Dong et al. (2010), the most widely used methods for estimating priorities in group AHP decision making processes consist of either the aggregation of individual judgements prior the calculation of the weights, or the aggregation of individual priorities. Given the difficulties in obtaining a consistent aggregated comparison matrix from the first method, the aggregation of individual weights is preferred.

For the aggregation, the relevance of each expert involved must be somehow determined. Biswas et al. (2016) propose to characterise each DM with a neutrosophic triad $\bar{E}_k=\langle\delta_k, \theta_k, \varepsilon_k\rangle$, being $\bar{E}_k$ the triad associated with the k^{th} expert. Then, the crisp relevance φ_k of the k^{th} expert is obtained as the normalised Euclidean distance between the point $\bar{E}_k$ and the ideal neutrosophic reliability point $\langle 1,0,0\rangle$:

$$\boldsymbol{\varphi_k} = \frac{1-\sqrt{\{(1-\delta_k)^2+\theta_k{}^2+\varepsilon_k{}^2\}/3}}{\sum_{k=1}^{p}\left(1-\sqrt{\{(1-\delta_k)^2+\theta_k{}^2+\varepsilon_k{}^2\}/3}\right)} \tag{15}$$

where p is the number of experts involved in the decision making problem. The mentioned ideal neutrosophic reliability point stands for an element that is true (T=1), absolutely certain (I=0) and not false (F=0) (Dezert, 2002). Sodenkamp et al. (2018) suggest an explicit way to define the neutrosophic triad introduced by Biswas et al. (2016). According to Sodenkamp et al. (2018), δ_k shall represent the expert's credibility, θ_k the expert's lack of confidence in his/her statements, and ε_k shall represent a measure of the inconsistencies of the expert's judgements. On the basis of the procedure suggested by Sodenkamp et al. (2018), we propose following expressions for determining the relevance of a DM. First, the expert's credibility is based on his/her experience in the fields being assessed (Sierra et al., 2016):

$$\boldsymbol{\delta_k} = \left(\frac{N_k}{\max_{k=1\ldots p}\{N_k\}} + \sum_{i=1}^{4} \boldsymbol{Kc_i}\right)/\mathbf{5} \tag{16}$$

where N_k are the years of professional experience of the k^{th} expert, p is the number of experts involved in the decision making problem, and Kc_i are coefficients defined between 0 and 1 to represent the specific knowledge in the particular fields under consideration. Four coefficients are assumed here to represent the knowledge of the DM in the environmental, economic, social, and design assessment of structures, respectively.

The expert's indeterminacy assessing sustainability is calculated as the mean of the complementary values of the certainties SC_{ij} expressed by the DM for each judgement:

$$\boldsymbol{\theta_k} = \sum_{i,j=1}^{n}(\mathbf{1} - \boldsymbol{SC_{ij}})\,/(\boldsymbol{n}^2) \tag{17}$$

where n is the number of elements to be compared. At last, the expert's incoherency is determined as the consistency of his/her judgements, measured by means of the consistency ratio (CR) of his/her comparison matrix, divided by the minimum consistency allowed in AHP comparison matrices for the number of elements considered:

$$\boldsymbol{\varepsilon_k} = \boldsymbol{CR_k}/\boldsymbol{CR_{lim}} \tag{18}$$

Once the relevance φ_k of each expert has been defined, the neutrosophic weights of each element shall be aggregated as follows:

$$\boldsymbol{W_{m,i}} = \sum_{k=1}^{p} \boldsymbol{\varphi_k} \cdot \boldsymbol{w_{m,i}^k} \tag{19}$$

$$\boldsymbol{W_{l,i}} = \boldsymbol{W_{m,i}} - \boldsymbol{max_{k=1\ldots p}}\{\boldsymbol{w_{m,i}^k} - \boldsymbol{w_{l,i}^k}\} \tag{20}$$

$$\boldsymbol{W_{u,i}} = \boldsymbol{W_{m,i}} + \boldsymbol{max_{k=1\ldots p}}\{\boldsymbol{w_{u,i}^k} - \boldsymbol{w_{m,i}^k}\} \tag{21}$$

where $W_{m,i}$, $W_{l,i}$ and $W_{u,i}$ are the center value, the lower and the upper bound, respectively, of the group aggregated neutrosophic weight of element *i*. It shall be noted that the resulting neutrosophic weights obtained hereby are not triangular, but their truth, falsity and indeterminacy functions ($\mu_i(x)$, $v_i(x)$ and $\lambda_i(x)$, respectively) follow a generalized membership function defined by the aggregation of the individual membership functions of each expert's weight $w_{i,k}$ centered at $W_{m,i}$. The resulting generalized neutrosophic weights are represented as $\bar{W}_i=\langle(W_{l,i},W_{m,i},W_{u,i});\ t_i,\ i_i,\ f_i\rangle$, with $t_i=\sum\varphi_k\cdot t_{ik}$; $i_i=\sum\varphi_k\cdot i_{ik}$ and $f_i=\sum\varphi_k\cdot f_{ik}$ being the maxima of the group aggregated weight membership functions defined within the range $x\in[W_{l,i};\ W_{u,i}]$.

7.2.2.4 *Deneutrosophication technique*

The resulting generalized neutrosophic weights shall be transformed into crisp weights using the deneutrosophication technique defined by Sodenkamp et al. (2018) for single-valued neutrosophic numbers. In this study, the methodology suggested by Sodenkamp et al. (2018) has been extended to handle with multi-valued neutrosophic numbers associated with general defined membership degree functions. This method consists of two steps. Firstly, the neutrosophic weights $\bar{W}_i=\langle(W_{l,i},W_{m,i},W_{u,i});\ t_i,\ i_i,f_i\rangle$ are transformed into generalized fuzzy weights $\hat{W}_i=\langle(W_{l,i},W_{m,i},W_{u,i});\ \eta_i\rangle$. The fuzziness function $\eta_i(x)$ of weight $\hat{W}_i$ is obtained from the Euclidean distance between each point $\langle\mu_i(x),v_i(x),\lambda_i(x)\rangle$ and the ideal neutrosophic estimates reliability point $\langle 1,0,0\rangle$:

$$\eta_i(x) = \mathbf{1} - \sqrt{\{(\mathbf{1}-\boldsymbol{\mu}_i(\mathbf{x}))^2 + \mathbf{v}_i(\mathbf{x})^2 + \boldsymbol{\lambda}_i(\mathbf{x})^2\}/\mathbf{3}}\ \forall\mathbf{x}\in[\ \mathbf{W_{l,i}};\ \mathbf{W_{u,i}}] \tag{22}$$

The second step consists in the defuzzification of the obtained fuzzy weights. The most commonly applied defuzzification technique is the one based on the center of gravity (CoG) of the fuzzy membership function $\eta_i(x)$:

$$\boldsymbol{CoG_x}(\widehat{\boldsymbol{W}}_i) = \frac{\int_{x\in[W_{l,i},W_{u,i}]} x\cdot\eta_i(x)dx}{\int_{x\in[W_{l,i},W_{u,i}]} \eta_i(x)dx} \tag{23}$$

However, such one-dimensional technique is only accurate if the maximum of the fuzzy membership function is equal to unity. When handling with general fuzzy numbers, which are not required to fulfill such condition, a two-dimensional approach is preferable. Chu and Tao (2002) improved this technique for its use on generalized fuzzy numbers by proposing a defuzzification based on the area between the centroid point (x,y) of a fuzzy number and the origin of the considered coordinate system. So, an area index is defined as:

$$\boldsymbol{S}_{\widehat{\boldsymbol{W}}_i} = \boldsymbol{CoG_x}(\widehat{\boldsymbol{W}}_i)\cdot\boldsymbol{CoG_y}(\widehat{\boldsymbol{W}}_i) \tag{24}$$

The synthetical crisp weights of each element *i* can then be obtained by normalising the resulting area indices for each element under consideration:

$$\boldsymbol{W}_i^* = \boldsymbol{S}_{\widehat{\boldsymbol{W}}_i}/\sum\boldsymbol{S}_{\widehat{\boldsymbol{W}}_i} \tag{25}$$

7.3. Sustainability assessment of bridge preventive designs

The present paper is intended to analyse the sustainability of different design options for concrete bridges located in coastal environments from a life cycle perspective. The study considers a particular bridge, namely the bridge of Terrón in Galicia (Spain), as the baseline for the definition of the alternative designs. The bridge is 234m long and has a span distribution of 5x34.5m+3x50m+34.5m. It has a continuous box-girder deck which is 12.0m wide and 2.50m deep (www.copasagroup.com). This baseline design is assumed to have a concrete cover of 40mm, with a passive reinforcement amount of 100kg/m^3 of concrete, as usual for this type of structures (Fomento, 2000). Regarding the reference concrete mix, a cement content of 350kg/m^3 is assumed here, with a water/cement ratio of 0.40 (Spanish Ministry of Public Works, 2008).

The most relevant deterioration mechanism of concrete structures exposed to marine environments is derived from the reinforcement corrosion by chlorides. Thus, on the basis of this baseline design (REF hereafter), different alternatives are proposed so as to increase the durability of the reference design against chlorides. First, two alternative designs are considered that increase the concrete cover to 45 mm and 50 mm (alternatives CC45 and CC50, respectively). To reduce the chloride diffusivity throughout the cover, the water/cement ratio has been reduced from 0.40 to 0.35 (alternative C/W35). An alternative way to increase the resistance of concrete against chloride diffusion is the use of additions. Here, additions of 5% and 10% silica fume (designs SF5 and SF10, respectively), and additions of 10% and 20% fly ash (alternatives FA10 and FA20, respectively) to the baseline concrete are analysed. The addition of polymers, such as styrene butadiene, has shown to be beneficial for the durability performance of concrete in aggressive environments (Yang et al., 2009). Consequently, additions of 10% and 20% of styrene butadiene latex (alternatives PMC10 and PMC20, respectively) to the original concrete mix have also been considered here. At last, the effect of organic corrosion inhibiting additives to the baseline concrete mix has been studied here as well (alternative OCI hereafter).

The durability of concrete structures exposed to chlorides can also be improved by substituting the conventional carbon steel reinforcement with corrosion resistant steels, such as galvanized or stainless steels. Designs based on both types of steel are evaluated here (alternatives GALV and INOX hereafter). To impede the chloride ingress into concrete, surface treatments are often used so as to ensure its isolation from aggressive agents. The present assessment considers hydrophobic and sealant surface treatments, applied periodically to the reference design (alternatives HYDRO and SEAL, respectively). The last type of design option considered in this study consists in the use of cathodic protection of the reinforcing steel bars by impressed current (alternative ICCP).

In total, 16 different options are presented here as alternative design options to the baseline bridge design. Table 7.2 shows the concrete mixes resulting for each design. The sustainability performance of each alternative will depend, among other aspects, on their respective maintenance needs (García-Segura et al., 2018). The following subsections describe how maintenance needs are calculated, as well as how the different life cycle impacts are quantified.

Concrete mix components	REF[1]	W/C35	SF5	SF10	FA10	FA20	PMC10	PMC20	OCI
Cement (kg/m^3)	350.0	350.0	315.0	280.0	339.5	329.0	350.0	350.0	350.0
Water (l/m^3)	140.0	122.5	140.0	140.0	140.0	140.0	140.0	140.0	140.0
Gravel (kg/m^3)	1016.9	1037.0	1016.9	1016.9	1016.9	1016.9	1016.9	1016.9	1016.9
Sand (kg/m^3)	1067.8	1094.9	1098.2	1128.7	1076.9	1086.1	1067.8	1067.8	1067.8
Fly Ash (kg/m^3)					35.0	70.0			
Silica Fume (kg/m^3)			17.5	35.0					
Styrene Butadiene Latex (kg/m^3)							35.0	70.0	
Organic Inhibitor (kg/m^3)									10.5
Plasticiser (kg/m^3)	5.25	7.00	4.73	4.20	5.09	4.94			
f_{ck} (Mpa)	46.5	54.8	46.5	46.5	46.5	46.5	58.1	58.1	58.1
E_c (GPa)	31	32	31	31	31	31	33	33	33

1. Concrete in alternatives CC45, CC50, INOX, GALV, HYDRO, SEAL, and ICCP are based on this reference mix

Table 7.2. Concrete mixes assumed in each design option

7.3.1. Reliability-based maintenance

Reinforcement corrosion in concrete occurs when the concentration of chlorides at the rebars is high enough to trigger this aggressive phenomenon. Such concentration is called the critical chloride content (C_{cr}), and depends mainly on the properties of the reinforcing steel. However, a certain time is needed for the chlorides to penetrate the concrete cover and reach this threshold at the bars. The advance of the chloride front follows a diffusive process that depends on the resistance that the concrete cover opposes to it. To evaluate the time-dependent evolution of the chloride concentration in concrete, a two-dimensional version of the Fickean model proposed in Fib Bulletin 34 (Fib, 2006) is used. Thus, the chloride concentration $C(x,y,t)$ at any depth in both x and y directions and at any time t is given by:

$$\boldsymbol{C(x,y,t) = C_s \cdot \left\{1 - erf\left(\frac{x}{2\sqrt{D_0 \cdot \left(\frac{t_0}{t}\right)^{\alpha} \cdot t}}\right) \cdot erf\left(\frac{y}{2\sqrt{D_0 \cdot \left(\frac{t_0}{t}\right)^{\alpha} \cdot t}}\right)\right\}} \tag{26}$$

where x and y are measured from the exposed concrete surfaces (in mm), t is the time of evaluation (in years), C_s is the surface chloride concentration (in wt%/binder), D_0 is the chloride diffusivity of the concrete cover (mm^2/year), assumed to be homogeneous in space, and *erf*(·) is the Gaussian error function. Given the closeness of the concrete deck under analysis to the sea water level, a surface chloride concentration C_s=3.29% is assumed here (Spanish Ministry of Public Works, 2008). In the present analysis, the reference time t_0 is considered to be t_0=0.0767 years (28 days), and the age factor α is assumed to be 0.5 (Spanish Ministry of Public Works, 2008). The particular values for the durability parameters considered here for each design alternative are based on Navarro et al. (2019) and are presented in Table 7.3.

Design	D_0 (x10^{-12} m^2/s)		C_{cr} (%)		Cover (mm)	
Option	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
REF	8.90	0.90	0.60	0.10	40	2
CC45	8.90	0.90	0.60	0.10	45	2.25
CC50	8.90	0.90	0.60	0.10	50	2.5
W/C35	5.80	0.47	0.60	0.10	40	2
INOX	8.90	0.90	5.00	0.94	40	2
GALV	8.90	0.90	1.20	0.21	40	2
SF5	2.94	0.23	0.60	0.06	40	2
SF10	1.23	0.17	0.60	0.03	40	2
FA10	5.48	0.43	0.60	0.10	40	2
FA20	4.65	0.35	0.60	0.10	40	2
PMC10	6.51	0.55	0.60	0.10	40	2
PMC20	2.71	0.22	0.60	0.10	40	2
HYDRO	6.88	0.60	0.60	0.10	40	2
SEAL	4.33	0.33	0.60	0.10	40	2
OCI	3.55	0.27	0.60	0.10	40	2
ICCP	8.90	0.90	0.60	0.10	40	2

Table 7.3. Durability parameters assumed in each design option

In the present assessment, maintenance operations are envisaged at most when the critical chloride threshold is reached at the outermost reinforcement. At this point, the rebars are still not corroded, and maintenance will basically consist of the replacement of the contaminated cover. However, if preventive maintenance is undertaken, i.e. before C_{cr} is reached at the rebars, only the affected cover depth is substituted. It shall be noted that the nature of some of the alternatives considered here imposes certain limits on the maximum allowed maintenance interval. So, in the design based on impressed current (ICCP), the titanium anode mesh must be replaced at most every 20 years according to manufacturer's specifications. Consequently, if the durability of ICCP results to be greater than 20 years, maintenance will consist only in the demolition of the 15 mm anode cover, the replacement of the titanium mesh, and the regeneration of the concrete cover. In the case of hydrophobic and sealant surface treatments, manufacturers usually require them to be re-applied every 5 years to ensure an adequate isolation level. In that case, the maintenance of the HYDRO and SEAL alternatives will simply consist of the new application of these treatments without the need to replace the cover.

The present assessment intends not only to find the most sustainable design, but its optimal maintenance interval as well. So, the life cycle impacts are quantified for each design considering every possible maintenance interval *t* for which a target failure probability (expressed in terms of a target reliability β_{lim}) is not exceeded:

$$\boldsymbol{\beta(t) = -\Phi^{-1}[p_f(t)] \geq \beta_{lim}} \tag{27}$$

where $\Phi^{-1}(\cdot)$ represents the inverse Gaussian cumulative distribution function. The annual reliability β(t) of a particular design represents its probability of failure p_f at the time of evaluation *t*, and is evaluated by means of Monte Carlo simulations. In particular, 30000 simulations have been needed here so as to get convergent results. Table 7.3 shows the stochastic characterization of the durability parameters assumed in this analysis. In this study, a durability limit state is assumed based on the deterioration mechanism induced by chlorides exposed above. Here, the structure is considered to reach an unacceptable state when the chloride content at the steel rebars exceeds the critical chloride threshold, i.e. $C(x,y,t)>C_{cr}$. Consequently, the limit state function *g* assumed for the evaluation of the reliability index shall be formulated as:

$$\boldsymbol{g = R - S = C_{cr} - C(x,y,t)} \tag{28}$$

where *R* represents the resistance of the structure against the considered deterioration mechanism, and *S* represents the deteriorating action. In this case, the deterioration advance is represented by the chloride concentration in the concrete cover at any time *t*, namely $S=C(x,y,t)$. The resistance of the structure against chloride corrosion of the steel is $R=C_{cr}$. Considering that this failure mode does not compromise the structural integrity of the deck, the limit state assumed here shall be considered as a serviceability limit state. Consequently, a target reliability index β_{lim}=1.30 is assumed here (Nogueira et al., 2012). Given the medium-high relative economic costs associated to bridge deck cover replacement, and given the small consequences of the proposed failure, such target reliability index is in good accordance with the recommendations of standards and codes such as ISO (2015) and JCSS (2001). In this study, it is assumed that each maintenance operation restores the reliability of the deck to its initial state (Stewart et al., 2004). But for the designs based on surface treatments or impressed current, such assumption implies a complete restoration of the contaminated concrete cover depth of the chloride exposed deck surface. By doing so, the appearance of cracks derived from shrinkage-related deformation incompatibilities between a locally applied repair concrete and the existing one is avoided.

7.3.2. Life cycle assessment

The main goal of the present study is first to analyse the life cycle impacts of alternative bridge designs from an economic, environmental and social perspective, and then to apply an MCDM model to evaluate and compare the resulting sustainability of each of these designs. According to ISO 14040 (ISO, 2006a), a rigorous life cycle assessment requires an adequate functional unit to be defined, and the system boundaries, the impact assessment techniques and the impact inventories to be clearly presented. Following sub-sections are intended for that purpose.

7.3.2.1 *Functional unit*

Both the economic, the environmental and the social life cycle assessments (LCCA, LCA and SLCA, respectively) must be based on the same functional unit in order to compare the results. The functional unit considered in this analysis is a 1m long section of a 12 m wide concrete bridge deck providing vehicular and pedestrian connection between Vilanova de Arousa and the Southern sector of the village on the other side of the existing estuary, including the construction and maintenance works required to guarantee a service life of the structure of 100 years. The baseline design is assumed to provide the described functionality.

The alternative designs shall not only result in the same service life as the reference option, but shall present the same structural behavior as well. As some of the alternatives have greater stiffness values than that of the baseline design, the deck depth in those cases has been modified so that the resulting structural behavior under ultimate and serviceability limit states matches the response of the reference design (Navarro et al., 2019). Consequently, the design W/C35 has resulted in a structural deck depth of 2.437 m, and the options PMC10 and PMC20 in a depth of 2.416 m.

7.3.2.2 *System boundaries*

The system under analysis covers from the production of the different construction materials in their respective production centres up to the end of the service life of the bridge, where the structure is supposed to be demolished. So, a "gate-to-grave" approach has been followed, considering the impacts derived from the materials production involved both in the construction phase and during the maintenance phase, from the transport activities held, as well as from the specific construction and maintenance activities undertaken at the structure location. As a cut-off criterion, and considering the comparison-oriented scope of the present assessment, processes identical and common to every alternative have been excluded from the system definition (Martínez-Blanco et al., 2014). Consequently, the activities related to the execution and maintenance of the road pavement, the bridge piers, the tendons prestressing or the wall parapets of the deck have been excluded. Fig. 7.2 summarises the system boundaries considered in this assessment.

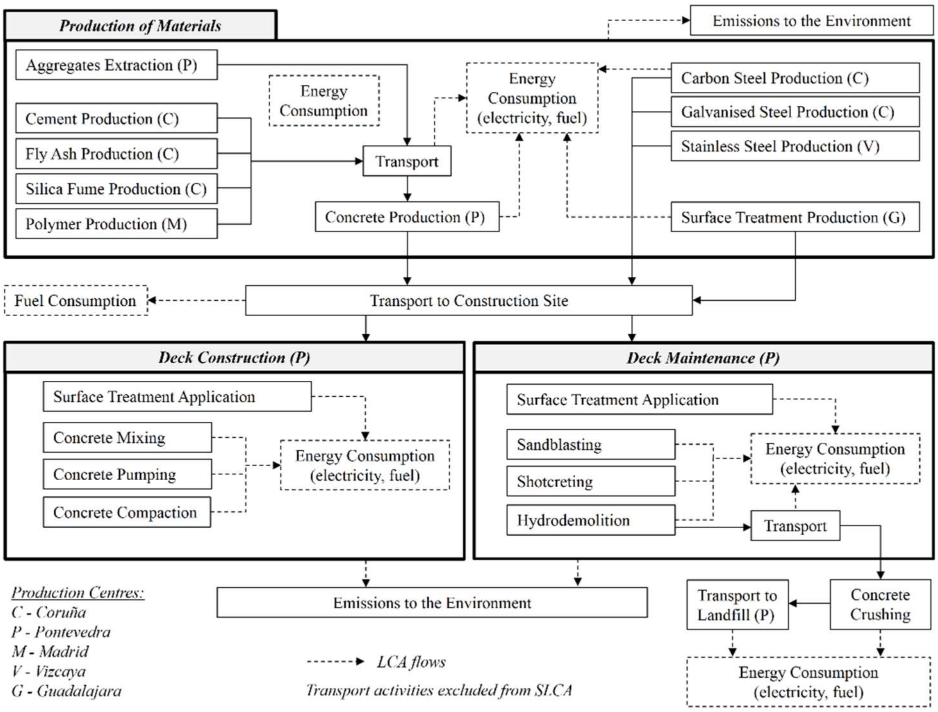


Figure 7.2. System boundaries considered in the sustainability assessment

7.3.2.3 *Impact assessment*

The assessment of the environmental life cycle impacts follows the ReCiPe 2008 methodology (Goedkoop et al., 2009). This method allows for the conversion of 18 midpoint indicators into 3 endpoint indicators, namely damage to human health, depletion of natural resources, and damage to ecosystems. Further information on the environmental assessment can be found in Navarro et al. (2019).

