UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ICITECH
CIENCIA Y TECNOLOGÍA DEL HORMIGÓN

LIFE-CYCLE SUSTAINABILITY DESIGN OF POST-TENSIONED BOX-GIRDER BRIDGE OBTAINED BY METAMODEL-ASSISTED OPTIMIZATION AND DECISION-MAKING UNDER UNCERTAINTY

DOCTORAL THESIS

Autor

Vicent Penadés Plà

Directores

Dr. Victor Yepes Piqueras

Dra. Tatiana García Segura

València, December 2019

ACKNOWLEDGEMENTS

First of all, I would like to express my gratitude to my advisors: Victor and Tatiana. To Victor, for guiding me during the doctoral period, for his advices and for helping me to achieve each of the goals proposed in this doctoral thesis. To Tatiana, with whom I have worked side by side, for her great dedication, for her contributions that have allowed me to improve the work done on this doctoral thesis, and for her continuous support and encouragements. I would like to extend my appreciation to other professors with whom I have collaborated and from whom I have learned, especially Julián Alcalá, Ferran Navarro, Fernando Vidosa, and Jose Vicente Martí. Thank you all for your attention and your contributions.

I also wish to thank Professor Terje Haukaas for inviting me to join his research group at the University of British Columbia in Vancouver. It was a great opportunity to collaborate and learn in his research group, as well as to get to know a part of the world that I loved and hope to visit again.

In addition, I would like to acknowledge the economic support of the Spanish Ministry of Economy and Competitiveness, formerly called Spanish Ministry of Science and Innovation. This thesis has been possible thanks to the FPI fellowship and the financially support of BRIDLIFE (Research Project BIA2014-56574-R) and DIMALIFE (Project BIA2017-85098-R).

I would also like to remember other colleagues of this research group with whom I have worked. Those who were with me at the beginning of this way as Tatiana, Paquí, Leonardo, or Ignacio, and the newer ones as David. Also, I would like to thank all the colleagues who visited us from abroad to participate in our research group and from each of whom I have learned about other countries and customs, especially Phillip and Alexandre.

I cannot forget my colleagues and friends from ICITECH, with whom I have shared all these years. They supported me in different moments of my period at ICITECH, they advised me and they helped when I needed it. Thank you for making the day-to-day less monotonous, for the lunches *almuerzos*, and for all the moments that broke the routine. I know that after all the curinary discussions, with a little more dedication, I would have become an acceptable cooker. Someday I will cook you a *paella*. Thanks to Manolo, Aitor, Vicente, Ignazio, Elisa, Jesus, Ana, Enrique, Lourdes, Alba, Jose Manuel, y Eduard.

I must also remember the class of the *Master de Ingeniería del Hormigón*, with whom I shared the beginning of my doctoral period, probably the hardest, and they

turned it into a really great time. Thanks to all of them for being a bunch and for the *martes de confianza*. I know I have made great friends all over the world, and I hope to see you all again. I also would like to remember Raul, Salva, and Baudés with whom I started my university period. To Jose Miguel and Marina, for all the table tennis afternoons and championships shared these years. To Aguado, with whom I have shared a parallel way all these years, and every time we have gotten together we have shared nonsense things that made us laugh. To all the friends I have met at the Ausias March student residence, with whom I have lived a great time and I have built a strong friendship, especially Rivera, Marta, Sara, Raquel, Pedro, Garazi, Marina and Karim. To all my friends in Xàtiva, most of whom I have known for more than 20 years and have shared a large part of my life. Thanks for the friendly challenges, for the trips and the laughs, for the dumb jokes, the bike and the snow, for why something always happens, and for always being there.

At the end, I would like to thanks all my large family (all my uncles and cousins from Xàtiva and Canals) whose support has been essential to get everything done. Especially my uncle Rafa for always believing in everything I've done, my parents for giving me everything and supporting all my decisions, and my brother for always being there. Special mention to Lorena for being so supportive and for the daily joy of having you by my side.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Currently, there is a trend towards sustainability, especially in developed countries, where the concerns of society about environmental degradation and social problems have increased. Following this trend, the construction sector is one of the most influential sectors due to its high economic, environmental, and social impacts. At the same time, there is an increase in the demand for transport, which drives a need to develop and maintain the necessary infrastructure for this purpose. Taking all these factors into account, bridges become a key structure and therefore assessment of sustainability throughout their whole life-cycle is essential.

The main objective of this thesis is to propose a methodology that allows assessment of the sustainability of a bridge under uncertain initial conditions (subjectivity of the decision-maker or variability of initial parameters) and optimization of the design to obtain a robust optimal bridge. To this end, an extensive bibliographic review of all the works that perform assessments of the sustainability of bridges through the valuation of criteria related to their main pillars (economic, environmental, or social) has been carried out. In this review, it has been observed that the most comprehensive way to evaluate the environmental and social pillars is through the use of life-cycle impact assessment methods. These methods allow sustainability assessment to be performed for the whole life-cycle of the bridge. This process provides valuable information to decision-makers for the assessment and selection of the most sustainable bridge. However, the decision-makers' subjective assessments of the relative importance of the criteria influence the final assessment of sustainability. For this reason, it is necessary to create a methodology that reduces the associated uncertainty and seeks robust solutions according to the opinion of decision-makers.

In addition, for bridges, the design and decision-making are conditioned by the initially defined parameters. This leads to solutions that may be sensitive to small changes in these initial conditions. A robust optimal design makes it possible to obtain optimal solutions and structurally stable designs under variations of the initial conditions as well as sustainable designs that are not influenced by the preferences of the stakeholders who are part of the decision-making process. Thus, obtaining a robust optimal design becomes a probabilistic optimization process that has a high computational cost. For this reason, the use of metamodels has been integrated into the proposed methodology. Specifically, Latin hypercube sampling is used for the definition of the initial sample and a kriging model is used for the definition of the mathematical approximation. In this way, kriging-based heuristic optimization reduces the computational cost by more than 90% with respect to conventional heuristic optimization while obtaining very similar results.

The study of the optimal solution and structurally stable design under variations of the initial conditions is carried out by varying three initial parameters (modulus of

elasticity, overload, and prestressing force). The objective of the analyzed case study is to obtain the most economical design with the least variation in the structural response. In this way, a Pareto frontier is achieved that allows the selection of the optimum solution, the robust solution, or a solution that provides a compromise between these two. On the other hand, the study of sustainable designs that are little influenced by the preferences of decision-makers is carried out by generating a large number of random decision-makers to cover all the possible preferences of the stakeholders. The aim of the case study is to reduce the subjective participation of decision-makers. In this way, it is possible to reduce the whole range of possible designs to a small specific set of designs and to select the design with the best sustainable mean or the least variability in valuation.

This thesis provides, first of all, an extensive bibliographic review of both the criteria used for the assessment of sustainability of bridges and the different methods of life-cycle impact assessment to obtain a complete profile of the environmental and social pillars. Subsequently, a methodology is defined for the full assessment of sustainability, using life-cycle impact assessment methods. Likewise, an approach is proposed that makes it possible to obtain structures with little influence from the structural parameters, as well as from the preferences of the different decision-makers regarding the sustainability criteria. The methodology provided in this thesis is applicable to any other type of structure.

Key words: *Sustainability, Decision-making, Life-cycle assessment, LCA, E-LCA, S-LCA, Life-cycle impact assessment methods, LCIA methods, ReCiPe, Ecoinvent, SOCA, Metamodel, Kriging, Robust design optimization, RDO, Bridges.*

RESUMEN

Actualmente existe una tendencia hacia la sostenibilidad, especialmente en los países desarrollados donde la preocupación de la sociedad por el deterioro ambiental y los problemas sociales ha aumentado. Siguiendo esta tendencia, el sector de la construcción es uno de los sectores que mayor influencia tiene debido a su alto impacto económico, ambiental y social. Al mismo tiempo, existe un incremento en la demanda de transporte que provoca la necesidad de desarrollo y mantenimiento de las infraestructuras necesarias para tal fin. Con todo esto, los puentes se convierten en una estructura clave, y por tanto, la valoración de la sostenibilidad a lo largo de toda su vida es esencial.

El objetivo principal de esta tesis es proponer una metodología que permita valorar la sostenibilidad de un puente bajo condiciones iniciales inciertas (subjetividad del decisor o variabilidad de parámetros iniciales) y optimizar el diseño para obtener puentes óptimos robustos. Para ello, se ha realizado una extensa revisión bibliográfica de todos los trabajos en los que se realiza un análisis de la sostenibilidad mediante la valoración de criterios relacionados con sus pilares principales (económico, medio ambiental o social). En esta revisión, se ha observado que la forma más completa de valorar los pilares medioambientales y sociales es mediante el uso de métodos de análisis de ciclo de vida. Estos métodos permiten llevar a cabo la valoración de la sostenibilidad durante todas las etapas de la vida de los puentes. Todo este procedimiento proporciona información muy valiosa a los decisores para la valoración y selección del puente más sostenible. No obstante, las valoraciones subjetivas de los decisores sobre la importancia de los criterios influyen en la evaluación final de la sostenibilidad. Por esta razón, es necesario crear una metodología que reduzca la incertidumbre asociada y busque soluciones robustas frente a las opiniones de los agentes implicados en la toma de decisiones.

Además, el diseño y toma de decisiones en puentes está condicionado por los parámetros inicialmente definidos. Esto conduce a soluciones que pueden ser sensibles frente a pequeños cambios en dichas condiciones iniciales. El diseño óptimo robusto permite obtener diseños óptimos y estructuralmente estables frente a variaciones de las condiciones iniciales, y también diseños sostenibles y poco influenciables por las preferencias de los decisores que forman parte del proceso de toma de decisión. Así pues, el diseño óptimo robusto se convierte en un proceso de optimización probabilística que requiere un gran coste computacional. Por este motivo, el uso de metamodelos se ha integrado en la metodología propuesta. En concreto, se ha utilizado hipercubo latino para la definición de la muestra inicial y los modelos kriging para la defininción de la aproximación matemática. De esta forma, la optimización heurística basada en kriging ha permitido reducir más de un

90% el coste computacional respecto a la optimización heurística conveniconal obteniendo resultados muy similares.

El estudio del diseño óptimo y estructuralmente estable frente a variaciones de las condiciones iniciales se ha llevado a cabo variando tres parámetros iniciales (módulo de elasticidad, sobrecarga, y fuerza de pretensado). El objetivo del caso de estudio analizado ha sido obtener el diseño más económico y con menor variación de la respuesta estructural. De esta forma, se consigue una frontera de Pareto que permite seleccionar la solución óptima, la solución más robusta o una solución de compromiso entre las dos. Por otro lado, el estudio de diseños sostenibles y poco influenciables por las preferencias de los decisores se ha llevado a cabo generando una gran cantidad de decisores aleatorios para cubrir todas las posibles preferencias de los interesados. El objetivo del caso de estudio ha sido reducir la participación subjetiva de los decisores. De esta forma, se ha podido reducir todo el abanico de diseños posibles a un número reducido de diseños concretos, y seleccionar aquel diseño con mejor media sostenible o menor variabilidad en la valoración.

Esta tesis proporciona en primer lugar, una amplia revisión bibliográfica, tanto de los criterios utilizados para la valoración de la sostenibilidad en puentes como de los diferentes métodos de análisis de ciclo de vida para obtener un perfil completo de los pilares ambientales y sociales. Posteriormente, se define una metodología para la valoración completa de la sostenibilidad, usando métodos de análisis de ciclo de vida. Asimismo, se propone un enfoque que permite obtener estructuras poco influenciables por los parámetros estructurales, así como por las preferencias de los diferentes decisores frente a los criterios sostenibles. La metodología proporcionada en esta tesis es aplicable a cualquier otro tipo de estructura.

Palabras clave: *Sostenibilidad, Toma de decisiones, Análisis de ciclo de vida, Métodos de valoración del impacto del análisis de ciclo de vida, ReCiPe, Ecoinvent, SOCA, Metamodelos, Kriging, Diseño óptimo robusto, Puentes.*

RESUM

Actualment existeix una tendència cap a la sostenibilitat, especialment en els països desenrotllats on la preocupació de la societat pel deteriori ambiental i els problemes socials ha augmentat. Seguint aquesta tendència, el sector de la construcció és un dels sectors que major influència té a causa del seu alt impacte econòmic, ambiental i social. Al mateix temps, existeix un increment en la demanda de transport que provoca la necessitat de desenrotll i manteniment de les infraestructures necessàries per a tal fi. En tot açò, els ponts es converteixen en una estructura clau, i per tant, la valoració de la sostenibilitat al llarg de tota la seua vida és essencial.

L'objectiu principal d’aquesta tesi doctoral és proposar una metodologia que permeta valorar la sostenibilitat d'un pont baix condicions inicials incertes (subjectivitat del decisor o variabilitat dels paràmetres inicials) i optimitzar el disseny per a obtenir ponts òptims robusts. Per a això, s'ha realitzat una extensa revisió bibliogràfica de tots els treballs en els quals es realitza un anàlisis de la sostenibilitat mitjançant la valoració de criteris relacionats amb els seus pilars principals (econòmic, ambiental o social). En aquesta revisió s'ha observat que la forma més completa de valorar els pilars ambientals i socials és mitjançant l'ús de mètodes d'anàlisis de cicle de vida. Aquests mètodes permeten realitzar la valoració de la sostenibilitat al llarg de totes les etapes de la vida dels ponts. Tot aquest procediment proporciona informació molt valuosa als decisors per a la valoració i selecció del pont més sostenible. No obstant això, les valoracions subjectives dels decisors sobre la importància dels criteris influeixen en l'avaluació final de la sostenibilitat. Per aquesta raó, és necessari crear una metodologia que reduïsca la incertesa associada i busque solucions robustes enfront de les opinions dels agents implicats en la presa de decisions.

A més, el disseny i la presa de decisions en ponts està condicionat pels paràmetres inicialment definits. Açò condueix a solucions que poden ser sensibles front a menuts canvis en les dites condicions inicials. El disseny òptim robust permet obtenir dissenys òptims i estructuralment estables front a variacions de les condicions inicials, i també dissenys sostenibles i poc influenciables per les preferències dels decisors que formen part del procés de presa de decisió. D’aquesta manera, el disseny òptim robust es converteix en un procés d’optimització probabilística que requereix un gran cost computacional. Per aquest motiu, l'ús de metamodels s'ha integrat en la metodologia proposta. En concret, s'ha utilitzat l'hipercub llatí per a la definició de la mostra inicial i els models kriging per a la definició de l'aproximació matemàtica. D'aquesta forma, l'optimització heurística basada en kriging ha permés reduir més d'un 90% el cost computacional respecte a l'optimització heurística convencional obtenint resultats molt similars.

L'estudi del disseny òptim i estructuralment estable front a variacions de les condicions inicials s'ha realitzat variant tres paràmetres inicials (mòdul d'elasticitat, sobrecàrrega, i força de pretensat). L'objectiu del cas d'estudi analitzat ha sigut obtenir el disseny més econòmic i en menor variació de la resposta estructural. D'aquesta forma, s'aconsegueix una frontera de pareto que permet seleccionar la solució òptima, la solució més robusta o una solució de compromís entre aquestes dos. Per una altra banda, l'estudi de dissenys sostenibles i poc influenciables per les preferències dels decisors s'ha realitzat generant una gran quantitat de decisors aleatoris per a cobrir totes les possibles preferències dels interessats. L'objectiu del cas d'estudi ha sigut reduir la participació subjectiva dels decisors. D'aquesta forma, s'ha pogut reduir tot el conjunt de dissenys possibles a un grup reduït de dissenys concrets, i seleccionar aquell disseny en millor mitja sostenible o menor variabilitat en la valoració.

Aquesta tesi doctoral proporciona en primer lloc, una ampla revisió bibliogràfica, tant dels criteris utilitzats per a la valoració de la sostenibilitat en ponts com dels diferents mètodes d'anàlisis de cicle de vida per a obtenir un perfil complet dels pilars ambientals i socials. Posteriorment, es defineix una metodologia per a la valoració completa de la sostenibilitat, utilitzant mètodes d'anàlisis de cicle de vida. Així mateix, es proposa un enfocament que permet obtenir estructures poc influenciables pels paràmetres estructurals, així com per les preferències dels diferents decisors enfront dels criteris sostenibles. La metodologia proporcionada en aquesta tesi doctoral és aplicable a qualsevol altre tipus d'estructura.

Paraules clau: *Sostenibilitat, Presa de decisions, Anàlisis de cicle de vida, Mètodes de valoració d'impacte d'anàlisis de cicle de vida, ReCiPe, Ecoinvent, SOCA, Metamodels, Kriging, Disseny òptim robust, Ponts.*

CHAPTER 1. INTRODUCTION AND OBJECTIVES

1.1. Introduction

Traditionally, the designs of bridges took into account only the economic aspect. However, concern in society about other aspects is increasing [1], leading to a search for designs that not only satisfy the economic aspect but also take into account sustainability aspects. This trend towards sustainability is of vital importance in the design of bridges, since the construction sector is one of the most important and active in the generation of emissions [2], [3] and consumption of natural resources [4]. In addition, for many years, only the short-term impact of bridges has been considered, although bridges must be designed to provide a service for the entire life of the structure. Therefore, it is necessary to consider the whole life-cycle of the bridge to obtain a complete sustainability assessment.

The term “sustainable development” appeared for the first time in the report *Our Common Future* by The World Commission on Environment and Development [5] and can be defined as “development that meets the needs of the present generation without compromising the needs of the future generation”. This report already considers it necessary to take into account economic, environmental, and social aspects to achieve sustainable development. Later, many other definitions were developed, most of them considering the intergenerational balance of these three aspects [6]–[8]. Thus, economic, environmental, and social aspects are the basic pillars for considering sustainability. This implies a need to integrate different ratings in a final assessment that can be carried out through a decision-making process.

However, defining the criteria that best represent each of the pillars of sustainability throughout the whole life-cycle of the bridge is a very complex task. After a previous study [9], it was observed that, in most works, sustainability assessments of bridges carried out so far are usually simple or limited to a few criteria related to the design phase [10]–[12]. For this reason, it is essential to use new tools that are emerging such as databases or life-cycle assessment (LCA) methodologies to obtain a complete assessment of each of the pillars of sustainability. LCA is one of the most commonly used procedures [13]. In the case of the economic pillar, it is known as *life-cycle cost (LCC)* [14], and in the case of the environmental and social pillars, it is often called environmental or social *LCA* [15], [16].

In addition, LCC and LCA methodologies not only provide an assessment of the sustainability of a defined bridge but also, combined with the decision-making process, become a powerful resource that makes it possible, given the input design variables of the bridge, to obtain the most sustainable design. However, this optimization problem is extremely complex due to the variability of the assessment of the subjective criteria and the importance of each criterion, which depends on the point of view of decision-makers.

Therefore, combined use of the decision-making process, the accurate assessment of the pillars of sustainability, and the optimization processes allows engineers to obtain the most sustainable bridge design under deterministic conditions. At the moment when some type of uncertainty is considered, the computational cost of solving this problem increases exponentially [17], [18]. The use of metamodels makes it possible to decrease the computational cost of this process, decreasing the time needed in the optimization processes. Therefore, the possibility of obtaining robust designs with a low influence of the uncertainty conditions is a pending task.

The study of this doctoral thesis has been developed at the Instituto Universitario de Ciencia y Tecnología del Hormigón (ICITECH) de la Universitat Politècnica de València (UPV). This research group has long experience and a multitude of works and previous publications related to these topics, which have allowed the development of this doctoral thesis to start from a very solid base.

In addition, the preparation of the doctoral thesis has been supported by various sources of public funding, including the Spanish Ministry of Science and Innovation (BIA2014-56574-R and BIA2017-85098-R).

1.2. Research objectives

The main objective of this thesis is to propose a methodology that allows the sustainability assessment of a bridge under uncertainty conditions and its optimization to achieve the optimal robust design. For this purpose, first, different types of bridges that have already been defined are considered in order to perform a complete assessment of the different pillars of sustainability throughout the whole life-cycle of the bridge. Subsequently, Matlab software is used to program the design of a post-tensioned concrete box-girder pedestrian bridge in which the cross-section geometry and concrete strength are the design variables. The code of this bridge is integrated in the proposed methodology to compare the conventional heuristic optimization and kriging-based heuristic optimization. Besides, probabilistic optimization is used to obtain robust designs with a low influence of the variability of decision-makers or uncertain initial parameters. The specific objectives that will allow the main objective to be achieved are:

- To study the most appropriate decision-making method to carry out sustainability assessment of bridges.
- To discover and determine the most useful criteria that better represent each of the pillars of sustainability throughout the whole life-cycle of the bridge.
- To define a methodology to assess the complete sustainability of bridges.
- To compare conventional heuristic optimization with kriging-based heuristic optimization to show a reduction in the computational cost and the prediction quality of the optimum design.
- To obtain the most sustainable design to reduce the life-cycle impact of the three pillars of sustainability.
- To obtain robust bridge designs under conditions of uncertainty. This methodology is intended to be applied to take into account both the uncertainty due to the subjectivity of the decision-makers and the uncertainty of some design parameters.

Therefore, this thesis contributes to a better understanding of the sustainability assessment of bridges. The study of the different pillars of sustainability provides a complete way to carry out sustainability assessment of bridges. Also, the combination of the evaluation of these pillars using the decision-making process allows a single assessment of sustainability to be performed. In addition, the results of the comparison between conventional heuristic optimization and kriging-based heuristic optimization show the advantages of using the metamodels in the optimization process. Finally, a new research approach is introduced, in which the uncertainty is included in the optimization process. In this way, it is possible to obtain not only optimal designs but also designs that have low sensitivity to the associated variability in both decision-making problems and structural problems.

1.3. Research methodology

The process followed in the preparation of this thesis can be divided into the stages shown in Figure 1.1. First of all, the state of the art was reviewed in order to know how to carry out a sustainability assessment and identify the existing gaps that require further investigation in bridges. This includes the criteria used for the assessment of the three pillars of sustainability, the multi-criteria decision-making methods (MCDM), and the life-cycle techniques.

Later, some LCAs were conducted, using different databases and *life-cycle impact assessment (LCIA*) methods, with the objective of learning how environmental and social impacts influence cost-optimized bridges. In this way, a global sustainability assessment of bridges can be performed. However, the influence of the subjective assessments of the decision-makers on the final sustainability assessment was observed. For this reason, the need to create a methodology to reduce the associated uncertainty emerges.

This uncertainty generates a probabilistic optimization problem with a high computational cost. Metamodels are used to achieve the required computational cost reduction. Therefore, a review of the different metamodels is performed, and the kriging technique is selected as the one with the best behavior in structural problems. At this point, it was decided to code a three-span continuous box-girder bridge located in a coastal region to continue the research, and a comparison between conventional heuristic optimization and kriging-based heuristic optimization was carried out to find out how kriging works in optimization problems. Finally, the defined methodology is applied to reduce the associated uncertainty in both sustainability assessment problems and structural problems with the aim of achieving robust sustainable designs and robust structural designs.

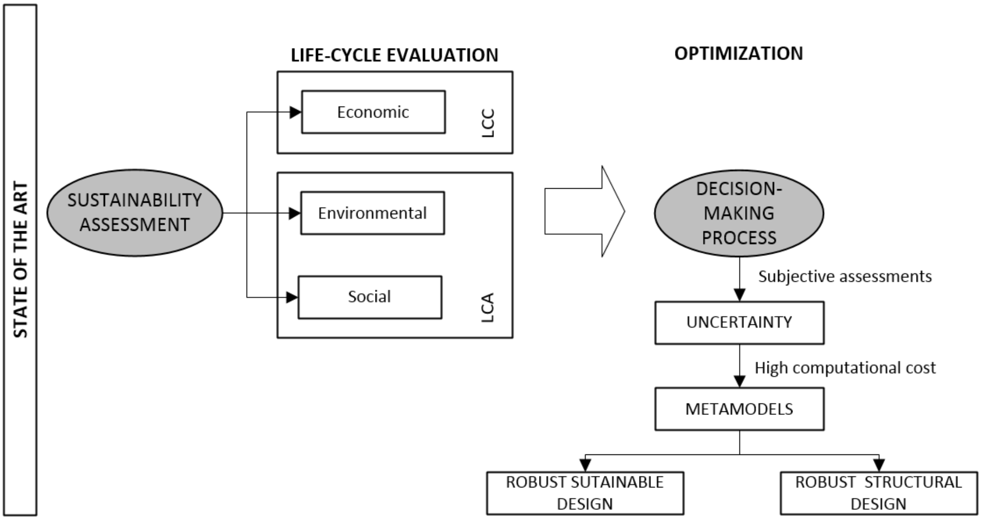

Figure 1.1. Research structure

1.4. Dissertation structure

The content of the dissertation has been organized into different chapters, after which the references cited in the document are provided. This dissertation is a compendium thesis, where the articles that form it correspond to Chapters 4, 5, 6, and 7. However, due to the need to carry out a complete review of the state of the art and to explain the methodology applied in these chapters, Chapter 2 (State of the Art) and Chapter 3 (Methodology) have been rewritten for this dissertation. Finally, Chapter 8 presents the conclusions of this work.

Chapter 2 provides a review of relevant literature to contextualize the design of bridges based on sustainable and life-cycle concepts as well as the methodology used to reduce the computational cost and obtain robust structures.

Chapter 3 develops the methodologies applied in this thesis. This chapter describes in detail the methods and processes chosen to develop this thesis among the wide range of methods explained in Chapter 2.

Chapter 4 presents the first three papers related to the LCA. The first two papers focus on the environmental assessment. The first is a comparison between two optimal post-tensioned concrete box-girder bridges with different designs and the second is an optimization of a prestressed concrete precast bridge. The third paper introduces the social assessment and carries out a complete sustainability assessment of the last three optimal bridges mentioned.

Chapter 5 presents the fourth paper. This paper shows a comparison between the conventional heuristic optimization and the kriging-based heuristic optimization.

Chapter 6 presents the fifth paper, which applies kriging-based optimization to obtain a sustainable robust bridge design under the influence of uncertainty due to the subjectivity of decision-makers.

Chapter 7 presents the seventh paper, which applies kriging-based optimization to perform a robust design optimization (RDO) due to the uncertainty of some design parameters.

Finally, Chapter 8 compiles the conclusions obtained in the development of the doctoral thesis, emphasizing its original contribution with respect to the previous works found in Chapter 2 and establishing the possible future lines of research.

References

[1] Intergovernmental Panel On Climate Change, *Climate change: Fifth assessment report*. 2014.

[2] T. Ramesh, R. Prakash, and K. K. Shukla, "Life cycle energy analysis of buildings: An overview," *Energy and Buildings*, vol. 42, no. 10, pp. 1592–1600, 2010.

[3] M. Taylor, C. Tam, and D. Gielen, "Energy efficiency and CO2 emissions from the global cement industry," in *International Energy Agency*, 2006, p. 13.