Regarding the economic impacts, no assessment phase exists as such, as all the impacts are expressed in the same unit of measure and no normalization of the inventory data is required (Swarr et al., 2011). Here, two different economic impact categories are identified, namely the costs associated with the construction of the structure, and the discounted costs derived from the different maintenance needs in which the design incurs throughout its service life. There is no consensus on which discount rate is more appropriate to choose when assessing the life cycle costs of a particular product, in this case a structure. High discount rates, which are usually preferred from a private perspective, emphasize costs in the near future, almost neglecting future expenses. Such approach is not consistent with the definition of sustainability. According to the definition of sustainable development first established in 1987 by the Brundtland Commission, sustainability seeks to ensure the satisfaction of present needs without compromising the capacity of future generations to satisfy their own (WCED, 1987). Consequently, so as to give relevance to future expenses that will burden coming generations, a lower, social discount rate of 2% (Allacker, 2012) has been chosen for the present sustainability-oriented assessment.

At last, social impacts are assessed following the indicator-based methodology proposed by Navarro et al. (2018b) for bridge structures. This methodology considers four impact categories to evaluate the effects that the construction and maintenance activities have on different stakeholders. The first impact category includes the workers involved both in the material production and in the installation and maintenance activities. Gender discrimination levels, the unemployment rates and the salaries of the particular regions, as well as the safety level at the particular working places are considered here as sub-categories. The second category comprises the users of the infrastructure and considers how maintenance affects the accessibility and safety of the users. The third category evaluates the public opinion of the local community towards infrastructure. In particular, it takes into consideration how maintenance works alter the aesthetics of the construction site, as well as the impacts derived from the noise or vibration problems resulting from such works. Finally, this assessment method considers the effects that the alternative designs have on the economic development of the regions included in the product system of each option. This methodology considers as activity variables the working time and the economic flows in each region within the system boundaries (UNEP/SETAC, 2009). It shall be noted that the impact categories to be considered in a SLCA depend on the social context of the structure under evaluation. Given the geographical proximity of the structure to be assessed here and the bridge analysed by Navarro et al. (2018b), the same social impact categories have been assumed.

In summary, 9 different impact categories are considered for the present sustainability assessment: damage to human health, damage to the ecosystems and the natural resources depletion, the construction and maintenance costs, and the social impacts on workers, on infrastructure users, on local communities and on the economic development of the regions. Impact categories are considered as decision criteria in the present MCDM assessment. Table 7.4 summarises the decision criteria assumed here. A sustainability indicator is then obtained by applying TOPSIS MCDM technique taking into consideration the criteria weights resulting after applying the exposed neutrosophic group AHP technique.

Sustainability Field	Criterion Id.	Criterion description
Economy	1	Construction Costs
	2	Maintenance and EOL Costs
Environment	3	Damage to Human Health
	4	Damage to Ecosystem

	5	Damage to Resource Availability
Society	6	Workers
	7	Economic development
	8	Consumer
	9	Local Community

Table 7.4. Criteria considered in the present sustainability MCDM assessment

7.3.2.4 *Inventory analysis*

The inventory data relevant for the environmental characterization of the different activities to be assessed have been gathered from the database Ecoinvent 3.2. This information has been complemented with the performance values and energy consumption rates of the different production activities presented in Table 7.5.

Activity	Performance	Energy Demand/Machine Power
Concrete mixing	7.2 min/m^3	75 kW
Galvanization[1]		0.3 kWh/kg
Emulsion mixing[1]		0.025 kWh/kg
Hydrophobic surface treating	120 l/h	1.3 kW
Cathodic protection[1]		0.4 kWh/m^2/year
Cover hidrodemolition	0.6 m^3/h	0.75 kW
Reinforcement sandblasting	13.2 m^2/h	2.27 l fuel/h
Shotcreting	18 m^3/h	26.5 kW

1. Where activity performance is not given, energy demand is provided per unit of product output

Table 7.5. Life cycle inventory data regarding activity processes

The transport distances existing between the assumed material production sites and the structure location are shown in Table 7.6. The assessment of the transport impacts is based on the premise that when the transport distance exceeds 100 km, 80% of the route is done by freight train. The environmental impacts associated to industry by-products, such as fly ash or silica fume, have been allocated economically according to Chen et al. (2010). For the environmental assessment, it has been assumed that the demolished concrete resulting from both the maintenance activities as well as from the demolition of the structure itself is recycled to serve as embankment protection. The present analysis accounts for the environmental effect of the atmospheric CO_2 uptake resulting from the carbonation of this concrete. More detailed information on the environmental inventory data can be found in the studies by Navarro et al. (2018c, 2019).

Production process	Transport distance (km)
Aggregates	14[1]

Portland cement	12[1]
Fly ash	101[1]
Silica fume	93.1[1]
Styrene butadiene latex, Plasticiser	649[1]
Organic inhibitor	632[1]
Concrete	13.3[2]
Carbon and Galvanised steel	147[2]
Stainless steel	640[2]
Hydrophobic and sealant treatments	708[2]
Cathodic protection	650[2]
Landfill	20

1. Distance to concrete production facility

2. Distance to installation site

Table 7.6. Inventory data regarding transport activities

As regards the economic inventory, data on the costs concerning construction materials and activities have been obtained from national construction specific databases. The unitary costs considered for each foreground concept are presented in Table 7.7. These costs are updated in 2019 and include the indirect costs of each background process along each product's life cycle (Martínez-Blanco et al., 2014), such as those associated with raw materials extraction, energy consumption or transportation activities.

Product	Steel Prod.	Cement Prod.	Concrete Prod.	Additives Prod.	Surf. treat. Prod.	Cathodic System Prod.	Installation	
	(Coruña)	(Coruña)	(Pontevedra)	(Madrid)	(Guadalajara)	(Madrid)	(Pontevedra)	
HA-30 (REF)		30.72	31.69				31.56	€/m^3
HA-30 (W/C35)		30.72	32.38				36.68	€/m^3
HA-30 (FA10)		44.75	33.15				31.34	€/m^3
HA-30 (FA20)		43.37	34.61				31.12	€/m^3
HA-30 (SF5)		41.52	52.07				42.43	€/m^3
HA-30 (SF10)		36.91	72.44				30.11	€/m^3
HA-30 (HMP10)		46.14	31.69	173.55			24.33	€/m^3
HA-30 (HMP20)		46.14	31.69	347.10			24.33	€/m^3
HA-30 (OCI)		30.72	31.69	70.60			31.56	€/m^3
Carbon steel	0.86						0.38	€/kg
Stainless steel	4.86						0.38	€/kg

Galvanised steel	3.24			0.38	€/kg
Hydrophobic treatment		2.87		1.62	€/m^2
Sealant treatment		14.13		1.62	€/m^2
Impressed current system			37.10	26.44	€/m^2
40 mm cover Hydrodemolition				27.68	€/m^2
Sandblasting and reinforcement priming				16.02	€/m^2

Table 7.7. Economic flows per output unit

To properly characterise the social context of each activity location, data have been gathered from national statistical databases, in particular from the Spanish Tax Office and the Spanish National Statistics Institute. Given the long-term perspective of the present assessment, the expected values for each social parameter have been obtained from the analysis of the historical series of the gathered data. Table 7.8 presents the expected values of each social parameter in terms of most probable, maximum and minimum.

Social background data	Pontevedra	A Coruña	Vizcaya	Madrid	Guadalajara
Unemployment rate (%)	(7.5-16.8-25.8)	(6.8-13.9-21.7)	(6.6-12.5-18.9)	(5.9-12.4-20.5)	(3.3-14-24.9)
Men unemployment (%)	(5.7-15-26.1)	(4.7-12.5-22.8)	(4.9-11.8-19.8)	(3.9-11.6-20)	(2.2-12.2-24.2)
Women unemployment (%)	(8.3-19.1-26.4)	(8.5-15.8-22.2)	(7.7-13.4-18.7)	(6.8-13.3-21.9)	(3.7-16.7-29.1)
Salary (x10^3 €/year)	(18-19.6-20.6)[1]; (13.1-14.3-14.9)[2]	(18-19.6-20.6)	(19.7-20.3-21.6)	(27.9-32-34.6)	(21.4-23.6-25)
Men salary (x10^3€/year)	(17.8-18.8-19.6)	(19.8-20.9-21.7)	(26.6-28.2-29.5)	(26.6-27.4-28)	(20.6-21.9-22.7)
Women salary (x10^3€/year)	(13.6-14.2-14.8)	(15.2-15.9-16.5)	(19.3-20.1-21.1)	(19.3-20.1-20.8)	(15.7-16-16.3)
Mean region salary (x10^3€/year)	(16.1-16.7-17.3)	(17.9-18.6-19.2)	(23.6-24.6-25.7)	(23.3-24-24.5)	(18.7-19.4-19.6)
Accident rate (accidents/1.000 employees)	(55-84-116)[2]; (44-76-133)[3]	(65-95-142)[4]; (47-73-114)[3]	(67-94-156)[4]	(23-33-50)[5]	(39-54-84)[5]

Maximum national accident rate (accidents/1.000 employees)	(84-111-156)[2]; (67-100-180)[3]	(92-129-220)[4]; (67-100-180)[3]	(92-129-220)[4]	(40-55-85)[5]	(40-55-85)[5]
Minimum national accident rate (accidents/1.000 employees)	(43-60-81)[2]; (34-54-90)[3]	(47-70-112)[4]; (34-54-90)[3]	(47-70-112)[4]	(20-29-45)[5]	(20-29-45)[5]
Gross Domestic Product ($x10^6$ €)	(2429-3210-4316)[1]; (1136-1562-2126)[2]	(1773-2695-3351)[1]	(3986-4908-5603)[1]	(13121-14030-15082)[1]	(529-872-1071)[1]

1. Industry sector; 2. Construction sector; 3. Extraction industry; 4. Metallurgic industry; 5. Chemical industry

Table 7.8. Expected social inventory data of each production location, based on Navarro et al. (2018b)

From these values, a Beta-PERT distribution is assigned to each social indicator to quantify its expected variability over time (Navarro et al., 2018b). To evaluate the working time related to material production and construction/maintenance activities, data have been gathered from both local companies and official construction databases provided by Spanish regional governments. The considered performance values are shown in Table 7.9. To evaluate the regional economic development, the regional economic flows presented in Table 7 have been used.

Activity	Unitary working time
Cement production	0.17 h/tn
Aggregates extraction	0.19 h/tn
Concrete production	0.18 h/tn
Hydro. treatment production	0.05 h/m^2
Seal. treatment production	0.07 h/m^2
Polymer production	0.03 h/l
Inhibitor production	0.04 h/kg
Carbon steel production	0.41 h/tn
Galvanised steel production	0.41 h/tn
Stainless steel production	4.90 h/tn
Concreting	0.35 h/m^3
Steel disposal	0.02 h/kg
Concrete surface treatment	0.11 h/m^2

Steel surface treatment	0.12 h/m^2
40 mm cover demolition	0.36 h/m^2
40 mm cover repair	1.12 h/m^2

Table 7.9. Working time performance of each activity

7.4. Results and discussion

7.4.1. Neutrosophic Group AHP results

The present section shows the results of the neutrosophic group weighting method exposed in Section 2.2.2. In particular, a group of three experts has been consulted. Each of them has been required to make pairwise comparisons regarding the nine decision criteria defined above. Was the resulting comparison matrix not consistent, the DM was required to repeat the process until the resulting matrix consistency ratio fell below 0.10. The comparison matrices A_{DMi} for each DM are presented below. It shall be noted that each element a_{jk} of these matrices represents the judgement emitted by the decision maker DM$_i$ when comparing the decision criterion j with the criterion k. The identification number assigned to each criterion follows the criterion Id presented in Table 7.4.

The comparison matrix of the first decision maker A_{DM1} is shown below. The matrix containing the certainty expressed by the expert on each of his/her judgements SC_{DM1} is also presented. As with the comparison matrices, each element sc_{jk} of the certainty matrices represent the certainty expressed by the decision maker DM$_i$ when comparing criterion j and criterion k, according to Table 7.4.

$$A_{DM1} = \begin{bmatrix} 1 & 1/3 & 1/6 & 1/6 & 1/6 & 1/3 & 1/4 & 1/4 & 1/4 \\ 3 & 1 & 1/2 & 1/5 & 1/4 & 1/2 & 3 & 1/2 & 1/2 \\ 6 & 2 & 1 & 1 & 1/2 & 3 & 7 & 6 & 6 \\ 6 & 5 & 1 & 1 & 1/2 & 3 & 7 & 6 & 6 \\ 6 & 4 & 2 & 2 & 1 & 2 & 6 & 5 & 5 \\ 3 & 2 & 1/3 & 1/3 & 1/2 & 1 & 2 & 1/2 & 1/2 \\ 4 & 1/3 & 1/7 & 1/7 & 1/6 & 1/2 & 1 & 1/2 & 1/2 \\ 4 & 2 & 1/6 & 1/6 & 1/5 & 2 & 2 & 1 & 1 \\ 4 & 2 & 1/6 & 1/6 & 1/5 & 2 & 2 & 1 & 1 \end{bmatrix}$$

$$SC_{DM1} = \begin{bmatrix} 1 & 0.8 & 0.5 & 0.7 & 0.9 & 0.8 & 0.8 & 0.6 & 0.2 \\ 0.8 & 1 & 0.7 & 0.8 & 0.6 & 0.6 & 0.4 & 0.7 & 0.7 \\ 0.5 & 0.7 & 1 & 0.8 & 0.8 & 0.7 & 0.8 & 0.7 & 0.6 \\ 0.7 & 0.8 & 0.8 & 1 & 0.8 & 0.3 & 0.4 & 0.5 & 0.6 \\ 0.9 & 0.6 & 0.8 & 0.8 & 1 & 0.2 & 0.7 & 0.6 & 0.4 \\ 0.8 & 0.6 & 0.7 & 0.3 & 0.2 & 1 & 0.8 & 0.8 & 0.4 \\ 0.8 & 0.4 & 0.8 & 0.4 & 0.7 & 0.8 & 1 & 0.5 & 0.5 \\ 0.6 & 0.7 & 0.7 & 0.5 & 0.6 & 0.8 & 0.5 & 1 & 0.4 \\ 0.2 & 0.7 & 0.6 & 0.6 & 0.4 & 0.4 & 0.5 & 0.4 & 1 \end{bmatrix}$$

The comparison matrix and certainty matrix of the second expert are presented below:

$$A_{DM2} = \begin{bmatrix} 1 & 3 & 1/3 & 1/3 & 1/5 & 7 & 7 & 5 & 9 \\ 1/3 & 1 & 1/3 & 1/3 & 1/5 & 7 & 7 & 1/3 & 3 \\ 3 & 3 & 1 & 1 & 1/2 & 7 & 5 & 5 & 9 \\ 3 & 3 & 1 & 1 & 1/3 & 7 & 5 & 5 & 9 \\ 5 & 5 & 2 & 3 & 1 & 7 & 7 & 5 & 7 \\ 1/7 & 1/7 & 1/7 & 1/7 & 1/7 & 1 & 1 & 1/2 & 1/2 \\ 1/7 & 1/7 & 1/5 & 1/5 & 1/7 & 1 & 1 & 1/2 & 1/2 \\ 1/5 & 3 & 1/5 & 1/5 & 1/5 & 2 & 2 & 1 & 1 \\ 1/9 & 1/3 & 1/9 & 1/9 & 1/7 & 2 & 2 & 1 & 1 \end{bmatrix}$$

$$SC_{DM2} = \begin{bmatrix} 1 & 0.7 & 0.6 & 0.6 & 0.6 & 0.8 & 0.8 & 0.8 & 0.9 \\ 0.7 & 1 & 0.5 & 0.5 & 0.6 & 0.8 & 0.9 & 0.4 & 0.8 \\ 0.6 & 0.5 & 1 & 0.4 & 0.4 & 0.7 & 0.6 & 0.6 & 0.8 \\ 0.6 & 0.5 & 0.4 & 1 & 0.7 & 0.7 & 0.7 & 0.7 & 0.9 \\ 0.6 & 0.6 & 0.4 & 0.7 & 1 & 0.8 & 0.8 & 0.7 & 0.8 \\ 0.8 & 0.8 & 0.7 & 0.7 & 0.8 & 1 & 0.6 & 0.6 & 0.6 \\ 0.8 & 0.9 & 0.6 & 0.7 & 0.8 & 0.6 & 1 & 0.7 & 0.8 \\ 0.8 & 0.4 & 0.6 & 0.7 & 0.7 & 0.6 & 0.7 & 1 & 0.8 \\ 0.9 & 0.8 & 0.8 & 0.9 & 0.8 & 0.6 & 0.8 & 0.8 & 1 \end{bmatrix}$$

At last, the comparison and the certainty matrices of the third DM are presented below:

$$A_{DM3} = \begin{bmatrix} 1 & 6 & 1/5 & 1/6 & 1/5 & 4 & 1 & 1/4 & 1/3 \\ 1/6 & 1 & 1/7 & 1/7 & 1/6 & 1/3 & 1/3 & 1/6 & 1/7 \\ 5 & 7 & 1 & 1/2 & 1 & 5 & 5 & 2 & 2 \\ 6 & 7 & 2 & 1 & 1 & 7 & 6 & 2 & 5 \\ 5 & 6 & 1 & 1 & 1 & 5 & 4 & 1 & 1 \\ 1/4 & 3 & 1/5 & 1/7 & 1/5 & 1 & 1/4 & 1/6 & 1/6 \\ 1 & 3 & 1/5 & 1/6 & 1/4 & 4 & 1 & 1/5 & 1/3 \\ 4 & 6 & 1/2 & 1/2 & 1 & 1/6 & 5 & 1 & 2 \\ 3 & 7 & 1/2 & 1/5 & 1 & 6 & 3 & 1/2 & 1 \end{bmatrix}$$

$$SC_{DM3} = \begin{bmatrix} 1 & 0.8 & 0.8 & 0.9 & 0.9 & 0.6 & 0.6 & 0.7 & 0.2 \\ 0.8 & 1 & 0.8 & 0.9 & 0.9 & 0.7 & 0.7 & 0.8 & 0.2 \\ 0.8 & 0.8 & 1 & 0.7 & 0.8 & 0.7 & 0.5 & 0.5 & 0.5 \\ 0.9 & 0.9 & 0.7 & 1 & 0.9 & 0.8 & 0.8 & 0.9 & 0.9 \\ 0.9 & 0.9 & 0.8 & 0.9 & 1 & 0.7 & 0.7 & 0.7 & 0.9 \\ 0.6 & 0.7 & 0.7 & 0.8 & 0.7 & 1 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.7 & 0.5 & 0.8 & 0.7 & 0.8 & 1 & 0.5 & 0.5 \\ 0.7 & 0.8 & 0.5 & 0.9 & 0.7 & 0.8 & 0.5 & 1 & 0.6 \\ 0.2 & 0.2 & 0.5 & 0.9 & 0.9 & 0.8 & 0.5 & 0.6 & 1 \end{bmatrix}$$

From the crisp AHP comparison matrices and their associated certainty matrices, the triangular neutrosophic weights resulting from the judgements of each DM for each criterion are evaluated following the methodological steps presented in Fig. 7.1. The results are presented in Table 7.10.

Criterion	Decision Maker 1	Decision Maker 2	Decision Maker 3
C1-Construction costs	⟨(0.01,0.02,0.07); 0.68,0.35,0.67⟩	⟨(0.06,0.13,0.34); 0.86,0.26,0.86⟩	⟨(0.02,0.05,0.15); 0.74,0.33,0.55⟩
C2-Service life costs	⟨(0.02,0.05,0.24); 0.68,0.32,0.67⟩	⟨(0.03,0.07,0.27); 0.86,0.34,0.86⟩	⟨(0.01,0.02,0.05); 0.74,0.30,0.55⟩
C3-Damage to human health	⟨(0.07,0.21,0.60); 0.68,0.28,0.67⟩	⟨(0.06,0.20,0.63); 0.86,0.40,0.86⟩	⟨(0.05,0.18,0.56); 0.74,0.32,0.55⟩
C4-Damage to ecosystem	⟨(0.07,0.23,0.66); 0.68,0.38,0.67⟩	⟨(0.06,0.19,0.55); 0.86,0.33,0.86⟩	⟨(0.10,0.25,0.59); 0.74,0.14,0.55⟩
C5-Damage to resource availability	⟨(0.07,0.25,0.72); 0.68,0.39,0.67⟩	⟨(0.11,0.30,0.71); 0.86,0.31,0.86⟩	⟨(0.06,0.16,0.46); 0.74,0.17,0.55⟩
C6-Workers	⟨(0.02,0.07,0.36); 0.68,0.44,0.67⟩	⟨(0.01,0.02,0.07); 0.86,0.28,0.86⟩	⟨(0.01,0.02,0.06); 0.74,0.24,0.55⟩
C7-Regional economic development	⟨(0.01,0.04,0.15); 0.68,0.38,0.67⟩	⟨(0.10,0.02,0.07); 0.86,0.24,0.86⟩	⟨(0.02,0.05,0.16); 0.74,0.34,0.55⟩
C8-Users	⟨(0.02,0.07,0.23); 0.68,0.38,0.67⟩	⟨(0.01,0.05,0.14); 0.86,0.32,0.86⟩	⟨(0.05,0.15,0.49); 0.74,0.30,0.55⟩
C9-Public opinion	⟨(0.01,0.07,0.26); 0.68,0.51,0.67⟩	⟨(0.01,0.03,0.07); 0.86,0.18,0.86⟩	⟨(0.03,0.11,0.38); 0.74,0.46,0.55⟩

Table 7.10. Triangular neutrosophic weights according to each expert's judgements

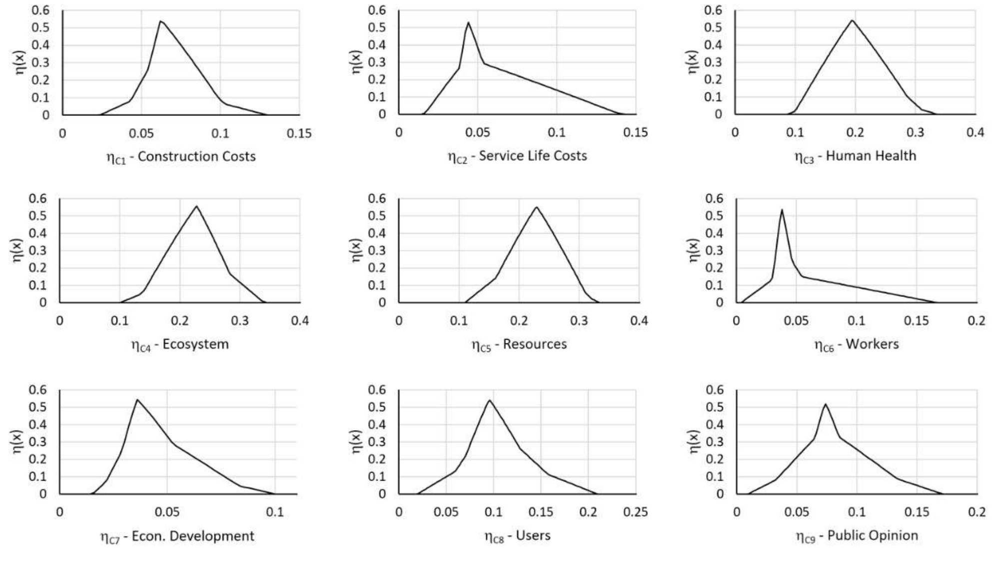
To evaluate the relevance of each DM in the sustainability assessment, the credibility δ, indeterminacy θ and incoherency ε parameters of each of them shall be quantified according to the methodology proposed in Section 2.2.3. Table 7.11 presents the profile characterization of each expert, as well as their associated assessment relevance ϕ.

Expert's profile characterisation	Decision Maker 1	Decision Maker 2	Decision Maker 3
Years of professional experience	5	19	15
Specific knowledge in structural design	0.6	1	1

Specific knowledge in environmental projects assessment	1	0.4	0.8
Specific knowledge in social projects assessment	0.8	0.8	0.4
Specific knowledge in economic projects assessment	0.6	1	0.6
Expert's credibility δ	0.653	0.84	0.718
Expert's mean self confidence	0.657	0.721	0.741
Expert's mean indeterminacy θ	0.343	0.279	0.259
Comparison matrix consistency ratio	0.072	0.096	0.059
Expert's incoherency ε	0.722	0.959	0.595
Expert's assessment relevance ϕ	0.330	0.277	0.393

Table 7.11. Characterisation of the panel of experts

The individual neutrosophic weights resulting from the judgements of each DM are then aggregated considering the particular expert's assessment relevance following the described aggregation methodology. Fig. 7.3 shows the resulting fuzzy weights after the deneutrosophication process of the aggregated weights. Finally, Fig. 7.3 also presents the crisp weight of each criterion after applying the defuzzification method proposed by Chu (2002) for generalized fuzzy numbers.



Resulting crips weights after defuzzification:

W^*_{C1}	W^*_{C2}	W^*_{C3}	W^*_{C4}	W^*_{C5}	W^*_{C6}	W^*_{C7}	W^*_{C8}	W^*_{C9}
0.061	0.045	0.188	0.225	0.224	0.039	0.036	0.0930	0.089

Figure 7.3. Aggregated weights deneutrosophication results and defuzzified crisp weights

7.4.2. LCCA results

Here, the life cycle economic impacts of each design alternative are analysed, namely the construction and the discounted maintenance costs. It shall be noted that, for the good of the analysis, the results shown here consist in the aggregation of both criteria into a single economic score considering the crisp weights obtained above. Fig. 7.4 shows the results for the particular maintenance intervals that lead to the lowest life cycle costs for each option.

From the results, it is derived that the design that leads to the greatest economic impact is the baseline option (REF). It can be observed that in the case of those designs that incur the highest costs of the life cycle (REF, GALV, CC50, CC45, PMC10), the impact of the maintenance phase is quite significant, being in some cases up to 3.8 times greater than the construction costs (REF, CC45, CC50). But for the case of GALV, such results shall be explained by the fact that alternatives REF, CC45, CC50 and PMC10 are present worst durability performance. This dependence on the durability and the resulting life cycle costs was reported by García-Segura et al. (2017). However, it is observed that solutions with very low maintenance costs, such as INOX or PMC20 do not necessarily lead to the best economic performances, as they require significant construction costs.

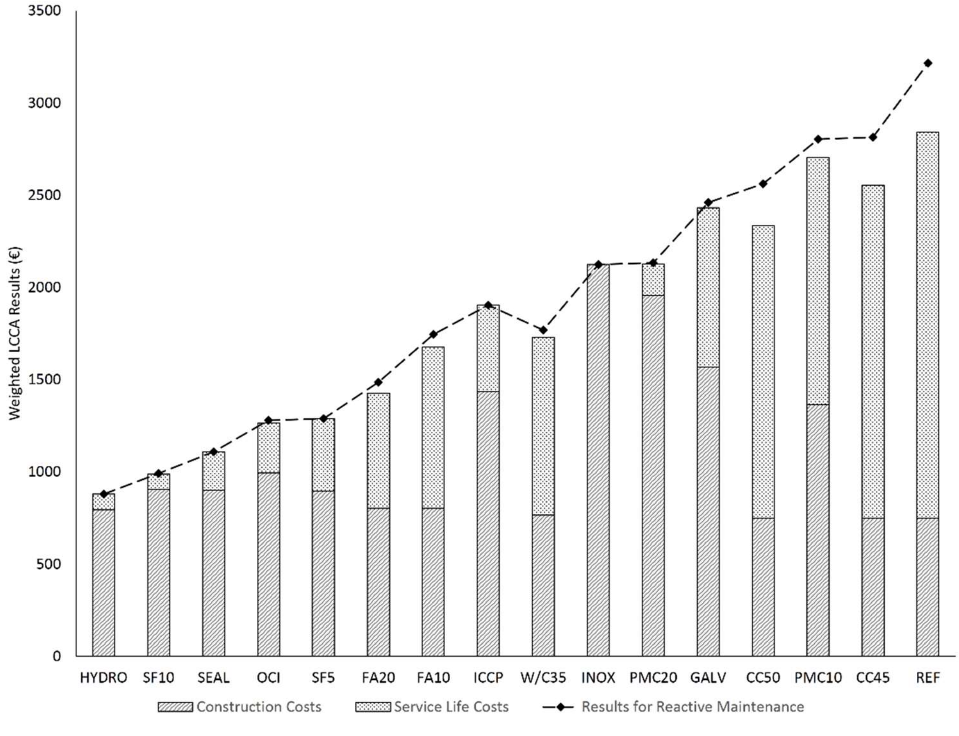


Figure 7.4. Economic life cycle assessment results

Here, alternatives based on surface treatments (HYDRO and SEAL), and the design option based on silica fume addition SF10, have resulted in the lowest life cycle costs. Their economic scores range from 30.9% to 39.0% of the weighted economic impact associated to the baseline design. It is interesting to note that, contrarily to what is expected for such good economic results, the surface treatments require almost the greatest maintenance, at least every 5 years. However, the reduced construction costs, together with the low repair costs, explain the obtained competitive performance of these options. On the other hand, the good performance of SF10 relies on its low construction costs, as well as on the great durability of this type of concrete, as previously reported by Navarro et al. (2018a, 2019).

Fig. 7.4 includes the LCCA results when reactive maintenance is assumed. Here, the differences between preventive and reactive maintenance strategies are not greater than 13% in the worst case (alternative REF). Alternatives with long spanning maintenance intervals, or those with very competitive maintenance costs, such as options based on surface treatments, show very slight differences with respect to preventive maintenance.

7.4.3. LCA results

Fig. 7.5 shows the results regarding the three environmental categories considered in the present assessment. Only the results of the best maintenance strategy for each option are shown. Again, the presented results are aggregated according to the crisp weights resulting from the neutrosophic AHP exposed above. Surface treatments and the silica fume option provide the best environmental performance. This agrees with Petcherdchoo (2015), who already reported that surface treatments are much more preferable from an environmental point of view than other designs in which the concrete cover has to be replaced periodically. This is due to the machinery with lower energy demand involved in the re-application of surface treatments. In addition, the design based on cathodic protection has also yielded a very good environmental response. These four design options have resulted in life cycle environmental impacts that range from 24.2% to 31.1% of the impact of the reference design. On the contrary, the worst environmental performances are those of the baseline design and the option based on stainless steel reinforcement. Such result confirms the relevant environmental burdens associated with the use of stainless steel in concrete reported by Mistry et al. (2016).

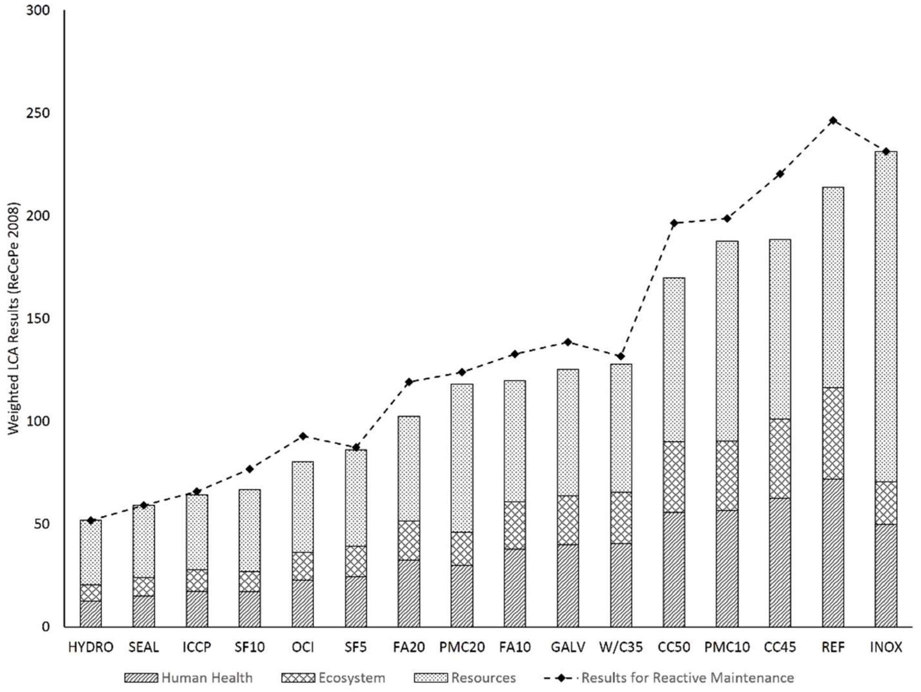


Figure 7.5. Environmental life cycle assessment results

Fig. 7.5 includes LCA scores for each design alternative considering reactive maintenance strategies. Here, reactive maintenance may lead to environmental impacts up to 17% greater than those of a properly chosen preventive strategy. Such is the case of design options CC45, FA20, OCI or REF.

7.4.4. SLCA results

Fig. 7.6 shows the social life cycle impact criteria of each design aggregated according to the obtained AHP weights. According to the resulting social scores, alternatives INOX, SF10 and PMC20 are by far the most preferable options. It shall be noted that these are alternatives with very low maintenance requirements due to their high durability. In consequence, the negative impacts on the local community and infrastructure users derived from maintenance works are reduced to nearly zero. In view of the resulting weights derived from the judgements of the panel of experts, these two stakeholders are almost three times more relevant from the point of view of sustainability than the workers or the regional economies. Therefore, those alternatives with greater maintenance demands that could be more beneficial to workers or could generate more economic flows are prejudiced against those that clearly benefit the users or the public opinion by reducing maintenance needs (Navarro et al., 2018b). Alternatives INOX, SF10 and PMC20 show social scores that are 5.62, 5.38 and 4.97 times higher than those of the reference design, respectively. In social terms, the option that performs the worst is the baseline design.

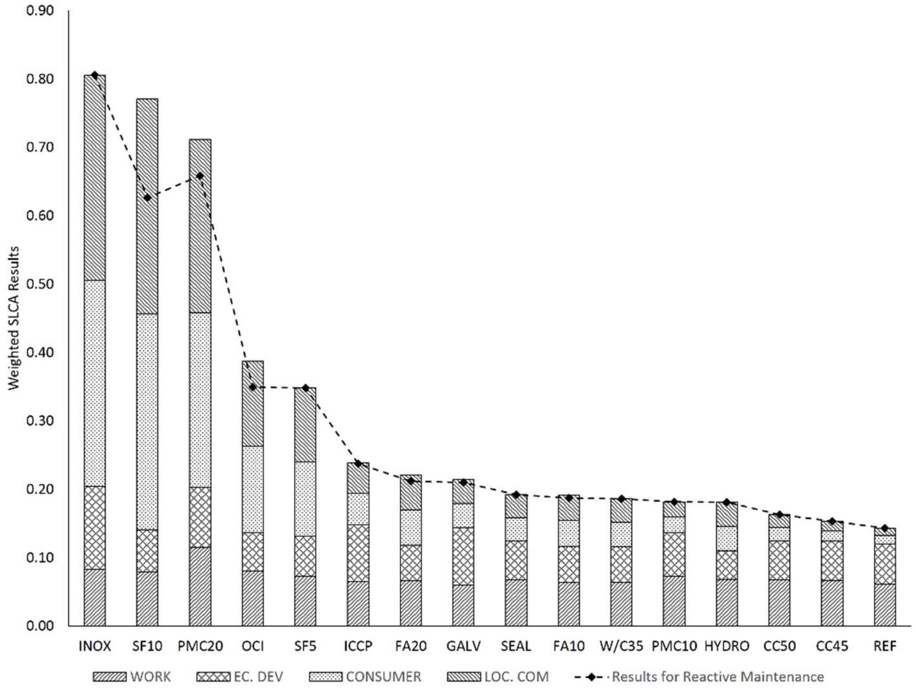


Figure 7.6. Social life cycle assessment results

Fig. 7.6 includes the social scores of each alternative if reactive maintenance strategies are applied. It is observed that the greatest differences are obtained for those solutions with the greatest durability performances, such as SF10, OCI or PMC20. In those cases, the social performance with respect to preventive maintenance is reduced up to 14%, 5.3% and 3.8% respectively if reactive maintenance is chosen.

7.4.5. Sustainability results

On the basis of the crisp weights obtained in Fig. 7.3, the conventional TOPSIS technique is applied to aggregate the 9 different impact categories into a single sustainability score for each of the design options to be compared. Fig. 7.7 shows the results for each design alternative, considering in each case the maintenance interval that leads to the highest score. In addition, each alternative's economic, environmental and social scores obtained for its respective optimum interval are also presented as a fraction of the best obtained score in the particular field under assessment.

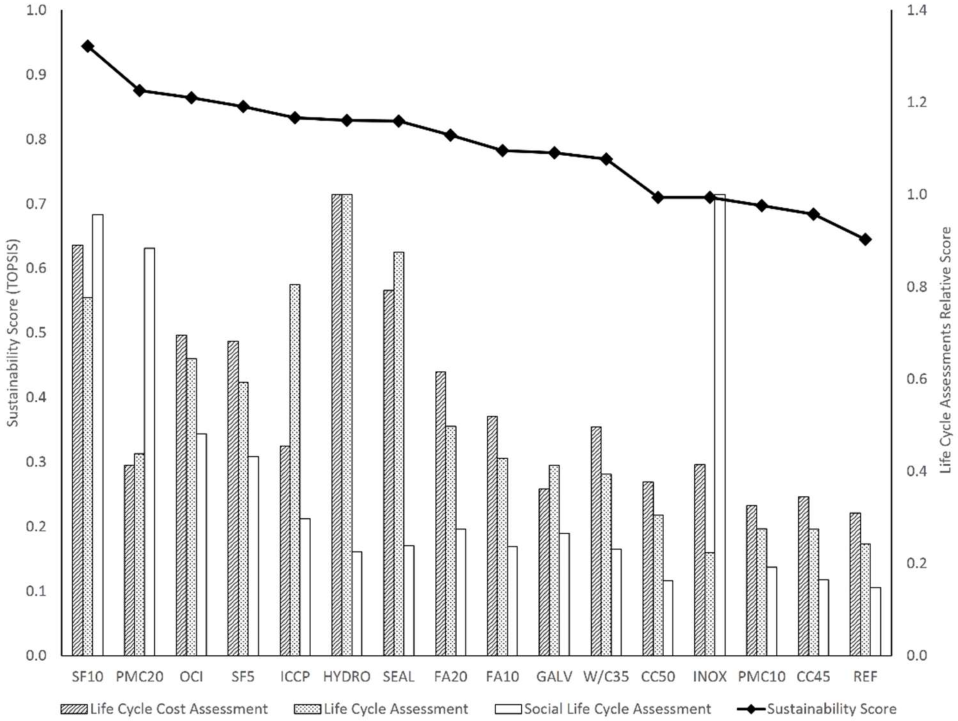


Figure 7.7. Sustainability assessment results

The design alternative that has resulted to perform the best from a sustainability perspective is SF10, with an overall score of 94.4%. In economic terms, although the construction costs of this design are greater than those of the baseline design, this solution incurs in almost negligible maintenance costs due to its high durability. Such reduced maintenance demand results in less negative affection to users and local community during the life cycle of the structure. In addition, the partial substitution of cement by silica fume allows for reduced cement production volumes, as well as the recycling of this industry by-product. On the contrary, the worst alternative has resulted to be the baseline option, scoring only 64.5%. Reactive maintenance can reduce the sustainability score up to an additional 8% in the case of the baseline design or CC45. It is worth noting that alternatives HYDRO and INOX, which have resulted in the best LCCA, LCA and SLCA scores, have resulted to perform not significantly in the final sustainability assessment. In contrast, solutions that did not stand out from the rest in those individual evaluations, have resulted to perform brilliantly when aggregated into a sustainability score. This has happened with the alternatives PMC20, OCI or SF5, with sustainability scores of 87.5%, 86.4% and 85.1%, respectively. In consequence, it is derived that those designs that perform best in any of the three pillars of sustainability independently, are not necessarily those that will perform best from a sustainability point of view.

7.5. Conclusions

This study evaluates the sustainability of 16 different design options for a prestressed concrete bridge deck exposed to an aggressive coastal environment. The life cycle economic, environmental and social impacts of each design alternative have been evaluated on the basis of the same functional unit and product system definition. The comparison of the sustainability associated with each design has been performed using the TOPSIS technique, so as to include the different impact categories in the final assessment. For the determination of the particular relevance of each criterion, a group AHP has been applied. However, given the conflicting nature of the sustainability criteria, the AHP pairwise comparisons are often complex and uncertain. In order to capture the inner sources of uncertainty in the judgements emitted by DM, AHP has been applied on the basis of the recently formulated neutrosophic logic, defined as a generalization of the fuzzy and intuitionistic logic.

Methodological gaps have been detected in the neutrosophic approach to the AHP technique. The present paper proposes an extension of the fuzzy method suggested by Enea and Piazza (2004) to deal with neutrosophic environments. In addition, the deneutrosophication method proposed by Sodenkamp et al. (2018) for single-valued neutrosophic numbers has been successfully adapted to handle with multi-valued neutrosophic numbers defined by general membership functions.

The proposed method is characterised by its ease of use for the decision makers, as they are only required to complete a comparison matrix as if it was a conventional AHP process. They are required to additionally express the certainty that they have when providing their judgements. The application of the proposed method results in crisp weights, that can directly be used with conventional MCDM techniques.

Under the assumptions adopted in the particular case study evaluated in the present paper, following specific conclusions are drawn:

- From the consultation with the panel of experts, environmental aspects have resulted to be the most relevant when assessing sustainability. In particular, damage to the ecosystem and depletion of natural resources have been considered of greater importance in comparison with the rest of the sustainability criteria. Weights of 22.5% and 22.4% have been assigned to those two criteria, respectively.
- With regards to social criteria, the effect on an infrastructure's life cycle on its users and on the public opinion of the local community has resulted to be three times more relevant than the effects on the mobilised working force and on the economic regional development resulting from the different construction and maintenance works. At last, construction and maintenance costs have been

regarded as almost equally important from the point of view of the sustainability of an infrastructure.

- The use of concrete mixes where the cement is partially replaced by silica fume has resulted to provide the best life cycle response from the perspective of sustainability. Designing concrete structures exposed to chloride-laden environments with silica fume concretes results in highly durable solutions, with reduced environmental and economic impacts during its service life. This low maintenance demanding solution provides one of the best options from the social point of view, reducing to the minimum the negative effects on the local communities and on the infrastructure users. Design SF10 has resulted in a sustainability score 46.3% higher than that of the baseline design.
- Designs based on periodically reapplied surface treatments provide a highly desirable solution in economic and environmental terms due to the reduced costs and energy demands of their associated maintenance works. Their short durability makes them perform very poorly when considering the social dimension.
- When it comes to the evaluation of sustainability, designs that have provided the best results in the economic or environmental field individually have been overtaken by options with more balanced effects in all three dimensions of sustainability. In view of the obtained results, it is a matter of course that an adequate sustainable design of infrastructures should consider the three dimensions of sustainability simultaneously.

Chapter 8

Discussion of the results

The present PhD thesis has raised several research questions regarding the sustainability assessment of infrastructures. To cope with them, this research proposes a methodology for the sustainability assessment of infrastructures from an integrated, holistic perspective.

8.1. Research Question Q1

How could we effectively integrate the three dimensions of sustainability into an ISO 14040-oriented sustainability assessment of infrastructures?

The present thesis proposes a sustainability life cycle assessment based on the combination of three independent techniques (LCA, LCCA and SLCA) focused on each of the three dimensions of sustainability. However, so as to combine the results of the economic, environmental and social assessments, particular aspects shall be taken into consideration so as to make such results comparable and aggregatable. Life cycle assessments, according to ISO 14040 standard, shall be carried out in four phases, namely Goal and scope, Inventory, Impact assessment and Interpretation of the results. Here, a discussion is presented on how to approach some of the ISO 14040 proposed analysis stages when using LCA, LCCA and SLCA as stand-alone techniques so as to make them coherent prior to its combination into a single and consistent sustainability-LCA.

First of all, it shall be highlighted that ISO 14040 standard was initially meant to be used for environmental life cycle assessments of products. Such standard seeks to provide a useful guidance for conducting rigorous and consistent life cycle assessments in a systematic way. Such methodology is strongly accepted by the scientific community and has been widely applied in the environmental field. However, it is not until 2009 when such transparent and robust methodology is proposed to be applied for social assessments through the publication of the 'Guidelines for social life cycle assessment of products' (UNEP/SETAC, 2009). Due to its recent publication, such Guidelines have been only marginally used to assess social impacts related to the construction sector, as exposed in Chapter 6. In addition, such assessments do not consider the complete life cycle of the assessed products (Hosseinjou et al., 2014; Hossain et al., 2018; Hu et al., 2013; Dong & Ng, 2015), despite the fact that the maintenance and use stage of infrastructures is a main source of impacts throughout its life cycle, as derived from the results exposed in the present thesis. To overcome such knowledge gap, a consistent SLCA methodology based on the UNEP Guidelines and coherent with an ISO 14040 standard approach has been proposed. This is considered an essential step prior to establishing an integrated, holistic sustainability assessment methodology for infrastructures.

The initial assessment stage, namely the goal and scope definition, is characterised by the definition of the functional unit, the establishment of the system boundaries and other relevant assumptions that will condition the results of the analysis. It shall be said that the scope of the presented assessment is oriented to the comparison of different designs, which will take particular significance when defining the system and the functional unit to be analysed.