[4] A. Petek Gursel, E. Masanet, A. Horvath, and A. Stadel, "Life-cycle inventory analysis of concrete production: A critical review," *Cement and Concrete Composites*, vol. 51, pp. 38–48, 2014.

[5] United Nations., *World Commission on Environment and Development Our*

common future. New York, USA, 1987.

[6] A. Laurent, S. I. Olsen, and M. Z. Hauschild, "Limitations of carbon footprint as indicator of environmental sustainability," *Environmental Science & Technology*, vol. 46, no. 7, pp. 4100–4108, 2012.

[7] H. Gervásio and L. Simões Da Silva, "A probabilistic decision-making approach for the sustainable assessment of infrastructures," *Expert Systems with Applications*, vol. 39, no. 8, pp. 7121–7131, 2012.

[8] D.-S. Chang, S.-H. Chen, C.-W. Hsu, A. Hu, and G.-H. Tzeng, "Evaluation framework for a alternative fuel vehicles: sustainable development perspective," *Sustainability*, vol. 7, no. 9, pp. 11570–11594, Aug. 2015.

[9] V. Penadés-Plà, T. García-Segura, J. Martí, and V. Yepes, "A review of multi-criteria decision-making methods applied to the sustainable bridge design," *Sustainability*, vol. 8, no. 12, p. 1295, 2016.

[10] Y. Itoh, L. Sunuwar, T. Hirano, A. Hammad, and T. Nishido, "Bridge type selection system incorporating environmental impacts," *Journal of Global Environment Engineering*, vol. 6, pp. 81–101, 2000.

[11] S. Ohkubo, P. B. R. Dissanayake, and K. Taniwaki, "An approach to multicriteria fuzzy optimization of a prestressed concrete bridge system considering cost and aesthetic feeling," *Structural Optimization*, vol. 15, no. 2, pp. 132–140, 1998.

[12] V. Balali, A. Mottaghi, O. Shoghli, and M. Golabchi, "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*, vol. 2431, pp. 79–87, 2014.

[13] J. B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. Wegener Sleeswijk, H. a. Udo De Haes, J. a. de Bruijn, R. van Duin, and M. a. J. Huijbregts, "Life cycle assessment: An operational guide to the ISO standards," *III: Scientific background*, no. May, p. 692, 2001.

[14] C. Utomo and A. Idrus, "Value – based Group Decision on Support Bridge Selection," *World Academy of Science, Engineering and Technology*, vol. 4, no. 7, pp. 188–193, 2010.

[15] G. Du and R. Karoumi, "Life cycle assessment framework for railway bridges: Literature survey and critical issues," *Structure and Infrastructure Engineering*, vol. 10, no. 3, pp. 277–294, 2014.

[16] V. Penadés-Plà, J. V. Martí, T. García-Segura, V. Yepes, V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, "Life-Cycle Assessment: A

Comparison between Two Optimal Post-Tensioned Concrete Box-Girder Road Bridges," *Sustainability*, vol. 9, no. 10, p. 1864, Oct. 2017.

[17] M. A. Valdebenito and G. I. Schuëller, "A survey on approaches for reliability-based optimization," *Structural and Multidisciplinary Optimization*, vol. 42, no. 5, pp. 645–663, Nov. 2010.

[18] F. Jurecka, M. Ganser, and K.-U. Bletzinger, "Update scheme for sequential spatial correlation approximations in robust design optimisation," *Computers & Structures*, vol. 85, no. 10, pp. 606–614, May 2007.

CHAPTER 2. STATE OF THE ART

2.1. Introduction

Sustainability is a concept that was first defined in 1987 [1]. However, it is becoming more and more important due to the environmental and social problems that exist in the world. This increase in importance is reflected in new standards or guidelines. One of the more important of these guidelines is the 2030 Agenda for Sustainable Development [2], adopted by the United Nations Members on 25 September 2015. This guideline provides seventeen Sustainable Development Goals (SDGs) (Figure 2.1) to eradicate poverty, protect the planet, and ensure prosperity for all as part of a new sustainable development agenda [2]. Each goal has specific targets to be achieved over the next 15 years.

Figure 2.1. Sustainable development goals [2]

Bridges are an important part of the construction sector and are very important to achieve simpler land communication. Their construction and sustainability assessment would help to meet some of these general goals, such as: (9) industry, innovation, and infrastructure, (11) sustainable cities and communities, (12) responsible consumption and production, and (13) climate action. However, due to the large number of criteria and stakeholders that can play role in the sustainability assessment of bridges, it becomes a decision-making problem.

Many researchers have studied and applied the decision-making process and assessed the sustainability of different products, processes, and services [3], [4]. The construction sector, and more specifically bridges, is no exception [5]. In this area of research, different works have applied decision-making processes to carry out sustainability assessment of bridges [6]–[9]. To this end, each author has considered the decision-making method that he or she considered most appropriate and a set of criteria representing the sustainability of the bridge or part of it. In addition, assessment of the importance of the different criteria is usually performed according to the perspective of a single decision-maker.

However, many of these studies do not carry out a complete assessment of sustainability of bridges, since the criteria considered do not include the three basic pillars of sustainability (economic, environmental, and social) [10], [11] or do not take into account the whole life-cycle of the bridge [12], [13]. In addition, within each of these pillars, the criteria considered must achieve a complete evaluation of these pillars. LCA is one of the most commonly used procedures to obtain a complete assessment of each of the pillars of sustainability. The terms “LCC”, “Environmental Life-Cycle Assessment (E-LCA)”, and “Social Life-Cycle Assessment (S-LCA)” are used for the economic, environmental, and social pillars, respectively. The LCA procedure provides a guide to obtain a set of environmental or/and social indicators that make it possible to obtain a complete evaluation of each of these pillars [14]. However, depending on the objectives and priorities of the study, there are multiple LCIA methods that can be used, which provide different sets of indicators.

In order to find the most sustainable bridge, optimization processes must be used. Many works have used heuristic algorithms to optimize bridges under specific objective functions, such as cost, CO_2 emissions, or energy [15], [16]. However, these criteria are not sufficient to represent a complete sustainability assessment [17]. To obtain the most sustainable bridge, it is necessary to take into account the LCA procedure. On the other hand, optimization leads to designs that are close to the limits. In these cases, the variability of the initial parameters can cause great variations in the objective response. Something similar happens when different stakeholders with different points of views take part in the decision-making process. For this reason, the search for robust bridges is necessary, as it provides designs that are insensitive to variations of the initial uncertain parameters. The main problem when aiming to achieve a robust design is the high computational cost [18]. To solve this problem, the use of metamodels in optimization processes has been studied in order to reduce the computational cost [19]. With this reduction in the time consumption, the variability associated with the different problems can be considered in the optimization processes, allowing robust solutions to be achieved.

In this chapter, the state of the art of all the information studied to develop this thesis is exposed. In Section 2.2, the definition of sustainability and the importance of its assessment in the structures are explained. In Section 2.3, the different decision-making methods are defined, as well as a bibliographic review of the methods and criteria most frequently used in the sustainability assessment of bridges. In Section 2.4, the different LCIA methods used to evaluate both the environmental and social aspects are also explained. Finally, in the subsections, a review of the optimization processes and the use of metamodels (Section 2.5) and their application to obtain robust structures (Section 2.6) is presented.

2.2. Sustainability

2.2.1. Introduction to sustainability

The term "sustainable development" appeared for the first time in the report *Our Common Future* by The World Commission on Environment and Development [1] and can be defined as "development that meets the needs of the present generation without compromising the needs of the future generation". This report already considers that it is necessary to take into account economic, environmental, and social aspects to achieve sustainable development. Later, many other definitions were developed, most of them considering the intergenerational balance of these three aspects. Thus, economic, environmental, and social aspects are the basic pillars to be considered in order to achieve sustainability. This implies the integration of different ratings in a final assessment that can be carried out through a decision-making process.

The construction sector is one of the most important and active sectors, and therefore achieving sustainability is crucial. Sustainable construction can be defined as construction that achieves a agreement among economic, environmental, and social aspects throughout its whole life. Some authors [3], [5] conducted reviews of the decision-making methods used to achieve sustainability in the construction sector. Waas et al. [20] stated that sustainable development must be considered as a decision-making strategy. Thus, it is necessary to first evaluate these three pillars of sustainability and then apply the decision-making process to obtain a single assessment of its sustainability.

It is clear that we are facing environmental problems and that human influence is a key factor in these problems. For this reason, concern about environmental issues has been increasing in society. The *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change [21] shows that greenhouse gas (GHG) emissions have increased since 1950. This increment of the GHG concentration in the atmosphere has caused changes in the environmental system, the most well-know of which is global warming. In addition, the *Fifth Assessment Report* includes estimates of the evolution of the GHG concentration in the atmosphere throughout the twenty-first century. In these scenarios, there is one path along which no policy changes are made to reduce the emissions (RCP 8.5), two intermediate paths (RC 6 and RC 4.5), and one more path along which major changes are made to reduce the emissions (RC 2.6). Of these four scenarios, the only one that manages to reduce the GHG concentration by the end of the twenty-first century is path RC 2.6. Thus, to achieve sustainable development, it is crucial to carry out major changes and to attach more importance to environmental issues.

The construction sector is responsible for a major part of these GHG emissions [22], [23]. The materials that are used most in the construction sector are steel, wood, and concrete. Steel has the advantage of being a recyclable material and wood has the advantage of being a renewable material. Although these two materials have their own environmental impacts, concrete is the material that has the greatest impact on climate change, with the disadvantage that it is neither recyclable nor renewable. Nowadays, concrete production accounts for more than 5% of anthropogenic GHG emissions per year, mostly attributable to the production of cement clinker, where 1 tonne of cement production amounts on average to 0.87 tons of CO_2 emission [23]. Some authors [24] indicate that the current annual production of cement is about 3 Gton and that it will increase until it reaches about 5.5 Gton in the year 2050. The environmental impact of concrete production has been studied by several authors [25], [26], highlighting the influence of the components of the concrete matrix on the final impact. All of this implies that environmental assessment is essential in the construction sector. However, despite the importance of GHG emissions, there are other environmental impacts that should be taken into account to achieve a complete environmental assessment [17].

On the other hand, despite the inclusion of the social pillar in the most important definitions of sustainability, some authors indicate that its valuation is underestimated or relatively weak compared to the other pillars of sustainability [27], [28]. However, social equity, education, basic health, and participatory democracy are important for sustainable development [29]. For this reason, the social pillar must be given the same importance as the others pillars of sustainability when sustainable development is assessed [30].

In the construction sector, several social groups with different objectives are affected. Hill and Bowen [31] stated that construction projects should improve the quality of human life, taking into account social self-determination and cultural diversity, implementing skills training and improving the capacity of disadvantaged people, seeking intergenerational equity, and seeking the equitable allocation of social costs and benefits. Valdes-Vasquez and Klotz [32] indicated that projects in the construction sector involve clients, employees, the community, and industry, with the intention of satisfying current and future needs. Later, Almahmoud and Doloi [33] stated that the social aspect in the construction sector can be represented through the satisfaction of the different stakeholders involved in projects, such as industry, users, and the community. They also indicated that the impact of the project on future generations and the impact on present generations through the health, safety, and conditions of workers must be taken into account.

2.2.2. Life-cycle perspective

For many years, structures have been designed taking into account their impact from the short-term perspective. However, structures are designed to provide a service for many years. Therefore, in order to know the global sustainability of a structure, all of its life-cycles phases structure [34] must be considered: design, construction, use and maintenance, and end of Life. This is also known as "cradle-to-grave" assessment. This study across the life-cycle of the structure is known as LCC for the economic pillar and LCA for the environmental and social pillars. However, most papers identify the LCA only with the environmental pillar [35], [36], and other authors differentiate environmental and social life-cycle assessment as E-LCA and S-LCA. However, both E-LCA and S-SCA have a common core and share similar characteristics. So, when reference is made to any of these similar characteristics, the acronym LCA will be used, and when the environmental or social aspect must be specified, E-LCA or S-LCA will be used, respectively.

In this sense, the study of the global sustainability of a bridge must consider its whole life-cycle, "from cradle to grave". Therefore, the sustainability assessment must consider the deterioration of the structure and the maintenance activities necessary to keep it in optimum condition as well as its demolition or dismantling and possible reuse. Sarma and Adeli [37] provided a review of cost-optimized concrete structures and indicated the need to consider the LCC rather than just the initial cost of the structure. In addition, other authors [6], [34], [38] have shown the importance of considering all the life-cycle phases of bridges.

2.3. Multi-criteria decision-making

2.3.1. Multi-criteria decision-making process

Decision-making occurs frequently in everyone’s day-to-day life. This could due to situations of minor importance, such as choosing what hour to set the alarm clock to or which way to go from one point to another, or situations of major importance, such as deciding which house is better to live in. However, in the construction sector, companies or institutions must make decisions that affect other people. For this reason, decision-making has become a methodology of great importance to which attention must be paid when it comes to choosing between alternatives.

When problems of greater importance are presented and the decision-making process becomes a rational problem, five steps are defined: (1) define the problem, (2) develop alternatives, (3) define and weight the criteria, (4) assess the alternatives, and (5) choose an alternative (Figure 2.2).

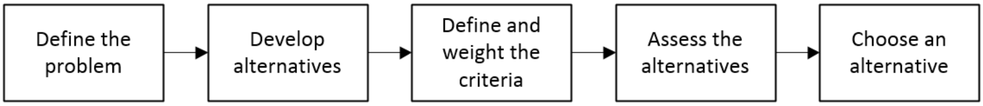

Figure 2.2. Decision-making process steps

When the decision-making problem depends on only one criterion (mono-criterion), the optimal solution is the one that optimizes this criterion. This type of problem offers a reduced vision of reality, since normally the solution to a problem is influenced by different aspects that can be contradictory and conflicting. This is where decision-making problems that take into account two or more criteria (multi-criteria) come into play.

Multi-criteria decision-making (MCDM) is the process used to obtain the optimal solution to a problem with different criteria. Therefore, its main goal is the assessment of a set of solutions or alternatives A_j (i = 1, 2, ..., n) to a problem based on the r_{ij} scores in relation to a series of criteria Ci (j = 1, 2, ..., m). The interaction between the two sets of elements is usually expressed as the decision-making matrix M_{mn} (Figure 2.3):

$M_{mn}=$		A_1	A_2		A_n
	C_1	r_{11}	r_{12}	...	r_{1n}
	C_2	r_{21}	r_{22}	...	r_{2n}
	...	...	...	...	...
	C_m	r_{m1}	r_{m2}	...	r_{mn}

Figure 2.3. Decision-making matrix

The characteristics of the r_{ij} scores vary depending on whether the criterion assessed is quantitative or qualitative. Quantitative criteria are objective criteria that are evaluated numerically. Otherwise, when trying to evaluate subjective criteria, such as qualitative criteria, confusion arises and it becomes difficult to assign a numerical value to a qualitative criterion. With this in mind, it is simpler to create an assessment scale using linguistic terms that are later associated with numerical values.

As explained above, the criteria to be evaluated can be quantitative or qualitative. In addition, the unit of measurement of each criterion will be different. For this reason, prior to the assessment of the alternatives, the decision-making matrix must be normalized so that the r_{ij} scores become normalized r'_{ij} scores. Parallel to the normalization of the decision-making matrix, the weights w_i of each criterion C_i should be obtained according to the greater or lesser importance of these criteria for the achievement of the final goal. Therefore, the decision-making matrix prior to the evaluation becomes a decision-making matrix where the r_{ij} scores are converted into normalized scores with associated weights, obtaining v_{ij} (Eq. 2.1.):

$$v_{ij} = w_i \cdot r'_{ij} \qquad (2.1)$$

Both the evaluation of the different criteria and the assignment of the relative weights of each of them are of vital importance in the decision-making process. A small variation of one or both of these points may lead to a change in the choice of the final alternative for the same decision-making problem. Depending on how these two steps are carried out, a wide variety of decision-making methods can be defined.

2.3.2. Multi-criteria decision-making methods

Originally, the concept of MCDM methods was used to describe a set of methods that served as a tool for the decision-making process [39]. However, the exponential development of this type of technique has led to the creation of new subdivisions for the classification of these methods.

Hwang and Yoon [40] proposed a first division of MCDM methods into *Multi-Attribute Decision-Making (MADM)* and *Multi-Objective Decision-Making (MODM)* methods. MADM methods are used to solve discrete problems. The different alternatives are predetermined and the participation of the experts takes place in order to *a priori* assess each criterion and indicate the importance of each. MODM methods are used to solve continuous problems. The different alternatives are not predetermined, but rather the approach is characterized by obtaining a group of equally good solutions under a series of restrictions, and the participation of experts takes place *a posteriori* (Figure 2.4).

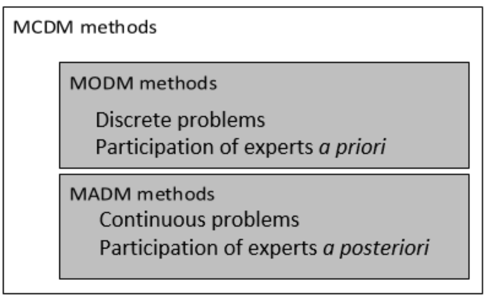

Figure 2.4. General classification of MCDM methods

The different MADM methods can be classified in different ways, for example depending on the type of initial information (deterministic, stochastic, or uncertain) or on the groups of decision-makers (a single group or several groups), although the most usual classification depends on the common characteristics of these methods proposed by Hajkwociz and Collins [41] and De Brito and Evers [42]. These methods can be grouped into [41], [42]: (1) scoring methods, (2) distance-based methods, (3) pairwise comparison methods, (4) outranking methods, and (5) methods based on utility or value functions. Table 2.1 shows each of these groups, along with its MADM methods and their acronyms and references, where long descriptions can be found.

Table 2.1. Classification of MADM methods

MADM group	MADM method	
Scoring methods	Simple additive weighting (SAW)	[43]
	Complex proportional assessment (COPRAS)	[43]
Distance-based methods	Goal programming (GP)	[44]
	Compromise programming (CP)	[45]
	Technique for order of preference by similarity to ideal solution (TOPSIS)	[46]
	Multicriteria optimization and compromise solution (VIKOR)	[46]
Pairwise comparison methods	Analytic hierarchy process (AHP)	[47]
	Analytic network process (ANP)	[47]
	Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH)	[48]
Outranking methods	Preference ranking organization method for enrichment of evaluations (PROMETHEE)	[49]
	Elimination and choice expressing reality (ELECTRE)	[50]
Utility/Value function methods	Multi-attribute utility theory (MAUT)	[51]
	Multi-attribute value theory (MAVT)	[51]
	Modelo integrado de valor para evaluaciones sostenibles (MIVES)	[52]

2.3.2.1 Scoring methods

The scoring methods are the simplest MADM methods. They are based on evaluating the different alternatives using basic arithmetic operations. The SAW and COPRAS methods assess the different alternatives by the sum of the weighted normalized value of each criterion. The SAW method [40] is the oldest method and can be used only for decision-making problems in which the criteria are maximized. The COPRAS method [53] is an adaptation of the SAW method and can be applied to decision-making problems in which the criteria are maximized and minimized.

2.3.2.2. Distance-based methods

The distance-based methods have the basic principle of calculating the distance between each alternative and a specific point. Within the distance-based methods, there are two approaches depending on the specific point. One is the GP method [44], whose objective is to obtain the alternative that accomplishes a set of goals, which means that the point is not the optimal one but the one that satisfies a set of conditions. The other is the CP method [54], [55], whose objective is to obtain the closest alternative to the optimum point. The VIKOR and TOPSIS methods are based on the CP method. The differences between the two methods are based on the way in which the criteria are normalized and the fact that the VIKOR method [56] only takes into account the distance to the positive ideal solution (PIS) and the TOPSIS method [40], [57] takes into account both the distance to the negative ideal solution (NIS) and the distance to the non-ideal solution.

2.3.2.3. Pairwise comparison methods

The pairwise comparison methods are very useful to obtain the weights of the different criteria and to evaluate subjective criteria by comparing the alternatives with each other by the generation of a comparison matrix. The Analytic Hierarchy Process (AHP) method [58] was the first to be developed and one of the most used methods in decision-making problems. The ANP method [59] is a further evolved version of the AHP method that makes it possible to solve the AHP main problem, which assumes that the criteria are independent. The MACBETH method [48] is an alternative to the AHP that is very similar in form but with some differences in concepts.

2.3.2.4. Outranking methods

The outranking methods consist of establishing a preference relationship between a set of alternatives where each of them shows a degree of dominance over the others with respect to a criterion. The concept of outranking was proposed by Roy in 1968 [60], with the basic principle being that if an alternative surpasses another alternative on many criteria, the first alternative may be better than the second even though it does not have the best global assessment. These methods are capable of dealing with incomplete or uncertain information and make it possible to obtain a classification of the alternatives according to the preference relationship between them. Within this group are the PROMETHEE method [61], [62] and the ELECTRE method [60].

2.3.2.5. Utility/value methods

The methods based on utility or value functions such as MAUT or MAVT define functions that determine the degree of satisfaction of an alternative with respect to a criterion. These functions convert the valuations that define the behavior of the alternatives in relation to a criterion into a degree of satisfaction. The expression of these functions can have different forms depending on the relationship between the valuation and the degree of satisfaction. The MIVES method is a derivative of the previous ones in which the equations that define the different satisfaction functions are provided.

The difference between these methods is that the MAUT method identifies the degree of satisfaction in conditions of uncertainty and the MAVT method does so in conditions of certainty. Both methods come from the concepts defined in the theories of utility [63] and value engineering [64]. The functions for each criterion are chosen by the decision-maker. The MIVES method was developed by Pons and de la Fuente in 2013 [52]. This method is a derivative of the previous ones in which the equations that define the different degree of satisfaction are provided. Therefore, of this group of methods, MIVES is a novel method.

2.3.2.6. Others

However, in real life, the valuations or comparisons are not subject to a single discrete number but there is uncertainty. This is why many of these methods can be based on tools that take into account the uncertainty in the real world such as fuzzy theory [65], the Monte Carlo simulation, or grey numbers [66], [67]. Moreover, when decision-making is not individual, there are often different groups with different interests, so it is necessary to reach a consensus among them. The Delphi method [68] is a useful tool when there are different decision-makers.

2.3.3. Applications of multi-criteria decision-making to bridge design

2.3.3.1. Multi-criteria decision-making methods

In this part, a bibliographic review of the works that use the most common methods of multi-attribute decision-making to assess the sustainability of bridges is presented. For this purpose, the Scopus search website is used, and the combination of words represented in Figure 2.5 is applied to the title, abstract, and keywords fields.

.

[TITLE-ABS-KEY (bridge) AND TITLE-ABS-KEY (saw OR copras OR vikor OR topsis OR ahp OR anp OR macbeth OR electre OR promethee OR maut OR mavt OR mives) AND TITLE-ABS-KEY (sustainability OR sustainable OR decision AND making)]

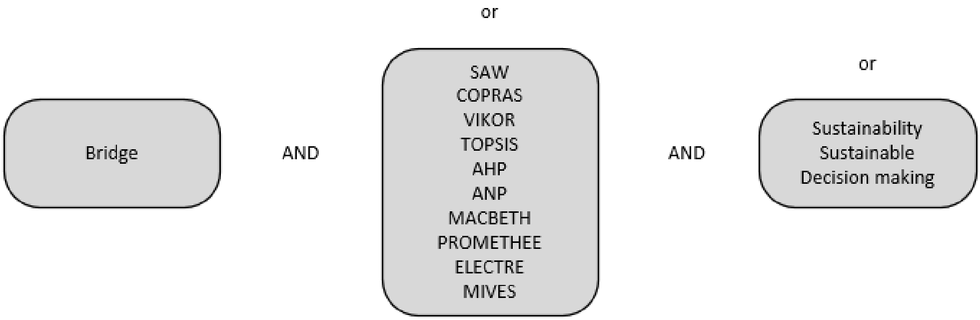

Figure 2.5. Word combination used in Scopus

This combination of words and years provides a total of 94 results, which decreases to 54 when the search is limited to the field of engineering and to articles and conferences. Most of these works correspond to decision-making processes; however many do not correspond to the evaluation of the sustainability of bridges. This is because in some cases the word “bridge” is used as a link and in other cases the decision-making methods are used to evaluate the behavior of a bridge. In this work, only those articles or conference papers that use the different decision-making methods for the choice of an alternative within a discrete group of alternatives under different criteria have been considered.

Only a total of 20 works were found to satisfy these conditions. These works can also refer to the design of the bridge (which can consider the whole life-cycle or part of it) as well as the production processes, construction, maintenance activities, or operations after the service life of the bridge is finished. However, there are no works that refer only to the production processes, since when the initial phase is considered, it also includes the construction stage. Therefore, the different works are divided into the next stages of the bridge life-cycle: (a) design, (b) construction, (c) use and maintenance, and (d) end of life. Tables 2.2, 2.3, 2.4, and 2.5 show the works found divided into the four different life-cycle stages. The first column indicates the author of the work, the second column the title, and the third the MADM method used.

Table 2.2. MADM methods in design stage

AUTHOR	TITTLE	MADM method
Malekly et al. [69]	A fuzzy integrated methodology for evaluating conceptual bridge design	Fuzzy QFD / Fuzzy TOPSIS
Hui-li Wang et al. [70]	Fuzzy optimum model of semi-structural decision for lectotype	Fuzzy AHP
Farkas [71]	A. Multi-criteria comparison of bridge designs	AHP
Aghdaie et al. [72]	Prioritizing constructing projects of municipalities based on AHP and COPRAS-G	COPRAS-G (AHP para pesos)
Gervasio et al. [6]	A probabilistic decision-making approach for the sustainable assessment of infrastructures	PROMETHEE (AHP para pesos)
Ardeshir et al. [73]	Selection of a bridge construction site using Fuzzy Analytical Hierarchy Process in Geographic Information System	Fuzzy AHP
Balali et al. [10]	Selection of appropriate material, construction technique, and structural system of bridges by use of multicriteria decision-making method	PROMETHEE
Jaikel et al. [38]	FAHP model used for assessment of highway RC bridge structural and technological arrangements	Fuzzy AHP

Table 2.3. MADM methods in construction

AUTHOR	TITTLE	MADM method
Pan [12]	Fuzzy AHP approach for selecting the suitable bridge construction method	Fuzzy AHP
Gu et al. [9]	Method for selecting the suitable bridge construction projects with interval-valued intuitionistic Fuzzy information	Fuzzy TOPSIS
Chou et al. [74]	Bidding strategy to support decision-making by integrating Fuzzy AHP and regression-based simulation	Fuzzy AHP
Mousavi et al. [11]	A new hesitant fuzzy Analytical Hierarchy Process method for decision-making problems under uncertainty	Fuzzy AHP
Balali et al. [10]	Selection of appropriate material, construction technique, and structural system of bridges by use of multicriteria decision-making method	PROMETHEE
Chen [75]	Decision support for construction method selection in concrete buildings: Prefabrication adoption and optimization	Fuzzy PROMETHEE

Table 2.4. MADM methods in use and maintenance stage

AUTHOR	TITTLE	MADM method
Sobanjo et al. [76]	Evaluation of projects for rehabilitation of highway bridges	Fuzzy AHP
El-Mikawi [77]	A methodology for evaluation of the use of advanced composites in structural civil engineering applications	AHP
Dabous et al. [78]	A multi-attribute ranking method for bridge management	AHP
Dabous and Alkass [79]	Decision support method for multi-criteria selection of bridge rehabilitation strategy	AHP

Table 2.5. MADM methods in end of life stage

AUTHOR	TITTLE	MADM method
Chen et al. [13]	ANP experiment for demolition plan evaluation	ANP

The MADM method most commonly used to assess the sustainability of bridges is the AHP method, which is used 11 times and combined with other methods twice. The PROMETHEE method is the second most used method, being used four times, followed by TOPSIS, which is used twice, and COPRAS and ANP, which are used once each. The remaining methods (MACBETH, VIKOR, ELECTRE, and MIVES) have not been used in scientific literature for the selection of a sustainable alternative from a discrete group of alternatives for bridges. In addition, it can be seen that the main MADM methods are associated with complementary tools to take into account some uncertainty, such as fuzzy theory or grey numbers.