The first consideration to take into account is that the assessment of each dimension shall be based on the same functional unit so as to make the results valid and coherent. The functional unit shall be understood as the amount of function required by the product to be assessed. Therefore, the functional unit defined in each of the three approaches should not differ from one assessment dimension to the other. In the different assessments presented here, the functional unit has been defined as 1 m of a concrete bridge deck to provide terrestrial connection at a particular location during a service life of 100 years.

When assessing design alternatives based on the use of different materials, it shall be taken into consideration that the geometry of the alternatives to be assessed might need to be modified so as to make alternatives comparable in terms of functionality, as already discussed in Chapters 4 to 7 of the present thesis. This is of paramount relevance when conducting comparative assessments, as not considering it may lead to overestimated asessment results, where the performance of some alternatives is hindered by the fact of assigning to them more material than the strictly needed to fulfill the required functionality (see Chapter 3).

It shall be highlighted that the specification of the geographical location of the bridge is not directly related to the functionality provided by the product under assessment, but is of paramount importance for the latter definition of the system boundaries and analysis assumptions during the assessment of the environmental and, most of all, the social life cycle impacts.

Within a comparative life cycle assessment, irrespective of the sustainability dimension assessed, the different product alternatives shall also be compared on an equivalent basis. Here, based on the assumption that the different deck alternatives analysed provide the same terrestrial connection, two additional aspects are identified as essential for the characterisation of the functionality of a concrete bridge deck, namely the structural strength of the deck and its behavior under service conditions. So, in the economic, environmental and social life cycle assessments presented here (Chapters 3 to 6), the geometry of the alternative decks has been modified depending on the construction material used in order to make the resulting deck provide the same ultimate strength and service behaviour. In addition to the foregoing, an adequate maintenance for each design alternative is here the third element needed for the deck alternatives to provide the same functionality during the required 100 years service life. Here, in all three assessments, the same criterion to determine when maintenance is mandatory has been considered, namely when an unacceptable reliability is reached. Reliability is evaluated here considering the durability as the only deterioration mechanism existing, given that the strength and service behaviour throughout the service life of the deck are assumed to be the same and to be guaranteed by each alternative. Consequently, given the different durability performance of each alternative, adequate maintenance shall ensure in each case the attainment of the desired functionality.

Here, it is also relevant to emphasize the fact that the maintenance criterion considered will have an essential influence on the obtained results. As derived from the results of Chapter 3, where a deterministic, reactive maintenance is considered, the socio-economic life cycle impacts associated to the maintenance phase of each alternative take on average half of the respective installation costs, while the results presented in Chapter 5 and Chapter 7 show that the economic impacts of the maintenance phase are on average greater than the installation costs.

In addition, when considering the economic dimension of sustainability, such consequences are increased by the discount rate assumed in the analysis. So, when performing conventional LCCA, as in Chapter 3, high discount rates are usually considered when assessing infrastructures such as bridges, as has been observed in the state of the art review presented in Chapter 2. This assumption will reduce the economic impacts along the maintenance phase, when compared with economic assessments that assume social discount rates, as in Chapters 5 and 7, which provide greater relevance to the impacts on future generations.This will have a great influence in the social impacts derived from the assessment, which are also affected by such discounting when applying conventional approaches. As a result, the social impacts observed in Chapter 3 could be practically neglected if compared with the economic impacts. However, as results from Fig 7.3 presented in Chapter 7, social impacts associated to the life cycle of an infrastructure such as a bridge can take a decision relevance greater than the economic impacts (in this particular case, social impacts are assigned a decision weight of 25.7% against the 10.6% associated with the economic criteria). This highlights that an adequate consideration of the social dimension and of the different stakeholders involved is relevant and missing in conventional analyses, which are usually based on the quantification of *VOC* and *VDC* social costs.

The system boundaries are defined in order to determine the temporal, spatial and production chain limits associated with the proccesses to be analysed. The sustainability assessment shall be based on a single and consistent activity system. Consequently, each sub-assessment should consider the same system boundaries and rely on the same activity system. However, when applied individually, each dimension assessment tends to consider different boundaries based on the importance that each process has on the particular perspective assessed, namely the economy, environment or society. So, while some processes might be particularly relevant under some perspectives, such as transport activities of construction materials in environmental LCA, they might have only negligible impacts on other dimensions, such as the social perspective. Therefore, although the system under study shall be the same in each assessment, the specific consideration of the particular unit processes involved might be conditioned by their associated relevance on the resulting social, economic or environmental impacts. Such relevance-defined cut-off criterion has been assumed in other studies (Li et al., 2014; Martínez-Blanco et al., 2014) and is accepted by ISO standards (2006a, b). Here, while both LCA and LCCA consider the same system boundaries, some unit processes have been excluded from the SLCA on the basis of the aforementioned cut-off criterion, namely transport activities of materials and the processes related to energy production. Also, when the impacts of industry by-products such as fly ash or silica fume are quantified, the economic and environmental impacts associated with its use in deck designs have been evaluated as an allocation of a proportion of the impacts associated with the particular industry production activities from which they result. Such impact allocation has not been considered relevant from a social perspective.

Another cut-off criterion used when conducting comparative life cycle assessments (ISO, 2006b) consists in leaving out of the analysis those processes that are considered to produce equal impacts irrespective from the considered alternative. In the present thesis, while the End of Life environmental impacts have been shown to be relevant and different from one deck alternative to the other, this life cycle stage has been excluded from the social assessment. Another example of the application of such cut-off criterion used in the present analysis is related to the secondary life of the waste concrete resulting from maintenance and demolition operations: while their economic and social impacts during this period are negligible, the environmental assessment considers the positive impacts associated to the carbon dioxide uptake resulting from its carbonation process.

At last, the definition of the system boundaries is also conditioned by the existence of relevant data regarding the impacts to be assessed (Martínez-Blanco et al., 2014). So, while systematic databases allow for an accurate characterisation of processes under an economic and environmental perspective, such databases are not currently available for SLCA. Consequently, the assessment of the social impacts derived from particular background processes, such as those related to the extraction of raw materials, would require a very time-consuming study given the current state of SLCA data availability and have been excluded. Such cut-off criterion has been widely used in the existing LCA literature (Suh et al., 2004; Li et al., 2014).

So, the three cut-off criteria used (relevance, equality and data availability) here allow for a practical definition of different system boundaries depending on the dimension of sustainability considered. The important fact to take into account when dealing with a sustainability assessment is that every individual system is defined considering the same unit processes, and that no impact considered to produce relevant results is excluded from each analysis. Given the aforementioned cut-off criteria, the resulting system boundaries assumed for each dimension assessment are compatible with each other, and the consequent analysis system for the sustainability life cycle assessment performed is coherent and results in the boundaries shown in Fig. 7.2.

Regarding the inventory analysis, one of the main aspects to be taken into account in this phase is the selection of the relevant impact indicators for each assessment. It shall be noted that the economic and environmental indicators considered in LCA and LCCA are universally accepted, and that they are relatively easy to quantify since they respond to biophysical laws. Here, the indicators considered for the environmental life cycle assessment are those included in recognised environmental assessment methodologies, such as Eco-indicator 95 or ReCiPe. As exposed in Chapters 4 and 5 of the present thesis, the considered environmental indicators are grouped into three categories, namely damage to human health, damage to ecosystems, and resources. Regarding the economic assessment, the costs related to the different manufacturing, construction and maintenance operations measured in currency units are considered as impact indicators, as usual in LCCA.

On the contrary, there is not an accepted reference for the selection of social indicators. The usually considered monetized social impacts assumed in conventional LCCA of bridge infrastructures, such as the one presented in Chapter 3, are traditionally focused on one single stakeholder, namely the structure users. However, it has been shown in Chapter 6 that there are plenty of other social dimensions that might be affected when selecting a particular bridge design alternative. Given the current state of development of SLCA techniques, the selection of social indicators is highly subjective and case-dependent. The "Guidelines for social life cycle assessment of products" and "The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA)" (UNEP/SETAC, 2009, 2013) have been considered here as the basis for the social indicator selection, together with an analysis of the social context derived from the regional development plan designed for the region where the bridge is located, as exposed in Chapter 6.

In line with the above, in the present there are process-based available databases that are universally accepted to characterise the economic and environmental indicators selected for the assessments. In the studies presented in chapters 3, 4 and 6 of the present thesis, Ecoinvent 3.2 database has been used as a reference for the quantification of the environmental impacts of the processes included in the system analysed. Regarding the inventory data considered for the LCCA, the cost data are highly country- and time-related. In the presented assessments, these inventory data have been gathered from the construction cost database developed by CYPE, as specified in Chapter 5. However, other databases are available and could have been used, such as those developed by the Spanish Ministry of Public Works, PREOC, and others.

With regards to social impacts, several databases exist from which to gather data to quantify the selected social indicators. The most known one is the Social Hotspot Database, issued in 2013 by the project New Earth, and oriented to the characterisation of indicators related to labour rights, working conditions, human rights, health and safety and governance conditions. The Social Hotspot Database has been used in a variety of SLCA studies to date (Du et al., 2019; Shemfe et al., 2018). The official sources from which this database has been constructed are organisations such as the World Bank, the International Labor Organization, or the World Health Organization. Other accepted social databases exist, such as EORA database. It shall be emphasized that the information provided by current social databases is said to have a low granularity, as they are focused for macro-scale assessments involving several countries. Such databases do not allow to catch social differences between regions within a country. Consequently, when assessing sustainability from a micro-scale perspective, such as the one considered here when evaluating design alternatives for one single bridge deck, the designer is required to gather information from country-specific databases. In the presented study, the databases consulted have been the Spanish National Statistics Institute and the Spanish Tax Office database, as exposed in Chapter 6. However, if other social indicators had been selected different than those considered relevant here, other specific databases would have been needed. The non-availability of SLCA oriented databases on a regional scale has been found to be one of the main limitations of the current state of SLCA for its application on the assessment of design alternatives.

With regards to the assessment of life cycle impacts, given that the sustainability performance of each design alternative is evaluated by means of a MCDM technique, it shall be noted that the selection and definition of indicators of each sustainability dimension, as well as the assessment of impacts, are not conditioned by the measure units or methodologies used to quantify the impacts of the other dimensions. However, the above is valid as long as the impact assessments are approached from a similar perspective. Life cycle assessments are usually conducted on the basis of a so-called bottom-up approach. That means that the assessments are based on data for specific unit processes, which are then linked together into the final life cycle model. Such is the case of the economic and environmental LCA conducted in the present work, where the impacts are directly associated to the quantification of the unitary processes involved in the production and activity chains modelled. In the case of LCCA, the costs of machinery, fuel, material production, transport services or workers are considered, to mention some examples. Examples of process related indicators considered in the presented environmental assessments are the emission of pollutants, water use, energy consumption or resources consumption, among others. The economic and environmental assessments are based on the aggregation of such quantitative impacts according to the assessment techniques, as exposed in Chapters 4 and 5 of the present thesis.

So as to make every three assessments coherent and compatible for its latter aggregation into a single sustainability result, the social LCA should also be based on a bottom-up approach, i.e. on directly quantifiable processes. Such assumption is also required by the desired micro-scale oriented, comparative sustainability assessment of alternative infrastructure designs. In the approach presented in Chapter 6 of the present thesis, such quantification is done by means of variables such as working hours, economic flows, or number of accidents per output of each unit process. However, the present analysis has combined such a process-based approach with national statistics so as to socially contextualise the impact of these measurements (Sierra et al., 2017b).

In summary, the consideration of the modelling particularities discussed here for each ofthe three stand-alone life cycle assessments (LCA, SLCA and LCCA) allow for the construction of a single micro-scale oriented and comparative sustainability life cycle assessment focused on the determination of the life cycle sustainability of alternative infrastructure designs. The methodology has been applied to a particular case study, consisting in the selection of the design alternative of a concrete bridge deck exposed to marine chlorides considering the social life cycle impacts of the structure. It shall be derived that the social impacts resulting from the construction stage and those derived from the maintenance phase are both equally contributing to the final score, which is in line with the results of previous studies in the field of SLCA applied to bridges (Gervásio & Da Silva, 2013; Soliman & Frangopol, 2014). Such finding confirms the need of integrating every life cycle stage into social impact assessments of structures.

8.2. Research Question Q2

> *Could we develop a sustainability life cycle assessment methodology oriented towards the attainment of the recently established Sustainable Development Goals?*

The suggested bottom-up, ISO 14040 based sustainability life cycle assessment allows for the consideration of the Sustainable Development Goals through the selection of appropriate impact indicators. The recently established Sustainable Development Goals are 17, namely: No poverty (SDG 1); Zero hunger (SDG 2); Good health and well-being

(SDG 3); Quality education (SDG 4); Gender equality (SDG 5); Clean water and sanitation (SDG 6); Affordable and clean energy (SDG 7); Decent work and economic growth (SDG 8); Industry, innovation and infrastructure (SDG 9); Reduced inequalities (SDG 10); Sustainable cities and communities (SDG 11); Responsible consumption and production (SDG 12); Climate action (SDG 13); Life below water (SDG 14); Life on land (SDG 15); Peace, justice and strong institutions (SDG 16); Partnership for the goals (SDG 17).

First of all, basing the design of an infrastructure on its sustainability life cycle performance is in directly related to the attainment of SDG 9, in particular with SDG target 9.1, which is focused on the development of quality, reliable, sustainable and resilient infrastructure to support economic development and human well-being.

The environmental indicators considered in the presented environmental assessments are those included in recognised methodologies such as Eco-indicator 99 or ReCiPe, which can be grouped under three main impact categories, namely damage to human health, damage to ecosystems, and resources. The reduction of the impacts on human health are directly related to the achievement of SDG 3 (Good health and well-being). Similarly, those impacts grouped under the impact category ‘Damage to the ecosystems’ will provide useful information in relation to the achievement of SDG 14 (Life below water) and SDG 15 (Life on land), as the methods’ midpoint impact categories allow for the quantification of the damages resulting to freshwater, terrestrial and marine species. At last, the third impact category, namely ‘Damage to resource availability’, is to be direcly related to SDG 12 (Responsible consumption and production).

Some of the midpoint indicators of the used methodologies, such as those measuring freshwater ecotoxicity, eutrophication and water use, also provide useful information to evaluate the attainment of SDG 6 (Clean water and sanitation), as they are directly related to SDG target 6.3 (reduce pollution and emissions to water), target 6.4 (increase water-use efficiency), target 6.6 (protection and restoration of water-related ecosystems). The used environmental assessment methods also measure the global warming potential increase derived from the modelled process activities, thus providing data towards the achievement of SDG 13 (Climate action).

The suggested social indicators are related to workers, the economic development of regions, the users of the infrastructure and the public opinion of the local community. The definition of the social indicators is done in such a way that the regional context is taken into consideration, which is in accordance with other authors (Sierra et al., 2017a, 2017b). These indicators are in line with several Sustainable Development Goals. In particular, the indicator related to the economic development of regions supports the achievement of SDG 8 (Decent work and economic growth), by considering how much a particular investment can contribute to the economic growth of a region measured in terms of gross domestic product increase. In particular, goal target 8.1 explicitly mentions the importance of contextualizing such growth within the national circumstances, which supports the way the indicator has been defined.

The social indicator related to workers is also closely related to the achievement of SDG 8 and SDG 10 (Reduced inequalities), since special relevance is provided to the creation of job opportunities in regions with higher unemployment rates, thus reducing unequal access to jobs. An additional relation to SDG 8 is also established when considering the social aspects associated to the promotion of safe and secure working environments (SDG target 8.8), as well as those related to the creation of decent jobs where a fair salary is guaranteed (SDG target 8.5). The social indicators considered here also seek to promote those designs that contribute to the guarantee of equal work opportunities irrespective of gender, which is in line with SDG 10 and SDG 5 (Gender equality).

The indicator considered here related to the public opinion of local communities is closely related to the affection to the site aesthetics and how this could harm the incomes derived from tourism. Such premise is in line with SDG 8, in particular with SDG target 8.9. The consideration of the increase of accidents related to maintenance works is consistent with SDG 3 (Good health and well-being), in particular with SDG target 3.6, which is explicitly oriented to reduce the number of deaths and injuries from road traffic accidents. In addition, such indicator also provides useful information towards the attainment of SDG 11 (Sustainable cities and communities), in particular SDG target 11.2, which puts emphasis on the improvement of road safety.

At last, the cost indicators included in the life cycle cost assessments performed here, are in line with SDG 12 (Responsible consumption and production), as economic resources should be managed with caution by government agencies so as to guarantee their economic capacities to incurr in new investments in the future.

In summary, a sustainability life cycle assessment of alternative designs for an infrastructure such as the one conducted here can effectively contribute to the attainment of the goals established by the 2030 Agenda for Sustainable Development, providing information and supporting the achievement of 11 out of the 17 established Sustainability Development Goals

8.3. Research Question Q3

> *How could we enhance the existing Multi-Criteria Decision-Making (MCDM) techniques applied to sustainable design so as to effectively deal with the experts' subjectivity along the decision making process?*

As shown in Chapter 2, the use of MCDM methods is highly recommended for the integration of the different dimensions of sustainability, as they allow for the simultaneous consideration of conflicting criteria often related in a complex way. Results of Chapter 2 show that SAW is by far the most applied MCDM technique due to its ease of use. However, the use of such technique is limited, since it can only deal with positive defined, maximizing criteria. As stated in the existing literature, estimates derived from the application of SAW technique may not always reveal properly a real situation, and the results obtained may therefore result not logical (Velasquez & Hester, 2013). Given the complex relations between sustainability criteria, and their often conflicting nature, other techniques have been used by the scientific community, being TOPSIS the most applied due to its relative ease of use and the direct interpretation of the conclusions derived from its application. TOPSIS technique has also been shown to work well when large numbers of alternatives and criteria are involved, due to its direct application (Thor et al., 2013). Similar results have been previously reported by other authors (Zavadskas et al., 2016).

So as to apply a MCDM technique to integrate the three perspectives of sustainability into one single assessment, all three dimensions shall be assessed on the same basis so as to make economic, environmental and social performances comparable. In this context, ISO 14040 provides a solid starting point on which to construct a robust methodology to properly assess the sustainability of infrastructures. Such idea was already considered by UNEP when defining the Guidelines, which suggest taking profit of the well-known LCA methodology and use it as a basis of the social assessments.

ISO methodology requires the assessments to be based on a consistent functional unit and requires the system boundaries to be unambiguously defined. However, such methodology has been only poorly used in MCDM related to that field. Such methodological gap shall be explained by the lack of a consistent methodology for the social assessment of infrastructures on the same basis. Once a methodology for social assessment is defined coherent with the accepted LCA methodology, as proposed in Chapter 6, the integration has resulted to be straightforward when applying a MCDM technique such as TOPSIS, as shown in Chapter 7.

The resolution of MCDM problems in the field of sustainability is usually based on the criteria relevancies derived from the subjective judgements of one or several experts. As resulting from Chapter 2, the most used technique to derive criteria weights has been found to be by far AHP. However, when dealing with complex problems associated with criteria that are very different in nature and often conflicting, the certainty assumption associated with the traditional, crisp AHP is severely questioned by the scientific community (Radwan et al., 2016).

As shown in Chapter 2, although crisp approach is still used for assessing sustainability by the vast majority of studies, in recent times researchers have started using fuzzy or intuitionistic based perspectives so as to capture the non-probabilistic uncertainties associated to the cognitive information in complex decision making problems. The literature review has revealed that the most advanced generalisation of the fuzzy sets theory, namely the neutrosophic sets theory, has not yet been used in sustainability assessments.

In particular, the detected application of neutrosophic logic when dealing with general MCDM has resulted to be inconsistent for several reasons. Firstly, it is commonly accepted the use of Buckley's method to derive weights out of neutrosophic AHP matrices, as a practical alternative to the eigenvector method proposed by Saaty.

However, it has been first in 2017 when Ye (2017) defined the subtraction and division operations of neutrosophic sets, thus consistently forming the integral theoretical framework to operate with neutrosophic sets. In addition, although in the fuzzy field it was found that the direct application of Buckley's method for the derivation of weights from AHP matrices defined according to Saaty's fundamental scale resulted in fuzzy weights with unreasonably high and asymmetrical uncertainty ranges (Wang & Elhag 2006). A method was suggested by Enea and Piazza (2004) to derive an adequate constrained fuzziness range of weights using a scalar mathematical programming model. The novel model suggested in the present PhD thesis has adapted the weighting method from Enea and Piazza (2004) to handle with generalised neutrosophic weights.

This is considered as a main contribution of the presented research, as it helps to further expanding the rigorous use of neutrosophic logic to capture cognitive uncertainties of decision makers. It shall be said that the proposed MCDM weighting model is easy to use by the experts, as they are only required to complete a comparison matrix as if it was a conventional AHP process. They are required to additionally express the certainty that they have when providing their judgements. The application of the proposed method results in crisp weights that can directly be used with conventional MCDM techniques.

8.4. Research Question Q4

> *Are there significant differences when assessing the design of maintenance-demanding structures in coastal environments from a holistic perspective or from one-dimensional approaches?*

As exposed in Chapter 1, focus has been put on concrete bridges exposed to marine environments, given the relevant impacts expected to result from the maintenance required to guarantee the provision of an adequate functionality along their long service lives. Consequently, the proposed three-dimensional sustainability assessment methodology has been applied to a particular prestressed concrete bridge deck exposed to marine chlorides in Chapter 7. Different design alternatives have been evaluated so as to identify which one performs best from a sustainability perspective along the life cycle of the structure.

In order to compare the results obtained from the two perspectives suggested by the research question raised, the same assumption shall be made, namely that results will be compared for the preventive maintenance interval that provides the best performance of the alternative considered in the particular field under analysis (economic, environmental, social, or the holistic perspective). From the results derived from the studies presented in this PhD thesis, it shall be derived that the differences between dimensions are significant depending on the design approach that is considered.

So, when assessing the coastal infrastructure from an economic point of view, the resulting preferred design options are those based on surface treatments, as can be concluded from the results presented in Chapter 7. These alternatives, although requiring a significant amount of maintenance operations throughout the service life of the analysed bridge deck, are really competitive in economic terms, thus leading to the preferred solutions. However, when observing the economic life cycle results derived from the study presented in Chapter 5, it is observed that the most preferred alternative is the one based on the addition of silica fume. When comparing the results of both studies, it is observed that both the alternatives based on the adition of silica fume, and those based on the application of surface tretaments, show similar performance results, being included in both studies among the best options from an economic perspective. The less preferred alternative is the baseline design, as it shows bad durability performance against chlorides and its associated maintenance operations are quite expensive when compared to the surface treatments. Such result is consistent with the case study presented in Chapter 5 of the present thesis. It shall be mentioned that the discussed results will always depend on the particular aggressiveness of the environment to which the structure to be assessed is exposed. However, from the results derived from Chapter 7, it can be concluded with generality that, although the costs derived from construction are quite relevant, the life cycle costs associated to maintenance in coastal environments shall not be neglected, taking more than 60-70% of the life cycle costs for some design alternatives. In line with the above, it shall be observed that, although incurring in reduced maintenance costs does not always guarantee the design alternative to perform well from an economic point of view, as it can incurr in expensive installation costs (see stainless steel based solutions, for example), it is observed that all the competitive designs have reduced maintenance costs. Although it is not a sufficient condition, in view of the obtained results it seems that investing in solutions with reduced maintenance costs is a necessary condition to achieve competitive designs from an economic life cycle perspective.