2.3.3.2. Sustainability criteria

The assessment of the sustainability of a bridge by means of the decision-making process requires not only the use of a decision-making method but also the definition of a set of criteria that represent the sustainability of bridges. The works used to carry out the bibliographic review of the criteria are the same as the works used to carry out the bibliographic review of the MADM methods, because the assessment of the sustainability of bridges requires both MADM methods and criteria. In this way, the aim of this part is to study the criteria for the assessment of each pillar of sustainability of bridges (economic, environmental, and social). As in the previous part, the papers are divided according to the following stages of the bridge life-cycle: (a) design, (b) construction, (c) use and maintenance, and (d) end of life. Table 2.6 shows the criteria that are considered in the design stage. This stage can consider criteria for the whole life-cycle or part of it, since the design of the bridge conditions its behavior throughout its life-cycle. However, there are also criteria that focus exclusively on a specific stage of the life-cycle of the bridge such as construction (Table 2.7), use and maintenance (Table 2.8), or end of life (Table 2.9).

Table 2.6. Criteria in design stage

AUTHOR	CRITERIA	METHOD
Malekly et al. [69]	*Design complexity, Speed of Construction, Durability, Environment, Aesthetics, Construction Complexity, and Geometric design*	Fuzzy QFD / Fuzzy TOPSIS
Hui-li Wang et al. [70]	*Economic rationale (Production cost, Construction period, Construction cost), Function completeness (Deformation adaptability, Anti.wind ability), Environmental adaptability and Advanced Technology*	Fuzzy AHP
Farkas [71]	*Engineering Feasibility, Capital Cost, Maintenance, Aesthetics, Environmental Impact, Durability*	AHP
Aghdaie et al. [72]	*Environmental (traffic related, accident related, average speed limit), influence of physical area attributes), Socio-economic (rate of transportation of families, children and business dates, situation of area growth in the future, special importance of each road or boulevard to the city, vision of roads or boulevards about issues) and Total cost.*	COPRAS-G (AHP para pesos)
Gervasio et al. [6]	*Environmental (Waste production, Abiotic, depletion, Acidification, Eutrophication, Global Warning, Human toxicity, Photochemical oxidation, Ozone depletion layer, and Terrestrial ecotoxicity), Economical (Construction cost, Maintenance cost, and End of life cost), and Social (Vehicle operation cost, Driver delay cost, and Safety cost)*	PROMETHEE (AHP para pesos)
Ardeshir et al. [73]	*Transportation (minimizes the total distance traveled), Economic, and Morphology site*	Fuzzy AHP
Balali et al. [10]	*Quantitative (Cost, Span, Inspection and Maintenance, Construction speed) and Qualitative (Ease of construction, Traffic load, Dependence on Imported technologies, Architecture Design, Irregular geometric, Complexity in construction, and Symbolic and Aesthetics)*	PROMETHEE
Jaikel et al. [38]	*Bridge structure geometry adjustable to locality conditions (Topography, Resistance to natural hazards, and complexity of erection), Mitigation of impact upon natural environment (Project area minimization, Minor interference on landscape and harmoniously integrated into landscape, Contamination), Structure design technologic ability (Complete mechanization of manufacturing and construction process, assembly technology universalism, assembly work in various weather conditions), Safety and sustainability of structure (Structure design safety in challenging topography, Structure design safety in natural hazards and contingencies), and Economic criterion (Total initial cost, Project duration, and Maintenance costs)*	Fuzzy AHP

Table 2.7. Criteria in construction stage

AUTHOR	CRITERIA	METHOD
Pan [12]	*Quality (Durability and Suitability), Cost (Damage cost and Construction cost), Safety (Traffic conflict and Site condition), Duration (Constructability and Weather condition) and Shape (Landscape, Geometry and Environmental preservation)*	Fuzzy AHP
Gu et al. [9]	*Quality, Cost, Safety, and Duration*	Fuzzy TOPSIS
Chou et al. [74]	*Construction (Project complexity, Government level, Project duration and Experience of project staff), Environment (Site condition, Geologic types, Climate, and Cultural conditions), Planning (Design concepts, Design drawings, Construction method, and Interface management), and Estimation (Contractors fitness, Indirect costs, Direct costs, and Risk assessment)*	Fuzzy AHP
Mousavi et al. [11]	*Quality, Cost, Safety, Duration and Shape*	Fuzzy AHP
Balali et al. [10]	*Quantitative (Cost, Usability in Height, Construction speed), and Qualitative (Environmental issues, Quality of construction, Module installation of deck, and traffic interference)*	PROMETHEE
Chen [75]	*Durability, Damage cost, Construction cost, Traffic conflict, Site condition, Weather condition, Landscape, and Environmental effect*	Fuzzy PROMETHEE

Table 2.8. Criteria in use and maintenance stage

AUTHOR	CRITERIA	METHOD
Sobanjo et al. [76]	*Ratio of the average daily traffic (ADT) to the project cost (ADT/Cost), Expected improvement in structural condition appraisal rating, In deck geometry appraisal rating, In clearance appraisal rating, In load capacity appraisal rating, In waterway adequacy appraisal rating, In approach roadway alignment appraisal rating, and Expected extension in bridge service life.*	Fuzzy AHP
El-Mikawi [77]	*Structural Performance Indicators, Economic Indicators, Environmental Aspects, Codes and Regulations, Material availability, Architectural Aspects*	AHP
Dabous et al. [78]	*Agency cost (Direct cost: material, labor, and equipment), User cost (Indirect cost), User cost (Delay cost, Increased vehicle operating cost and cost of accidents and crashes that may happen during the projects), Bridge safety, Useful life and Environmental impact*	AHP
Dabous and Alkass [79]	*Maximize bridge condition preservation and safety (Condition rating, Load carrying and capacity and Seismic risk), Maximize effectiveness of investment (Average daily traffic (ADT) and Supporting road type, and Minimize bridge deficiency (Vertical clearance, Approach condition and Draining system)*	AHP

Table 2.9. Criteria in end of life stage

AUTHOR	CRITERIA	METHOD
Chen et al. [13]	*Structure characteristics (height, type of structure, stability, scope of demolition, and usage), Conditions (Safety risk on/off site, Acceptable level of noise, Proximity to adjacent structures), Cost (Machinery and Manpower), Experiences (Familiarity with technologies, Aviability of equipment, Aviability of expertise), Environmental impacts and Time (Worksite preparation and Entire demolition process)*	ANP

2.4. Life-cycle cost and life-cycle assessment

2.4.1. Life-cycle evaluation

LCC and LCA are procedures that are improving over time. Consideration of all of the economic, environmental, or social impacts throughout the whole life-cycle of a product, service, or process is necessary for a correct assessment of the different alternatives. This is even more important in the construction sector, where buildings and infrastructures are built to provide a service over a long time.

The first LCC studies were carried out in the 1960s to find the cost during the whole life-cycle associated with project investments [80]. Later, in the 1980s, the situation had not changed greatly [81]. However, the energy crisis of 1973 caused an increment of the interest in LCC [82]. This led US government agencies and many private companies to require the LCC to compare and assess different alternatives and evaluate which one would prove most beneficial in the long term.

For bridges, the most developed pillar is the economic pillar. Although some of the first works only studied the initial cost of the bridge to assess sustainability [83], the LCC is, nowadays, widely used [38], [84].

On the other side, the first E-LCA studies were conducted in the late 1960s by the US Department of Energy to quantify the energy consumption and energy efficiency of some products and materials [85]. At the end of that decade, other initiatives also appeared, such as that of Coca Cola, which aimed to quantify the resources used and the emissions associated with its containers. Subsequently, in 1979, an inventory was made of all the energy consumed in the production of different types of beverage containers including glass, plastic, steel, and aluminum [86]. This type of study was common throughout this decade with the oil crisis in Europe and the USA.

In 1988, when solid waste became a big problem, E-LCA studies were widely studied to mitigate environmental problems and to create an inventory of environmental emissions until SETAC (Society of of Environmental Toxicology

And Chemistry) made an advance by using E-LCA to perform an environmental impact assessment. Subsequently, pressure from environmental organizations and the need for a tool to standardize the E-LCA procedure led the International Organization for Standardization (ISO) to develop a set of standards to guide the LCA procedure [14], which became a reference standard for environmental impact assessment.

In bridges, it is clear that only a few studies apply E-LCA. The first studies were carried out by Horvath and Hendrickson [87] and Widman [88]. After that, some other authors assessed the environmental impact of bridges, but most of them did not make this assessment for all stages of the life-cycle and instead focused on just one [89], [90] or took into account a small number of environmental indicators, normally CO_2 and energy [91], [92]. It was not until the study of Steele et al. [93] that the first complete LCA was carried out, and most of the complete LCA studies are much more recent. On the one hand, Du and Karoumi [94], Du et al. [95], and Hammervold et al. [96] compare different bridge designs, and on the other hand Pang et al. [97] focus on comparing different maintenance activities. All of them divide the life-cycle of the bridge into four stages: manufacturing, construction, use and maintenance, and end of life. In some works [6], [13], [98], the manufacturing stage is the one with the highest environmental impact, but in Pang et al. [97] it is maintenance that has the greatest environmental impact.

Normally, the social pillar of sustainability has been neglected or not given enough importance [27], [28]. Vallance et al. [99] stated that the social pillar of sustainability is difficult to define and therefore to apply. Other authors say that the social pillar of sustainability has not been implemented in an integrated way in practice [27]. However, the social pillar of sustainability is often seen as general human development, which could be defined as the provision of all the essential needs of all human beings, the acquisition of a satisfactory level of comfort, living with meaning and interest, and equitable participation in social opportunities for health and education [29]. For bridges, the social pillar of sustainability is the most unclear. There is a high level of disagreement in defining the criteria that best represent the S-LCA. Criteria such as detour time, dust, and noise have been used in different works [6], [13], [98].

2.4.2. Life-cycle cost

Nowadays, there are too many definition of the concept of LCC. Including the common aspects of these definitions, the LCC can be defined as a technique for assessing the economic effect of a product, process, or service during its whole life-cycle [100]. The purpose of an LCC is to estimate the overall costs of alternatives and to select the design that ensures the lowest overall cost of ownership consistent with its quality and function. The LCC should be studied early in the design process while there is still a chance to refine the design to ensure a reduction in costs.

2.4.3. Life-cycle assessment

Following the definition of ISO 14040 [14], the LCA is defined as a technique for assessing the environmental and/or social aspect and the impacts caused by a product, process, or service through a system of input flows (data) that cause output flows (impacts). ISO 14040 [14] divides the LCA into four phases:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation of results

The impact assessment step of the LCA is crucial. In this step, the information obtained from the life-cycle inventory is transformed into a set of understandable indicators. Because of the complexity of this transformation, some methodologies have been developed to simplify this step, called LCA methods. In this way, the assessment and comparison of different cases is easier.

2.4.4. Environmental life-cycle assessment methods

In E-LCA, there are two approaches to transform the life-cycle inventory into understandable indicators: the *midpoint approach* and the *endpoint approach*. The midpoint approach refers to the environmental impact, while the endpoint approach refers to environmental damage. In addition, there is a set of new methods that combine the methods of the midpoint and endpoint approaches. Table 2.10 shows the most common E-LCIA methods used for each group.

Another way to understand the differences between these two approaches is to consider that the midpoint approach considers the direct effect, while the endpoint approach considers the long-term consequences. Thus, for example, any process, product, or service that affects climate change has gas emissions to the atmosphere that cause different environmental problems such as global warming or ozone depletion (midpoint approach). But in the long-term, these gas emissions will cause damage to ecosystems, human health, or resources. In this example, ozone depletion can lead to increased skin cancer problems (endpoint approach).

Table 2.10. Classification of E-LCIA methods

E-LCIA group	E-LCIA method	
Midpoint approach	Centre for Environmental Studies (CML 2000)	[14]
	Environmental Design of Industrial Products (EDIP 2003)	[101]
	Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI)	[102]
Endpoint approach	Eco-Indicator (EI99)	[103]
	Environmental Priority Strategies in product design (EPS)	[104]
	Eco scarcity	[105]
Midpoint/Endpoint approach	ReCiPe 2008	[106]
	LIME	[107]
	IMPACT 2000+	[108]

2.4.4.1. Midpoint approach methods

Midpoint approach methods are classical methods, such as the CML, EDIP 2003, and TRACI. These methods provide a set of impact categories that indicate the direct effects of a product, process, or service. The total number of these indicators is usually quite high, providing information that is accurate but sometimes difficult to interpret.

CML 2000

The CML 2000 (Centre for Environmental Studies) is a midpoint approach method proposed by Guinée et al. [14] and is an adaptation of the work carried out in 1992 by the Institute of Environmental Sciences of the University of Leiden. The CML 2000 method clusters the impact categories into two different groups: mandatory impact categories (or baseline impact categories), which are the impact categories most used in LCA studies, and additional impact categories, which are operational impact categories that depend on the requirements of the study.

The mandatory impact categories considered in this methodology are as follows: depletion of abiotic resources, land competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, acidification, and eutrophication.

The optional impact categories that may be included in the study depending on its requirements are one or more of the following: loss of life support function, loss of biodiversity, freshwater sediments ecotoxicity, marine sediments ecotoxicity, impacts of ionization radiation, malodorous air, noise, waste heat, casualties, lethal, non-lethal, depletion of biotic resources, desiccation, and malodorous water.

EDIP 2003

The EDIP (Environmental Design of Industrial Products) is a midpoint approach method developed by the Institute for Product Development of the Danish Technical University [101]. The first method proposed was EDIP 1997, which considered the following impact categories: global warming, ozone depletion, acidification, terrestrial eutrophication, aquatic eutrophication, photochemical ozone formation, human toxicity, ecotoxicity, and noise.

Subsequently, some improvements relating to characterization factors were introduced in EDIP 2003. These improvements are represented in the development of the characterization factor of EDIP 2003 in a site-dependent form and in a site-generic form, rather than only in a site-generic form as in EDIP 1997. The difference between the two forms of characterization is that the site-generic form does not take into account the spatial variation in the dispersion and distribution of the substance and exposure of the target.

TRACI

The TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) is a midpoint approach method developed by the Environmental Protection Agency (EPA) in the USA [102]. The TRACI method has the goal of carrying out impact assessments of process designs and achieves pollution prevention.

The impact categories considered in this method are: ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health non-cancer, human health criteria pollutants, eco-toxicity, and fossil fuel depletion.

2.4.4.2. Endpoint approach methods

Endpoint approach methods are damage-oriented methods, such as the Eco-Indicator (EI) 99, EPS, and ecopoints. These methods provide a set of damage categories that indicate the long-term consequences of a product, process, or service. The total number of these indicators is usually quite small, so the information is not as accurate as in the case of midpoint methods but is much easier to interpret.

Eco-Indicator 99

The EI (Eco-Indicator) is an endpoint approach method developed by PRé Consultants [103]. The first method proposed was the EI 95 in 1995, but several improvements were made until EI 99 was developed in 1999. The improvements made in the EI 99 enable the provision of a better scientific basis for the damage models, such that the approach is more reliable. Besides, the indicator list is expanded and the methodology for calculating the indicators is further improved.

The environmental damage categories included are as follows: climate change, ozone layer depletion, acidification, eutrophication, carcinogenicity, respiratory effects, ionizing radiation, ecotoxicity, land use, mineral resources, and fossil resources. These categories are further aggregated into three areas of protection: ecosystem quality, human health, and natural resources.

EPS 2000

The EPS (Environmental Priority Strategies in product design) is an endpoint approach method developed in 1989 by a collaboration between Volvo Car Corporation, the Swedish Environmental Research Institute (IVL), and the Swedish Federation of Industries [104]. The EPS method has the goal of meeting the efficient environmental requirements of the product development process.

The environmental damage categories included are as follows: life expectancy, severe morbidity and suffering, morbidity, severe nuisance, nuisance crop production capacity, wood production capacity, fish and meat production capacity, base cation capacity, production capacity for water, share of species extinction, depletion of element reserves, depletion of fossil reserves (gas), depletion of fossil reserves (coal), depletion of fossil reserves (oil), and depletion of mineral reserves. These categories are further aggregated into four areas of protection: human health, ecosystem production capacity, biodiversity, and abiotic stock resources.

ECO SCARCITY

The Eco Scarcity method, also called the ecopoints method, is an endpoint approach method developed in 1997 in Switzerland [105].

The damage categories are defined according to the environmental law or political targets of each country or region. However, this method covers the following damage categories: ozone depletion, photochemical oxidant formation, respiratory effects, air emissions, surface water emissions, radioactive emissions, cancer caused by radio nuclides emitted to the sea, emissions to groundwater, emissions to soil, landfilled municipal (reactive) wastes, hazardous wastes (stored underground), radioactive wastes, water consumption, gravel consumption, primary energy resources, endocrine disruptors, and biodiversity losses.

2.4.4.3. Combined midpoint and endpoint approach methods

Midpoint/endpoint approach methods are methods that combine the midpoint and endpoint approaches, such as ReCiPe 2008, LIME, and IMPACT 2008.

RECIPE 2008

The ReCiPe 2008 method is a midpoint/endpoint approach method that combines the midpoint approach method CML and the endpoint approach method EI. The development of the ReCiPe method was carried out through the cooperation of many developers working in the LCA field such as RIVM, CML, PRé Consultants, Radboud University Nijmegen, and CE Delft [106].

This method distinguishes two levels of indicators (midpoint approach and endpoint approach). On the one hand, the midpoint categories considered are climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion, and fossil fuel depletion. On the other hand, the endpoint damage categories are damage to human health, damage to ecosystem diversity, and damage to resource availability.

LIME

The LIME 1 method is a midpoint/endpoint approach method developed by METI/NEDO [107]. This method is widely used in Japan and quantifies the environmental impacts that are induced by incidents of environmental loadings. There is another version of this method, called LIME 2, that considers the uncertainties of all the damage factors.

This method distinguishes two levels of indicators (midpoint approach and endpoint approach). On the one hand, the midpoint categories considered are ozone layer depletion, global warming, acidification, photochemical oxidant formation, regional air pollution, chemicals toxic to humans, eco-toxic chemicals, eutrophication, land use, waste landfill, resources, and consumption. The following endpoint damage categories are considered: cataracts, skin cancer, other cancers, respiratory disease, thermal stress, infectious disease, hypoalimentation, disaster causality, agricultural production, forestry production, fishery production, loss of land use, energy consumption, user cost, terrestrial ecosystems, and aquatic ecosystems. On the other hand, the endpoint damage categories are human health, social welfare, net primary production, and biodiversity

IMPACT 2002+

The IMPACT 2002+ method is a midpoint/endpoint approach method developed by the Swiss Federal Institute of Technology [108] and the Federal Polytechnic School of Lausanne (EPFL). The first method proposed was IMPACT 2002, but several improvements were made until IMPACT 2002+ was developed.

This method distinguishes two levels of indicators (midpoint approach and endpoint approach). On the one hand, the midpoint categories considered are human toxicity, respiratory effects, ionizing radiation, ozone depletion, photochemical oxidant formation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic eutrophication, terrestrial eutrophication and acidification, land occupation, global warming, non-renewable energy, and mineral extraction. On the other hand, the endpoint damage categories are human health, ecosystem quality, climate change, and resources.

2.4.5. Social life-cycle assessment methods

The social pillar of sustainability is the least studied and probably the most diffuse and weakest pillar of sustainability. However, for a complete sustainability assessment it is necessary to obtain a complete set of social indicators that can be used to carry out a complete comparison and assessment of alternatives. Currently, there are only two important S-LCA methods that transform the life-cycle inventory into understandable indicators: PSILCA (Product Social Impact Life Cycle Assessment) and SHDB (Social Hotpots database). These models have similar features, but there are some differences that must be kept in mind.

2.4.5.1. PSILCA

The PSILCA (Product Social Impact Life Cycle Assessment) database is a social database developed by GreenDelta [109] and presented in 2013. This database provides information to carry out the assessment of the social pillar of products, processes, or services during their whole life-cycles. This method uses the EORA MRIO *(Multi-Regional Input-Output)* database [110] as an input/output backbone. This database covers 189 individual countries represented by around 15000 units classified by entities: industries and commodities.

The social indicators and their structure are inspired by the UNEP/SETAC guidance [30]. Currently, there are 88 qualitative and quantitative indicators addressing 25 topics and five affected stakeholder groups. The PSILCA database use worker-hours as its activity variable in order to quantify the social impacts (but other activity variables are being investigated).

2.4.5.2. SHDB

The SHDB (Social Hotpots database) database is a project developed by New Earth [111] in 2009 and presented in 2013. In addition, New Earth is working on its development and making it available with different product system models. The project aims to provide detailed information on human rights and working conditions along supply chains in order to enable risk assessments and provide methods to calculate social footprints. This method uses the GTAP *(Global Trade Analysis Project)* database as an input/output model [112]. This database covers 113 individual countries represented by around 6500 units classified by entities: industries and commodities.

The social indicators and their structure are inspired by the UNEP/SETAC guidance [30]. Currently, there are nearly 157 qualitative and quantitative indicators addressing 26 topics and five big groups. The SHDB method use worker-hours as its activity variable in order to quantify the social impacts.

2.4.6. Applications of life-cycle assessment to bridge design

In this part, a bibliographic review of the works that use the most common LCIA methods to assess the environmental and social pillars of sustainability of bridges is presented. For this purpose, the Scopus search website is used and the combination of words represented in Figure 2.6 is applied in the *title, abstract,* and *keywords* fields.

[TITLE-ABS-KEY (bridge) AND TITLE-ABS-KEY (CML OR EDIP OR TRACI OR EI99 OR EPS OR ECO-SCARCITY OR RECIPE OR LIME OR IMPACT2002+) AND TITLE-ABS-KEY (LCA OR "life-cycle assessment" OR "life cycle assessment")]

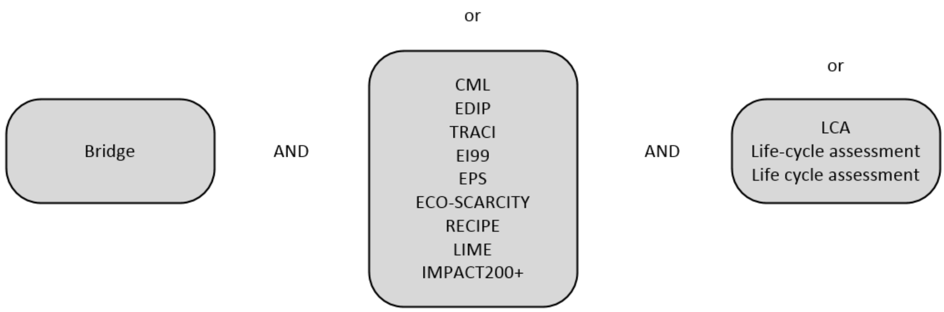

Figure 2.6. Word combination used in Scopus

This combination of words and years provides a total of 16 results. However, due to the limitations explained in Section 2.3.3, only nine works refers to the topic studied in this thesis. All the works found correspond to the LCIA methods to assess the environmental aspect of bridges. There are no works that refer to the LCIA methods to assess the social aspect of bridges. Tables 2.11, 2.12, and 2.13 show the LCIA methods used to assess the environmental pillar of bridges grouped into the approaches considered. The first column indicates the author of the work, the second the title, and the third the MADM method used.

Table 2.11. E-LCA midpoint approach methods

AUTHOR	TITTLE	LCA method
Hettinger et al. [35]	Sustainable bridges - LCA for a composite and a concrete bridge	CML 2000
Du and Karoumi [94]	Life cycle assessment of a railway bridge: Comparison of two superstructure designs	CML 2000
Hammervold et al. [96]	Environmental life cycle assessment of bridges	CML 2000
Stengel and Schiessl [90]	Life cycle assessment of UHPC bridge constructions : Sherbrooke Footbridge , Kassel Gärtnerplatz Footbridge and Wapello Road Bridge	CML 2000

Table 2.12. E-LCA endpoint approach methods

AUTHOR	TITTLE	LCA method
Pang et al. [97]	Life cycle environmental impact assessment of a bridge with different strengthening schemes	Eco-Indicator 99
Navarro et al. [113]	Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks	Eco-Indicator 99

Table 2.13. Combined midpoint and endpoint approach methods

AUTHOR	TITTLE	LCA method
Du et al. [95]	Life cycle assessment as a decision support tool for bridge procurement: Environmental impact comparison among five bridge designs	ReCiPe
Du and Karoumi [114]	Environmental life cycle assessment comparison between two bridge types : Reinforced concrete bridge and steel composite bridge	ReCiPe
Penadés-Plà [115]	Life-Cycle Assessment: A Comparison between Two Optimal Post-Tensioned Concrete Box-Girder Road Bridges	ReCiPe

This review shows that only three LCIA methods have been used to carry out the environmental assessment of bridges, one method for each approach: for the midpoint approach, the LCIA method CML has been used four times; for the endpoint approach, the LCIA method EI 99 has been used twice; and for the midpoint/endpoint approach, the LCIA method ReCiPe has been used three times. The CML and EI 99 methods are the most popular LCIA methods, and the ReCipe method is an LCIA method that combines the first two.

2.5. Optimization and metamodels

2.5.1. Bridge design optimization

Traditionally, the design of structures is based on an iterative trial and error process based on the engineer's experience. In the case of bridges, the typology is chosen according to the traffic and the topography. Once the typology is determined, the geometry of the cross-section, the concrete strength, and finally the steel reinforcement are defined according to the codes. After this phase has been completed, some of the design variables can be modified to reduce the objective function studied (for example, the cost). Contrarily, the optimization process follows an automatic process to choose the best design by modifying the design variables.