Considering the environmental perspective, the same preferred solution has been obtained, namely that one based on surface treatments. This agrees with Petcherdchoo (2015), who already reported that surface treatments are much more preferable from an environmental point of view than other designs in which the concrete cover has to be replaced periodically. Studies presented in Chapters 4 and 5 based on different case studies have yielded the same conclusions regarding surface treatments than those reflected in Chapter 7. The less preferred solution is in this case that one based on the use of stainless steel rebars, given the severe environmental impacts associated to the production of such steel. Such finding was previously reported by Mistry et al. (2016). Similar conclusions regarding the environmental implications of using stainless steel rebars have been exposed in the case study presented in Chapter 4. In the study presented in Chapter 5, however, although using stainless steel rebars has turned out to be one of the worst performing solutions in environmental terms, it has been overtaken by the performance of the baseline design. In that particular study, a greater surface chloride content was considered, thus increasing the maintenance demand of the baseline design. This is considered as the main reason for being the baseline design less preferable in environmental terms than the use of stainless steel in that specific case. Again, the presented results are case sensitive, i.e. they will vary depending on the aggressiveness of the considered ecoastal environment, for example. However, some general conclusions shall be drawn in view of the obtained results. Observing the life cycle performances presented in Chapter 6, it is derived that there is not a direct relationship between the economic and the environmental life cycle results. Basing a sustainability assessment on the sole consideration of one single dimension of sustainability is therefore shown to be ineffective, and it can be concluded with general validity that a holistic approach is required when assessing sustainable designs. Again, the impact of the maintenance phase in the life cycle environmental performance of coastal structures has been shown to be of paramount relevance, as revealed in Chapters 4 and 5 of the present PhD thesis. In addition, optimizing maintenance intervals can lead to significant reductions of the resulting life cycle impacts of up to 10-12% in some cases, as presented in Chapters 5 and 7.

Assuming a social perspective, the design that would be chosen is the one based on stainless steel. Such result is consistent with the results of the case study presented in Chapter 6. Considering the weights related to the different social sub-criteria, particular relevance is given to the workers and the regional development rather than to infrastructure users and the public opinion of local communities. In consequence, and given the social methodology assumed here, it is not only a matter of how much work is generated throughout the life cycle of the structure, as usually considered when dealing with social assessments (Hunkeler et al., 2008), but of the context quality of such work. Thus, the consideration of contextual aspects such as workers safety, gender equality, fair salaries or the existing unemployment in the region is essential to properly characterise the social impact of a particular decision (Sierra et al., 2017b). A similar reasoning shall be drawn for the subcriteria dealing with the economic development of the regions. The less preferred design was here the baseline design.

Finally, when assessing a design choice based on a holistic sustainability perspective, it comes that the most preferred solution here was that one consisting on the use of silica fume additions to the base concrete. When observing the obtained results on each dimension of sustainability, it is concluded that, when it comes to the evaluation of sustainability, designs that have provided the best results in the economic or environmental field individually have been overtaken by options with more balanced effects in all three dimensions of sustainability. Again, it shall be highlighted that the results of a sustainability assessment are highly dependent on the regional and social context where the particular infrastructure is designed, as well as on the aggressiveness of the coastal environment under consideration. However, and in view of the obtained results, it is a matter of course that an adequate sustainable design of infrastructures shall consider the three dimensions of sustainability simultaneously. The integral methodology proposed here provides therefore a useful tool for the sustainability assessment of infrastructures.

Chapter 9

Conclusions and future work

This dissertation proposes a methodology for the life cycle sustainability assessment of infrastructures. The suggested model is based on the environmental standarised LCA methodology, on which the three-dimensional model is constructed. Particular efforts have been put on the development of the social dimension of the assessment, where an important knowledge gap has been detected. The methodology is applied to the assessment of alternative concrete bridge deck designs in a coastal region and exposed to marine chlorides.

The present Chapter summarises the main general conclusions of this study, as well as the case-specific conclusions related to the design of resilient structures in aggressive environments.

9.1. General conclusions

The general conclusions drawn from this PhD thesis are:

9.1.1. Main conclusions

- In the light of the results obtained in the present thesis, it is derived that conclusions regarding the sustainability of an infrastructure design shall not be drawn solely by taking into account its individual performance in the various dimensions of sustainability. Here, the designs that have provided the best results in the economic or environmental field individually have been overtaken by options with more balanced effects on all three dimensions of sustainability. In view of the obtained results, it is a matter of course that the adequate sustainable design of infrastructures should assume a holistic design perspective and consider the three dimensions of sustainability simultaneously.

- The impact of the maintenance phase in the life cycle performance of coastal structures has been shown to be of paramount relevance in every dimension of sustainability and shall therefore not be neglected when performing life cycle assessments.
- Optimising maintenance intervals can lead to significant reductions of the resulting life cycle impacts in both the environmental, economic and social fields. The optimal maintenance interval is different depending on which dimension of sustainability is assessed. In addition, not every sustainability dimension is equally sensitive to maintenance optimisation. It has been observed that the economic life cycle impacts are less sensitive to optimization than environmental impacts. The social dimension has resulted to be the least sensitive to maintenance optimisation. In general, the greater the life cycle impacts expected from a design, the greater the achieved impacts reduction through maintenance optimisation.
- In the economic dimension, both the economic impacts derived from constructing the infrastructure and those resulting from its maintenance have resulted to be equally important from the perspective of sustainability. It is observed that all the competitive designs have reduced maintenance costs. However, reducing maintenance costs does not necessarily lead to competitive solutions.
- After consulting the panel of experts, environmental aspects have resulted to be the most important when assessing the sustainability of transport infrastructures. In particular, the impact categories considered to be the most relevant have turned out to be damage to the ecosystem and depletion of natural resources. Weights of 22.5% and 22.4% have been assigned to these two criteria, respectively.
- Regarding the social dimension, impacts on the infrastructure users and the public opinion of the local communities have resulted to be three times more relevant than the effects on the economic regional development and on the mobilised working force resulting from the different construction and maintenance works.
- The consideration of contextual aspects such as workers safety, gender equality, fair salaries or the existing unemployment in the region when evaluating social impacts is essential to properly characterise the social impact of a particular decision, in contrast with the usually considered social indicator based on the sole consideration of the working hours generated.
- In general, the proposed sustainability life cycle assessment methodology

considers a variety of criteria that are in line with the recently defined Sustainable Development Goals, both in the economic, the environmental and the social dimension.

9.1.2. Methodological conclusions

- An important methodological gap has been detected when dealing with sustainability assessments. Although recognised standards exist that provide guidelines for coherent and robust life cycle analyses, it has been found that sustainability assessments are only marginally based on such standards. An integrated, holistic sustainability assessment methodology has been proposed here based on the ISO 14040 standard series.
- It has been shown that the life cycle assessments on bridge structures, such as conventionally performed, show a series of drawbacks and limitations that are not compatible with coherent and robust sustainability assessments. The holistic methodology proposed here bridges such gaps efficiently, dealing with every one of the dimensions of sustainability in a robust way.
- A social life cycle assessment methodology based on the Guidelines (UNEP/SETAC, 2009) is proposed here that is compatible with the ISO 14040 standard series. The suggested methodology allows for the optimisation of the maintenance interval so as to find the maintenance strategy that maximises social benefits.
- A neutrosophic group-AHP is proposed here to evaluate the sustainability criteria weights by taking into consideration the subjectivity inherent to the judgements emitted by decision makers when dealing with complex assessments.
- A method is suggested here to determine the relevance of each decision maker from a neutrosophic perspective, on the basis of measurable factors, such as their experience, the coherency of their judgements and the certainty with which they express their opinions.
- An extension of the fuzzy method suggested by Enea and Piazza (2004) has been developed to deal with neutrosophic environments. The application of the proposed method allows to derive constrained truth, falsity and indeterminacy ranges for the criteria weights obtained from a neutrosophic comparison matrix based on the Saaty’s scale.
- The deneutrosophication method proposed by Sodenkamp et al. (2018) for single-valued neutrosophic numbers has been successfully adapted to handle with multi-valued neutrosophic numbers defined by general membership functions.
- The proposed method is characterised by its ease of use for the decision makers, as they are only required to complete a comparison matrix as if it was a

conventional AHP process. In addition, they should only express the certainty with which they provide their judgements.

- The application of the proposed method results in crisp weights that can directly be used with conventional MCDM techniques.

9.2. Specific conclusions

The context-specific conclusions drawn from the presented studies are:

- The use of concrete mixes with silica fume has resulted to provide the best life cycle performance with regards to sustainability. Designing concrete structures in coastal regions with silica fume concretes results in solutions with reduced environmental and economic impacts during its service life as a result of their associated high durability. The consequent low maintenance demand of this solution makes it to perform well from the social point of view, reducing to the minimum the negative effects on the local communities and on the infrastructure users.
- Regardless of the sustainability dimension assessed (economic, social or environmental), impacts derived from the maintenance phase of a structure can be critical with respect to the resulting life cycle impacts. It has been observed that there is no linear relationship between the life cycle impacts and the maintenance interval chosen. For example, no maintenance does not necessarily lead to better life cycle performances, as observed in the case of using stainless steel rebars. Consequently, a compromise solution shall be reached between the durability of the particular design solution and the impacts associated to the materials involved.
- It is essential to reuse the concrete as filling material so as to reach its complete carbonation, thus reducing the carbon dioxide emissions and reducing the design life cycle impact of concrete on climate change up to 16%.
- Irrespective of the material and installation costs and impacts, every prevention design considered in this study reduces both the economic and the environmental impacts, and increases the social benefits, throughout the service life of the bridge deck when compared to the impacts associated with the durability design of the actual bridges. The only exception to that is the use of stainless steel, that performs environmentally worse than the baseline design.
- Designs based on periodically reapplied surface treatments provide a highly desirable solution from both the economic and the environmental perspective, given the reduced costs and energy demands associated to the resulting maintenance works. However, their short durability and their consequently high maintenance demand has proved to be decisive for making such designs undesirable from a sustainability point of view, as the impacts on the users and on the local public opinion are excessively high.
- It has been observed that preventive maintenance results in better sustainability

performance values when compared with reactive maintenance strategies. The optimisation of the maintenance intervals reduces the economic and environmental life cycle impacts derived from reactive maintenance up to 13% and 19%, respectively.

9.3. Future lines of research

The complexity of the sustainability concept and its implications is very extensive and cannot be covered by a single dissertation. Additional efforts should be put towards defining refined and robust methodologies so as to assess the sustainable design of infrastructures. Under such premise, and considering the research gaps not covered by the present study, recommendations on future lines of research are given.

Regarding the social assessment of long-lasting structures, the present thesis bases its conclusions on the fact that the future social context during the structure's service life will follow the trends registered in the national statistical databases for the last years. More refined forecasting models should be investigated so as to reach more accurate social impact evaluations along the life cycle of the infrastructure under analysis.

Regarding the presented neutrosophic group AHP methodology, the proposed model results in the acquisition of some crisp weights that are directly to be used by conventional MCDM techniques. Research could be conducted towards adapting the existing MCDM techniques to a neutrosophic environment, thus avoiding the weights deneutrosophication stage. Working with the complete neutrosophic information throughout the whole MCDM process will lead to more accurate results.

Additional research could be conducted to investigate which criteria have a greater subjectivity load among the ones characterising sustainability. Such subjectivity could be consistently related to the particular background of the experts involved in the decision making process and their perception of each sustainability dimension. Thus, the expert's relevance proposed here based on the years of experience in different assessment fields could be refined to obtain more accurate results and conclusions.

The presented methodology has been applied to the sustainability assessment of alternative designs for a particular bridge deck. As a future line of research, it is suggested that a holistic life cycle sustainability assessment methodology such as the one proposed in the present dissertation is applied to enhance the existing Bridge Management Systems. When dealing with bridge systems, the optimal management of each element of the system is not independent from the others. The consideration of such relational aspects in the sustainability assessment of bridge systems poses a new challenge for the near future.

Chapter 10

References

Abdel-Basset, M., Manogaran, G., Mohamed, M., & Chilamkurti, N. (2018) Three-way decisions based on neutrosophic sets and AHP-QFD framework for supplier selection problem. *Future Generation Computer Systems, 89*, 19-30. https://doi.org/10.1016/j.future.2018.06.024.

Abdullah, L., & Najib, L. (2016). Sustainable energy planning decision using the intuitionistic fuzzy analytic hierarchy process: choosing energy technology in Malaysia. *International Journal of Sustainable Energy, 35(4)*, 360-377. https://doi.org/10.1080/14786451.2014.907292.

Abrishamchi, A., Ebrahimian, A., Tajrishi, M., & Mariño, M. A. (2005). Case study: Application of multicriteria decision making to urban water supply. *Journal of Water Resources Planning and Management, 131*, 326-335. https://doi.org/10.1061/~ASCE!0733-9496~2005!131:4~326!.

Afshar, A., Mariño, M., Saadatpour, M., & Afshar, A. (2011). Fuzzy TOPSIS multi-criteria decision analysis applied to Karum reservoirs system. *Water Resources Management, 25*, 545 – 563. https://doi.org/10.1007/s11269-010-9713-x.

Ahmine, M. E., Pailles, J., & Perry, N. (2014). Comparison of different Multiple-criteria decision analysis methods in the context of conceptual design: application to the development of a solar collector structure. *Advanced Manufacturing*.

Akadiri, P. O., Olomolaiye, P. O., & Chintio, E. A. (2013). Multi-criteria evaluation model for the selection of sustainable materials for building projects. *Automation in Construction, 30*, 113-125. https://doi.org/10.1016/j.autcon.2012.10.004.

Ali, M., Aslam, M. S., & Mirza, M. S. (2016). A sustainability assessment framework for bridges – a case study: Victoria and Champlain Bridges, Montreal. *Structure and Infrastructure Engineering, 12(11)*, 1381-1394. https://doi.org/10.1080/15732479.2015.1120754.

Allacker, A. (2012). Environmental and economic optimisation of the floor on grade in residential buildings. *International Journal of Life Cycle Assessment, 17*, 813-827. https://dx.doi.org/10.1007/s11367-012-0402-2.

Alwaer, H., & Clements-Croome, D. (2010). Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. *Building and Environment, 45*, 799 – 807. https://doi.org/10.1016/j.buildenv.2009.08.019.

Andrews, E., Lesage, P., Benoît, C., Parent, J., Norris, G., & Revéret, J. P. (2009). Life cycle attribute assessment—case study of Quebec tomatoes. *Journal of Industrial Ecology, 13(4)*, 565–578. https://dx.doi.org/10.1111/j.1530-9290.2009.00142.x.

Årskog, V., Fossdal, S., & Gjørv, O. E. (2004). Life-cycle assessment of repair and maintenance systems for concrete structures. *International Workshop on Sustainable Development and Concrete Technology*, Beijing.

Asgari, N., Hassani, A., Jones, D., & Nguye, H. H. (2015). Sustainability ranking of the UK major ports: Methodology and case study. *Transportation Research Part E, 78*, 19 – 39. https://doi.org/10.1016/j.tre.2015.01.014.

Atanassov, K. (1986). Intuitionistic Fuzzy Sets. *Fuzzy Sets and Systems, 20*, 87–96. https://doi.org/10.1016/S0165-0114(86)80034-3.

Babbitt, C. W., & Lindner, A. S. (2008). A life cycle comparison of disposal and beneficial use of coal combustion products in Florida. Part 1: methodology and inventory of materials, energy and emissions. *International Journal of Life Cycle Assessment, 13*, 202–11. http://dx.doi.org/10.1065/lca2007.07.353.

Balali, V., Mottaghi, A., Shoghli, O., & Golabchi, M. (2014). Selection of appropriate material, construction technique, and structural system of bridges by use of multicriteria decision-making method. *Transportation Research Record: Journal of the Transportation Research Board, 2431*, 79 – 87. https://doi.org/10.3141/2431-11.

Baltazar, L, Santana, J., Lopes, B., Rodrigues, M.P., & Correia, J.R. (2014). Surface skin protection of concrete with silicate-based impregnations: influence of the substrate roughness and moisture. *Construction and Building Materials, 70*, 191–200. https://doi.org/10.1016/j.conbuildmat.2014.07.071.

Banias, G., Achillas, C., Vlachokostas, C., Moussiopoulos, N., & Tarsenis, S. (2010). Assessing multiple criteria for the optimal location of a construction and demolition waste management facility. *Building and Environment, 45*, 2317 – 2326. https://doi.org/10.1016/j.buildenv.2010.04.016.

Barone, G., & Frangopol, D. (2014). Life-Cycle Maintenance of Deteriorating Structures by Multi-Objective Optimization Involving Reliability, Risk, Availability, Hazard and Cost. *Structural Safety, 48*, 40-50. https://doi.org/10.1016/j.strusafe.2014.02.002.

Barros, J., Coira, M., López, M., & Gochi, A. (2015). Assessing the global sustainability of different electricity generation systems. *Energy, 89*, 473 – 489. https://doi.org/10.1016/j.energy.2015.05.110.

Begic, F., & Afgan, N. H. (2007). Sustainability assessment tool for the decision making in selection of energy system – Bosnian case. *Energy, 32*, 1979 – 1985. https://doi.org/10.1016/j.energy.2007.02.006.

Benoît-Norris, C., Vickery-Niederman, G., Valdivia, S., Franze, J., Traverso, M., Ciroth, A., & Mazijn, B. (2011). Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. *International Journal of Life Cycle Assessment, 16(7)*, 682e690. https://dx.doi.org/10.1007/s11367-011-0301-y.

Bertolini, L., Bolzoni, F., Gastaldi, M., Pastore, T., Pedeferri, P., & Redaelli, E. (2009). Effects of cathodic prevention on the chloride threshold for steel corrosion in concrete. *Electrochimica Acta, 54*, 1452 – 1463. https://dx.doi.org/10.1016/j.electacta.2008.09.033.

Bertolini, L., Bolzoni, F., Pastore, T., & Pedeferri, P. (1996). Behaviour of stainless steel in simulated concrete pore solution. *British Corrosion Journal, 31*, 218–22. https://dx.doi.org/10.1179/000705996798114572.

Biswas, P., Pramanik, S., Giri, B. (2016). TOPSIS method for multi-attribute group decision-making under single-valued neutrosophic environment. *Neural Computing and Applications, 27(3)*, 727-737. https://doi.org/10.1007/s00521-015-1891-2.

Blakey, S. G., & Beck, S. B. M. (2004). Energy consumption and capacity utilization of galvanizing furnaces. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 218*, 251–9. https://dx.doi.org/10.1243/0954408042466927.

Blanco, A., De la Fuente, A., & Aguado, A. (2016). Sustainability analysis of steel fibre reinforced concrete slabs. *2nd International Conference on Concrete Sustainability*, Madrid, Spain.

Bolturk, E., & Kahraman, C. (2018). A novel interval-valued neutrosophic AHP with cosine similarity measure. *Soft Computing, 22(15)*, 4941-4958. https://doi.org/10.1007/s00500-018-3140-y.

Bolzoni, F., Brenna, A., Fumagalli, G., Goidanich, S., Lazzari, L., Ormellese, M., & Pedeferri, M. P. (2014). Experiences on corrosion inhibitors for reinforced concrete. *International Journal of Corrosion and Scale Inhibition, 3*, 254 – 278. https://dx.doi.org/10.17675/2305-6894-2014-3-4-254-278.

Bouzid, A., & Padilla, M. (2014). Analysis of social performance of the industrial tomatoes food chain in Algeria. *New Medit, 1*, 60–65.

Braga, A. M., Silvestre, J. D., & de Brito, J. (2017) Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. *Journal of Cleaner Production*, *162*, 529-543. https://doi.org/10.1016/j.jclepro.2017.06.057.

Buckley, J. J. (1985). Fuzzy hierarchical analysis. *Fuzzy Sets and Systems, 17(3)*, 233–247. https://doi.org/10.1016/0165-0114(85)90090-9.

Büyüközkan, G., & Ger, F. (2017) Application of a new combined intuitionistic fuzzy MCDM approach based on axiomatic design methodology for the supplier selection problem. *Applied Soft Computing, 52*, 1222-1238. https://doi.org/10.1016/j.asoc.2016.08.051.

Cebeci, U. (2009). Fuzzy AHP-based decision support system for selecting ERP systems in textile industry by using balanced scorecard. *Expert Systems with Applications, 36*, 8900-8909. https://doi.org/10.1016/j.eswa.2008.11.046.

Cellura, M., Longo, S., & Mistretta, M. (2011). Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: The case study of an Italian tile. Renewable and *Sustainable Energy Reviews, 15*, 4697 – 4705. https://doi.org/10.1016/j.rser.2011.07.082.

Chapman, P. F., & Roberts, F. (1983). Metal resources and energy, in: Ashby, M., Charles, J., Evans, A.G. (Eds.), Butterworths monographs in materials, 1st edition.

Cheewaket, T., Jaturapitakkul, C., & Chalee, W. (2014). Concrete durability presented by acceptable chloride level and chloride diffusion coefficient in concrete: 10-year results in marine site. *Materials and Structures, 47*, 1501–11. https://dx.doi.org/10.1617/s11527-013-0131-4.

Chen, C. (2009). A study of traditional and alternative structural concretes by means of the life cycle assessment method, PhD thesis (Troyes, University of Technology of Troyes).

Chen, C., Habert, G., Bouzidi, Y., Jullien, A., & Ventura, A. (2010). LCA allocation procedure used as an incitative method for waste recycling: an application to mineral additions in concrete. *Resources, Conservation and Recycling, 54(12)*, 1231–1240. https://doi.org/10.1016/j.resconrec.2010.04.001.

Chen, T. (2014). The extended linear assignment method for multiple criteria decision analysis based on interval-valued intuitionistic fuzzy sets. *Applied Mathematical Modelling, 38*, 2101 – 2117. https://doi.org/10.1016/j.apm.2013.10.017.

Cheng, Y., Zhang, Y., Tan, G., & Jiao, Y. (2018). Effect of Crack on Durability of RC Material under the Chloride Aggressive Environment. *Sustainability, 10*, 430. https://dx.doi.org/https://doi.org/10.3390/su10020430.

Chhipi-Shrestha, G., Hewage, K., & Wadiq, R. (2017). Selecting sustainability indicators for small to medium sized urban water systems using fuzzy-ELECTRE. *Water Environment Research, 89*, 238 – 249. https://doi.org/10.2175/106143016X14798353399494.