However, obtaining an exact optimum solution through mathematical programming methods [116] becomes unfeasible for complex problems due to the exponential growth of the computational cost with the increment in the number of design variables. This limitation explains the success of heuristic algorithms [117], for which, although the global optimum of the problem is not guaranteed, the computational cost is much lower, which means that heuristic algorithms become very competitive for the optimization of complex structures. The most common heuristic algorithms are the genetic algorithms (GAs) [118], swarm optimization [119], and simulated annealing (SA) [120].

Bridge optimization was first applied in the 1970s, including reinforcement slab bridges [121], cast-in-place prestressed concrete box-girders [122], [123], precast prestressed concrete girders [124], and steel girders [125]. Later, heuristic optimization began to be used to carry out bridge optimizations. Thus, many works have performed different optimizations using different heuristic algorithms [84], [126], [127].

2.5.1.1. Genetic algorithm

Genetic algorithms (GAs) are population-search techniques inspired by the process of natural evolution [118]. GAs generate better-adapted individuals through genetic crossover and mutation. The crossover technique creates the new generation by combining the characteristics of the two chosen solutions. The new generation will have the characteristics of the two previous solutions. The probability of selecting each individual is usually proportional to its aptitude, according to Coello [128]. Therefore, the population is chosen in an elitist way. The mutation operator randomly modifies some characteristics of the new solution.

2.5.1.2. Swarm optimization

Swarm intelligence is also a population-search technique. However, this type of heuristic is based on interactions with neighbors. It imitates the collective behavior of some agents, which follow a global pattern. In addition, the agents learn from the interaction between the individuals. Swarm algorithms differ in philosophy from GAs because they use cooperation rather than competition [129]. Particle Swarm Optimization (PSO) [130], which simulates a simplified social system, can be categorized among the biologically inspired types of artificial intelligence.

2.5.1.3. Simulated annealing

Simulated Annealing (SA) was suggested by Kirkpatrick et al. [120]. SA is a popular local search algorithm in structural optimization. This algorithm is based on the physical phenomenon of the annealing process. SA has a jump property as the algorithm supports lower quality working solutions. This characteristic prevents the algorithm from being trapped in local optima and ensures good convergence [15].

2.5.2. Metamodeling

Metamodeling creates a mathematical approximation of the objective response (an objective surface) from the assessment of specific points within the design space. In this way, once the mathematical approximation of the objective response is generated, it can replace the calculation of all the designs, providing the value of the objective response more quickly. Metamodeling is used to solve the main limitation of probabilistic optimization, which is the high computational cost due to the large number of designs that must be calculated to assess the sensitivity of the objective response of the problem [131], [132]. In this sense, metamodeling helps reduce the computational cost.

The basis of metamodels consists of constructing an approximate mathematical model of a detailed simulation model, which predicts the output data (objective response) from input data (design variables) in the whole design space more efficiently than the detailed simulation models. It could, as such, be called a *model of a model*. The construction process of a metamodel focuses on three main parts: (a) obtaining the initial input dataset points inside the design space, (b) choosing the metamodel type to construct the approximate mathematical model, and (c) choosing the fitting model. There are a large number of options for carrying out these steps [132]. Regardless of the choice for each step, the main objective of constructing a metamodel is to obtain a model with the best accuracy possible to predict the objective response.

There are several ways to obtain the initial input dataset points or sampling inside the design space. The choice of the initial input dataset is defined by the sample size and the position of the points, because both aspects have an influence on the model construction. On one hand, the sample size is fundamentally related to the number of design variables. When the number of design variables is larger, the sample size must be higher to achieve the same accuracy of the metamodel, and therefore the computational cost of constructing the model will be higher. On the other hand, once the sample size has been defined, the position of the points must be placed within the design space in order to obtain the best possible information. This process is called *Design of Experiments (DoE).*

DoE can be divided into two different groups. The first group clusters the classic designs, which include the *factorial* or *fractional factorial designs*, *central composite designs*, *Box-Behnken designs*, *Plackett-Burman designs*, *Koshal designs*, and *D-optimal designs* [133]. These types of designs tend to spread the sample points around the border of the design space and only include a few points inside it. The classic designs are mainly used to construct polynomial metamodels. When the initial input data points were used to construct more advanced metamodels, other designs, called space-filling designs, were preferred. These types of designs tend to spread the sample points all over the design space (often with a uniform distribution), so it is possible to take into account the local phenomena in any region of the design space. The most popular space-filling designs are *Latin hypercube sampling (LHS)* [134], distance-based designs [135], and low-discrepancy sequences, which include Hammersley sequence sampling [136] and uniform design [137].

There are several mathematical approximations to construct metamodels with different characteristics [132], [131]. Although these metamodels have been compared [19], [138], [139], it is not possible to determine whether one is better than the others as this depends on the problem posed. However, the most used metamodels are polynomial regression, artificial neural networks, and kriging [131], [140].

2.5.2.1. Polynomial

Polynomial-based metamodel techniques were first developed to study the results of physical problems and to generate a response surface of these observed response values. The idea behind polynomial-based approximation is that the deterministic response y(x) can be described as (Eq. 2.2):

$$y(x) = f(x) + \varepsilon \qquad (2.2)$$

where f(x) is the polynomial approximation function and ε is random error that is assumed to be normally distributed with mean zero and variance 2σ. At each observation, the error, ε, is assumed to be independent and identically distributed. In most cases, the polynomial approximation function, f(x), uses a low-order polynomial to approximate the response y(x), for example, the linear approximation (Eq. 2.3.) or the quadratic approximation (Eq. 2.4.)

$$f(x) = \beta_0 + \sum_{i=1}^{n} \beta_i \cdot x_i \tag{2.3}$$

$$f(x) = \beta_0 + \sum_{i=1}^{n} \beta_i \cdot x_i + \sum_{i=1}^{n} \beta_{ii} \cdot x_i^2 + \sum_{i=1} \sum_{j<1} \beta_{ij} \cdot x_i \cdot x_j \tag{2.4}$$

where the parameters β_0, β_i, β_{ii}, and β_{ij} are determined by means of the least-squares regression method, which minimizes the sum of the squares of the deviations of predicted values from the actual values.

2.5.2.2. Artificial neural network

The first artificial neural network was developed by Frank Rosenblatt in 1958 [141] in order to model the processing of the visual data by human brains. Later, other researches saw in the artificial neural networks a technique with great capacity to solve problems beyond the problems related to the perception of the human mind, and they are beginning to be used for other purposes.

The artificial neural network works by creating connections between many different elements (or neurons). This technique is organized into different layers, where the neurons learn from the input elements, adjusting weights through an iterative process, and the output generated is sent as input to another neuron. The last layer provides the final output.

The numbers of neurons in the input and output layers correspond, respectively, to the numbers of input and output parameters. Inputs are multiplied by weights and combined linearly with an independent term according to Eq. 2.5. Then, each neuron generates an output, and this output layer follows the same procedure.

$$\sum x_i \cdot w_{i,j} + b \tag{2.5}$$

2.5.2.3. Kriging

Kriging is a metamodel that has its origins in geostatic applications involving spatially and temporally correlated data and was developed by a South African mining engineer called Danie Gerhardus Krige. Later, many researches contributed to the problem of optimal spatial prediction, but the approach was formalized in 1963 by Matheron [142], who used the term "kriging" in honor of the contribution of Danie Gerhardus Krige [143]. The idea behind kriging is that the deterministic response *y(x)* can be described as (Eq. 2.6):

$$y(x) = f(x) + Z(x) \tag{2.6}$$

where *f(x)* is the known approximation function and *Z(x)* is a realization of a stochastic process with mean zero, variance σ^2, and non-zero covariance. The first term of the equation, *f(x)*, is similar to a regression model that provides a global approximation of the design space (Eq. 2.7.). The second term, *Z(x)*, creates local deviations so that the kriging model interpolates the initial sample points (Eq. 2.8.). In many cases, *f(x)* is simply a constant term and the method is then called ordinary kriging. If f(x) is set to 0, implying that the response *y(x)* has a mean of zero, the method is called simple kriging [144].

$$f(x) = \sum_{i=1}^{n} \beta_i \cdot f_i(x) \tag{2.7}$$

$$cov[Z(x_i), Z(x_j)] = \sigma^2 \cdot R(x_i, x_j) \tag{2.8}$$

where the process variance σ^2 scales the spatial correlation function $R(x_i,x_j)$ between two data points. In engineering design, the Gaussian correlation function (Eq. 2.9.) is the most commonly used [144] function that can be defined with only one parameter (θ) that controls the area of influence of nearby points [145]. A low value of θ means that all the sample points have a high correlation, and thus the term *Z(x)* will be similar all over the design space. As the value of θ increases, the points with higher correlation will be closer, and thus the term *Z(x)* will differ depending on the point in the design space:

$$R(x_i, x_j) = e^{-\sum_{k=1}^{m} \theta \left| x_k^i - x_k^j \right|^2} \tag{2.9}$$

2.6. Robust design

Traditionally, uncertainties in loading conditions, material properties, geometry, or structural contour conditions have been included in the design process through hypotheses based on experience or engineering criteria such as the use of safety factors. Using these hypotheses, a simplified model is obtained, based on the nominal values of the variables and design parameters. However, the optimal solutions that have been reached with this deterministic approach have an optimum behavior only under conditions close to those fixed in the optimization process and can deteriorate too much when the conditions move away from those of the design.

However, the real behavior of structures takes place under uncertain conditions, which can cause modifications in the objective response under the same initial conditions. This is known as robust design [18], and its optimization is known as probabilistic optimization. Nowadays, the optimal probabilistic design of structures includes two approaches: Reliability-Based Design Optimization (RBDO) [146] and Robust Design Optimization (RDO) [147]. In RBDO, the probability of failure is studied from the variations of the initial parameters. RDO is used to obtain the design that is least sensitive to variations of the initial parameters.

Several authors have applied RBDO to optimize maintenance of existing bridges [127], [148], [149]. However, RDO has been applied infrequently to structures and even less to bridges. The review of RDO works applied to structures shows that this methodology has been used relatively little and always for simple structures. Lee et al. [150] applied the RDO to a two-bar structure where the uncertain initial variables are the load, modulus of elasticity, and one geometrical variable and the objective is to reduce the mean and standard deviation of the volume. Jurecka et al. [18] used RDO for a 10-bar structure where the initial uncertain variable is the load and the objective is to reduce the mean and standard deviation of the vertical displacement. Frutos et al. [151] applied the RDO to a four-bar structure and a 25-bar truss structure. In the four-bar structure problem, the initial uncertain variable is the modulus of elasticity and the objective is to reduce the mean and standard deviation of the horizontal displacement, while in the 25-bar truss structure problem the initial uncertain variables are the modulus of elasticity and the load and the objective is to reduce the mean of the weight and standard deviation of the vertical displacement. Finally Doltinis et al. [147] applied RDO to a three-bar structure, a 10-bar structure, and a 25-bar truss structure, varying different uncertain initial parameters and objectives.

References

[1] United Nations., *World Commission on Environment and Development Our common future*. New York, USA, 1987.

[2] United Nations, "Indicators for sustainable development goals," 2014.

[3] D. Jato-Espino, E. Castillo-Lopez, J. Rodriguez-Hernandez, and J. C. Canteras-Jordana, "A review of application of multi-criteria decision making methods in construction," *Automation in Construction*, vol. 45, pp. 151–162, 2014.

[4] E. K. Zavadskas and Z. Turkis, "Multiple criteria decision making (MCDM) methods in economics: An overview," *Technological and Economic Development of Economy*, vol. 18, no. 4, pp. 672–695, 2012.

[5] V. Penadés-Plà, T. García-Segura, J. Martí, and V. Yepes, "A review of multi-criteria decision-making methods applied to the sustainable bridge design," *Sustainability*, vol. 8, no. 12, p. 1295, 2016.

[6] H. Gervásio and L. Simões Da Silva, "A probabilistic decision-making approach for the sustainable assessment of infrastructures," *Expert Systems with Applications*, vol. 39, no. 8, pp. 7121–7131, 2012.

[7] E. K. Zavadskas, R. Liias, and Z. Turskis, "Multi-attribute decision-making methods for assessment of quality in bridges and road construction: State-of-the-art surveys," *The Baltic Journal of Road and Bridge Engineering*,

vol. 3, no. 3, pp. 152–160, 2008.

[8] O. O. Ugwu, M. M. Kumaraswamy, A. Wong, and S. T. Ng, "Sustainability appraisal in infrastructure projects (SUSAIP): Part 2: A case study in bridge design," *Automation in Construction*, vol. 15, no. 2, pp. 229–238, 2006.

[9] X. Gu, Y. Wang, and B. Yang, "Method for selecting the suitable bridge construction projects with interval-valued intuitionistic Fuzzy information," *International Journal of Digital Content Technology and its Applications*, vol. 5, no. 7, pp. 201–206, 2011.

[10] V. Balali, A. Mottaghi, O. Shoghli, and M. Golabchi, "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*, vol. 2431, pp. 79–87, 2014.

[11] S. M. Mousavi, H. Gitinavard, and A. Siadat, "A new hesitant fuzzy Analytical Hierarchy Process method for decision-making problems under uncertainty," in *IEEE International Conference on Industrial Engineering and Engineering Management*, 2014, pp. 622–626.

[12] N.-F. Pan, "Fuzzy AHP approach for selecting the suitable bridge construction method," *Automation in Construction*, vol. 17, no. 8, pp. 958–965, 2008.

[13] Z. Chen, A. B. Abdullah, C. J. Anumba, and H. Li, "ANP experiment for demolition plan evaluation," *Journal of Construction Engineering and Management*, vol. 140, no. 2, pp. 51–60, 2013.

[14] J. B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. Wegener Sleeswijk, H. a. Udo De Haes, J. a. de Bruijn, R. van Duin, and M. a. J. Huijbregts, "Life cycle assessment: An operational guide to the ISO standards," *III: Scientific background*, no. May, p. 692, 2001.

[15] J. V. Martí, T. García-Segura, and V. Yepes, "Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy," *Journal of Cleaner Production*, vol. 120, pp. 231–240, May 2016.

[16] T. García-Segura, V. Yepes, J. Alcalá, and E. Pérez-López, "Hybrid harmony search for sustainable design of post-tensioned concrete box-girder pedestrian bridges," *Engineering Structures*, vol. 92, pp. 112–122, 2015.

[17] A. Laurent, S. I. Olsen, and M. Z. Hauschild, "Limitations of carbon footprint as indicator of environmental sustainability," *Environmental Science & Technology*, vol. 46, no. 7, pp. 4100–4108, 2012.

[18] F. Jurecka, M. Ganser, and K.-U. Bletzinger, "Update scheme for sequential spatial correlation approximations in robust design optimisation," *Computers & Structures*, vol. 85, no. 10, pp. 606–614, May 2007.

[19] Y. F. Li, S. H. Ng, M. Xie, and T. N. Goh, "A systematic comparison of metamodeling techniques for simulation optimization in decision support systems," *Applied Soft Computing*, vol. 10, no. 4, pp. 1257–1273, 2010.

[20] T. Waas, J. Hugé, T. Block, T. Wright, F. Benitez-Capistros, and A. Verbruggen, "Sustainability Assessment and Indicators: Tools in a Decision-Making Strategy for Sustainable Development," *Sustainability*, vol. 6, no. 9, pp. 5512–5534, Aug. 2014.

[21] Intergovernmental Panel On Climate Change, *Climate change: Fifth assessment report*. 2014.

[22] T. Ramesh, R. Prakash, and K. K. Shukla, "Life cycle energy analysis of buildings: An overview," *Energy and Buildings*, vol. 42, no. 10, pp. 1592–1600, 2010.

[23] A. Petek Gursel, E. Masanet, A. Horvath, and A. Stadel, "Life-cycle inventory analysis of concrete production: A critical review," *Cement and Concrete Composites*, vol. 51, pp. 38–48, 2014.

[24] M. Taylor, C. Tam, and D. Gielen, "Energy efficiency and CO2 emissions from the global cement industry," in *International Energy Agency*, 2006, p. 13.

[25] M. W. Tait and W. M. Cheung, "A comparative cradle-to-gate life cycle assessment of three concrete mix designs," *The International Journal of Life Cycle Assessment*, vol. 21, no. 6, pp. 847–860, Jun. 2016.

[26] D. K. Panesar, K. E. Seto, and C. J. Churchill, "Impact of the selection of functional unit on the life cycle assessment of green concrete," *The International Journal of Life Cycle Assessment*, vol. 22, no. 12, pp. 1969–1986, Dec. 2017.

[27] K. Murphy, "The social pillar of sustainable development: a literature review and framework for policy analysis," *Sustainability: Science, Practice and Policy*, vol. 8, no. 1, pp. 15–29, Apr. 2012.

[28] I. Omann and J. H. Spangenberg, "Assessing social sustainability: The social dimension of sustainability in a socio-economic scenario," 2002.

[29] J. M. Harris, T. A. Wise, K. P. Gallagher, and N. R. Goodwine, *A survey of sustainable development: Social and economic dimension*. Washinton, 2001.

[30] C. Benoît and B. Mazijn, *Guidelines for Social Life Cycle Assessment of Products. UNEP/SETAC Life Cycle Initiative, Sustainable Product and Consumption Branch*, vol. 15, no. 2. 2009.

[31] R. C. Hill and P. A. Bowen, "Sustainable construction: principles and a framework for attainment," *Construction Management and Economics*, vol. 15, no. 3, pp. 223–239, May 1997.

[32] R. Valdes-Vasquez and L. E. Klotz, "Social sustainability considerations during planning and design: Framework of processes for construction projects," *Journal of Construction Engineering and Management*, vol. 139, no. 1, pp. 80–89, 2013.

[33] E. Almahmoud and H. K. Doloi, "Assessment of social sustainability in construction projects using social network analysis," *Facilities*, vol. 30, no. 3/4, pp. 152–176, 2015.

[34] V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, "Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges," *Sustainability (Switzerland)*, vol. 9, no. 10, p. 1864, 2017.

[35] A. Hettinger, J. Birat, O. Hechler, and M. Braun, "Sustainable bridges - LCA for a composite and a concrete bridge," in *Economical Bridge Solutions Based on Innovative Composite Dowels and Integrated Abutments*, Springer., E. Petzek and R. Bancila, Eds. Wiesbaden, Germany, 2015, pp. 45–54.

[36] G. Du and R. Karoumi, "Life cycle assessment framework for railway bridges: Literature survey and critical issues," *Structure and Infrastructure Engineering*, vol. 10, no. 3, pp. 277–294, 2014.

[37] K. C. Sarma and H. Adeli, "Cost optimization of concrete structures," *Journal of Structural Engineering*, vol. 124, no. 5, pp. 570–578, May 1998.

[38] P. Jakiel and D. Fabianowski, "FAHP model used for assessment of highway RC bridge structural and technological arrangements," *Expert Systems with Applications*, vol. 42, no. 8, pp. 4054–4061, 2015.

[39] M. Cinelli, M. Coles, and K. Kirwan, "Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment.," *Ecological indicators*, vol. 46, pp. 138–148, 2014.

[40] C. L. Hwang and K. Yoon, *Multiple attribute decision making: Methods and Applications*. 1981.

[41] S. Hajkowicz and K. Collins, "A review of multiple criteria analysis for water resource planning and management," *Water Resources Management*,

vol. 21, no. 9, pp. 1553–1566, 2007.

[42] M. M. De Brito and M. Evers, “Multi-criteria decision-making for flood risk management: A survey of the current state of the art,” *Natural Hazards and Earth System Sciences*, vol. 16, no. 4, pp. 1019–1033, 2016.

[43] V. Podvezko, “The Comparative Analysis of MCDA methods SAW and COPRAS,” *Engineering Economics*, vol. 22, no. 2, pp. 134–146, 2011.

[44] M. Tamiz, D. Jones, and C. Romero, “Goal programming for decision making : An overview of the current state-of-the-art,” *European Journal of Operational Research*, vol. 111, no. 3, pp. 569–581, 1998.

[45] E. Ballestero, “Compromise programming: A utility-based linear-quadratic composite metric from the trade-off between achievement and balanced (non-corner) solutions,” *European Journal of Operational Research*, vol. 182, no. 3, pp. 1369–1382, 2007.

[46] S. Opricovic and G.-H. Tzeng, “Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS,” *European Journal of Operational Research*, vol. 156, no. 2, pp. 445–455, 2004.

[47] A. Görener, “Comparing AHP and ANP: An application of strategic decisions making in a manufacturing company,” *International Journal of Business and Social Science*, vol. 3, no. 11, pp. 194–208, 2012.

[48] C. A. Bana e Costa and J. Vansnick, “MACBETH-An interactive path towards the construction fo cardinal value functions,” *International Transactions in Operational research*, vol. 1, no. 4, pp. 489–500, 1994.

[49] M. Behzadian, R. B. Kazemzadeh, A. Albadvi, and M. Aghdasi, “PROMETHEE: A comprehensive literature review on methodologies and applications,” *European Journal of Operational Research*, vol. 200, no. 1, pp. 198–215, 2010.

[50] K. Govindan and M. B. Jepsen, “ELECTRE: A comprehensive literature review on methodologies and applications,” *European Journal of Operational Research*, vol. 250, no. 1, pp. 1–29, 2016.

[51] P. Sarabando and L. C. Dias, “Simple procedures of choice in multicriteria problems without precise information about the alternatives’ values,” *Computers and Operations Research*, vol. 37, no. 12, pp. 2239–2247, 2010.

[52] O. Pons and A. De La Fuente, “Integrated sustainability assessment method applied to structural concrete columns,” 2013.

[53] E. K. Zavadskas and A. Kaklauskas, “Determination of an efficient contractor by using the new method of multicriteria assessment,”

Assessment, in International Symposium for the Organization and Management of Construction: Shaping Theory and Prac- tice; vol. 2; Managing the Construction Project and Managing Risk, pp. 94–104, 1996.

[54] P. L. Yu, "A class of solutions for group decision problems," *Management Science*, vol. 19, no. 8, pp. 936–946, 1973.

[55] M. Zeleny, *Multiple criteria decision making*, McGraw-Hil. New York, 1982.

[56] S. Opricovic, *Multicriteria optimization of civil engineering systems*. Faculty of civil engineering, Belgrade, 1998.

[57] S. J. Chen and C. L. Hwang, *Fuzzy multiple attribute decision making: Methods and applications*, Springer-V. Berlin.

[58] T. L. Saaty, *The Analytic Hierarchy Process*. New York, 1980.

[59] T. L. Saaty, *Decision making with dependence and feedback: The analytic network process*, Ellsworth. Pittsburgh, 1996.

[60] B. Roy, "Classement et choix en présence de points de vue multiples (le méthode ELECTRE)," *Revue Francaise D Informatique de Recherche Operationnelle*, vol. 8, pp. 57–75, 1968.

[61] J. P. Brans, B. Mareschal, and P. Vincke, "PROMETHEE: A new family of outranking methods in multicriteria analysis," *Operational Research*, pp. 408–421, 1984.

[62] J. P. Brans, P. Vincke, and B. Mareschal, "How to select and how to rank projects: The Promethee method," *European Journal of Operational Research*, vol. 24, no. 2, pp. 228–238, 1986.

[63] W. Edwards, "How to use multiattribute utility measurement for social decisionmaking," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 7, no. 5, pp. 326–340, 1977.

[64] R. L. Keeney and H. Raiffa, *Decisions with multiple objective: Preferences and value tradeoffs*, Wiley. New York, 1976.

[65] L. A. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, no. 3, pp. 338–353, 1965.

[66] J. L. Deng, "Introduction to grey system theory," *The Journal of Grey Theory*, vol. 1, pp. 1–24, 1989.

[67] Y. Lin, M. Chen, and S. Liu, "Theory of grey systems: capturing uncertainties of grey information," *Kybernetes*, vol. 33, no. 2, pp. 196–218, Feb. 2004.

[68] N. Dalkey and O. Helmer, "An experimental application of the Delphi method to the use of experts," *Managment Science*, vol. 9, no. 3, pp. 458–467, 1963.

[69] H. Malekly, S. Meysam Mousavi, and H. Hashemi, "A fuzzy integrated methodology for evaluating conceptual bridge design," *Expert Systems with Applications*, vol. 37, no. 7, pp. 4910–4920, 2010.

[70] H.-L. Wang, Z. Zhang, S.-F. Qin, and C.-L. Huang, "Fuzzy optimum model of semi-structural decision for lectotype," *China Ocean Engineering*, vol. 15, no. 4, pp. 453–466, 2001.

[71] A. Farkas, "Multi-criteria comparison of bridge designs," *Acta Polytechnica Hungarica*, vol. 8, no. 1, pp. 173–191, 2011.

[72] M. H. Aghdaie, S. H. Zolfani, and E. K. Zavadskas, "Prioritizing constructing projects of municipalities based on AHP and COPRAS-G: A case study about footbridges in Iran," *The Baltic Journal of Road and Bridge Engineering*, vol. 7, no. 2, pp. 145–153, 2012.

[73] A. Ardeshir, N. Mohseni, K. Behzadian, and M. Errington, "Selection of a bridge construction site using Fuzzy Analytical Hierarchy Process in Geographic Information System," *Arabian Journal for Science and Engineering*, vol. 39, no. 6, pp. 4405–4420, 2014.

[74] J.-S. Chou, A.-D. Pham, and H. Wang, "Bidding strategy to support decision-making by integrating Fuzzy AHP and regression-based simulation," *Automation in Construction*, vol. 35, pp. 517–527, 2013.

[75] Y. Chen, G. E. Okudan, and D. R. Riley, "Decision support for construction method selection in concrete buildings: Prefabrication adoption and optimization," *Automation in Construction*, vol. 19, no. 6, pp. 665–675, 2010.

[76] J. O. Sobanjo, G. Stukhart, and R. W. James, "Evaluation of projects for rehabilitation of highway bridges," *Journal of Structural Engineering*, vol. 120, no. 1, pp. 81–99, 1994.

[77] M. Ei-Mikawi and A. S. Mosallam, "A methodology for evaluation of the use of advanced composites in structural civil engineering applications," *Composites Part B: Engineering*, vol. 27, no. 3–4, pp. 203–215, 1996.

[78] S. Abu Dabous and S. Alkass, "A multi-attribute ranking method for bridge management," *Engineering, Construction and Architectural Management*, vol. 17, no. 3, pp. 282–291, 2010.

[79] S. Abu Dabous and S. Alkass, "Decision support method for multi-criteria selection of bridge rehabilitation strategy," *Construction Management and*

Economics, vol. 26, no. 786929861, pp. 883–893, 2008.

[80] E. Grant and W. Ireson, *Principles of engineering economy*. 1960.

[81] R. Flanagan, A. Kendell, G. Norman, and G. D. Robinson, "Life cycle costing and risk management," *Construction Management and Economics*, vol. 5, no. 4, pp. S53–S71, Dec. 1987.

[82] H. E. Marshall, "Building economics in the United States," *Construction Management and Economics*, vol. 5, no. 4, pp. S43–S52, Dec. 1987.

[83] S. Ohkubo, P. B. R. Dissanayake, and K. Taniwaki, "An approach to multicriteria fuzzy optimization of a prestressed concrete bridge system considering cost and aesthetic feeling," *Structural Optimization*, vol. 15, no. 2, pp. 132–140, 1998.

[84] T. García-Segura, V. Yepes, D. M. Frangopol, and D. Y. Yang, "Lifetime reliability-based optimization of post-tensioned box-girder bridges," *Engineering Structures*, vol. 145, 2017.

[85] M. A. Curran, *Environmental Life-Cycle Assessment*. 1996.

[86] I. Boustead and G. F. Hancock, *Handbook of industrial energy analysis*. 1979.

[87] A. Horvath and C. Hendrickson, "Steel versus steel-reinforced concrete bridges: Environmental assessment," *Journal of Infrastructure Systems*, vol. 4, no. 3, pp. 111–117, 1998.

[88] J. Widman, "Environmental impact assessment of steel bridges," *Journal of Construction Steel Research*, vol. 46, no. 412, pp. 291–293, 1998.

[89] H. Gervasio and L. Simoes da Silva, "Comparative life-cycle analysis of steel-concrete composite bridges," *Structure and Infrastructure Engineering*, vol. 4, no. 4, pp. 251–269, 2008.

[90] T. Stengel and P. Schiessl, "Life cycle assessment of UHPC bridge constructions : Sherbrooke Footbridge , Kassel Gärtnerplatz Footbridge and Wapello Road Bridge," *Architecture Civil Engineering Environment*, vol. 1, pp. 109–118, 2009.

[91] L. Bouhaya, R. Le Roy, and A. Feraille-Fresnet, "Simplified environmental study on innovative bridge structure," *Environmental Science & Technology*, vol. 43, no. February, pp. 2066–2071, 2009.

[92] Y. Itoh and T. Kitagawa, "Using CO2 emission quantities in bridge lifecycle analysis," *Engineering Structures*, vol. 25, no. 5, pp. 565–577, 2003.

[93] K. N. P. Steele, G. Cole, and G. Parke, "Application of life cycle assessment technique in the investigation of brick arch highway bridges," in *6th International Masonry Conference*, 2002, pp. 1–8.

[94] G. Du and R. Karoumi, "Life cycle assessment of a railway bridge: Comparison of two superstructure designs," *Structure and Infrastructure Engineering*, vol. 9, no. Iso14040 2006, pp. 1149–1160, 2012.

[95] G. Du, M. Safi, L. Pettersson, and R. Karoumi, "Life cycle assessment as a decision support tool for bridge procurement: Environmental impact comparison among five bridge designs," *The International Journal of Life Cycle Assessment*, vol. 19, no. 12, pp. 1948–1964, 2014.

[96] J. Hammervold, M. Reenaas, and H. Brattebø, "Environmental life cycle assessment of bridges," *Journal of Bridge Engineering*, vol. 18, no. 2, pp. 153–161, 2013.

[97] B. Pang, P. Yang, Y. Wang, A. Kendall, H. Xie, and Y. Zhang, "Life cycle environmental impact assessment of a bridge with different strengthening schemes," *The International Journal of Life Cycle Assessment*, vol. 20, no. 9, pp. 1300–1311, 2015.

[98] S. Sabatino, D. M. Frangopol, and Y. Dong, "Sustainability-informed maintenance optimization of highway bridges considering multi-attribute utility and risk attitude," *Engineering Structures*, vol. 102, pp. 310–321, 2015.

[99] S. Vallance, H. C. Perkins, and J. E. Dixon, "What is social sustainability? A clarification of concepts," *Geoforum*, vol. 42, no. 3, pp. 342–348, Jun. 2011.

[100] E. Sterner, "Green procurement of building: Estimation of life cycle cost and environmental impact," 2002.

[101] M. Hauschild and J. Potting, "Background for spatial differentiation in LCA impact assessment - The EDIP2003 methodology," *Environmental news*, no. 996, 2005.

[102] J. C. Bare, "The Tool for the reduction and assessment of chemical and other environmental impacts," *Journal of Industrial Ecology*, vol. 6, no. 3–4, pp. 49–78, Jun. 2002.

[103] M. Gocdkoop, P. Hofstetter, R. Müller-Wenk, and R. Spriemsma, "The Eco-Indicator 98 explained," *International Journal of Life Cycle Assessment*, vol. 3, no. 6, pp. 352–360, 1998.

[104] B. Steen, "A systematic approach to environmental priority strategies in product development (EPS)," 1999.

[105] R. Frischknecht, R. Steiner, and N. Jungbluth, “Methode der ökologischen Knappheit – Ökofaktoren 2006,” p. 190, 2009.

[106] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, *ReCiPe 2008. A life cycle impact assessment which comprises harmonised category indicators at midpoint and at the endpoint level*. Netherlands, 2009.

[107] N. Itsubo, M. Sakagami, T. Washida, K. Kokubu, and A. Inaba, “Weighting across safeguard subjects for LCIA through the application of conjoint analysis,” *International Journal of Life Cycle Assessment*, vol. 9, no. 3, pp. 196–205, 2004.

[108] O. Jolliet, M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer, and R. Rosenbaum, “IMPACT 2002+: A new Life Cycle Impact Assessment Methodology,” *International Journal of Life Cycle Assessment*, vol. 8, no. 6, pp. 324–330, 2003.

[109] GreenDelta, “PSILCA database,” 2013. [Online]. Available: https://psilca.net/. [Accessed: 01-Oct-2019].

[110] M. Lenzen, D. Moran, K. Kanemoto, and A. Geschke, “Building Eora: A global multi-regional Input-Output Database at high country and sector resolution,” *Economic Systems Research*, vol. 25, no. 1, pp. 20–49, Mar. 2013.

[111] New Earth, “SHDB database,” 2009. [Online]. Available: https://www.socialhotspot.org/for-more-information.html. [Accessed: 01-Oct-2019].

[112] Purdue University, “Global trade analysis project,” West Lafayette, Indiana, 2013.

[113] I. J. Navarro, V. Yepes, J. V. Martí, and F. González-Vidosa, “Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks,” *Journal of Cleaner Production*, vol. 196, pp. 698–713, Sep. 2018.

[114] G. Du and R. Karoumi, “Environmental life cycle assessment comparison between two bridge types : Reinforced concrete bridge and steel composite bridge,” in *3th International Conference on Sustainable Construction Materials and Technologies*.

[115] V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, “Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges,” *Sustainability*, vol. 9, no. 10, p. 1864, 2017.

[116] M. Z. Cohn and A. S. Dinovitzer, “Application of structural optimization,”

Journal of Structural Engineering, vol. 120, no. 2, pp. 617–650, 1994.

[117] C. Blum, J. Puchinger, G. R. Raidl, and A. Roli, “Hybrid metaheuristics in combinatorial optimization: A survey,” *Applied Soft Computing*, vol. 11, no. 6, pp. 4135–4151, 2011.

[118] J. H. Holland, *Adaptation in natural and artificial systems*. 1975.

[119] K. N. Krishnanand and D. Ghose, “Glowworm swarm optimisation: A new method for optimising multi-modal functions,” *International Journal of Computational Intelligence Studies*, vol. 1, no. 1, pp. 93–119, 2009.

[120] S. Kirkpatrick, C. D. Gelatt, and M. P. Vecchi, “Optimization by simulated annealing.,” *Science (New York, N.Y.)*, vol. 220, no. 4598, pp. 671–80, May 1983.

[121] A. S. Barr, S. c. Sarin, and A. G.Bishara, “Procedure for structural optimization,” *ACI Structural Journal*, vol. 86, no. 5, pp. 524–531, Sep. 1989.

[122] D. Bond, “An examination of the automated design of prestressed concrete bridge deck by computer,” *Proceedings of the Institution of Civil Engineers*, vol. 59, no. 4, pp. 669–697, Dec. 1975.

[123] C. Yu, H. Gupta, N. C. Das, and H. Paul, “Optimization of prestressed concrete bridge girders,” *Engineering Optimization*, vol. 10, no. 1, pp. 13–24, Jan. 1986.

[124] Z. Lounis and M. Z. Cohn, “Optimization of precast prestressed concrete bridge girder systems,” *PCO Journal*, vol. 38, no. 4, pp. 60–78, 1993.

[125] J. Wills, *A mathematical optimization procedure and its application to the design of bridge structures*. Wokingham, United Kingdom, 1973.

[126] T. García-Segura and V. Yepes, “Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety,” *Engineering Structures*, vol. 125, pp. 325–336, 2016.

[127] T. García-Segura, V. Yepes, and D. M. Frangopol, “Multi-objective design of post-tensioned concrete road bridges using artificial neural networks,” *Structural and Multidisciplinary Optimization*, vol. 56, no. 1, pp. 139–150, 2017.

[128] C. Coello, “Uso de algoritmos genéticos para el diseño óptimo de armaduras,” in *Congreso Nacional de Informática: Herramientas Estratégicas para los Mercados Globales*, 1994, pp. 290–305.

[129] R. Dutta, R. Ganguli, and V. Mani, “Swarm intelligence algorithms for

integrated optimization of piezoelectric actuator and sensor placement and feedback gains," *Smart Materials and Structures*, vol. 20, no. 10, p. 105018, 2011.

[130] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proceedings of ICNN'95 - International Conference on Neural Networks*, 1995, vol. 4, pp. 1942–1948.

[131] T. W. Simpson, J. D. Poplinski, P. N. Koch, and J. K. Allen, "Metamodels for computer-based engineering design: Survey and recommendations," *Engineering with Computers*, vol. 17, no. 2, pp. 129–150, 2001.

[132] R. R. Barton and M. Meckesheimer, "Metamodel-based simulation optimization," vol. 13, 2006.

[133] R. H. Myers, D. C. Montgomery, and C. M. Anderson-Cook, *Response surface methodology: Process and product optimization using designed experiments*. Toronto, Canada: Wiley, 1995.

[134] M. D. McKay, R. J. Beckman, and W. J. Conover, "Comparison of three methods for selecting values of input variables in the analysis of output from a computer code," *Technometrics*, vol. 21, no. 2, pp. 239–245, 1979.

[135] M. E. Johnson, L. M. Moore, and D. Ylvisaker, "Minimax and maximin distance designs," *Journal of Statistical Planning and Inference*, vol. 26, no. 2, pp. 131–148, 1990.

[136] J. R. Kalagnanam and U. M. Diwekar, "An efficient sampling technique for off-line quality control," *Technometrics*, vol. 39, no. 3, p. 308, Aug. 1997.

[137] K.-T. Fang, D. K. J. Lin, P. Winker, and Y. Zhang, "Uniform design: Theory and application," *Technometrics*, vol. 42, no. 3, p. 237, Aug. 2000.

[138] B.-S. Kim, Y.-B. Lee, and D.-H. Choi, "Comparison study on the accuracy of metamodeling technique for non-convex functions," *Journal of Mechanical Science and Technology*, vol. 23, no. 4, pp. 1175–1181, Apr. 2009.

[139] R. Jin, W. Chen, and T. W. Simpson, "Comparative studies of metamodelling techniques under multiple modelling criteria," *Structural and Multidisciplinary Optimization*, vol. 23, no. 1, pp. 1–13, Dec. 2001.

[140] R. D. Bäckryd, A.-B. Ryberg, and L. Nilsson, "Multidisciplinary design optimisation methods for automotive structures," *International Journal of Automotive and Mechanical EngineeringOnline*, vol. 14, no. 1, pp. 2229–8649, 2017.

[141] F. Rosenblatt, "The perceptron: A probabilistic model for information

storage and organization in the brain.," *Psychological Review*, vol. 65, no. 6, pp. 386–408, 1958.

[142] G. Matheron, "Principles of geostatistics," *Economic Geology*, vol. 58, no. 8, pp. 1246–1266, 1963.

[143] N. Cressie, "The origins of kriging," *Mathematical Geology*, vol. 22, no. 3, pp. 239–252, 1990.

[144] T. W. Simpson, T. M. Mauery, J. Korte, and F. Mistree, "Kriging models for global approximation in simulation-based multidisciplinary design optimization," *AIAA Journal*, vol. 39, no. December, pp. 2233–2241, 2001.

[145] A. I. J. Forrester and A. J. Keane, "Recent advances in surrogate-based optimization," *Progress in Aerospace Sciences*, vol. 45, no. 1–3, pp. 50–79, 2009.

[146] M. A. Valdebenito and G. I. Schuëller, "A survey on approaches for reliability-based optimization," *Structural and Multidisciplinary Optimization*, vol. 42, no. 5, pp. 645–663, Nov. 2010.

[147] I. Doltsinis and Z. Kang, "Robust design of structures using optimization methods," *Computer Methods in Applied Mechanics and Engineering*, vol. 193, no. 23–26, pp. 2221–2237, Jun. 2004.

[148] T. García-Segura, V. Yepes, D. M. Frangopol, and D. Y. Yang, "Lifetime reliability-based optimization of post-tensioned box-girder bridges," *Engineering Structures*, vol. 145, pp. 381–391, 2017.

[149] I. J. Navarro, J. V. Martí, and V. Yepes, "Reliability-based maintenance optimization of corrosion preventive designs under a life cycle perspective," *Environmental Impact Assessment Review*, vol. 74, pp. 23–34, Jan. 2019.

[150] K.-H. Lee and D.-H. Kang, "A robust optimization using the statistics based on kriging metamodel," *Journal of Mechanical Science and Technology*, vol. 20, no. 8, pp. 1169–1182, Aug. 2006.

[151] J. Martínez-Frutos and P. Martí, "Diseño óptimo robusto utilizando modelos Kriging: aplicación al diseño óptimo robusto de estructuras articuladas," *Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería*, vol. 30, no. 2, pp. 97–105, Apr. 2014.

CHAPTER 3. METHODOLOGY

3.1. Introduction

The sustainability assessment of a structure is a complex decision-making process in which there are many options for each of the steps. The choice of decision-making method and the choice of criteria that broadly and comprehensively define each of the pillars of sustainability are part of the decision-making process.

In addition, once the sustainability assessment of the structure is defined, the sustainability of the structure can be maximized through heuristic optimization processes. The choice of heuristic algorithm is another point for which the decision-maker is responsible. Furthermore, if some uncertainties in the heuristic optimization problem are considered, the metamodeling process is necessary to reduce the computational cost. As before, the choice of the DoE and metamodel technique should be made.

Chapter 2 reviews the most important possibilities for each of these steps. In this chapter, the selection of one of these possibilities is discussed, and a wide description of the methods or techniques selected is given. In Section 3.2, the MADM methods used are justified. In Section 3.3, the criteria or LCIA methods considered to assess each of the pillars of sustainability are explained. In Section 3.4, the metamodeling choices are discussed, and finally the criteria to assess the different types of robustness of the structure are explained in Section 3.5.

3.2. Multi-criteria decision-making

As shown in Chapter 2, the most important MADM methods can be divided into groups according to their common characteristics. Each MADM group has its advantages and disadvantages and therefore the method should be chosen according to the specific case. There are a large number of MADM methods and their applicability to sustainability assessment is high. However, assessment of the sustainability of bridges is more limited. This review shows that the AHP method is the most used, followed by PROMETHEE, TOPSIS, and COPRAS, each corresponding to a different MADM group.

In this thesis, the decision-making requires: (1) assignment of weights to different criteria, (2) assessment of qualitative criteria, and (3) selection of a solution on the Pareto front. Using pairwise comparison, MADM methods are selected for the first two cases and distance-based MADM methods are considered the most appropriate for the last case.

The assignment of weights to different criteria and the assessment of qualitative criteria are performed by the AHP method. This method has been successfully used to facilitate the judgment of complex problems, as decision-makers are not required to make numerical guesses as subjective judgments are easily included in the process and the judgments can be made entirely in a verbal mode [1]. In addition, this method can check inconsistencies in the decision-maker's assessments [2]. However, this method has two main problems: (a) the consideration of the independence of the criteria, and (b) the fact that a number of criteria higher than around seven can cause confusion in the pairwise comparison. For this reason, when independence of criteria and a small number of criteria are sought, the AHP method is combined with principal component analysis. Principal component analysis reduces the number of criteria into a small number of principal components that are linearly independent. On the other hand, the selection of an alternative on the Pareto front is made by the CP method. This method provides the closet solution to the ideal point. Therefore, this method can be used effectively with multi-objective optimization to select a solution on the Pareto front.

3.2.1. AHP

The AHP (Analytical Hierarchy Process) method was first developed by Thomas L. Saaty in the 1970s [3]. Its simplicity has made it a widely used and very popular decision-making method. To use this method, a decision-making problem must be organized in a hierarchical structure where the final goal is at the highest level and the criteria and sub-criteria are at the lowest levels as shown in Figure 3.1. The correct choice of criteria and sub-criteria, which must be well defined, relevant, and mutually exclusive, is very important.

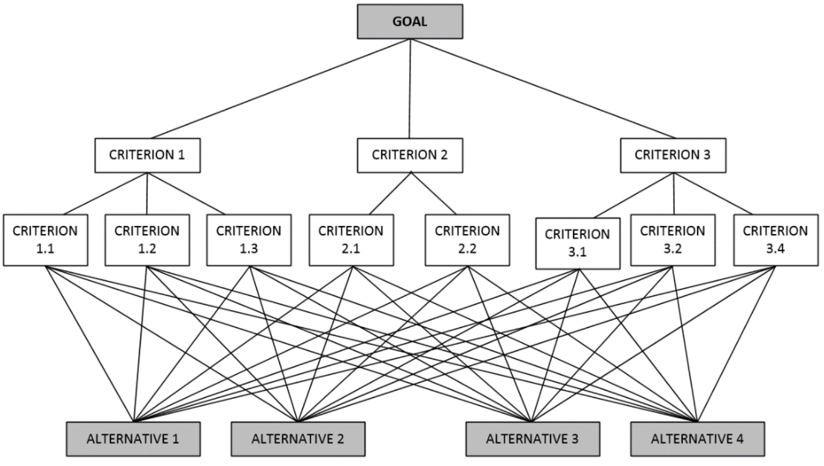

Figure 3.1. AHP hierarchical structure

The number of criteria when the hierarchical structure is defined must not be excessive. For example, according to Bahurmoz [4], the number of criteria and sub-criteria at each level should not be greater than seven to avoid an excessive number of peer comparisons, and Miller [5] says that the number of criteria assimilable by people is 7 ± 2.

After the hierarchical structure has been defined, a comparison of the criteria of each group on the same hierarchical level and a direct comparison of the alternatives with respect to the criteria on the lower level are carried out. This process is systematically repeated in an upward direction until the final objective is evaluated. These assessments are carried out using the fundamental scale proposed by Saaty [2] in Table 3.1.

Table 3.1. Fundamental scale of Saaty [2]

Degree of importance	Scale	Definition
1	Equal importance	The two activities contribute equally to the goal
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	One activity is strongly favored over another; element is very dominant as shown in practice
9	Extremely important	The evidence in favor of one activity over another, to the greatest extent possible
2,4,6,8	Intermediate values	They are used to express preferences that are between the values of the above scale

Both the comparison of the criteria of each group on the same hierarchical level and the direct comparison of the alternatives with respect to the criteria on the lower level are done using a matrix called a decision matrix. Each time a decision matrix is generated, its consistency is evaluated. This is done to avoid contradictions in the assessment by decision makers. This consistency is obtained by means of the Consistency Index (CI) (Eq. 3.1.), where λ_{max} is the maximum eigenvalue and n is the dimension of the decision matrix. A CI equal to 0 means that the consistency is complete. Once the CI is obtained, the Consistency Ratio (CR) (Eq. 3.2.) is obtained and is accepted as long as it does not exceed 10%.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (3.1)$$

$$CR = \frac{CI}{RI} \quad (3.2)$$

Once the consistency has been verified, the weights, which represent the relative importance of each criterion or the priorities of the different alternatives with respect to a given criterion, are obtained. For this, the original AHP uses the method of eigenvalues, and the following equation must be solved (Eq. 3.3.):

$$A \cdot w = \lambda_{max} \cdot w \tag{3.3}$$

where A represents the decision matrix, w the eigenvector, and λ_{max} the eigenvalue.

3.2.2. CP

The CP (Compromise Programming) method tries to find the compromise solution closest to the ideal point. The basis of the CP method was established by Yu in 1973 [6] and Zeleny in 1982 [7], and the method was used later as a basis for the development of other methods such as TOPSIS and VIKOR, which are two of the most representative methods of this group.

In order to apply the CP method, it is first necessary to define the efficient frontier, which is the one where the criteria cannot be improved. The ideal point is obtained from this frontier as the point formed by the best value of each criterion. Finally, the distance from each alternative to the ideal point is calculated. This distance is obtained with the following expression (Eq. 3.4.):

$$L_j = \min \left[\sum_{i=1}^{m} w_i^p \left| \frac{r*_i - r_{ij}}{k_i} \right|^p \right]^{\frac{1}{p}} \tag{3.4}$$

where p is the normalization metric (p = 1, 2, ..., ∞), m the total number of criteria, w_i the weight of criterion i, and k_i the normalization constants for each criterion [the difference between the best value of a criterion ($r*_i$) and the worst ($r-_i$), where r_{ij} is the score of criterion i for alternative j]. The compromise set is the set of optimal solutions to all CP problems, although usually only p = 1, 2, and ∞ are used.

3.3. Life-cycle evaluation

A bridge is designed to provide a service during its whole service life. For this reason, when the sustainability assessment is carried out, it is necessary to take into account the whole life-cycle of the bridge. This is because, in some cases, a bridge has a lower initial impact considering the manufacturing and construction stage, but the total impact is greater due to the maintenance activities necessary to preserve the structure [8]. Figure 3.2 shows a complete life-cycle flow diagram, including the manufacturing, construction, use and maintenance, and final life cycle phases. Therefore, the LCC process is considered for the evaluation of the economic pillar and the LCA process for the evaluation of the environmental and social pillars. Both processes carry out the assessment over the whole life-cycle of the bridge.

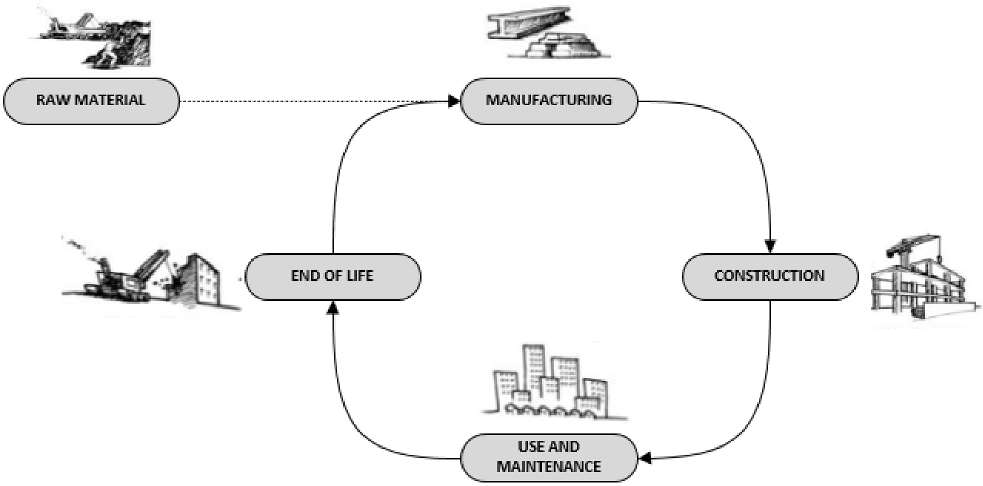

Figure 3.2. Life-cycle stages

There are many criteria to assess the different pillars of sustainability, especially the environmental and social pillars [9]–[12]. Chapter 2 reviews the most used criteria to assess each of the pillars of sustainability throughout the whole bridge life-cycle.

The bibliographic review shows that economic evaluation is the simplest, since direct cost is the most commonly used criterion. The environmental evaluation is more complex, as authors assess this pillar using different criteria. However, in the environmental evaluation of bridges, a trend can be observed, in which energy and CO_2 emissions are the most used criteria. On the other hand, some authors state that these criteria are not sufficient to obtain a complete environmental profile [13]. Finally, the social evaluation is the most uncertain and diffuse, due to the lower importance given to this pillar [14], [15].

3.3.1. Life-cycle cost

The LCC considers the economic impact of a process, product, or service. This economic assessment is measured in the monetary unit of the area where the study is carried out. In this thesis, the euro (€) is used as the only economic indicator for the evaluation of the economic pillar of a bridge throughout its life-cycle. In order to obtain the economic cost of the different processes, products, or services, the BEDEC database has been used [16]. Table 3.2 shows the most common unit cost used in this work.

Table 3.2 Unit costs

UNIT MEASUREMENTS	COST (€)
m^3 of scaffolding	10.2
m^2 of formwork	33.81
m^3 of lighting	104.57
kg of steel (B-500-S)	1.16
kg of post-tensioned steel (Y1860-S7)	3.40
m3 of concrete HP-35	104.57
m3 of concrete HP-40	109.33
m3 of concrete HP-45	114.10
m3 of concrete HP-50	118.87
m3 of concrete HP-55	123.64
m3 of concrete HP-60	128.41
m3 of concrete HP-70	137.95
m3 of concrete HP-80	147.49
m3 of concrete HP-90	157.02
m3 of concrete HP-100	166.56

3.3.2. Life-cycle assessment

The LCA studies the environmental (E-LCA) and social (S-LCA) impacts of a process, product, or service. This case is not like the LCC, as both E-LCA and S-LCA provide several indicators to achieve a complete profile of each pillar. For this reason, it is necessary to follow a process that converts a set of inputs (raw materials, energy, processes, transport, etc.) into a set of outputs (environmental or social indicators). For this purpose, the procedure established by the international standards ISO 14040 [17] and ISO 14044 [18] has been used as a reference guide. These standards define four phases for carrying out an LCA (Figure 3.3): (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation.