Choi, J. (2019). Strategy for reducing carbon dioxide emissions from maintenance and rehabilitation of highway pavement. *Journal of Cleaner Production*, *209,* 88-100. https://doi.org/10.1016/j.jclepro.2018.10.226.

Chu, T., & Tao, C. (2002). Ranking fuzzy numbers with an area between the centroid point and original point. *Computers & Mathematics with Applications, 43(1)*, 111-117. https://doi.org/10.1016/j.camwa.2010.11.020.

Collins, F. (2010). Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint. *International Journal of Life Cycle Assessment, 15(6)*, 549-556. http://dx.doi.org/10.1007/s11367-010-0191-4.

Cooper, J. S. (2003). Specifying functional units and reference flows for comparable alternatives. *International Journal of Life Cycle Assessment, 8*, 337. http://dx.doi.org/10.1007/BF02978507.

Cope, A., Bai, Q., Samdariya, A., & Labi, S. (2013). Assessing the efficacy of stainless steel for bridge deck reinforcement under uncertainty using Monte Carlo simulation. *Structure and Infrastructure Engineering, 9*. https://doi.org/10.1080/15732479.2011.602418.

Costa, A., & Appleton, J. (2001). Concrete carbonation and chloride penetration in marine environment. *Concrete Science Engineering, 3*, 242-249.

Courard, L., Lucquiaud, V., Gérard, O., Handy, M., Michel, F., Aggoun, S., & Cousture, A. (2014). Evaluation of the durability of hydrophobic treatments on concrete architectural heritage. Hydrophobe VII, *Seventh International Conference on Water Repellent Treatment and Protective Surface Technology for Building Materials*, ed. J. Charola and J. Delgado, Lisbon, 29–38.

Cuadrado, J., Zubizarreta, M., Rojí, E., & García, H. (2015). Sustainability-related decision making in industrial buildings: an AHP analysis. *Mathematical Problems in Engineering, 15*. http://dx.doi.org/10.1155/2015/157129.

Cuadrado, J., Zubizarreta, M., Rojí, E., Larrauri, M., & Álvarez, I. (2016). Sustainability assessment methodology for industrial buildings: three case studies. *Civil Engineering and Environmental Systems, 33*, 106 – 124. https://doi.org/10.1080/10286608.2016.1148143.

Dabous, S., & Alkass, S. (2008). Decision support method for multi-criteria selection of bridge rehabilitation strategy. *Construction Management and Economics, 26*, 883 – 893. http://dx.doi.org/10.1080/01446190802071190.

Dai, J.G., Akira, Y., Wittman, F.H., Yokota, H., & Zhang, P. (2010). Water repellent surface impregnation for extension of service life of reinforced concrete structures in marine environments: The role of cracks. *Cement and Concrete Composites, 32*, 101-109. https://dx.doi.org/http://dx.doi.org/10.1016/j.cemconcomp.2009.11.001.

Darwin, D., Browning, J., O'Reilly, M., Xing, L., & Ji, J. (2009). Critical Chloride Corrosion Threshold of Galvanized Reinforcing Bars. *ACI Materials Journal, 106*, 176–83. https://dx.doi.org/10.14359/56465.

De la Fuente, A., Armengou, J., Pons, O., & Aguado, A. (2017a). Multi-criteria decision-making model for assessing the sustainability index of wind-turbine support systems: application to a new precast concrete alternative. *Journal of Civil Engineering and Management, 23*. https://doi.org/10.3846/13923730.2015.1023347.

De la Fuente, A., Blanco, A., Armengou, J., & Aguado, a. (2017b). Sustainability based-approach to determine the concrete type and reinforcement configuration of TBM tunnels linings. Case study: Extension line to Barcelona Airport T1. *Tunneling and Underground Space Technology, 61*, 179 – 188. https://doi.org/10.1016/j.tust.2016.10.008.

De la Fuente, A., Blanco, A., Cavalaro, S., & Aguado, A. (2016a). Sustainability assessment of precast concrete segments for TBM tunnels. *2nd International Conference on Concrete Sustainability*, Madrid, Spain.

De la Fuente, A., Pons, O., Josa, A., & Aguado, A. (2016b). Multi-criteria decision making in the sustainability assessment of sewerage pipe systems. *Journal of Cleaner Production, 112*, 4762 – 4770. https://doi.org/10.1016/j.jclepro.2015.07.002.

De Luca, A. I., Iofrida, N., Strano, A., Falcone, G., & Gulisano, G. (2015). Social life cycle assessment and participatory approaches: a methodological proposal applied to citrus farming in Southern Italy. *Integrated Environmental Assessment and Management, 11(3)*, 383-396. https://dx.doi.org/10.1002/ieam.1611.

De Rus, G. (2010). Manual de evaluación económica de proyectos de transporte. Cedex Research Project PT2007-001-IAPP.

De Schepper, M., Van den Heede, P., Van Driessche, I., & De Belie, N. (2014). Life cycle assessment of completely recyclable concrete. *Materials, 7*, 6010-6027. http://dx.doi.org/10.3390/ma7086010.

De Simone Souza, H. H., Lima, Â. M. F., Esquerre, K. O., & Kiperstok, A. (2017). Life cycle assessment of the environmental influence of wooden and concrete utility poles based on service lifetime. *International Journal of Life Cycle Assessment, 22*, 2030-2041. http://dx.doi.org/10.1007/s11367-017-1293-z.

Deli, I., & Şubaş, Y. (2017). A ranking method of single valued neutrosophic numbers and its applications to multi-attribute decision making problems. *International Journal of Machine Learning and Cybernetics, 8(4)*, 1309-1322. https://doi.org/10.1007/s13042-016-0505-3.

Dette, G., & Sigrist, V. (2011). Performance indicators for concrete bridges. *Fib Symposium proceedings*. Prague. ISBN: 978-80-87158-29-6.

Dezert, J. (2002). Open questions in neutrosophic inferences. *Multiple-Valued Logic, 8(3)*, 439–472.

Diaz-Sarachaga, J.M., Jato-Espino, D., Alsulami, B., & Castro-Fresno, D. (2016). Evaluation of existing sustainable infrastructure rating systems for their application in developing countries. *Ecological Indicators, 71(1)*, 491–502. https://doi.org/10.1016/j.ecolind.2016.07.033

Dobrovolskiiene, N., & Tamosiuniene, R. (2016). An index to measure sustainability of a business project in construction industry: Lithuanian case. *Sustainability, 8*. https://doi.org/10.3390/su8010014.

Dong, X., Zeng, S., Chen, J., & Zhao, D. (2008). An integrated assessment method of urban drainage system: A case study in Shenzhen City, China. *Frontiers of Environmental Science & Engineering in China, 2*, 150 – 156. https://doi.org/10.1007/s11783-008-0014-z.

Dong, Y. H., & Ng, S. T. (2015). A social life cycle assessment model for building construction in Hong Kong. *International Journal of Life Cycle Assessment, 20*, 1166–1180. http://dx.doi.org/10.1007/ s11367-015-0908-5.

Dong, Y., Zhang, G., Hong, W., & Xu, Y. (2010). Consensus models for AHP group decision making under row geometric mean prioritization method. *Decision Support Systems, 49(3)*, 281-289. https://doi.org/10.1016/j.dss.2010.03.003.

Drejeris, R., & Kavolynas, A. (2014). Multi-criteria evaluation of building sustainability behavior. *Procedia - Social and Behavioral Sciences, 110*, 502 – 511. https://doi.org/10.1016/j.sbspro.2013.12.894.

Du, C., Ugaya, C., Freire, F., Dias, L., & Clift, R. (2019). Enriching the results of screening social life cycle assessment using content analysis: a case study of sugarcane in Brazil. *International Journal of Life Cycle Assessment, 24*, 781-793. https://doi.org/10.1007/s11367-018-1490-4.

Du, G., Safi, M., Pettersson, L., & Karoumi, R. (2014). Life cycle assessment as a decision support tool for bridge procurement: environmental impact comparison among five bridge designs. *International Journal of Life Cycle Assessment, 19(12)*, 1948-1964. https://dx.doi.org/10.1007/s11367-014-0797-z.

Dubois, D. (2011). The role of fuzzy sets in decision sciences: Old techniques and new directions. *Fuzzy Sets and Systems, 184(1)*, 3–28. https://doi.org/10.1016/j.fss.2011.06.003.

Eamon, C.D., Jensen, E.A., Grace, N.F., & Shi, X. (2012). Life-cycle cost analysis of alternative reinforcement materials for bridge superstructures considering cost and maintenance uncertainties. *Journal of Materials in Civil Engineering, 24*, 373–380. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000398.

Enea, M., & Piazza, T. (2004). Project selection by constrained fuzzy AHP. *Fuzzy Optimization and Decision Making, 3(1)*, 39-62. https://doi.org/10.1023/B:FODM.0000013071.63614.3d.

European Committee for Standarization (2002). EN 1990:2002: Eurocode – Basis of structural design.

European Institute for Gender Equality (2015). Gender Equality Index 2015 − Measuring gender equality in the European Union 2005-2012. https://dx.doi.org/10.2839/770576.

Farkas, A. (2011). Multi-criteria comparison of bridge design. *Acta Polytechnica Hungarica, 8*, 173 – 191.

Favier, A., De Wolf, C., Scrivener, K., & Habert, G. (2018). A sustainable future for the European cement and concrete industry. *Ecole Polytechnique Fédérale de Lausanne*, ETH Zürich. https://doi.org/10.3929/ethz-b-000301843.

Fetanat, A., & Khorasaninejad, E. (2015). A novel hybrid MCDM approach for offshore wind farm site selection: A case study of Iran. *Ocean and Coastal Management, 109*, 17 – 28. https://doi.org/10.1016/j.ocecoaman.2015.02.005.

Fib. Fib Bulletin 34 (2006). Model Code for Service Life Design. Lausanne: Fib.

Fomento (2000). Obras de paso de nueva construcción: conceptos generales. Madrid, Spain: Ministerio de Fomento.

Formisano, A., & Mazzolani, F. (2015). On the selection by MCDM methods of the optimal system for seismic retrofitting and vertical addition of existing buildings. *Computers and Structures, 159*, 1 – 13. https://doi.org/10.1016/j.compstruc.2015.06.016.

Fowler, D.W. (1999). Polymers in concrete: a vision for the 21st century. *Cement and Concrete Composites, 21*, 449-452. https://dx.doi.org/https://doi.org/10.1016/S0958-9465(99)00032-3.

Frangopol, D. M. (2011). Life-cycle performance, management, and optimisation of structural systems under uncertainty: accomplishments and challenges. *Structure and Infrastructure Engineering, 7*, 389–413. https://dx.doi.org/10.1080/15732471003594427.

Frangopol, D. M., & Soliman, M. (2016). Life-cycle of structural systems: recent achievements and future directions. *Structure and Infrastructure Engineering, 12*, 1–20. https://dx.doi.org/10.1080/15732479.2014.999794.

Frederiksen, J. M. (2000). Chloride threshold values for service life design. *Second International RILEM Workshop on Testing and Modelling the Chloride Ingress into Concrete*: Paris, France, 11-12 September 2000. RILEM Publications.

Frischknecht, R., Jungbluth, N., Althaus, H. J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., & Spielmann, M. (2005). The ecoinvent database: overview and methodological framework. *International Journal of Life Cycle Assessment, 10*, 3-9. http://dx.doi.org/10.1065/lca2004.10.181.1.

Gao, X. J., Wang, & X. Y. (2017). Impacts of Global Warming and Sea Level Rise on Service Life of Chloride-Exposed Concrete Structures. *Sustainability, 9(3)*, 460. http://dx.doi.org/10.3390/su9030460.

García-Segura, T., & Yepes, V. (2016). Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety. *Engineering Structures, 125*, 325-336. https://dx.doi.org/10.1016/j.engstruct.2016.07.012.

García-Segura, T., Penadés-Plà, V., & Yepes, V. (2018). Sustainable bridge design by metamodel-assisted multi-objective optimization and decision-making under uncertainty. *Journal of Cleaner Production, 202*, 904-915. https://doi.org/10.1016/j.jclepro.2018.08.177.

García-Segura, T., Yepes, V., Martí, J. V., & Alcalá, J. (2014a). Optimization of concrete I beams using a new hybrid glowworm swarm algorithm. *Latin American Journal of Solids and Structures*, *11*, 1190–1205. http://dx.doi.org/10.1590/S1679-78252014000700007.

García-Segura, T., Yepes, V., & Alcalá, J. (2014b). Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. *International Journal of Life Cycle Assessment, 19(1)*, 3-12. http://dx.doi.org/10.1007/s11367-013-0614-0.

García-Segura, T., Yepes, V., Alcalá, J., & Pérez-López, E. (2015). Hybrid harmony search for sustainable design of post-tensioned concrete box-girder pedestrian bridges. *Engineering Structures, 92*, 112–22. http://dx.doi.org/10.1016/j.engstruct.2015.03.015.

García-Segura, T., Yepes, V., Frangopol, D., & Yang, D. Y. (2017). Lifetime Reliability based Optimization of Post-Tensioned Box-Girder Bridges. *Engineering Structures, 145*, 381–391. https://doi.org/10.1016/j.engstruct.2017.05.013.

Gento, A. (2004) Selection of a dam in the river basin of river Duero by promethee method. *International Conference on Modelling and Simulation*, 341 – 347.

Gervásio, H. (2010). Sustainable design and integral life-cycle analysis of bridges. PhD Dissertation. University of Coimbra, Portugal.

Gervásio, H., & Da Silva, L. (2012). A probabilistic decision-making approach for the sustainable assessment of infrastructures. *Expert Systems with Applications, 39*, 7121–7131. https://doi.org/10.1016/j.eswa.2012.01.032.

Gervásio, H., & Da Silva, L. S. (2013). Life-cycle social analysis of motorway bridges. *Structure and Infrastructure Engineering, 9*, 1019–39. https://dx.doi.org/10.1080/15732479.2011.654124.

Gil, E., Vercher, J., Mas, A., & Fenollosa, E. (2015). Seguridad remanente a flexión en forjados con corrosión en las viguetas. *Informes de la Construcción, 67*, e054. http://dx.doi.org/10.3989/ic.13.084.

Gilani, G., Blanco, A., & De la Fuente, A. (2017). A new sustainability assessment approach based on stakeholder's satisfaction for building façades. *Energy Procedia, 115*, 50-58. https://doi.org/10.1016/j.egypro.2017.05.006.

Gjørv, O. (2013). Durability design and quality assurance of major concrete infrastructure. *Advances in Concrete Construction, 1(1)*, 45-63. http://dx.doi.org/10.12989/csm.2013.1.1.045.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Netherlands: Ministerie van Volkshuisvesting.

Goodwin, P., & Wright, G. (2000). Decision analysis for management judgment. *John Wiley & Sons*, Chichester.

Gumus, S., Kucukvar, M., & Tatari, O. (2016). Intuitionistic fuzzy multi-criteria decision making framework based on life cycle environmental, economic and social impacts: The case of U.S. wind energy. *Sustainable Production and Consumption, 8*, 78 – 92. https://doi.org/10.1016/j.spc.2016.06.006.

Gursel, A. P., & Ostertag, C. (2016). Comparative life-cycle impact assessment of concrete manufacturing in Singapore. *International Journal of Life Cycle Assessment, 22(2)*, 237-255. http://dx.doi.org/10.1007/s11367-016-1149-y.

Guzmán-Sánchez, S., Jato-Espino, D., Bombillo, i., & Diaz-Sarachaga, J. (2018). Assessment of the contributions of different flat roof types to achieving sustainable development. *Building and Environment, 141*, 182–192. https://doi.org/10.1016/j.buildenv.2018.05.063.

Hagerty, M. R., & Land, K. C. (2007). Constructing Summary Indices of Quality of Life: A Model for the Effect of Heterogeneous Importance Weights. *Sociological Methods and Research, 35*, 455-496. https://dx.doi.org/10.1177/0049124106292354.

Hammervold, J., Reenaas, M., & BrattebØ, H. (2013). Environmental life cycle assessment of bridges. *Journal of Bridge Engineering, 18*, 153-161. https://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000328.

Harvey, J. T., Rezaei, A., & Lee, C. (2012). Probabilistic approach to Life Cycle Cost Analysis of preventive maintenance strategies on flexible pavements. *Transportation Research Record: Journal of the Transportation Research Board, 2292*, 61–72. https://doi.org/10.3141/2292-08.

Harvey, J.T., Rezaei, A., & Lee, C. (2012). Probabilistic approach to Life Cycle Cost Analysis of preventive maintenance strategies on flexible pavements. *Transportation Research Record Journal of the Transportation Research Board, 2292*, 61-72. https://dx.doi.org/https://doi.org/10.3141/2292-08.

Hashemkhani, S., Pourhossein, M., Yazdani, M., & Zavadskas, E. K. (2018). Evaluating construction projects of hotels based on environmental sustainability with MCDM framework. *Alexandria Engineering Journal, 57*, 357-365. https://doi.org/10.1016/j.aej.2016.11.002.

Hashemkhani, S., Rezaeiniya, N., Zavadskas E. K., & Turskis, Z. (2011). Forest roads locating based on AHP and on COPRAS-G methods: an empirical study based on Iran. *Economics and Management, 4*, 6 – 20.

Heijungs, R., & Guinée, J. B. (2007). Allocation and 'what-if' scenarios in life cycle assessment of waste management systems. *Waste Management, 27(8)*, 997–1005. http://dx.doi.org/10.1016/j.wasman.2007.02.013.

Heravi, G., Fathi, M., & Faeghi, S. (2017). Multi-criteria group decision-making method for optimal selection of sustainable industrial building options focused on petrochemical projects. *Journal of Cleaner Production, 142*, 2999–3013. https://doi.org/10.1016/j.jclepro.2016.10.168.

Hooton, R. D., Pun, P., Kojundic, T., & Fidjestol, P., 1997. Influence of silica fume on chloride resistance of concrete. Proc., PCI/FHWA Int. Symp. on High Performance Concrete, Chicago, pp. 245-249.

Hossain, U., Poon, C. S., Dong, Y. H., Lo, I., & Cheng, J. (2018). Development of social sustainability assessment method and a comparative case study on assessing recycled construction materials. *International Journal of Life Cycle Assessment*, *23*, 1654-1674. http://dx.doi.org/10.1007/s11367- 017-1373-0.

Hosseini, S., De la Fuente, A., & Pons, O. (2016). Multicriteria decision-making method for sustainable site location of post-disaster temporary housing in urban areas. *Journal* *of Construction Engineering and Management, 142*. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001137.

Hosseinijou, S. A., Mansour, S., & Shirazi, M. A. (2014). Social life cycle assessment for material selection: a case study of building materials. *International Journal of Life Cycle Assessment, 19*, 620–645. https://dx.doi.org/10.1007/s11367-013-0658-1.

Hu, M., Kleijn, R., Bozhilova-Kisheva, K. P., & Di Maio, F. (2013). An approach to LCSA: the case of concrete recycling. *International Journal of Life Cycle Assessment, 18*, 1793–1803. https://dx.doi.org/10.1007/s11367-013-0599-8.

Hung, C. C., & Chen, L. H. (2009). A Fuzzy TOPSIS Decision Making Model with Entropy Weight under Intuitionistic Fuzzy Environment. *Proceedings of the International Multi-Conference of Engineers and Computer Scientists IMECS*, Hong Kong.

Hung, M. L., & Ma, H. (2009). Quantifying system uncertainty of life cycle assessment based on Monte Carlo simulation. *International Journal of Life Cycle Assessment, 14*, 19-27. https://doi.org/ 10.1007/s11367-008-0034-8.

Hunkeler, D., Lichtenvort, K., Rebitzer, G., Ciroth, A., Huppes, G., Klöpffer, W., Rüdenauer, I., Steen, B., & Swarr, T. (2008). Environmental life cycle costing. SETAC Publications, Brussels. ISBN: 9781420054705.

Ignatius, J., Rahman, A., Yazdani, M., Saparauskas, J., & Haron, S. H. (2016). An integrated fuzzy ANP-QFD approach for green building assessment. *Journal of Civil Engineering and Management, 22*, 551-563. https://doi.org/10.3846/13923730.2015.1120772.

Ilgin, M. A., Gupta, S. M., & Battaia, O. (2015). Use of MCDM techniques in environmentally conscious manufacturing and product recovery: State of the art. *Journal of Manufacturing Systems, 37*, 746-758. https://doi.org/10.1016/j.jmsy.2015.04.010.

Imbabi, M., Carrigan, C., & McKenna, S. (2013). *International Journal of Sustainable Built Environment, 1*, 194-216. http://dx.doi.org/10.1016/j.ijsbe.2013.05.001

Invidiata, A., Lavagna, M., & Ghisi, E. (2018). Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. *Building and Environment, 139*, 58-68. https://doi.org/10.1016/j.buildenv.2018.04.041.

ISO (2006a). Environmental Management:—Life Cycle Assessment— Principles and Framework. *International Standards Organization*, ISO 14040:2006, Geneva.

ISO (2006b) Environmental Management—Life Cycle Assessment— Requirements and Guidelines. *International Standards Organization*, ISO 14044:2006, Geneva.

ISO (2015). General Principles on Reliability for Structures. *International Standards Organization*, ISO 2394:2015, Geneva.

Jaber, J., & Mohsen, M. (2001). Evaluation of non-conventional water resources supply in Jordan. *Desalination, 136*, 83 – 92.

Jakiel, P., & Fabianowski, D. (2015) FAHP model used for assessment of highway RC bridge structural and technological arrangements. *Expert Systems with Applications, 42*, 4054-4061. https://doi.org/10.1016/j.eswa.2014.12.039.

Jalaei, F., Jrade, A., & Nassiri, M. (2015). Integrating Decision Support System (DSS) and Building Information Modeling (BIM) to Optimize the Selection of Sustainable Building Components. *Journal of Information Technology in Construction, 20*, 399-420.

Jato-Espino, D., Rodriguez-Hernandez, J., Andrés-Valeri, V., & Ballester-Muñoz, F. (2014). A fuzzy stochastic multi-criteria model for the selection of urban pervious pavements. *Expert Systems with Applications, 41*, 6807 – 6817. https://doi.org/10.1016/j.eswa.2014.05.008.

JCSS (2001). Probabilistic Model Code. Zurich: Joint Committee on Structural Safety. ISBN 978-3-909386-79-6.

Jørgensen, A. (2013). Social LCA—a way ahead? *International Journal of Life Cycle Assessment, 18*, 296–299. https://dx.doi.org/10.1007/s11367-012-0517-5.

Jovanovic, M., Afgan, N., Radovanovic, P., & Stevanovic, V. (2009). Sustainable development of the Belgrade energy system. *Energy, 34*, 532-539. https://doi.org/10.1016/j.energy.2008.01.013.