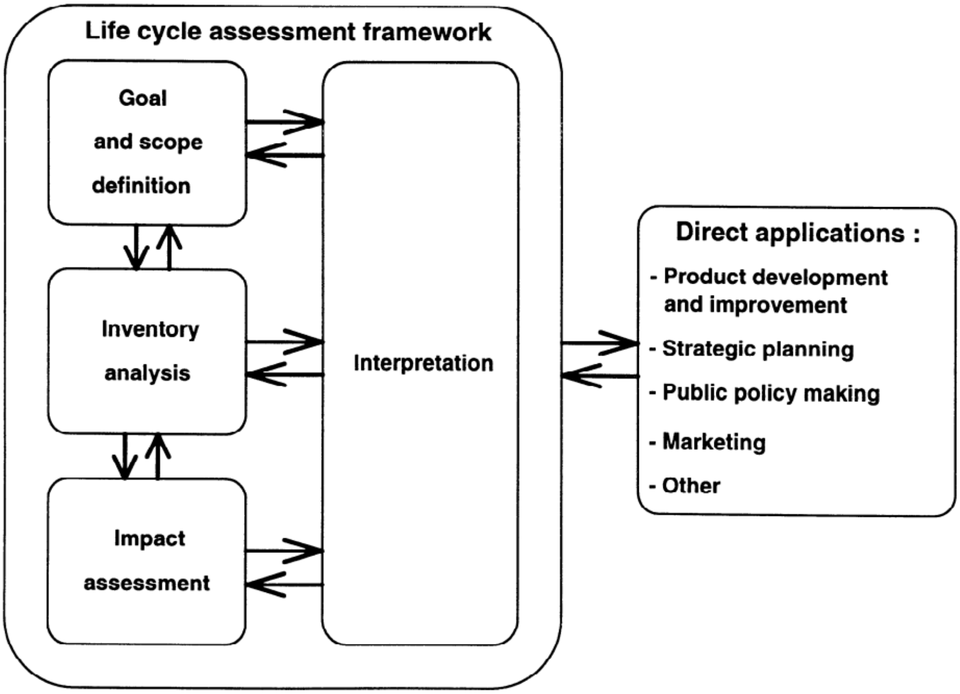

Figure 3.3. LCA stages [17]

3.3.2.1. Goal and scope definition

The goal and scope definition phase consists of clearly defining the LCA study. First, the goal of the LCA should be defined. The goal of the studies carried out in this thesis is to evaluate the environmental and social pillars to finally achieve an assessment of sustainability and compare different alternatives.

Second, the unit of measure, called the *functional unit*, should be determined. The functional unit considered is a linear meter of bridge. This is because in all the studies carried out, the bridges have the same width. In the case of bridges having different widths, the functional unit would be the square meter.

Third, the system boundaries should be delimited, which means that all the data covered in the studies need to be determined. The studies carried out in this thesis cover the whole life-cycle of the bridges. The products, processes, or services considered for each of these phases are shown in Figure 3.4.

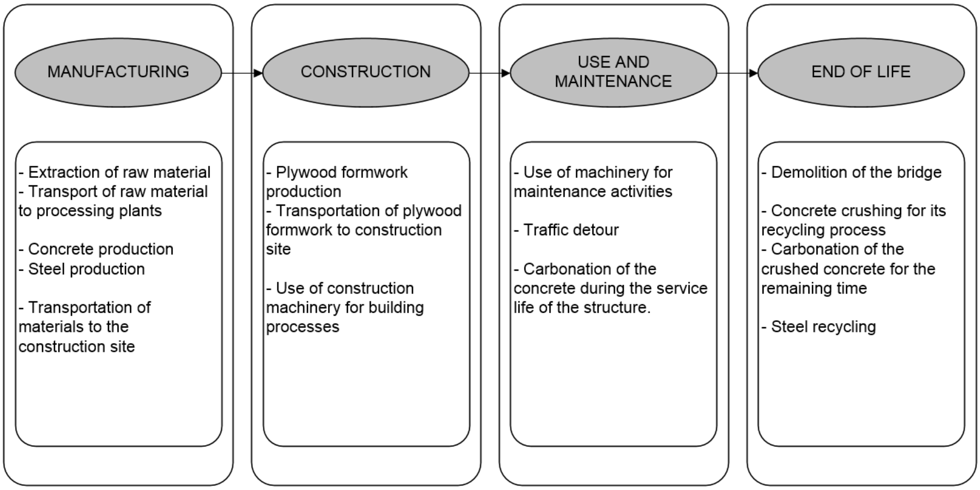

Figure 3.4. Processes, products, or services included in the LCA

Fourth, the data should have quality requirements. The data considered are obtained from verified and important databases. However, in the case that the data used do not cover all the data requirements necessary to carry out a precise analysis, an associated uncertainty will be considered.

3.3.2.2. Inventory analysis

The Life Cycle Inventory (LCI) phase consists of data collection and calculation procedures to quantify relevant inputs and outputs of a product system. Data can be obtained from various sources, such as scientific articles, international databases, industry experts, registers of specialized companies, and so on.

In addition, the sources should be as representative as possible of the data set, due to possible differences in geographical location, technology, the time at which the data were collected, and so on. However, in cases where the data used are not clearly representative for the study, an associated uncertainty will be considered.

The studies carried out in this thesis were modeled using the Ecoinvent database [19]. However, some adjustments have been made using the BEDEC database [16] of the Institute of Construction Technology (ITEC). The Ecoinvent database [19] was developed by the Federal Polytechnic Schools of Zurich (ETHZ) and Lausanne (EPFL) in conjunction with a large number of Swiss research institutes and companies. It contains more than 14,700 data sets on different industrial sectors such as energy production, transport, construction, agriculture, and so on. The data have been collected over 20 years from several international partners to enable companies, politicians, and consumers to take action to improve the environment. It is the world's largest life-cycle inventory and is recognized for its veracity, consistency, and transparency.

In addition, OpenLCA software [20], developed by Green Delta, has been used to implement the database and analyze the impact results. OpenLCA software makes it possible to carry out different LCAs with different levels of detail, according to the needs of each study. Figure 3.5 shows the interface of the OpenLCA software in which an example of the flowchart to assess one linear meter of bridge in the manufacturing stage is shown.

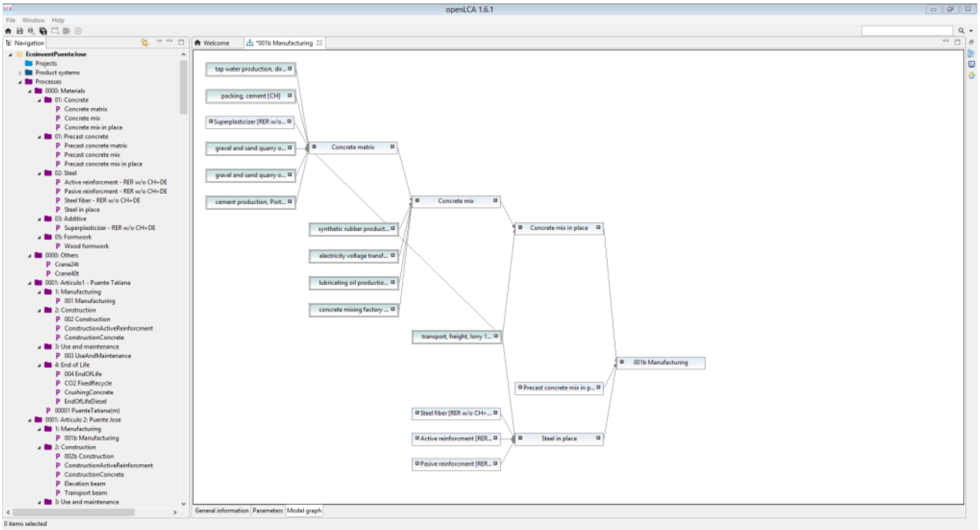

Figure 3.5. OpenLCA interface [20]

3.3.2.3. Environmental LCIA method

There are many E-LCIA methods. Chapter 2 reviews the most important E-LCIA methods, which can be divided into groups according to common characteristics. These groups are the midpoint approach, endpoint approach, and midpoint/endpoint approach.

Although the E-LCA is a methodology that is increasingly being implemented, its use in the construction sector is limited to research issues. The bibliographic review shows that only a few works have applied E-LCIA methods to evaluate the environmental pillar of sustainability. Furthermore, these works only use three different E-LCIA methods: CML 2000, EI 99, and ReCiPe.

The CML method is a midpoint approach and the EI 99 method is an endpoint approach. Both are the most used and accepted methods for their respective approaches [21]–[23]. However, when an E-LCA is carried out, it is appropriate to use both approaches in order to benefit from the advantages of both. For this reason, the studies carried out in this thesis consider the ReCiPe method [24], which combines the CML [25] and EI [26] methods.

On the one hand, the midpoint approach groups the results into 18 impact categories, measuring each with its respective units: agricultural land occupation (ALO), climate change (GWP), fossil depletion (FD), freshwater ecotoxicity (FEPT), freshwater eutrophication (FEP), human toxicity (HTP), ionizing radiation (IRP), marine ecotoxicity (MEPT), marine eutrophication (MEP), metal depletion (MD), natural land transformation (NLT), ozone depletion (OD), particulate matter formation (PMF), photochemical oxidant formation (POFP), terrestrial acidification (TAP), terrestrial ecotoxicity (TEPT), urban land occupation (ULO), and water depletion (WD). These environmental impact categories have a high level of detail, providing accurate results, although they are more difficult to interpret.

On the other hand, the endpoint approach integrates several impact categories into three damage categories: human health (HH), ecosystems (E), and resource availability (R). Each of these damage categories is measured in DALYs (Disability Adjusted Life Years), species per year, and US dollars, respectively. These have the advantage of being easier to interpret and understand. However, the uncertainty of these results increases due to their high level of integration.

In order to integrate all environmental impact categories into an overall score, the damage categories have been normalized using the method Europe ReCiPe H/H [person/year]. In this way, a score of the total environmental impact of the bridge throughout its whole life-cycle can be obtained. This overall score is measured in points.

In addition, in order to include the long-term perspective on environmental impacts, the hierarchical perspective (H) is used, due to the inclusion of recycling and the subsequent use of concrete and steel for other purposes after the end of the useful life of the structure.

Figure 3.6 shows the indicators considered by the ReCiPe method.

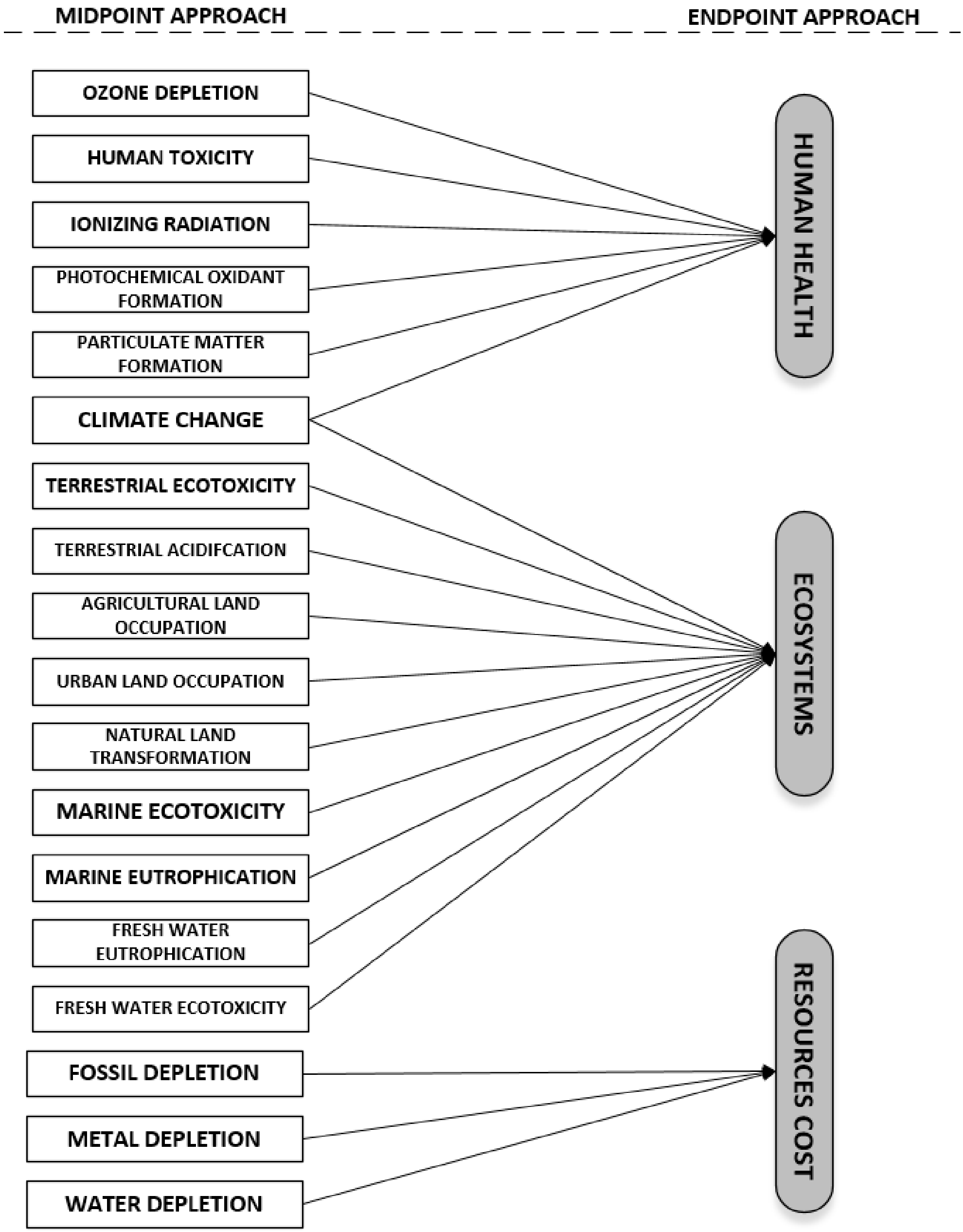

Figure 3.6. ReCiPe indicators

3.3.2.4. Social LCIA method

The assessment of the social pillar of sustainability is the most unclear. Therefore, the information for the S-LCA is weak. Only two S-LCIA methods have been found. Chapter 2 reviews these two methods: PSILCA and SHDB.

Although the S-LCA is a methodology that, according to some authors, should be more important, it has been studied little, and even less in the construction sector. The bibliographic review shows that these S-LCIA methods have not been used to assess the social pillar of sustainability of bridges. So, there is no information about it. However, the studies carried out in this thesis consider the PSILCA method because it has the most frequently updated available data source, transparent documentation of original data sources and risk assessment, and provision of data quality assessment.

The PSILCA groups the results into 88 indicators, which are grouped into 25 topics and five stakeholders. Figure 3.7 shows these indicators.

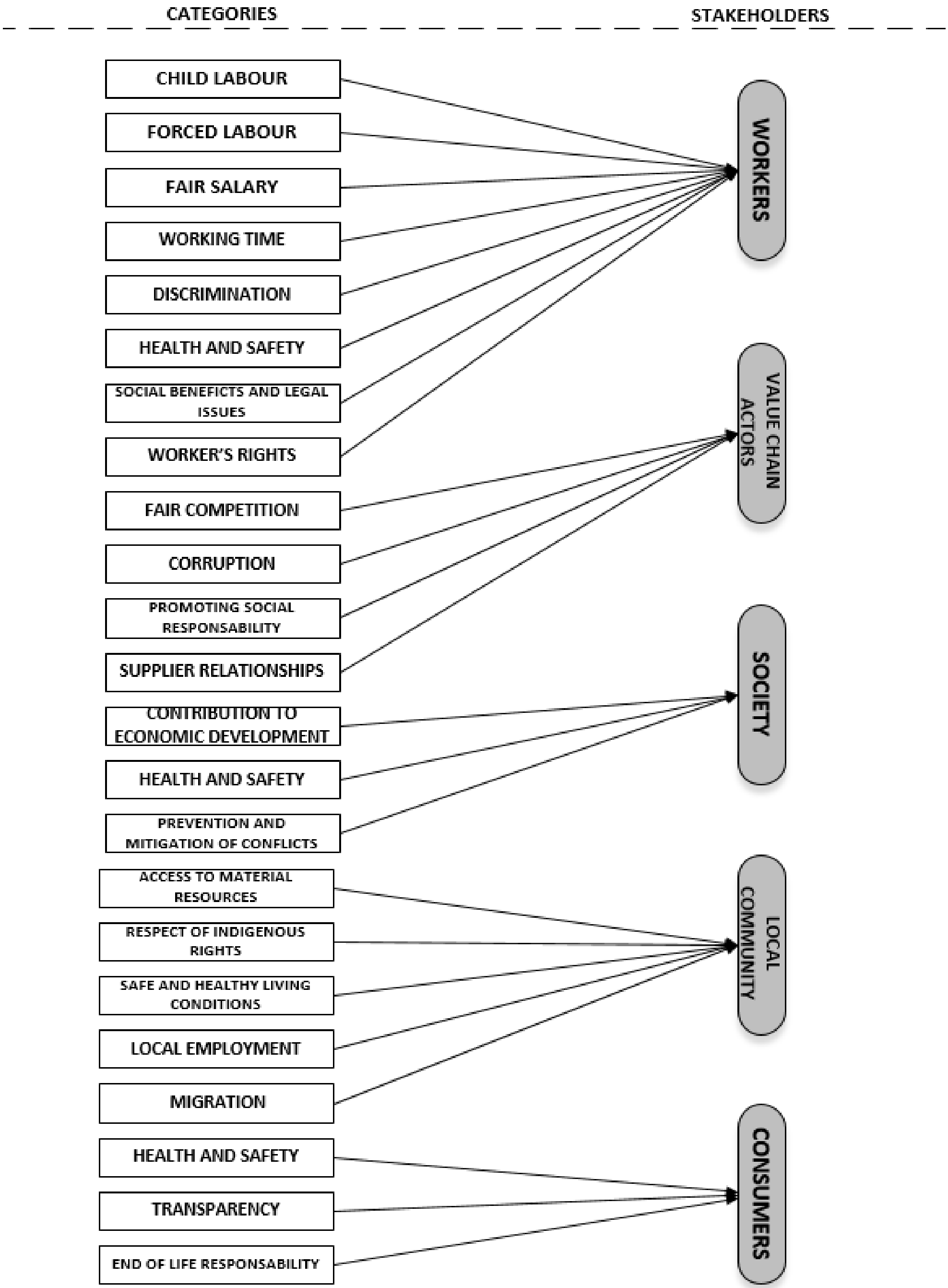

Figure 3.7. PSILCA indicators

3.3.2.5. Interpretation

Interpretation is the phase of the LCA in which the findings from the inventory analysis and the impact assessment are combined together (or, in the case of life cycle inventory studies, the findings of the inventory analysis only), in consistence with the defined goal and scope in order to reach conclusions and recommendations.

The findings of this interpretation may take the form of conclusions and recommendations to decision-makers, in consistence with the goal and scope of the study.

3.4. Optimization and metamodel

There are different ways to carry out the optimization. Chapter 2 reviews the different heuristic algorithms, DoE, and metamodels considered to carry out this work.

3.4.1. Heuristic algorithm

When optimization problems are very complex and have many variables, objectives, and constraints, the most appropriate heuristic algorithm is the population algorithm as it diversifies the search [27]. However, in the case of this thesis, the heuristic algorithm is used to carry out the optimization of a mathematical approach created by a metamodel, which directly relates the design variables to the final objective. Therefore, Simulated Annealing (SA) is used due to its versatile acceptance criterion, good convergence, and short calculation time and the fact that it can escape early local optima [28], [29].

Many works use SA to carry out conventional heuristic optimization [28]–[30]. In this work, the initial temperature is calibrated following Medina's [31] method, which proposes that the initial temperature is halved when the percentage of acceptances is greater than 40% and doubled when it is less than 20%. After that, the temperature decreases according to a coefficient of cooling k following the equation $T = k*T$, when a Markov chain ends. In this work, the calibration revealed that a coefficient of cooling of 0.8 and a Markov chain length of 1000 are appropriate. The algorithm finishes after three Markov chains have been obtained without improvement.

3.4.2. Design of experiment

In this work, to generate the sample, Latin hypercube sampling (LHS) has been considered; its effectiveness in the estimation of the objective response of the metamodel has been proven in several works [32], [33]. LHS was proposed by

McKay et al. in 1979 [34]. This method determines the number N of non-overlapping intervals for each variable (in this work these intervals are divided according to a uniform distribution) from a number of design variables (v) and a number of initial input dataset points (N). Therefore, the design space is divided into Nv regions. Each sample point will be located in one region so that each point corresponds to a combination of different intervals of each design variable range. In this way, each interval of each design variable range will only be associated with one sample point. Consequently, the LHS guarantees that all of the design variables are represented along their respective ranges. Figure 3.8 shows an example with two design variables and eight initial input dataset points.

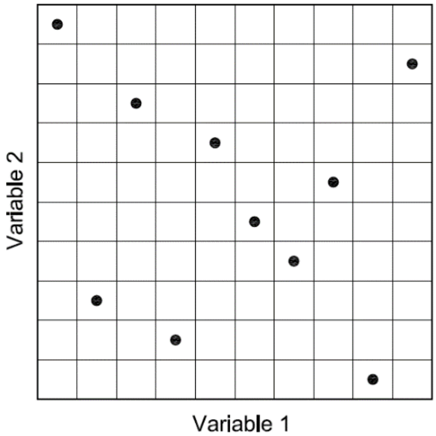

Figure 3.8. Latin hypercube sampling (v = 2 and n = 8)

3.4.3. Metamodel

The polynomial-based response surface model is sometimes difficult to use in complex engineering problems, and the neural network-based model requires many sample points and much computational time for the training of the network [35]. The kriging model is a promising metamodel as it is more flexible than polynomial-based models and less time consuming than neural network based techniques [36]. Thus, this work uses the kriging formulation to construct the metamodel.

Kriging is a metamodel that has its origins in geostatic applications involving spatially and temporally correlated data and was developed by a South African mining engineer called Danie Gerhardus Krige. Later, many researches contributed to the problem of optimal spatial prediction, but the approach was formalized by Matheron [37], who used the term kriging in honor of the contribution of Danie Gerhardus Krige [38]. The idea behind kriging is that the deterministic response y(x) can be described as (Eq. 3.4):

$$y(x) = f(x) + Z(x) \tag{3.4}$$

where f(x) is the known approximation function and Z(x) is a realization of a stochastic process with mean zero, variance σ^2, and non-zero covariance. The first term of the equation, f(x), is similar to a regression model that provides a global approximation of the design space (Eq. 3.5). The second term, Z(x), creates local deviations so that the kriging model interpolates the initial sample points (Eq. 3.6). In many cases, f(x) is simply a constant term and the method is then called ordinary kriging. If f(x) is set to 0, implying that the response y(x) has a mean of zero, the method is called simple kriging [39].

$$f(x) = \sum_{i=1}^{n} \beta_i \cdot f_i(x) \tag{3.5}$$

$$cov\left[Z(x_i), Z(x_j)\right] = \sigma^2 \cdot R(x_i, x_j) \tag{3.6}$$

where the process variance σ^2 scales the spatial correlation function $R(x_i,x_j)$ between two data points. In engineering design, the Gaussian correlation function (Eq. 3.7) is the most commonly used [38] function that can be defined with only one parameter (θ) that controls the area of influence of nearby points [35]. A low value of θ means that all the sample points have a high correlation, and thus the term Z(x) will be similar all over the design space. As the value of θ increases, the points with higher correlation will be closer, and thus the term Z(x) will differ depending on the point in the design space:

$$R(x_i, x_j) = e^{-\sum_{k=1}^{m} \theta \left| x_k^i - x_k^j \right|^2} \tag{3.7}$$

Finally, each metamodel type has its associated fitting method. In this case, the kriging formulation uses the search for the Best Linear Unbiased Predictor (BLUP). Simpson et al. [40] published a detailed review of the equations and fitting methods for common metamodel types.

Figure 3.9 show the steps explained in this part.

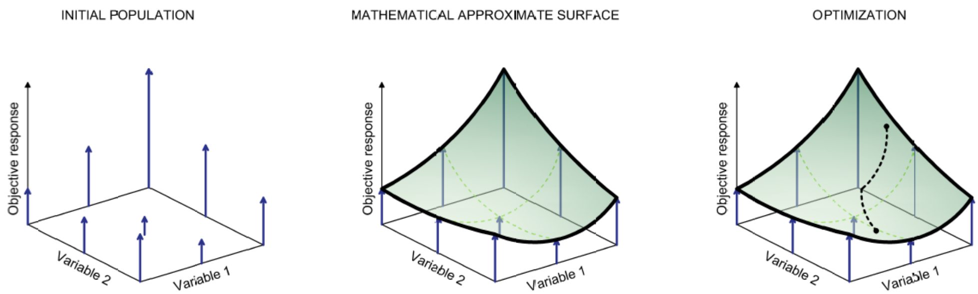

Figure 3.9. Kriging-based heuristic optimization process

3.5. Robustness

There are different methodologies of robust design (RBDO and RDO). This thesis uses the RDO methodology. Chapter 2 reviews the initial uncertain parameters and objective used in the structural RDO works. In these works, the most uncertain initial parameters used in this type of problem are the load and the modulus of elasticity and the objectives considered are the volume, weight, or displacement, including both its mean and standard deviation.

In this thesis, the RDO methodology is applied both to obtain the robust optimal-sustainability bridge and the robust structurally optimal bridge. In the first case, the objective is to minimize both the mean and the variability of the sustainability index, where the initial uncertain parameters are the different points of view of the stakeholders. In the second case, the objective is to minimize the mean cost and the variability of the vertical displacement in the midpoint of the bridge, which represents the structural behavior [41], [42], where the initial uncertain parameters are the loads and the modulus of elasticity.

References

[1] J. Korpela, A. Lehmusvaara, and M. Tuominen, "An analytic approach to supply chain development," *International Journal of Production Economics*, vol. 71, no. 1–3, pp. 145–155, May 2001.

[2] R. W. Saaty, "The analytic hierarchy process—what it is and how it is used," *Mathematical Modelling*, vol. 9, no. 3–5, pp. 161–176, Jan. 1987.

[3] T. L. Saaty, *The Analytic Hierarchy Process*. New York, 1980.

[4] A. M. A. Bahurmoz, "The analytic hierarchy process: A methodology for win-win management," *JKAU: Econ. & Adm*, vol. 20, no. 1, pp. 3–16, 2006.

[5] G. A. Miller, "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information."

[6] P. L. Yu, "A class of solutions for group decision problems," *Management Science*, vol. 19, no. 8, pp. 936–946, 1973.

[7] M. Zeleny, *Multiple criteria decision making*, McGraw-Hil. New York, 1982.

[8] T. García-Segura, V. Yepes, D. M. Frangopol, and D. Y. Yang, "Lifetime reliability-based optimization of post-tensioned box-girder bridges," *Engineering Structures*, vol. 145, pp. 381–391, 2017.

[9] S. Sabatino, D. M. Frangopol, and Y. Dong, "Sustainability-informed maintenance optimization of highway bridges considering multi-attribute

utility and risk attitude," *Engineering Structures*, vol. 102, pp. 310–321, 2015.

[10] Z. Chen, A. B. Abdullah, C. J. Anumba, and H. Li, "ANP experiment for demolition plan evaluation," *Journal of Construction Engineering and Management*, vol. 140, no. 2, pp. 51–60, 2013.

[11] H. Gervásio and L. Simões Da Silva, "A probabilistic decision-making approach for the sustainable assessment of infrastructures," *Expert Systems with Applications*, vol. 39, no. 8, pp. 7121–7131, 2012.

[12] A. Farkas, "Multi-criteria comparison of bridge designs," *Acta Polytechnica Hungarica*, vol. 8, no. 1, pp. 173–191, 2011.

[13] A. Laurent, S. I. Olsen, and M. Z. Hauschild, "Limitations of carbon footprint as indicator of environmental sustainability," *Environmental Science & Technology*, vol. 46, no. 7, pp. 4100–4108, 2012.

[14] K. Murphy, "The social pillar of sustainable development: a literature review and framework for policy analysis," *Sustainability: Science, Practice and Policy*, vol. 8, no. 1, pp. 15–29, Apr. 2012.

[15] L. Montalbán-Domingo, T. García-Segura, M. A. Sanz, and E. Pellicer, "Social sustainability criteria in public-work procurement: An international perspective," *Journal of Cleaner Production*, vol. 198, pp. 1355–1371, 2018.

[16] Catalonia Institute of Construction Technology, "BEDEC PR/PCT ITEC material database." Barcelona, Spain, 2016.

[17] International Organization for Standardization (ISO), *ISO 14040: Environmental managment - life cycle assessment - principles and framework*. Geneva, Switzerland, 2006.

[18] International Organization for Standardization (ISO), *ISO 14044: Environmental managment - life cycle assessment - requirments and guidelines*. Geneva, 2006.

[19] R. Frischknecht, N. Jungbluth, H.-J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, and M. Spielmann, "The Ecoinvent database: Overview and methodological framework," vol. 10, no. 1, pp. 3–9, 2005.

[20] GreenDelta, "Open LCA." .

[21] A. Hettinger, J. Birat, O. Hechler, and M. Braun, "Sustainable bridges - LCA for a composite and a concrete bridge," in *Economical Bridge Solutions Based on Innovative Composite Dowels and Integrated*

Abutments, Springer., E. Petzek and R. Bancila, Eds. Wiesbaden, Germany, 2015, pp. 45–54.

[22] J. Hammervold, M. Reenaas, and H. Brattebø, “Environmental life cycle assessment of bridges,” *Journal of Bridge Engineering*, vol. 18, no. 2, pp. 153–161, 2013.

[23] B. Pang, P. Yang, Y. Wang, A. Kendall, H. Xie, and Y. Zhang, “Life cycle environmental impact assessment of a bridge with different strengthening schemes,” *The International Journal of Life Cycle Assessment*, vol. 20, no. 9, pp. 1300–1311, 2015.

[24] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, *ReCiPe 2008. A life cycle impact assessment which comprises harmonised category indicators at midpoint and at the endpoint level*. Netherlands, 2009.

[25] J. B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. Wegener Sleeswijk, H. a. Udo De Haes, J. a. de Bruijn, R. van Duin, and M. a. J. Huijbregts, “Life cycle assessment: An operational guide to the ISO standards,” *III: Scientific background*, no. May, p. 692, 2001.

[26] M. Gocdkoop, P. Hofstetter, R. Müller-Wenk, and R. Spriemsma, “The Eco-Indicator 98 explained,” *International Journal of Life Cycle Assessment*, vol. 3, no. 6, pp. 352–360, 1998.

[27] V. Yepes, J. V. Martí, T. García-Segura, and F. González-Vidosa, “Heuristics in optimal detailed design of precast road bridges,” *Archives of Civil and Mechanical Engineering*, vol. 17, no. 4, 2017.

[28] C. V. Camp and F. Huq, “CO2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm,” *Engineering Structures*, vol. 48, pp. 363–372, Mar. 2013.

[29] T. García-Segura and V. Yepes, “Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety,” *Engineering Structures*, vol. 125, pp. 325–336, 2016.

[30] I. Paya, V. Yepes, F. González-Vidosa, and A. Hospitaler, “Multiobjective optimization of concrete frames by simulated annealing,” *Computer-Aided Civil and Infrastructure Engineering*, vol. 23, no. 8, pp. 596–610, 2008.

[31] J. R. Medina, “Estimation of incident and reflected waves using simulated annealing,” *Journal of Watery, Port, Coastal, and Ocean Engineering*, vol. 127, no. 4, pp. 213–221, 2001.

[32] C. H. Chuang, R. J. Yang, G. Li, K. Mallela, and P. Pothuraju,

"Multidisciplinary design optimization on vehicle tailor rolled blank design," *Structural and Multidisciplinary Optimization*, vol. 35, no. 6, pp. 551–560, Jun. 2008.

[33] R. Jin, W. Chen, and T. W. Simpson, "Comparative studies of metamodelling techniques under multiple modelling criteria," *Structural and Multidisciplinary Optimization*, vol. 23, no. 1, pp. 1–13, Dec. 2001.

[34] M. D. McKay, R. J. Beckman, and W. J. Conover, "Comparison of three methods for selecting values of input variables in the analysis of output from a computer code," *Technometrics*, vol. 21, no. 2, pp. 239–245, 1979.

[35] A. I. J. Forrester and A. J. Keane, "Recent advances in surrogate-based optimization," *Progress in Aerospace Sciences*, vol. 45, no. 1–3, pp. 50–79, 2009.

[36] Y. F. Li, S. H. Ng, M. Xie, and T. N. Goh, "A systematic comparison of metamodeling techniques for simulation optimization in decision support systems," *Applied Soft Computing*, vol. 10, no. 4, pp. 1257–1273, 2010.

[37] G. Matheron, "Principles of geostatistics," *Economic Geology*, vol. 58, no. 8, pp. 1246–1266, 1963.

[38] N. Cressie, "The origins of kriging," *Mathematical Geology*, vol. 22, no. 3, pp. 239–252, 1990.

[39] T. W. Simpson, T. M. Mauery, J. Korte, and F. Mistree, "Kriging models for global approximation in simulation-based multidisciplinary design optimization," *AIAA Journal*, vol. 39, no. December, pp. 2233–2241, 2001.

[40] T. W. Simpson, J. D. Poplinski, P. N. Koch, and J. K. Allen, "Metamodels for computer-based engineering design: Survey and recommendations," *Engineering with Computers*, vol. 17, no. 2, pp. 129–150, 2001.

[41] F. Jurecka, M. Ganser, and K.-U. Bletzinger, "Update scheme for sequential spatial correlation approximations in robust design optimisation," *Computers & Structures*, vol. 85, no. 10, pp. 606–614, May 2007.

[42] J. Martínez-Frutos and P. Martí, "Diseño óptimo robusto utilizando modelos Kriging: aplicación al diseño óptimo robusto de estructuras articuladas," *Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería*, vol. 30, no. 2, pp. 97–105, Apr. 2014.

CHAPTER 4. LIFE-CYCLE ASSESSMENT

4.1. Introduction

The assessment of each one of the pillars of sustainability is crucial for a comprehensive sustainability evaluation along the whole life-cycle of the structures. The Chapter 2 reviews the criteria and life-cycle impact assessment methods used to carry out the sustainability evaluation. This Chapter provides the papers related to the life-cycle assessment in bridges. The first two papers focus on environmental assessment using the Ecoinvent database and the ReCiPe method. The first paper carries out an E-LCA of a cost-optimized prestressed concrete precast bridge. The second paper compares the E-LCA of two cost-optimized post-tensioned concrete box-girder bridges with different design. The third paper introduces the assessment of the social pillar using the PSILCA database and the SOCA method. In addition, it considers environmental and economic assessment to obtain a complete sustainability assessment. All this is done using OpenLCA software.

4.2. An optimization-LCA of a prestressed concrete precast bridge[1]

[1] V. Penadés-Plà, T. García-Segura, J. V. Martí, and V. Yepes, “An optimization-LCA of a prestressed concrete precast bridge,” *Sustainability*, vol. 10, no. 3, pp. 1–17, 2018.

Vicent Penadés-Plà[a], Tatiana García-Segura[b], José V. Martí[c], Víctor Yepes[d*]
[a] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: vipepl2@cam.upv.es
[b] Dept. of Construction Engineering and Civil Engineering Projects, Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: tagarse@upv.es
[c] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain E-mail: jvmartia@upv.es
[d] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. Corresponding author. E-mail: vyepesp@cst.upv.es

Abstract: The construction sector is one of the most active sectors, with a high economic, environmental, and social impact. For this reason, the sustainable design of structures and buildings is a trend that must be followed. Bridges are one of the most important structures in the construction sector, as their construction and maintenance are crucial to achieve and retain the best transport between different places. Nowadays, the choice of bridge design depends on the initial economic criterion, but other criteria should be considered to assess the environmental and social aspects. Furthermore, for a correct choice, the influence of these criteria during the bridge life-cycle must be taken into account. This study aims to analyze the life-cycle environmental impact of efficient structures from the economic point of view. Life-cycle assessment process is used to obtain all the environmental information about bridges. In this paper, a prestressed concrete precast bridge is cost-optimized, and afterwards, the life-cycle assessment is carried out to achieve the environmental information about the bridge.

Keywords: Sustainability; Bridges; Life-cycle assessment; LCA; Optimization; ReCiPe

4.2.1. Introduction

The basis for the definition of sustainable development lies in the Brundtland Commission's report [1], which describes it as "development that meets the needs of the present generation without compromising the needs of the future generation". This idea implies the consideration of different aspects of three main components: economic, environmental, and social. Therefore, achieving sustainable development implies a consensus among these three main pillars, which usually have different goals. Wass et al. [2] stated that sustainable development implies that a decision-making strategy must be considered. Decision making is a process that can help to find a solution that provides a compromise between different aspects and therefore achieves a sustainable solution [3], [4].

The construction sector is one of the most active sectors and one of the ones with a greater influence on the economic, environment, and social aspects of the world. This indicates a need for a trend toward sustainability of buildings and structures. One of the most important structures in this sector is bridges. The construction and maintenance of bridges are crucial to generate and keep the best transport possible between different places. For this reason, the assessment of sustainable development during the whole life-cycle is necessary. Of the three main components of sustainable development, the social aspect is the least studied and there are more doubts about its assessment. On the contrary, the economic and environmental aspects have been studied more intensively, and it is convenient to assume that their consideration is sufficient. Considering the evaluation of these two components to achieve sustainability of bridges, the objective is to design the bridge with the lowest cost and lowest environmental impact. Although these two pillars of sustainability have different goals, some works have stated that there is a relationship between the cost and CO_2 emissions of structures [5], [6]. Therefore, reducing the cost implies a reduction of CO_2 emissions.

Obtaining the lowest cost or CO_2 emissions have been studied by several works. Optimization algorithms are most often used to reduce the cost or CO_2 emissions of structures. In some cases, this involves a mono-objective optimization of cost and CO_2 emissions [5]–[7], whereas other works carry out multi-objective optimization to achieve both objectives at the same time [8], [9]. Despite the relationship between cost and CO_2 emissions, the environmental impact cannot be assessed by taking into account CO_2 emissions alone [10]. For this reason, the environmental impact assessment must achieve a complete environmental profile. This complete environmental profile can be obtained using the life-cycle assessment (LCA) process. LCA is one of the most important and accepted methods of assessing the environmental impacts [11]–[16], making it an excellent tool for assessing the environmental impact of a bridge.

In this paper, a prestressed concrete precast 40-m bridge is selected as the subject of an optimization-LCA. The optimization of the cost will reduce the cost of the bridge directly and the associated CO_2 emissions indirectly. This process makes it possible to obtain a cost-optimized bridge with a low environmental impact. After finishing the optimization, all the features of the cost-optimized bridge will be known, including its cost, but the environmental impact will not yet have been obtained. The LCA makes it possible to obtain a complete environmental profile of this cost-optimized bridge. With this methodology, a bridge whose costs have been optimized directly and whose environmental impact has been improved is obtained, and finally the LCA for the whole life-time can be performed. For this purpose, a hybrid memetic algorithm is used to carry out the cost-optimization of the bridge. Then, the Ecoinvent database [17] and the ReCiPe method [18] are used to conduct the LCA process of the bridge.

4.2.2. Optimization

The optimization process is used to achieve the best solution to a problem. This process is a clear alternative to designs based on experience. Optimization methods can be categorized into exact methods and heuristic methods. On one hand, the exact methods are based on mathematical algorithms that make it possible to obtain the global optimal solution [19]. On the other hand, the heuristic methods, which include a large number of algorithms [20], obtain an optimal solution starting from an initial solution. The exact methods are very useful in problems where there are a small number of variables, because the computing time becomes unworkable for a large number of variables. Structural optimization problems are defined for a large number of design variables, and thus the heuristic method is the most useful for structural optimization. There are a large number of works that use heuristic algorithms for the optimization of different kinds of structures [8], [9], [21].

4.2.3. Life-cycle assessment

Life-cycle assessment (LCA) is one of the most important and accepted methods of evaluating the environmental impact of a product, process, or service during its whole life-cycle, taking into account all the activities involved, which are defined as inputs and outputs. The limits defined for these inputs and outputs are the boundaries of the system and represent the scheme to be considered. The LCA must be complete and thus it should consider all the activities needed for the achievement of the product, process, or service. Therefore, focusing on the construction sector, a full LCA of structures must consider all the activities from the acquisition of the raw material to the end of life. These activities associated with the whole life-cycle of the structures are grouped into the manufacturing phase, construction phase, use and maintenance phase, and end of life phase. The LCA makes it possible to carry out an environmental impact assessment of a set of activities associated with the different stages of a structure's life-cycle and the global environmental impact by adding these phases. For all that, the LCA is an excellent tool to evaluate the environmental impact of structures. ISO 14040:2006 [22] provides guidance on carrying out the LCA, divided into four steps: (1) definition of goal and scope, (2) inventory analysis, (3) impact assessment, and (4) interpretation.

The first step defines all the specifications that will be considered in the LCA. This involves other features besides the definition of the goal and scope, such as the life-cycle inventory to be taken into account, the life-cycle assessment methodology considered, the functional unit, and the assumptions and limitations that have been considered in the LCA. According to the guidance defined by ISO 14040:2006 [22], the characterization define some assumptions and limitations of the LCA that condition the following life cycle inventory and life cycle assessment. Another important feature is the functional unit that represents the unit in which the assessment will be referred.

The inventory analysis is the collection of the data needed to define the inputs and outputs that represent the system studied. This data can be obtained in different ways: from direct measurements, literature, or other sources such as databases. The most common way to obtain data is from databases.

Once these first steps have been defined, the environmental impact assessment is used to evaluate the result of the inventory analysis to obtain a set of environmental indicators that represent the environmental profile of the product, process, or service. There are different methods of representing the environmental profile. These methods can be grouped into two different approaches: midpoint and endpoint assessments. The midpoint approach defines the environmental profile by means of a set of impact categories and the endpoint approach defines the environmental profile by means of a set of damage categories. There are three damage categories (human health, resource depletion, and ecosystems) into which the impact categories are clustered. Therefore, although the midpoint approach provides a complete environmental profile, it is more difficult to interpret [23]. Conversely, the endpoint approach does not provide a detailed environmental profile like the midpoint approach but is easier to understand.

Finally, the information obtained must be interpreted. For this purpose, an analysis of the different stages of life-cycle of the bridge is carried out. In addition, a study of the environmental impact of a product, process, or service can be made to improve the environmental impact associated with its activities.

4.2.4. Case study

For the purpose of this work, a bridge is selected to carry out the optimization-LCA. First, a cost-optimization of the bridge will be carried out and then a LCA of the cost-optimized bridge will be applied to obtain a complete environmental profile. In the next points, a precise description of the bridge will be presented, and then the cost-optimization and the LCA will be described in detail for the bridge described.

4.2.4.1. Bridge description

The bridge studied is a single span prestressed concrete precast bridge of 40 m. The section of the bridge is formed by two prestressed concrete precast isostatic beams with a U-shaped cross-section. The cross-section integrates a 12 m upper reinforced concrete slab. Note that the substructure is not included in the analysis since it depends on the ground characteristics and the orography. Figure 4.2.1 shows a general view of the bridge. The bridge is located in the eastern coastal area of Spain and the environmental ambient corresponds to XC-4 according to EN 206-1 [24]. Thus, corrosion is mainly caused by carbonation.

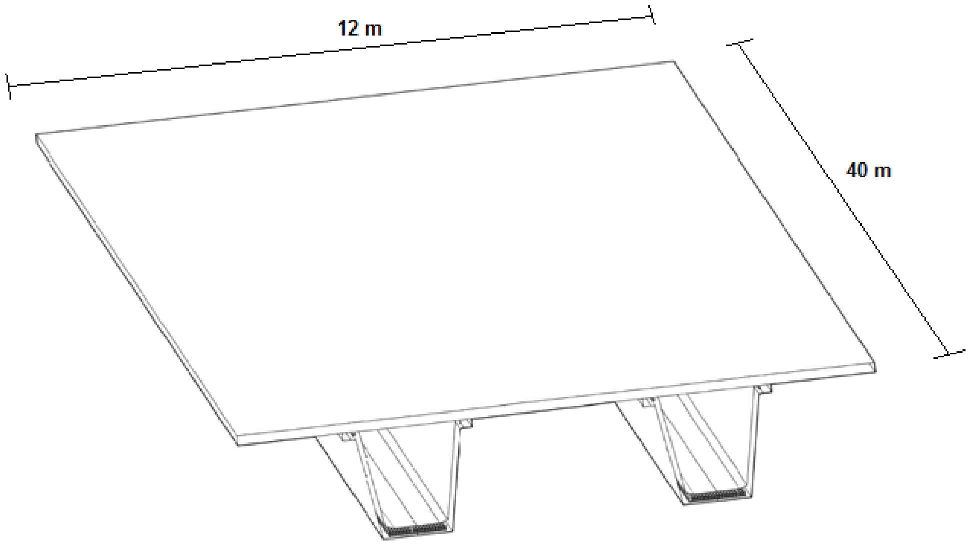

Figure 4.2.1. General view of the prestressed concrete precast bridge

4.2.4.2. Optimization

In this section, the cost-optimization of the prestressed concrete precast bridge will be explained. This optimization process consists in the minimization of the cost C while some restrictions g_j are satisfied.

$$C = f(x_1, x_2, \ldots, x_n) \quad (4.2.1)$$

$$g_j(x_1, x_2, \ldots, x_n) \leq 0 \quad (4.2.2)$$

Note that x_1, x_2, x_3 … , x_n are the design variables used for the optimization. The objective function C expresses the cost of the bridge and the restrictions gj are the serviceability limit states (SLS), the ultimate limit states (ULS), the durability limit states and the geometric and constructability constraints of the problem. There are 40 design variables, including eight variables that define the geometry of the section, two that define the concrete of the slab and the beam, four that define the prestressed steel, and 26 that define the reinforcing steel. Furthermore, there are a set of parameters that have no influence on the optimization problem, such as the width, span, and web inclination. Structural constraints have been considered according to the Spanish codes [25], [26]. The ULSs verify if the ultimate resistance is greater than the ultimate load effect. Besides, the minimum amount of reinforcing steel for the stress requirements and the geometrical conditions are also considered. The SLSs examine different aspects. Cracking limit state requires compliance of the compression and tension cracks, as well as the decompression limit state in the area where the post-tensioned steel is located. Deflections are limited to 1/1000 of the free span length for the quasipermanent combination. In addition, the concrete and steel fatigue has been considered in this study. Table 4.2.1 summarizes of the ULSs and SLSs considered.

Table 4.2.1. Ultimate and serviceability limit states

LIMIT STATES
Flexure
Vertical shear
Longitudinal shear
Punching shear
Torsion
Torsion combined with flexure and shear
Fatigue
Crack width <0.2 mm
Compression and tension stress. Decompression in post-tensioned steel depth
Deflection for the quasipermanent combination < 1/1000

In this optimization, a hybrid memetic algorithm (MA) is applied. The MA is a population-based approach to stochastic optimization that combines the parallel search used by evolutionary algorithms with a local search of the solutions forming a population [27]. Regarding the local search used, a variable-depth neighborhood search (VDNS) is used as a variant of the very large-scale neighborhood search (VLSN) [28]. In this MA-VDNS, a set of 500 random solutions (n) is generated as the population. Then each of these solutions is improved by means of a VDNS search to reach a local optimum. To this end, the algorithm begins by changing only one variable, and when ten consecutive movements have been performed without improvement (no_imp), there will be an increase in the number of variables (var) that are changed simultaneously, up to eight. Then, with this new improved population, a genetic algorithm is applied. The genetic algorithm develops the population, which is subjected to random movements (mutations and crossovers), preserving the better adapted solutions. The cost assessment takes into account a penalty cost; nevertheless, the VDNS does not consider the penalty cost (only feasible solutions are accepted) in order to avoid the early divergence of the algorithm. The VDNS is applied to the new generation up to 150 generations. Figure 4.2.2 shows a flow chart of the hybrid memetic algorithm.

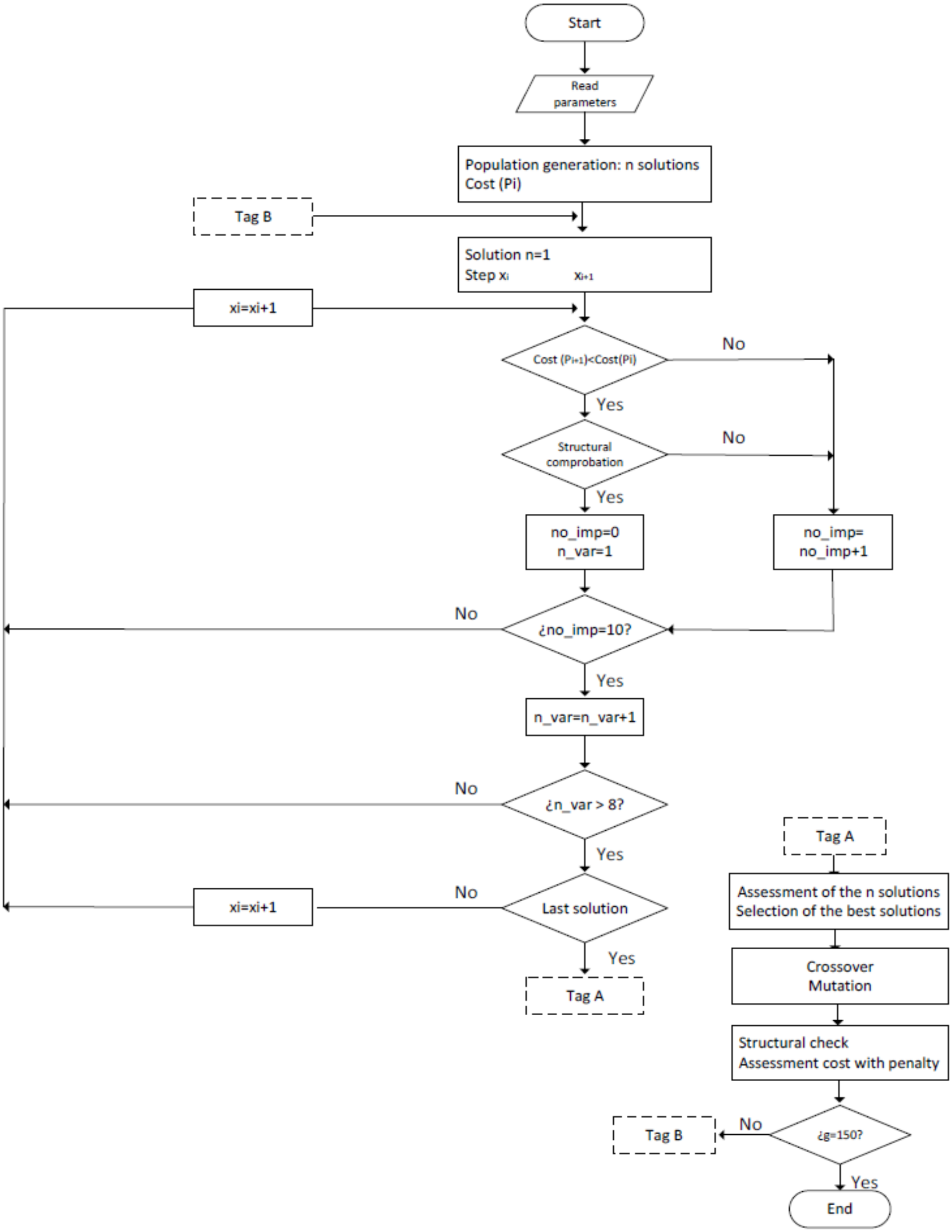

Figure 4.2.2. Hybrid memetic algorithm flow chart

The solution obtained for the 40-m-long prestressed concrete precast bridge has a total cost of 108274.45 €. The geometry of this bridge is shown in Figure 4.2.3. The amount of beam concrete used is 0.1117 m^3/m^2, with a strength of 35 MPa, while the amount of slab concrete used is 0.1797 m^3/m^2, with a strength of 40 MPa. Furthermore, the precast concrete beams require 6163 kg (12.52 kg/m^2) of reinforcing steel and 5184 kg (10.53 kg/m^2).of prestressed steel, while the concrete slab is defined by 11772 kg (23.92 kg/m^2) of reinforcing steel.

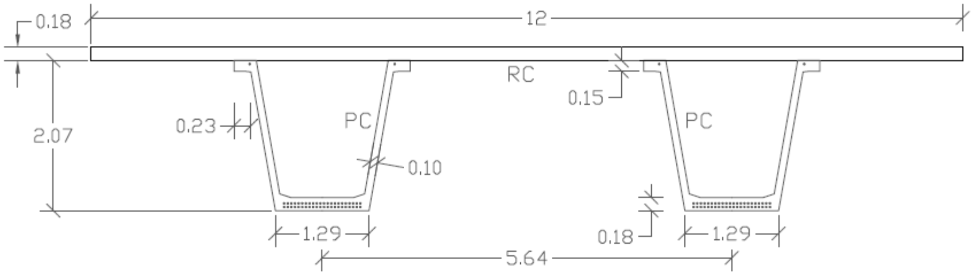

Figure 4.2.3. Geometry of optimized bridge

4.2.4.3. Life-cycle assessment

In this section, the guidance defined by ISO 14040:2006 [22] will be applied to the bridge studied. For this purpose, the different steps will be particularized to the case of study, describing and taking into account the specific characteristics considered for this study. Figure 4.2.4 show a general view of the LCA process carried out.