Kabir, G., Sadiq, R., & Tesfamariam, S. (2014). A review of multi-criteria decision-making methods for infrastructure management. *Structure and Infrastructure Engineering, 10*, pp. 1176-1210. https://doi.org/10.1080/15732479.2013.795978.

Kahraman, C., Cebi, S., Onar, S. C., & Oztaysi, B. (2018). A novel trapezoidal intuitionistic fuzzy information axiom approach: An application to multicriteria landfill site selection. *Engineering Applications of Artificial Intelligence, 67*, 157-172. https://doi.org/10.1016/j.engappai.2017.09.009.

Kamali, M., Hewage, K., & Milani, A. S. (2018). Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices. *Building and Environment, 138*, 21-41. https://doi.org/10.1016/j.buildenv.2018.04.019.

Kaya, T., & Kahraman, C. (2010). Multicriteria renewable energy planning using an integrated fuzzy VIKOR and AHP methodology: The case of Istanbul. *Energy, 35*, pp. 2517 – 2527. https://doi.org/10.1016/j.energy.2010.02.051.

Kaya, I., Çolat, M., & Terzi, F. (2018) .Use of MCDM techniques for energy policy and decision-making problems: A review. *Energy Research, 42*, 2344-2372. https://doi.org/10.1002/er.4016.

Kendall, A., Keoleian, G. A., & Helfand, G. E. (2008). Integrated life-cycle assessment and lifecycle cost analysis model for concrete bridge deck applications. *Journal of Infrastructure Systems, 14*, 214–22. https://dx.doi.org/10.1061/(ASCE)1076-0342(2008)14:3(214).

Kere, K., & Huang, Q. (2019). Life-cycle cost comparison of corrosion management strategies for steel bridges. *Journal of Bridge Engineering, 24*. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001361.

Khan, S. A., Chaabane, A., & Dweiri, F. T. (2018). Multi-criteria decision-making methods application in supply chain management: A systematic literature review. *IntechOpen*. http://dx.doi.org/10.5772/intechopen.74067.

Klein, S., & Whalley, S. (2015). Comparing the sustainability of U. S. electricity options through multi-criteria decision analysis. *Energy Policy, 79*, 127-149. http://dx.doi.org/10.1016/j.enpol.2015.01.007.

Kripka, M., Yepes, V., & Milani, C. J. (2019). Selection of sustainable short-span bridge design in Brazil. *Sustainability, 11*. https://doi.org/10.3390/su11051307.

Kucukvar, M., Gumus, S., Egilmez, G., & Tatari, O. (2014). Ranking the sustainability performance of pavements: An intuitionistic fuzzy decision making method. *Automation in Construction, 40*, 33 – 43. https://doi.org/10.1016/j.autcon.2013.12.009.

Kyriacou, A., Muinelo-Gallo, L., Roca-Sagalés, O. (2019).The efficiency of transport infrastructure investment and the role ofgovernment quality: An empirical analysis. *Transport Policy*, *74*, 93-102. https://doi.org/10.1016/j.tranpol.2018.11.017.

Lagerblad, B. (2005). Carbon dioxide uptake during concrete life-cycle: State of the art. Swedish Cement and Concrete Research Institute, Stockholm.

Lee, E. B., Kim, C., & Harvey, J. T. (2011). Value analysis using performance attributes matrix for highway rehabilitation projects: California Interstate 80 Sacramento case. *Transportation Research Record: Journal of the Transportation Research Board, 2228*, 23–32. https://doi.org/10.3141/2227-03.

León, J., Prieto, F., & Rodríguez, F. (2013). Proyecto de rehabilitación del puente de la Isla de Arosa. *Hormigón y Acero, 270*: 75-89.

Li, T., Zhang, H., Liu, Z., Ke, Q., & Alting, L. (2014). A system boundary identification method for life cycle assessment. *International Journal of Life Cycle Assessment, 19*, 646-660. https://doi.org/ 10.1007/s11367-013-0654-5.

Liang, R., Wang, J., & Zhang, H. (2018). A multi-criteria decision-making method based on single-valued trapezoidal neutrosophic preference relations with complete weight information. *Neural Computing and Applications, 30(11)*, 3383-3398. https://doi.org/10.1007/s00521-017-2925-8.

Liu, P., & Liu, Xi. (2018) The neutrosophic number generalized weighted power averaging operator and its application in multiple attribute group decision making. *International Journal of Machine Learning and Cybernetics, 9(2)*, 347-358. https://doi.org/10.1007/s13042-016-0508-0.

Liu, G., Stavem, P., & Gjørv, O.E. (2005). Effect of Surface Hydrophobation for Protection of Early Age Concrete Against Chloride Penetration. *Proceedings of the Fourth International Conference on Water Repellent Treatment of Building Materials*, ed. J. Silfwerbrand, Aedificatio Publishers, Freiburg, 93–104.

Lombera, J., & Aprea, I. (2010). A system approach to the environmental analysis of industrial buildings. *Building and Environment, 45*, 673 – 683. https://doi.org/10.1016/j.buildenv.2009.08.012.

Lounis, Z., & Daigle, L. (2010). Towards sustainable design of highway bridges. National Research Council of Canada. https://dx.doi.org/ 10.1201/b10430-178.

Maes, M., Caspeele, R., Van den Heede, P., & De Belie, N., (2012). Influence of sulphates on chloride diffusion and the effect of this on service life prediction of concrete in a submerged marine environment. *IALCCE 2012: proceedings of the third international symposium on life-cycle civil engineering,* 899-906. http://hdl.handle.net/1854/LU-3023500.

Maes, M., & De Belie, N. (2014). Resistance of concrete and mortar against combined attack of chloride and sodium sulphate. *Cement and Concrete Composites, 53*, 59–72. https://dx.doi.org/https://doi.org/10.1016/j.cemconcomp.2014.06.013.

Mahdiraji, H., Arzaghi, S., Stauskis, G., & Zavadskas, E. K. (2018). A hybrid fuzzy BWM-COPRAS method for analyzing key factors of sustainable architecture. *Sustainability, 10*. https://doi.org/10.3390/su10051626.

Malekly, H., Mousavi, S., & Hashemi, H. (2010). A fuzzy integrated methodology for evaluating conceptual bridge design. *Expert Systems with Applications, 37*, 4910 – 4920. https://doi.org/10.1016/j.eswa.2009.12.024.

Manera, M., Vennesland, Ø., & Bertolini, L. (2008). Chloride threshold for rebar corrosion in concrete with addition of silica fume. *Corrosion Science, 50*, 554–60. http://dx.doi.org/10.1016/j.corsci.2007.07.007.

Mardani, A., Jusoh, A., Nor, K., Khalifah, Z., Zakwan, N. & Valipour, A. (2015). Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014. *Economic Research, 28*. https://doi.org/10.1080/1331677X.2015.1075139.

Margallo, M., Aldaco, R., & Irabien, Á. (2014). Environmental management of bottom ash from municipal solid waste incineration based on a life cycle assessment approach. *Clean Technologies and Environmental Policy, 16*, 1319. http://dx.doi.org/10.1007/s10098-014-0761-4.

Martí, J. V., García-Segura, T., & Yepes, V. (2016). Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy. *Journal of Cleaner Production, 120*, 231-240. https://dx.doi.org/10.1016/j.jclepro.2016.02.024.

Martí, J. V., González-Vidosa, F., Yepes, V., & Alcalá, J. (2013). Design of prestressed concrete precast road bridges with hybrid simulated annealing. *Engineering Structures, 48*, 342-52. http://dx.doi.org/10.1016/j.engstruct.2012.09.014.

Martí, J. V., Yepes, V., & González-Vidosa, F. (2015). Memetic algorithm approach to designing of precast-prestressed concrete road bridges with steel fiber-reinforcement. *Journal of Structural Engineering, 141(2)*, 04014114. http://dx.doi.org/10.1061/(ASCE)ST.1943-541X.0001058.

Martin, C., Ruperd, Y., & Legret, M. (2007). Urban stormwater drainage management: the development of a multicriteria decision aid approach for best management practices. *European Journal of Operational Research, 181*, 338 – 349. https://doi.org/10.1016/j.ejor.2006.06.019.

Martínez-Blanco, J., Lehmann, A., Muñoz, P., Antón, A., Traverso, M., Rieradevall, J., & Finkbeiner, M. (2014). Application challenges for the social life cycle assessment of fertilizers within life cycle sustainability assessment. *Journal of Cleaner Production, 69*, 34–48. https://doi.org/10.1016/j.jclepro.2014.01.044.

Martínez-Martin, F., Gonzalez-Vidosa, F., Hospitaler, A., & Yepes, V. (2012). Multi-objective optimization design of bridge piers with hybrid heuristic algorithms. *Journal of Zhejiang University SCIENCE A, 13(6)*, 420-432. http://dx.doi.org/10.1631/jzus.A1100304.

Marzourk, M., & Azab, S. (2014). Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. *Resources, Conservation and Recycling, 82*, 41-49. http://dx.doi.org/10.1016/j.resconrec.2013.10.015.

Medeiros, M., Castro-Borges, P., Aleixo, D., Quarcioni, V. A., Marcondes, C., & Helene, P. (2012). Reducing water and chloride penetration through silicate treatments for concrete as a mean to control corrosion kinetics. *International Journal of Electrochemical Science, 7*, 9682-9696. https://dx.doi.org/10.1016/S09500618(00)00043-X.

Medina-González, S., Espuña, A., & Puigjaner, L. (2018). An efficient uncertainty representation for the design of sustainable energy generation systems. *Chemical Engineering Research and Design, 1231*, 144-159. https://doi.org/10.1016/j.cherd.2017.11.044.

Meent, D., & Klepper, O. (1997). Mapping the potential affected fraction (PAF) of species as an indicator of generic toxic stress. RIVM Report 607504001. RIVM, Bilthoven.

Mikawi, M. (1996). A methodology for the evaluation of the use of advanced composites in structural civil engineering applications. *Composites Part B, 27*, 203 – 215. https://doi.org/10.1016/1359-8368(95)00030-5.

Millman, L. R., & Giancaspro, J. W. (2012). Environmental Evaluation of Abrasive Blasting with Sand, Water, and Dry Ice. *International Journal of Architecture, Engineering and Construction, 1*, 174–82. https://dx.doi.org/10.7492/IJAEC.2012.019.

Mistry, M., Koffler, C., & Wong, S. (2016). LCA and LCC of the world's longest pier: a case study on nickel-containing stainless steel rebar. *International Journal of Life Cycle Assessment, 21*, 1637e1644. https://doi.org/10.1007/s11367-016-1080-2.

Miyazato, S., & Otsuki, N. (2010). Steel corrosion induced by chloride or carbonation in mortar with bending cracks or joints. *Journal of Advanced Concrete Technology, 8*, 135–44. http://dx.doi.org/10.3151/jact.8.135.

Moazami, D., Behbahani, H., & Muniandy, R. (2011). Pavement rehabilitation and maintenance prioritization of urban roads using fuzzy logic. *Expert Systems with Applications, 38(10)*, 12869-12879. https://doi.org/10.1016/j.eswa.2011.04.079.

Molina-Moreno, F., Martí, J. V., & Yepes, V. (2017). Carbon embodied optimization for buttressed earth-retaining walls: implications for low-carbon conceptual designs. *Journal of Cleaner Production, 164*, 872-884. http://dx.doi.org/10.1016/j.jclepro.2017.06.246.

Montajabiha, M. (2016). An extended PROMETHE II multi-criteria group decision making technique based on intuitionistic fuzzy logic for sustainable energy planning. *Group Decision and Negotiation, 25*, 221 – 244. http://dx.doi.org/10.1007/s10726-015-9440-z.

Montalbán-Domingo, L., García-Segura, T., Sanz, M. A., & Pellicer, E. (2018). Social sustainability criteria in public-work procurement: An international perspective. *Journal of Cleaner Production, 198*, 1355-1371. https://doi.org/10.1016/j.jclepro.2018.07.083.

Mosalam, K. M., Alibrandi, U., Lee, H., & Armengou, J. (2018). Performance based engineering and multi-criteria decision analysis for sustainable and resilient building design. *Structural Safety, 74*, 1-13. https://doi.org/10.1016/j.strusafe.2018.03.005.

Mosquera-Rey, E. R. (2015). Revision of validity for the factor of safety (EHE-08) of the service life in structures under chlorides. *Informes de la Construcción, 67*, e082. http://dx.doi.org/10.3989/ic.13.127.

Motuziene, V., Rogoza, A., Lapinskiene, V., & Vilutiene, T. (2016). Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: a case study. *Journal of Cleaner production, 112*, 532-541. http://dx.doi.org/10.1016/j.jclepro.2015.08. 103.

Moussavi, Z., Akbarnezhad, A., Ferre, J., & Xiao, J. (2017). Multi-criteria selection of façade systems based on sustainability criteria. *Building and environment, 121*, 67-78. https://doi.org/10.1016/j.buildenv.2017.05.016.

Murray, C., & Lopez, A. (1996). The global burden of disease. WHO World Bank and Harvard School of Public Health, Boston.

NACE – National Association of Corrosion Engineers (2016). International measures of prevention, application and economics of corrosion technologies study. NACE International, Houston.

Nassar, F. A., Ruparathna, R., Chhipi-Shrestha, G., Haider, H., Hewage, K., & Sadiq, R. (2016). Sustainability assessment framework for low rise commercial buildings: life cycle impact index-based approach. *Clean Technologies and Environmental Policy, 18*, 2579-25910. https://doi.org/10.1007/s10098-016-1168-1.

Navarro, I. J., Martí, J. V., & Yepes, V. (2018a). Life cycle cost assessment of preventive strategies applied to prestressed concrete bridges exposed to chlorides. *Sustainability, 10(3)*, 845. https://doi.org/10.3390/su10030845.

Navarro, I. J., Martí, J. V., & Yepes, V. (2019). Reliability-based maintenance optimization of corrosion preventive designs under a life cycle perspective. *Environmental Impact Assessment Review, 74*, 23-34. https://doi.org/10.1016/j.eiar.2018.10.001.

Navarro, I. J., Yepes, V., & Martí, J. V. (2018b). Social life cycle assessment of concrete bridge decks exposed to aggressive environments. *Environmental Impact Assessment Review, 72*, 50-63. https://doi.org/10.1016/j.eiar.2018.05.003.

Navarro, I. J., Yepes, V., Martí, J. V., & González-Vidosa, F. (2018c) Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks. *Journal of Cleaner Production*, *196*, 698-713. https://doi.org/10.1016/j.jclepro.2018.06.110.

NCE – The New Climate Economy (2016). The Sustainable Infrastructure Imperative. ISBN 978-0-9906845-9-6

Nogueira, C. G., Leonel, E. D., & Coda, H. B. (2012). Reliability algorithms applied to reinforced concrete structures durability assessment. *Revista IBRACON de Estruturas e Materiais, 5(4)*, 440–450. http://dx.doi.org/10.1590/S1983-41952012000400003.

Nokken, M., Boddy, A., Hooton, R. D., & Thomas, M. D. A. (2006). Time dependent diffusion in concrete—three laboratory studies. *Cement and Concrete Research, 36*, 200–7. https://dx.doi.org/10.1016/j.cemconres.2004.03.030.

Noryani, M., Sapuan, S. M., & Mastura, M. T. (2018). Multi-criteria decision-making tools for material selection of natural fibre composites: A review. *Journal of Mechanical*

Engineering and Sciences, 12, 3330-3353. https://doi.org/10.15282/jmes.12.1.2018.5.0299.

OECD (2008). Handbook on constructing composite indicators: Methodology and user guide. OECD Publications, Paris, France. ISBN: 978-92-64-04345-9.

Ohama, Y. (1995). Handbook of Polymer-Modified Concrete and Mortars. William Andrew. ISBN: 978-0815513582.

Olivier, J., Janssens-Maenhout, G., Muntean, M., & Peters, J. (2016). Trends in global CO2 emissions: 2016 Report. The Hague: PBL Netherlands Environmental Assessment Agency.

Oses, U., Rojí, E., Cuadrado, J., & Larrauri, M. (2017). Multiple-criteria decision-making tool for local governments to evaluate the global and local sustainability of transportation systems in urban areas: Case study. *Journal of Urban Planning and Development, 144*. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000406.

Otsuki, N., Nishida, T., Yi, C., & Nagata, T. (2014). Effect of blast furnace slag powder and fly ash on durability of concrete mixed with seawater. *4th International Conference on the durability of concrete structures*, 24-26 July 2014. Purdue University, West Lafayette, In, USA. http://dx.doi.org/10.5703/1288284315406.

Özkan, A., Günkaya, Z., Tok, G., Karacasulu, L., Metesoy, M., Banar, M., & Kara, A. (2016). Life cycle assessment and life cycle cost analysis of magnesia spinel brick production. *Sustainability, 8*, 662. https://dx.doi.org/10.3390/su8070662.

Ozturk, O., Ozbay, K., Yang, H., & Bartin, B. (2013). Crash Frequency Modeling for Highway Construction Zones. *Transportation Research Board's 92nd Annual Meeting*, Washington, D.C.

Pamucar, D., Badi, I., Sanja, K., & Obradovic, R. (2018). A Novel Approach for the Selection of Power-Generation Technology Using a Linguistic Neutrosophic CODAS Method: A Case Study in Libya. *Energies, 11(9)*, 2489. https://doi.org/10.3390/en11092489.

Pan, X., Shi, Z., Shi, C., Ling, T.C., & Li, N.. (2017). A review on concrete surface treatment Part I: types and mechanisms. *Construction and Building Materials, 132*, 578-590. https://dx.doi.org/http://dx.doi.org/10.1016/j.conbuildmat.2016.12.025.

Pang, B., Yang, P., Wang, Y., Kendall, A., Xie, H., & Zhang, Y. (2015). Life cycle environmental impact assessment of a bridge with different strenghtening schemes. *International Journal of Life Cycle Assessment, 20*, 1300-1311. http://dx.doi.org/10.1007/s11367-015-0936-1.

Pascal, U., Xie, Q., & Xu, L. (2017). A fuzzy TOPSIS model framework for ranking sustainable water supply alternatives. *Water Resources Management, 31*, 2579 – 2593. https://doi.org/10.1007/s11269-017-1636-3.

Pelletier, N., Ardente, F., Brandão, M., De Camillis, C., & Pennington, D. (2015). Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible? *International Journal of Life Cycle Assessment, 20*, 74–86. http://dx.doi.org/10.1007/s11367-014-0812-4.

Penadés -Plà, V., García-Segura, T., Martí, J.V., & Yepes, V. (2016). A review of multi-criteria decision making methods applied to the sustainable bridge design. *Sustainability, 8(12)*, 1295. http://dx.doi.org/10.3390/su8121295.

Penadés-Plà, V., García-Segura, T., Martí, J. V., & Yepes, V. (2019). A review of multi-criteria decision-making methods applied to the sustainable bridge design. *Sustainability, 8*. https://doi.org/10.3390/su8121295.

Penadés-Plà, V., García-Segura, T., Martí, J.V., & Yepes, V. (2018). An optimization-LCA of a prestressed concrete precast bridge. *Sustainability, 10*, 685. https://dx.doi.org/https://doi.org/ 0.3390/su10030685.

Penadés-Plà, V., Martí, J. V., García-Segura, T., & Yepes, V. (2017). Life cycle assessment: a comparison between two optimal post-tensioned concrete box-girder road bridges. *Sustainability, 9*, 1864. https://dx.doi.org/10.3390/su9101864.

Peng, J. J., Wang, J., & Yang, W. (2017). A multi-valued neutrosophic qualitative flexible approach based on likelihood for multi-criteria decision-making problems. *International Journal of Systems Science, 48(2)*, 425-435. https://doi.org/10.1080/00207721.2016.1218975.

Pérez-Fadón, S. (1985). Puente a la Isla de Arosa. *Hormigón y Acero, 157*, 197-218.

Pérez-Fadón, S. (1986). Puente sobre la Ría de Arosa. *Revista de Obras Públicas*. January 1986: 1-16.

Perini, K., & Rosasco, P. (2013). Cost-benefit analysis for green façades and living wall systems," *Building and Environment, 70*, 110-121. https://doi.org/10.1016/j.buildenv.2013.08.012.

Petcherdchoo, A. (2012). Predicting service life and cost of chloride exposed concrete structures with repairs by cover replacement or silane treatment. *Proceeding of the 17th National Convention on Civil Engineering: Civil Engineering for Integrated Developments*, Udon Thani, 9-11 May 2012.

Petcherdchoo, A. (2015). Environmental impacrts of combined repairs on marine concrete structures. *Journal of Advanced Concrete Technology, 13*, 205-213. http://dx.doi.org/10.3151/jact.13.205.

Pires, A., Chang, N. B., & Martinho, G. (2011). An AHP-based fuzzy interval TOPSIS assessment for sustainable expansion of the solid waste management system in Setúbal Peninsula, Portugal. *Resources, Conservation and Recycling, 56*, pp. 7-21. https://doi.org/10.1016/j.resconrec.2011.08.004.

Podvezko, V. (2011). The comparative analysis of MCDA methods SAW and COPRAS. *Engineering Economics*, *22*. http://dx.doi.org/10.5755/j01.ee.22.2.310.

Pons, O., & Aguado, A. (2012). Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain. *Building and Environment, 53*, 49-58. https://doi.org/10.1016/j.buildenv.2012.01.007.

Pons, O., & De la Fuente, A. (2013). Integrated sustainability assessment method applied to structural concrete columns. *Construction and Building Materials, 49*, 882 – 893. https://doi.org/10.1016/j.conbuildmat.2013.09.009

Pons, O., De la Fuente, A., Armengou, J., & Aguado, A. (2017). Towards the sustainability in the design of wind towers. *Energy Procedia, 115*, 41 – 49. https://doi.org/10.1016/j.egypro.2017.05.005.

Prascevic, N., & Prascevic, Z. (2017). Application of fuzzy AHP for ranking and selection of alternatives in construction project management. *Journal of Civil Engineering and Management, 23(8)*, 1123-1135. https://doi.org/10.3846/13923730.2017.1388278.

Pryn, M. R., Cornet, Y., & Salling, K. B. (2015). Applying sustainability theory to transport infrastructure assessment using a multiplicative AHP decision support model. *Transport, 30(3)*, 330-341. https://doi.org/10.3846/16484142.2015.1081281.

Radwan, N., Senousy, M., & Riad, A. (2016). Neutrosophic AHP Multi-Criteria Decision Making method applied on the selection of learning management system. *International Journal of Advancements in Computing Technology, 8(5)*, 95-105.

Ramesh, T., Prakash, R., & Shukla, K. (2010). Life cycle energy analysis of buildings: An overview. Energy and Buildings, 42(10), 1592-1600. http://dx.doi.org/10.1016/j.enbuild.2010.05.007.

Rashidi, M., Ghodrat, M.,Samali, B., Kendall, B., & Zhang, C. (2017). Remedial mdoelling of steel bridges through application of Analytical Hierarchy Process (AHP). *Applied Sciences, 7*. https://doi.org/10.3390/app7020168.

Rashidi, M., Samali, B., & Sharafi, P. (2016). A new model for bridge management: Part B: decision support system for remediation planning. *Australian Journal of Civil Engineering, 14*, 46 – 53. https://doi.org/10.1080/14488353.2015.1092642.

Renganath, K., & Suresh, M. (2016) Supplier selection using fuzzy MCDM techniques: A literature review. *IEEE International Conference on Computational Intelligence and Computing Research (ICCIC)*. https://doi.org/10.1109/ICCIC.2016.7919590.

Reyes, J., San-José, J., Cuadrado, J., & Sancibrian, R. (2014). Health and safety criteria for determining the sustainable value of construction projects. *Safety Science, 62*, 221 – 232. https://doi.org/10.1016/j.ssci.2013.08.023.

Reza, B., Sadiw, R., & Hewage, K. (2011). Sustainability assessment of flooring systems in the city of Tehran: An AHP life cycle analysis. *Construction and Building Materials, 25*, 2053-2066. https://doi.org/10.1016/j.conbuildmat.2010.11.041.

Rochikashvili, M., & Bongaerts, J. (2016). Multi-criteria decision-making for sustainable wall paints and coatings using Analytic Hierarchy Process. *Energy Procedia, 96*, 923 – 933. https://doi.org/10.1016/j.egypro.2016.09.167.

Roszkowska, E. (2011). Multi-criteria decision making models by applying the TOPSIS method to crisp and interval data. *Multiple Criteria Decision Making, 6.*

Saaty, T. L. (1980). The Analytic Hierarchy Process. New York, NY: McGraw-Hill.

Sabatino, S., Frangopol, D., & Dong, Y. (2016). Life cycle utility-informed maintenance planning based on lifetime functions: optimum balancing of cost, failure consequences and performance benefit. *Structure and Infrastructure Engineering, 12(7)*, 830-847. https://doi.org/10.1080/15732479.2015.1064968.

Safi, M., Sundquist, H., & Karoumi, R. (2015). Cost-efficient procurement of bridge infrastructures by incorporating life-cycle cost analysis with bridge management systems. *Journal of Bridge Engineering, 20*, 4014083. https://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000673.

Sajedi, S., & Huang, Q. (2019). Reliability-based life-cycle-cost comparison of different corrosion management strategies. *Engineering Structures, 186*, 52-63. https://doi.org/10.1016/j.engstruct.2019.02.018.

Samani, P., Mendes, A., Leal, V., Guedes, J., & Correia, N. (2015). A sustainability assessment of advanced materials for novel housing solutions. *Building and Environment, 92*, 182 – 191. https://doi.org/10.1016/j.buildenv.2015.04.012.

Sanjuan-Delmás, D., Hernando-Canovas, E., Pujadas, P., De la Fuente, A., Gabarrell, X., Rieradevall, J., & Josa, A. (2015). Environmental and geometric optimisation of cylindrical drinking water storage tanks. *International Journal of Life Cycle Assessment, 20(12)*, 1612–1624. http://dx.doi.org/10.1007/s11367-015-0963-y.

Santos, J., Bressi, S., Cerezo, V., & Presti, D. (2019). SUP&R DSS: A sustainability-based decision support system for road pavements. *Journal of Cleaner Production, 206*, 524-540. https://doi.org/10.1016/j.jclepro.2018.08.308.

Saparauskas, J. (2007). The main aspects of sustainability evaluation in construction. *9th International Conference on Modern Building Materials, Structures and Techniques*, Vilnius, Lithuania.

Saparauskas, J., Zavadskas, E. K., & Turskis, Z. (2010). Evaluation of alternative building designs according to the three criteria of optimality. *10nd International Conference on Modern Building, structures and Techniques*, Vilnius, Lithuania.

Šavija, B., & Schlangen, E. (2012). Chloride ingress in cracked concrete—A literature review. In *Proceedings of the International PhD Conference on Concrete Durability*, Madrid, Spain, 19 November 2010, Andrade, C., Gulikers, J., Eds., RILEM Publications: Madrid, Spain, 2012, 133–142.

Scholten, L., Schuwirth, N., Reichert, P., & Lienert, J. (2015). Tackling uncertainty in multi-criteria decision analysis–An application to water supply infrastructure planning. *European Journal of Operational Research*, *242*, 243-260. https://doi.org/10.1016/j.ejor.2014.09.044.

Seshadri, P., & Harrison, R. (1993). Workzone mobile source emission prediction. Center of Transportation Research. University of Texas at Austin.

Shaheen, F., & Pradhan, B. (2015). Effect of chloride and conjoint chloride–sulfate ions on corrosion of reinforcing steel in electrolytic concrete powder solution (ECPS). *Construction and Building Materials, 101*, 99–112. https://dx.doi.org/https://doi.org/10.1016/j.conbuildmat.2015.10.028.

Shemfe, M., Gadkari, S., & Sadhukhan, J. (2018). Social hotspot analysis and trade policy implications of the use of bioelectrochemical systems for resource recovery from wastewater. *Sustainability, 10*, 3193. https://doi.org/10.3390/su10093193.

Shen, L. Y., Lu, W. S., Yao, H., & Wu, D. H. (2005). A computer-based scoring method for measuring the environmental performance of construction activities. *Automation in Construction, 14*, 297-309.

Shi, J., & Sun, W. (2013). Effects of phosphate on the chloride-induced corrosion behavior of reinforcing steel in mortars. *Cement and Concrete Composites, 45*, 166-175. http://dx.doi.org/10.1016/j.cemconcomp.2013.10.002.

Shin, Y. B., Lee, S., Chun, S. G., & Chung, D. (2013). A critical review of popular multi-criteria decision making methodologies. *Issues in Information Systems, 14*, 358-365.

Sierra, L. A., Yepes, V., & Pellicer, E. (2018a). A review of multi-criteria assessment of the social sustainability of infrastructures. *Journal of Cleaner Production, 187*, 496-513. https://doi.org/10.1016/j.jclepro.2018.03.022.

Sierra, L. A., Pellicer, E., & Yepes, V. (2016). Social sustainability in the life cycle of chilean public infrastructure. *Journal of Construction Engineering and Management, 142(5)*. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001099.

Sierra, L. A., Pellicer, E., & Yepes, V. (2017a). Assessing the social sustainability contribution of an infrastructure project under conditions of uncertainty. *Environmental Impact Assessment Review, 67*, 61-72. https://doi.org/10.1016/j.eiar.2017.08.003.

Sierra, L. A., Pellicer, E., & Yepes, V. (2017b). Method for estimating the social sustainability of infrastructure projects. *Environmental Impact Assessment Review, 65*, 41-53. https://dx.doi.org/10.1016/j.eiar.2017.02.004.

Sierra, L. A., Yepes, V., García-Segura, T., & Pellicer, E. (2018b). Bayesian network method for decision-making about the social sustainability of infrastructure projects. *Journal of Cleaner Production*, *176*, 521-534. http://dx.doi.org/1016/j.jclepro.2017.12.140.

Sirivivatnanon, V., Khatri, R. P., Lacasse, M. A., & Vanier, D. J. (1999). Characterising chloride penetration resistance of concrete: Chloride penetration resistance of concrete. *Durability of Building Materials and Components, 8*, 386-398.

Sitorus, F., Cilliers, J. J., & Brito-Parada, P. R. (2019). Multi-criteria decision making for the choice problem in mining and mineral processing: Applications and trends. *Expert Systems with Applications, 121*, 393-417. https://doi.org/10.1016/j.eswa.2018.12.001.

Smarandache, F. (1999). A Unifying Field in Logics, Neutrosophy: Neutrosophic Probability, Set and Logic. *Rehoboth, NM: American Research Press*.

Sodenkamp, M. A., Tavana, M., & Di Caprio, D. (2018). An aggregation method for solving group multi-criteria decision-making problems with single-valued neutrosophic sets. *Applied Soft Computing, 71*, 715-727. https://doi.org/10.1016/j.asoc.2018.07.020.

Soliman, M., & Frangopol, D. M. (2014). Life-cycle cost evaluation of conventional and corrosion-resistant steel for bridges. *Journal of Bridge Engineering, 20 (1)*. https://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000647.

Spanish Ministry of Public Works (2008). EHE-08 Instrucción del Hormigón Estructural. ISBN: 978-84-498-0899-9.

Stewart, M. G., Estes, A. C., & Frangopol, D. M. (2004). Bridge deck replacement for minimum expected cost under multiple reliability constraints. *Journal of Structural Engineering, 130*. https://doi.org/10.1061/(ASCE)0733-9445(2004)130:9(1414).

Suh, S., Lenzen, M., Treloar, G., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., & Norris, G. (2004) System boundary selection in life-cycle inventories using hybrid approaches. *Environmental Sience & Technology, 38*. https://doi.org/ 10.1021/es0263745.

Sun, X., Ning, P., Tang, X., Yi, H., Li, K., Zhou, L., & Xu, X. (2013). Environmental risk assessment system for phosphogypsum tailing dams. *The Scientific World Journal, 2013*. http://dx.doi.org/10.1155/2013/680798.

Swarr, T., Hunkeler, D., Klöpffer, W., Pesonen, H., Ciroth, A., Brent, A., & Pagan, R. (2011). Environmental life-cycle costing: a code of practice. *International Journal of Life Cycle Assessment, 16*, 389-391. https://dx.doi.org/10.1007/s11367-011-0287-5.

Tahmasebi, Y., & Yazdandoost, F. (2018). An integrated framework to evaluate resilient-sustainable urban drainage management plans using a combined-adaptive

MCDM technique. *Water Resources Management, 32*, 2817–2835. https://doi.org/10.1007/s11269-018-1960-2.

Tait, M., & Cheung, W. (2016). A comparative cradle-to-gate life cycle assessment of three concrete mix designs. *International Journal of Life Cycle Assessment, 21(6)*, 847-860. http://dx.doi.org/10.1007/s11367-016-1045-5.

Terracciano, G., Di Lorenzo, G., Formisano, A., & Landolfo, R. (2015). Cold-formed thin-walled steel structures as vertical addition and energetic retrofitting systems of existing masonry buildings. *European Journal of Environmental and Civil Engineering, 19*. https://doi.org/10.1080/19648189.2014.974832.

Tesfamariam, S., & Sadiq, R. (2006). Risk-based environmental decision-making fuzzy analytic hierarchy process (F-AHP). *Stochastic Environmental Research and Risk Assessment, 21*, 35–50. https://doi.org/10.1007/s00477-006-0042-9.

Texeira, E. R., Mateus, R., Camões, A. F., & Bragança, L. (2016). Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. *Journal of Cleaner Production, 112*, 2221-2230. http://dx.doi.org/10.1016/j.jclepro.2015.09.124.

Thor, J., Ding, S., & Kamaruddin, S. (2013). Comparison of Multi Criteria Decision Making methods from the maintenance alternative selection perspective. *The International Journal of Engineering and Science, 2*, 27-34.

Titi, A., & Biondini, F. (2016). On the accuracy of diffusion models for life-cycle assessment of concrete structures. *Structure and Infrastructure Engineering, 12*, 1202–15. https://dx.doi.org/10.1080/15732479.2015.1099110.

Torres-Machí, C., Chamorro, A., Pellicer, E., Yepes, V., & Videla, C. (2015). Sustainable Pavement Management. Integrating Economic, Technical, and Environmental Aspects in Decision Making. *Transportation Research Record, 2523*, 56 – 63. https://doi.org/10.3141/2523-07.

Torres-Machi, C., Pellicer, E., Yepes, V., & Chamorro, A. (2017). Towards a sustainable optimization of pavement maintenance programs under budgetary restrictions. *Journal of Cleaner Production*, 148, 90-102. https://dx.doi.org/https://doi.org/10.1016/j.jclepro.2017.01.100.

Tuutti, K. Corrosion of steel in concrete. (1982). *Swedish Cement and Concrete Research Institute*, Report No 4-82.

Ugwu, O., & Haupt, T. (2007). Key performance indicators and assessment methods for infrastructure sustainability – a South African construction industry perspective. *Building and Environment, 42*, 665 – 680. https://doi.org/10.1016/j.buildenv.2005.10.018.

Umair, S., Björklund, A., & Ekener-Petersen, E. (2015). Social impact assessment of informal recycling of electronic ICT waste in Pakistan using SETAC SETAC guidelines. *Resources, Conservation and Recycling, 95*, 46–57. https://dx.doi.org/10.1016/j.resconrec.2014.11.008.

UNEP/SETAC (2009). Guidelines for Social Life Cycle Assessment of Products, United Nations Environment Program. In: Paris SETAC Life Cycle Initiative United Nations Environment Programme.

UNEP/SETAC (2013). The methodological sheets for subcategories in social life cycle assessment (S-LCA). *UNEP-SETAC Life-Cycle Initiative*, Paris, France.

Väisänen, S., Mikkilä, M., Havukainen, J., Sokka, L., Luoranen, M., & Horttanainen, M. (2016). Using a multi-method approach for decision-making about a sustainable local distributed energy system: A case study from Finland. *Journal of Cleaner Production, 137*, 1330 – 1338. https://doi.org/10.1016/j.jclepro.2016.07.173.

Valipour, M., Shekarchi, M., & Arezoumandi, M. (2017). Chlorine diffusion resistivity of sustainable green concrete in harsh marine environments. *Journal of Cleaner Production, 142*, 4092–4100. http://dx.doi.org/10.1016/j.jclepro.2016.10.015.

Van Den Heede, P., & De Belie, N. (2012). Environmental impact and life cycle assessment (LCA) of traditional and "green" concretes: Literature review and theoretical calculations. *Cement and Concrete Composites, 34*, 431–442. http://dx.doi.org/10.1016/j.cemconcomp.2012.01.004.

Van den Heede, P., & De Belie, N. (2014). A service life based global warming potential for high-volume fly ash concrete exposed to carbonation. *Construction and Building Materials*, *55*, 183-193. https://doi.org/10.1016/j.conbuildmat.2014.01.033.

Van den Heede, P., De Keersmaecker, M., Elia, A., Adriaens, A., & De Belie, N. (2017). Service life and global warming potential of chloride exposed concrete with high volumes of fly ash. *Cement and Concrete Composites, 80*, 210–23. http://dx.doi.org/10.1016/j.cemconcomp.2017.03.020.

Van den Heede, P., Maes, M., Gruyaert, E., & De Belie, N. (2012). Full probabilistic service life prediction and life cycle assessment of concrete with fly ash and blast-furnace slag in a submerged marine environment: A parameter study. International *Journal of Environment and Sustainable Development, 11*, 32–49. http://dx.doi.org/10.1504/IJESD.2012.049141.

Vedalakshmi, R., Saraswathy, V., Song, H. W., & Palaniswamy, N. (2009). Determination of diffusion coefficient of chloride in concrete using Warburg diffusion coefficient. *Corrosion Science, 51 (6)*, 1299–1307. http://dx.doi.org/10.1016/j.corsci.2009.03.017.

Velasquez, M., & Hester, P. T. (2013). An analysis of multi-criteria decision making methods. *International Journal of Operations Research, 10*, 56-66.

Velasquez, M., & Hester, P. T. (2013). An analysis of multi-criteria decision making methods. *International Journal of Operations Research, 10*, 56-66.

Vincke, P., & Brans, J. (1985). A preference ranking organization method. The PROMETHEE method for MCDM. *Management Science*, *31*, 647-656.

Walls, J., & Smith, M. (1998). Life-cycle cost analysis in pavement design: in search of better investment decisions. FHWA, U. S. Department of Transportation, FHWA-SA-98-079.

Wang, T., Lee, I., Kendall, A., Harvey, J., Lee, E., & Kim, C. (2012). Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production, 33*, 86-96. http://dx.doi.org/10.1016/j.jclepro.2012.05.001.

Wang, Y. M., & Elhag, T. M. (2006). On the normalization of interval and fuzzy weights. *Fuzzy Sets and Systems, 157(18)*, 2456–2471. https://doi.org/10.1016/j.fss.2006.06.008.

Wang, Y., Liu, J., & Elhag, T. (2008). An integrated AHP-DEA methodology for bridge risk assessment. *Computers and Industrial Engineering, 54*, 513 – 525. https://doi.org/10.1016/j.cie.2007.09.002.

WCED—World Commission on Environment and Development (1987). Our common future. Oxford University Press, Oxford ISBN: 9780192820808.

Wiertz, J., van Dijk & Latour, J. B. (1992). MOVE: Vegetatie-module; de kans op voorkomen van 700 plantensoorten als functie van vocht, pH, nutriënten en zout. RIVM report 711901006. RIVM, Bilthoven.

Wilhelm, M., Hutchins, M., Mars, C., & Benoit-Norris, C. (2015). An overview of social impacts and their corresponding improvement implications: a mobile phone case study. *Journal of Cleaner Production, 102*, 302–315. https://dx.doi.org/10.1016/j.jclepro.2015.04.025.

Worrell, E., Price, L., Martin, N., Hendriks, C., & Meida, L. O. (2001). Carbon dioxide emissions from the global cement industry. *Annual Review of Energy and the Environment, 26*, 303–329. http://dx.doi.org/10.1146/annurev.energy.26.1.303.

Xi, Y., & Bažant, Z. P. (1999). Modeling Chloride Penetration in Saturated Concrete. *Journal of Materials in Civil Engineering, 11*, 58–65. http://dx.doi.org/10.1061/(ASCE)0899-1561(1999)11:1(58).

Yang, Z., Shi, X., Creighton, A. T., & Peterson, M. M. (2009). Effect of styrene–butadiene rubber latex on the chloride permeability and microstructure of Portland cement mortar. *Construction and Building Materials, 23(6)*,2283-2290. https://doi.org/10.1016/j.conbuildmat.2008.11.011.

Yang, K.H., Singh, J., Lee, B.Y., & Kwon, S.J. (2017). Simple technique for tracking chloride penetration in concrete based on the crack shape and width under steady-state conditions. *Sustainability,* *9*, 282. https://dx.doi.org/http://dx.doi.org/10.3390/su9020282.

Ye, J. (2013). Multicriteria decision-making method using the correlation coefficient under single-value neutrosophic environment. *International Journal of General Systems, 42(4)*, 386-394. https://doi.org/10.1080/03081079.2012.761609.

Ye, J. (2017). Subtraction and Division Operations of Simplified Neutrosophic Sets. *Information, 8(2)*, 51-58. https://doi.org/10.3390/info8020051.

Yepes, V., Martí, J. V., García-Segura, T., & González-Vidosa, F. (2017). Heuristics in optimal detailed design of precast road bridges. *Archives of Civil and Mechanical Engineering*, *17*, 738-749. https://doi.org/10.1016/j.acme.2017.02.006.

Yepes, V., García-Segura, T., & Moreno-Jiménez, J. (2015a). A cognitive approach for the multi-objective optimization of RC structural problems. *Archives of Civil and Mechanical Engineering, 15*, 1024 – 1036. https://doi.org/10.1016/j.acme.2015.05.001.

Yepes, V., González-Vidosa, F., Alcalá, J., & Villalba, P. (2012). CO2-Optimization Design of Reinforced Concrete Retaining Walls based on a VNS-Threshold Acceptance Strategy. *Journal of Computing in Civil Engineering, 26(3)*, 378-386. http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000140.

Yepes, V., Martí, J. V., & García-Segura, T. (2015b). Cost and CO2 emission optimization of precast-prestressed concrete U-beam road bridges by a hybrid glowworm swarm algorithm. *Automation in Construction,* *49*, 123-134. http://dx.doi.org/10.1016/j.autcon.2014.10.013.

Yepes, V., Torres-Machí, C., Chamorro, A, & Pellicer, E. (2016). Optimal pavement maintenance programs based on a hybrid greedy randomized adaptive search procedure algorithm. *Journal of Civil Engineering and Management, 22*, 540-550. https://dx.doi.org/https://doi.org/10.3846/13923730.2015.1120770.

Yu, J., Dang, B., Clements-Croome, D., & Xu, S. (2012). Sustainability assessment indicators and methodology for intelligent buildings. *Advanced Materials Research, 368 – 373*, 3829 – 3832. https://doi.org/10.4028/www.scientific.net/AMR.368-373.3829.

Zadeh, L. (1965). Fuzzy Sets. *Information and Control 8*, 338–353.

Zadeh, L. (1973). Outline of a new approach to the analysis of complex systems and decision processes. *IEEE Transactions on Systems, Man, and Cybernetics, 3*, 28–44. https://doi.org/10.1109/TSMC.1973.5408575.

Zamarrón-Mieza, I., Yepes, V., & Moreno-Jiménez, J. M. (2017). A systematic review of application of multi-criteria decision analysis for aging-dam management. *Journal of Cleaner Production, 147*, 217-230. https://doi.org/10.1016/j.jclepro.2017.01.092.

Zastrow, P., Molina-Moreno, F., García-Segura, T., Martí, J., & Yepes, V. (2017). Life cycle assessment of cost-optimized buttress earth-retaining walls: a parametric study.

Journal of Cleaner Production, 140, 1037-1048. http://dx.doi.org/10.1016/j.jclepro.2016.10.085.

Zavadskas, E. K., & Antucheviciene, J. (2007). Multiple criteria evaluation of rural building's regeneration alternatives. *Building and Environment, 42*, 436-451. https://doi.org/10.1016/j.buildenv.2005.08.001.

Zavadskas, E. K., & Antucheviciene, J. (2010). Evaluation of buildings' redevelopment alternatives with an emphasis on the multipartite sustainability. *Journal of Strategic Property Management, 8*, 121 – 128. https://doi.org/10.1080/1648715X.2004.9637512.

Zavadskas, E. K., Mardani, A., Turskis, Z., Jusoh, A., & Nor, K. (2016). Development of TOPSIS method to solve complicated decision-making problems: An overview on developments from 2000 to 2015. *International Journal of Information Technology & Decision Making, 15*. https://doi.org/10.1142/S0219622016300019.

Zewdu, W., Taffese, & Sistonen, E. (2013). Service life prediction of repaired structures using concrete recasting method: State of the art. *Procedia Engineering*, *57*, 1138-1144.

Zhang, J. Z., & Buenfeld, N. R. (2000). Chloride profiles in surface-treated mortar specimens. *Construction and Building Materials, 14*, 359–64. https://dx.doi.org/10.1016/S0950-0618(00)00043-X.

Zhang, Y. R., Wu, W. J., & Wang, Y. F. (2016). Bridge life cycle assessment with data uncertainty. *International Journal of Life cycle Assessment*, *21*, 569-576. https://doi.org/10.1007/s11367-016-1035-7.

Zhu, X., Zi, G., Cao, Z., & Cheng, X. (2016). Combined effect of carbonation and chloride ingress in concrete. *Construction and Building Materials, 110*, 369–380. https://dx.doi.org/https://doi.org/10.1016/j.conbuildmat.2016.02.034.