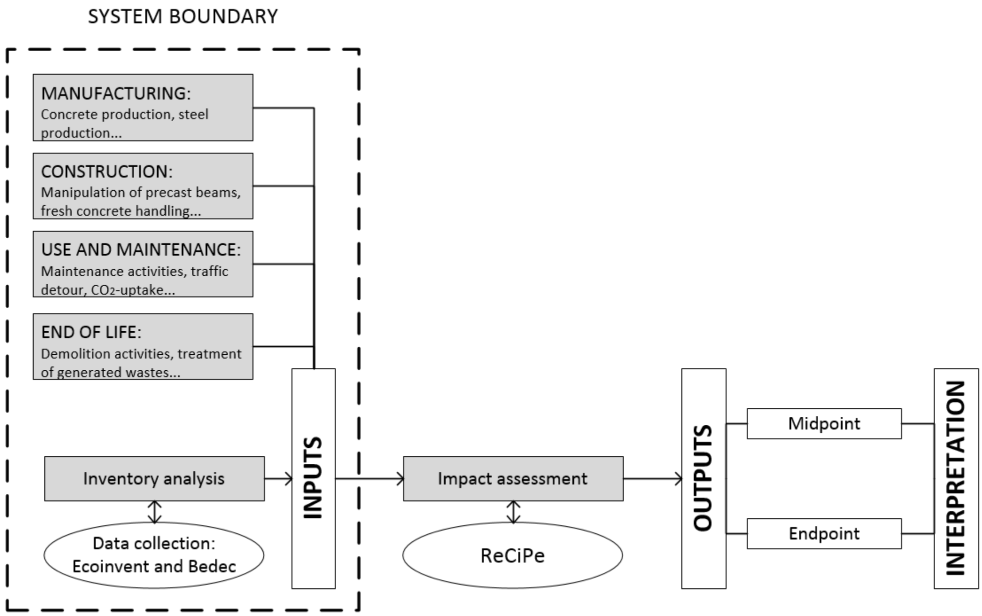

Figure 4.2.4. General scheme LCA process

4.2.4.3.1. Goal and scope

The LCA will be divided into the four main phases of the whole life-cycle of the bridge for a better understanding: (1) manufacturing, (2) construction, (3) use and maintenance, and (4) end of life. Each phase will be defined separately, and thus each phase will be limited by its own system boundary. The functional unit will be 1 m of the length of the bridge. The final goal is to find the environmental impact of each phase and consequently the global environmental impact of the bridge by adding the environmental impacts of different phases.

MANUFACTURING

The manufacturing phase includes the upstream processes of the products used in the bridge and the associated transport, from the acquisition of raw materials to materials that are ready to be used in the construction of the bridge. The prestressed concrete precast bridge has three main components: beams of precast concrete, fresh concrete, and steel. Therefore, first it is necessary delimit the activities associated with each product including the transport.

On one hand, the manufacture of the beams of precast concrete takes into account all the activities from the extraction of raw materials to the finishing of the beams in the precast plant, while the manufacture of the fresh concrete for the slab takes into account the activities from the extraction of raw material to the point when the concrete is ready to be used in the construction place. In both cases, the distance considered between the quarry and the precast plant or concrete plant is 50 km, the distance considered in the cement transportation is 20 km, and the distance between the concrete plant and the construction site is 50 km. Furthermore, the dosage of concrete is taken into account to achieve the strength required. On the other hand, the manufacture of the steel takes into account all the activities from the acquisition of the raw material to the point when the steel is ready to be used in the precast plant or construction site. Considering that the bridge is built in Spain, the analysis takes the Spanish steel production characteristics. This implies that 67% of the steel is produced in an electric arc furnace and the remaining 33% is produced in a basic oxygen furnace. This ratio generates a recycling rate of steel of 71%. The distance considered between the steel production plant and the precast plant or construction site is 100 km. Table 4.2.2 shows the amount of material needed for the beam and slab and the dosage of the concrete in both cases.

Table 4.2.2. Amount of materials

	Precast concrete beam	Concrete slab
Strength (MPa)	35	40
Reinforcing steel (kg/m^2)	12.52	23.92
Prestressed steel (kg/m^2)	10.53	–
Concrete (m^3/m^2)	0.1117	0.1797
Cement (kg/m^3)	300	320
Gravel (kg/m^3)	848	829
Sand (kg/m^3)	1088	1102
Water (kg/m^3)	160	162
Superplasticizer (kg/m^3)	4	5

CONSTRUCTION

The construction phase includes all the materials and construction machinery necessary for the erection of the bridge. It includes the transportation and elevation of precast beams using special transport over 50 km. Furthermore, the bridge slab is considered to be cast in place. The construction machinery considered for the slab construction was obtained from the Bedec database [29]. The concrete machinery consumes 123.42 MJ of energy and emits 32.24 kg of CO_2 per m^3 of concrete. The distance traveled considered by the construction machinery is 50 km. In addition, the formwork is made by wood and can be reused 3 times.

USE AND MAINTENANCE

The maintenance and use phase includes everything that happens in the service life of the bridge. It takes some activities and processes (considering its own maintenance activities and the traffic detour due to the closure of the bridge) and the fixed CO2. On one hand, the bridge needs one maintenance period of 2 days to satisfy with the regulations during its 120 years of service life. This maintenance activity considers that the concrete cover is replaced by a repair mortar. The maintenance action consists firstly of removing the concrete cover and providing a proper surface for the coating adhesion. Then, a bonding coat is applied between the old and new concrete. Finally, a repair mortar is placed to provide a new reinforcement corrosion protection [30]. Note that the study considers that the quality on-site work is adequate to guarantee that the bridge does not have durability problems during the service life. Besides, it is important to highlight that other maintenance activities to repair or replace equipment elements may take place. However, they are not evaluated in this study.

This study takes into account all the machinery necessary to repair the deterioration of the bridge including the transport to the bridge location and the increase in emissions generated due to the traffic detour [13], [14]. The traffic detour is considered taking into account the average daily traffic of 8500 vehicles/day, where trucks comprise 10% of vehicles, and a detour distance of 2.9 km. On the other hand, the fixation of the CO_2 by the concrete is a widely studied fact [31], [32] that has been considered in the bridge studied.

END OF LIFE

The end-of-life phase includes everything that happens after the service life of the bridge. All the activities and processes associated with this phase are related with the demolition of the bridge and the treatment of the generated wastes. On one hand, demolition activities for the destruction or dismantling of the bridge will be necessary. These demolition activities take into account all the machinery necessary for this purpose. On the other hand, the treatment of generated wastes takes into account a greater set of activities depending on the purpose of the processing. In this case, the bridge will be destroyed, after which all the wastes will be transported to a sorting plant where the concrete and steel will be separated. The concrete will be crushed and transported to a landfill, and in this way, the complete carbonation of the concrete [32] and thus a higher fixation of CO_2 are assured. Seventy-one per cent of the steel will be recycled, and in this way, the life-cycle of the bridge ends.

4.2.4.3.2. Inventory analysis

The major part of the information of the products or processes used to define the activities of the whole life-cycle of the bridge is obtained from Ecoinvent database [17]. In the case of the information of the products or processes needed for the environmental impact assessment that do not exist in the Ecoinvent database, the data will be created by means of the data obtained from the literature or the Bedec database [29].

The Ecoinvent database is one of the most complete databases for the construction sector and has been created and grown thanks to the information obtained from different institutions. It was created in 2004 through the efforts of the several Swiss Federal Offices and research institutes. That implies that the major part of the information existing in the first versions of Ecoinvent was obtained from Swiss institutions, but later, data from other countries were inserted. In this case, the bridge is located on the eastern coast of Spain. In the Ecoinvent database there is no information about this region, and therefore it is necessary to consider information about the products or processes from other regions that do not coincide exactly with the products or processes used on the eastern coast of Spain. That means that there is inconsistency between the real data and the data from the Ecoinvent database. For this reason, uncertainty is applied to the Ecoinvent data. The uncertainty is divided into two parts: the first part concerns the type of product or process [33] and the second part concerns the differences between the real data and the data considered by means of the pedigree matrix [34].

4.2.4.3.3. Impact assessment

There are many works in which the environmental impact assessment is carried out taking into account a small number of indicators, of which the CO_2 emissions are the most popular [35], [36]. Despite the importance of the emission of CO_2, a complete impact assessment must consider a set of indicators that represent a complete environmental profile. That implies the use of environmental impact assessment methods. These methods can be separated depending on the approach used: midpoint or endpoint. On one hand, the midpoint approach defines the environmental profile by means of a set of impact categories. One of the most popular methods that take into account the midpoint approach is the CML. On the other hand, the endpoint approach defines the environmental profile considering only a small set of damage categories. One of the most frequently used methods that consider the endpoint approach is the Eco-indicator. Both approaches are necessary to carry out a complete environmental interpretation of the bridge. On one hand, the midpoint approach can provide a more accurate and complete environmental profile. On the other hand, the endpoint approach can be easier to interpret. For these reasons, the environmental impact assessment method used in this work is the ReCiPe method [18], whose main objective is to provide a combination of the Eco-indicator and CML, considering the midpoint and endpoint approaches.

4.2.4.3.4. Interpretation

The results are obtained considering the descriptions presented in the preceding sections. As stated above, the ReCiPe method will be used to carry out the environmental impact assessment of the bridge. For this purpose, by means of the midpoint approach, 18 impact categories will be shown with the associated uncertainty. In addition, the contribution of the different processes of the bridge life-cycle for the most popular impact categories will be represented. In the endpoint approach, the three damage categories are studied. Both approaches allow a higher level of interpretation.

MIDPOINT APPROACH

The midpoint approach of the ReCiPe method provides a complete environmental profile of each stage of the bridge life-cycle represented by 18 impact categories: agricultural land occupation (ALO), climate change (GWP), fossil depletion (FD), freshwater ecotoxicity (FEPT), freshwater eutrophication (FEP), human toxicity (HTP), ionizing radiation (IRP), marine ecotoxicity (MEPT), marine eutrophication (MEP), metal depletion (MD), natural land transformation (NLT), ozone depletion (OD), particulate matter formation (PMF), photochemical oxidant formation (POFP), terrestrial acidification (TAP), terrestrial ecotoxicity (TEPT), urban land occupation (ULO), and water depletion (WD). This large amount of information makes the results difficult to interpret. Although it is difficult to achieve a global assessment of the environmental impact of the bridge with the information obtained by means of the midpoint approach, it is very helpful to obtain more accurate knowledge of the impact of each category and the contribution of each process to the different impact categories.

As explained above, the data used for the environmental impact assessment do not correspond with the real data. This implies that the uncertainty associated with the different products or processes should be taken into account to obtain more realistic results. Table 4.2.3 shows the mean and coefficient of variance of each impact category for each bridge life-cycle phase. Although it is not possible to carry out a global assessment for each bridge life-cycle phase, it is possible to obtain information about the phase in which each impact category is the most significant and the variance of the information obtained. In this way, it can be observed that the manufacturing phase is the phase in which there are a higher number of impact categories with the highest contribution followed by the use and maintenance phase. The impact categories with the highest contribution in the manufacturing phase are ALO, GWP, FEPT, FEP, HTP, IRP, MEPT, MD, TETP, ULO, and WD, and the impact categories with the highest contributions to the use and maintenance phase are FD, MEP, NLT, ODP, PMFP, POFP, and TAP. Neither the construction phase nor the end of life phase has impact categories with the highest contribution. All of this can be seen better in Figure 4.2.5 and 4.2.6, in which the bars represent the ratio of the contribution of each impact category to each life-cycle phase in relation to the highest contribution. In addition, Table 4.2.3 shows the variance of each result. In this way, although the GWP has the highest variance in the manufacturing phase, the manufacturing phase is the one in which more impact categories have the lowest variance, with a mean of 7.13%. The construction phase has the highest mean of variances (17.15%), followed by the end-of-life phase (13.16%) and the use and maintenance phase (10.58%). Furthermore, the impact category with the highest coefficient of variation is the ULO (17.28%), and the impact category with the lowest coefficient of variation is the ALO (8.04%).

Table 4.2.3. Midpoint approach

Acronym	Reference unit	Manufacturing		Construction		Use and Maintenance		EoL	
		m	cv (%)	m	cv (%)	m	cv (%)	m	cv (%)
ALO	m^2 x year	79.76	3.77%	2.59	7.46%	6.16	14.09%	1.73	6.84%
GWP	kg CO_2 eq	1838.55	16.86%	267.85	9.61%	1095.77	5.29%	-117.68	-6.97%
FD	kg oil eq	316.90	6.90%	51.48	17.52%	394.59	4.94%	11.00	16.57%
FEPT	kg 1,4-DB eq	38.15	2.93%	0.93	18.86%	8.53	26.70%	0.19	7.94%
FEP	kg P eq	0.82	4.19%	0.01	10.56%	0.08	14.00%	0.01	7.16%
HTP	kg 1,4-DB eq	1470.92	3.01%	22.58	16.26%	110.30	16.36%	5.77	7.80%
IRP	kg U235 eq	244.70	12.29%	18.96	10.35%	78.57	5.22%	10.22	7.14%
MEPT	kg 1,4-DB eq	37.90	2.92%	0.96	17.91%	7.65	26.08%	0.17	8.01%
MEP	kg N eq	0.29	8.79%	0.05	20.79%	0.49	2.90%	0.01	22.26%
MD	kg Fe eq	926.19	3.22%	5.34	17.35%	49.38	11.06%	0.77	22.90%
NLT	m^2	0.24	8.28%	0.05	18.78%	0.43	4.67%	0.01	24.03%
ODP	kg CFC-11 eq	0.00	8.59%	0.00	17.82%	0.00	4.61%	0.00	17.63%
PMFP	kg PM_{10} eq	3.84	5.67%	0.50	19.84%	4.33	3.12%	0.11	20.31%
POFP	kg NMVOC	5.76	9.12%	1.51	21.63%	14.03	2.77%	0.26	26.69%
TAP	kg SO_2 eq	5.30	8.90%	1.00	19.21%	8.40	3.12%	0.25	16.97%
TETP	kg 1,4-DB eq	0.45	4.60%	0.02	27.71%	0.06	12.68%	0.00	15.79%
ULO	m^2 x year	23.29	9.86%	3.50	29.32%	6.75	21.00%	0.17	8.93%
WD	m^3	8807.20	8.35%	219.49	7.63%	625.36	11.89%	146.17	6.83%

Figure 4.2.5. Impact categories of manufacturing and construction stage

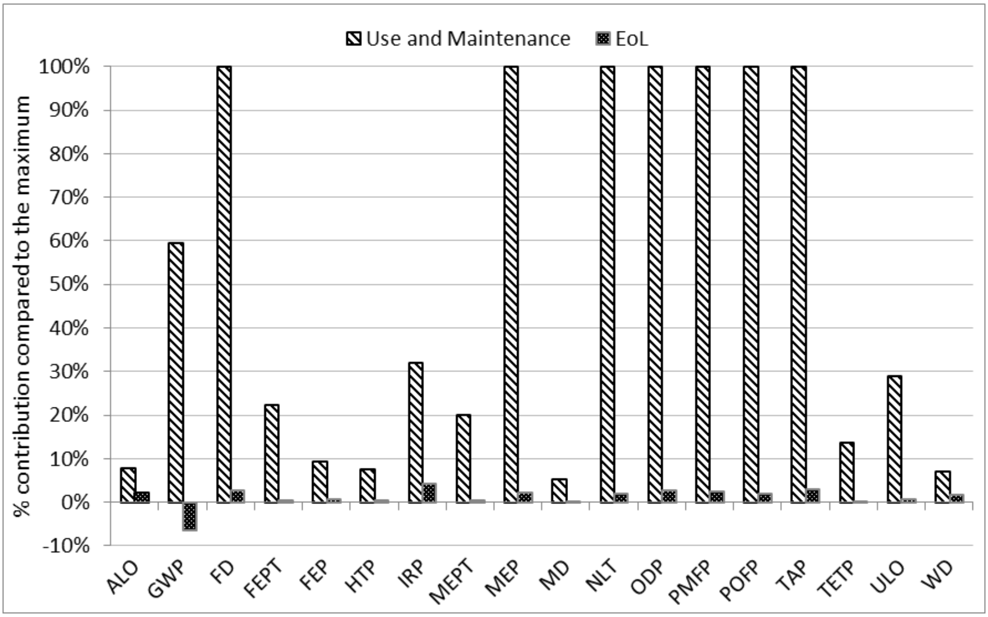

Figure 4.2.6. Impact categories of use and end of life stage

Another type of information that can be obtained by the midpoint approach is the contribution of the different products or processes to each impact category. For illustrative purposes, only three of the most popular impact categories (GWP, OD, and PMF) will be studied more exhaustively and will display the contribution of the different products or processes to each bridge life-cycle phase. Figures 4.2.7 to 4.2.10 show the contributions of the most important processes for each bridge life-cycle phase. Figure 4.2.7 corresponds to the manufacturing phase and it is possible to see that the most important associated processes are the cement production, steel production, and transport. Cement production makes the highest contribution to the GWP, namely 46.49% of the total, but in the PMF and OD categories, steel production has the higher ratio with percentages of 76.14 and 57.44% respectively. Furthermore, it can be seen that, although the GWP has a low percentage of other processes (6.07%), the cement production, steel production, and transport represent a larger part of the environmental impact of this bridge life-cycle phase. Figure 4.2.8 corresponds to the construction phase and the processes that lead to practically all the environmental impacts are those due to the manipulation of fresh concrete and the transport and elevation of the precast beams. Figures 4.2.9 and 4.2.10 show the use and maintenance phase and end-of-life phase, in which the CO_2 fixed is taken into account. In the GWP impact category, it can be seen that there is a positive impact. On one hand, in the use and maintenance phase, the amount of CO_2 fixed is much lower than the CO_2 eq produced by the maintenance activities and the traffic detour because the concrete surface in contact with the environment represents a very low proportion of the total of amount of concrete in the bridge. The percentage of the CO_2 fixed is –3.84%, while the percentages of maintenance activities and traffic detour are 89.95% and 13.89%, respectively, adding a total of 100% due to that the global GWP impact in this phase is positive. The ratio of the contribution of the maintenance activities and traffic detour can be modified considerably in function of the features of the traffic diversion (distance, average daily traffic, and percentage of trucks). On the other hand, in the end-of-life phase, the amount of CO_2 fixed is higher (–254.05%) than the CO_2 eq produced by the demolition activities (22.40%), the waste treatment (36.21%), and the associated transport (96.18%). The total contribution of the processes in the end-of-life phase is negative, adding a total of –100%. In the other impact categories (PMF and OD), the maintenance activities and transport make the major contribution to each bridge life-cycle.

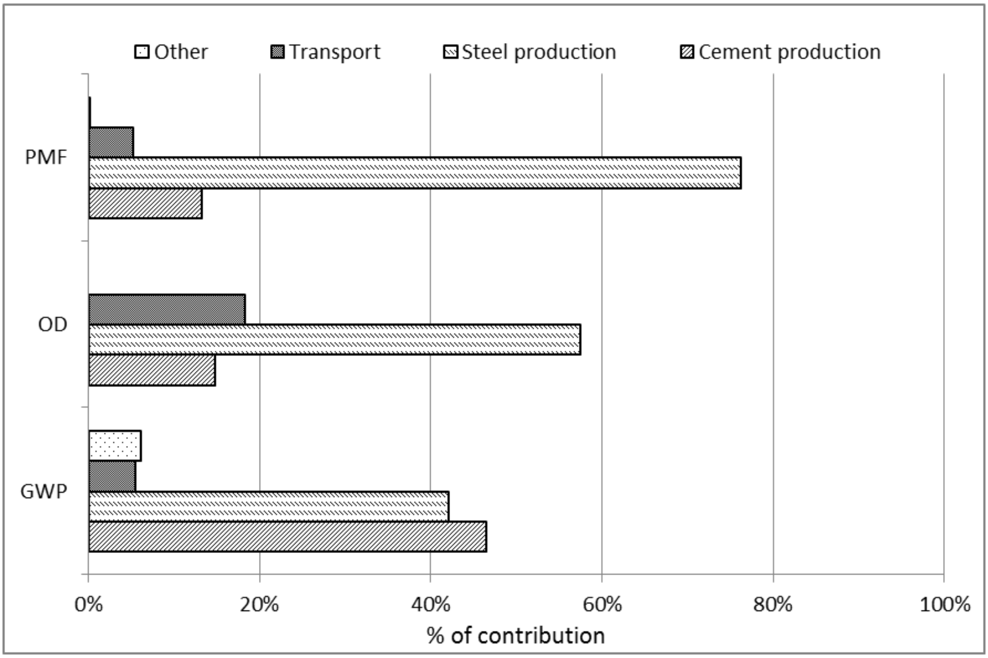

Figure 4.2.7. Manufacturing phase

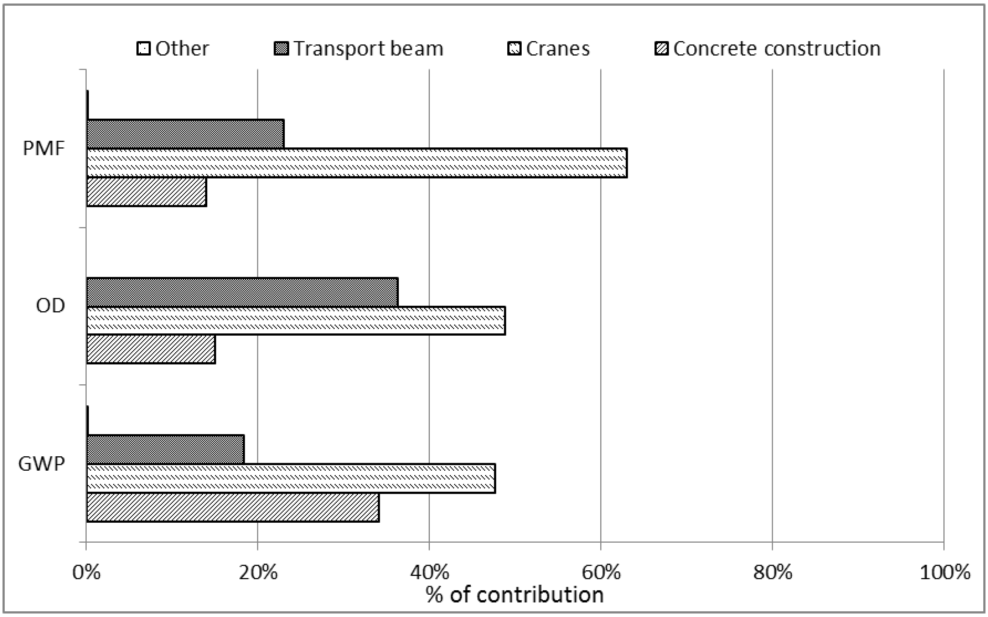

Figure 4.2.8. Construction phase

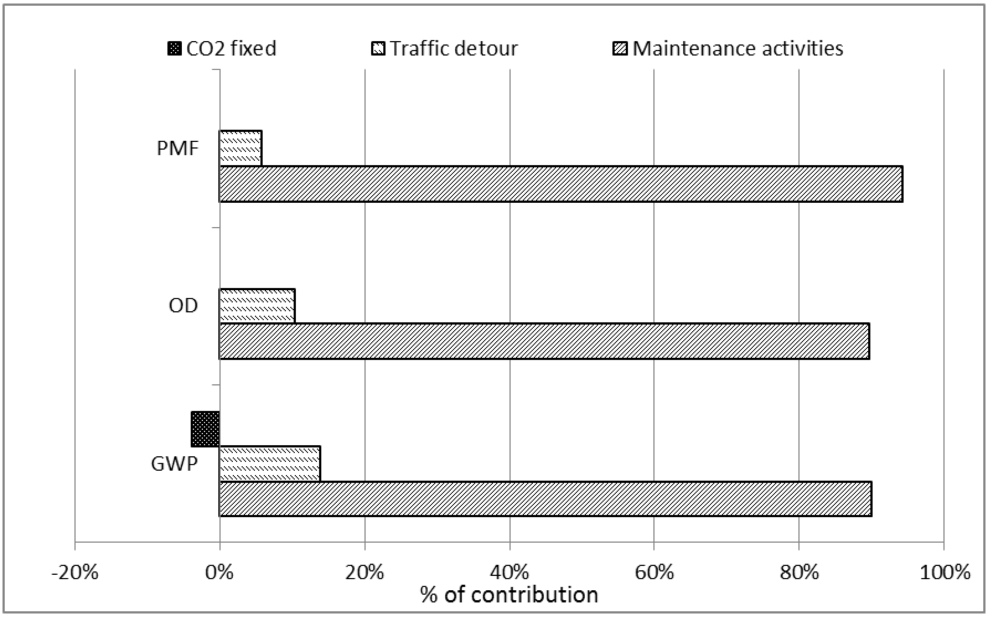

Figure 4.2.9. Use and maintenance phase

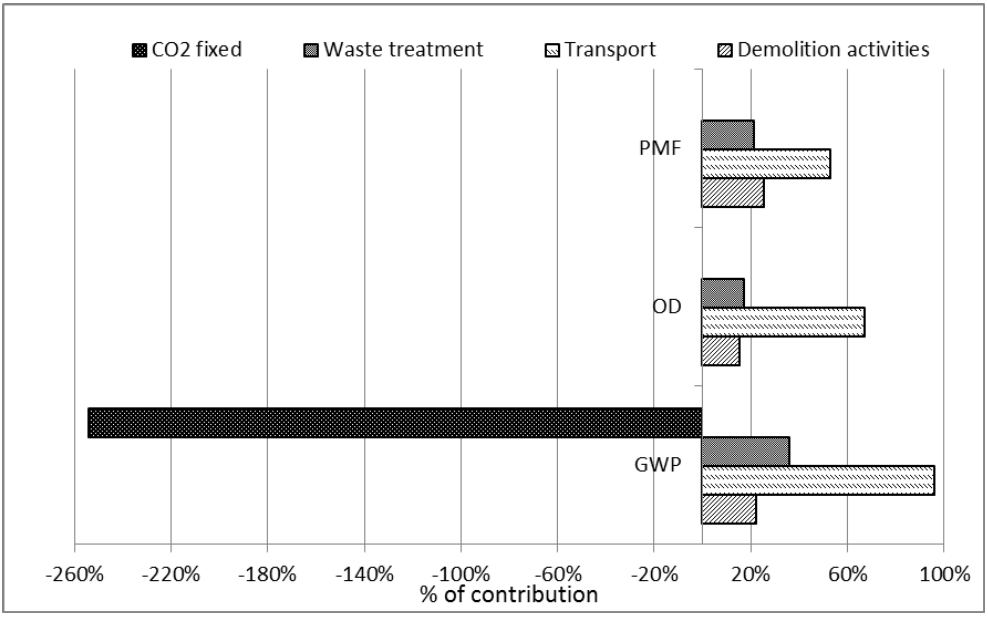

Figure 4.2.10. End-of-life phase

ENDPOINT APPROACH

Despite the large amount of information obtained by means of the midpoint approach, it is very difficult to obtain a global environmental impact assessment. For this purpose, the endpoint approach is more useful. This approach provides only three damage categories (human health, resources, and ecosystem), which are easier to interpret. Table 4.2.4 shows the mean and coefficient of variance of the three damage categories. Although the reference unit of the different damage categories remains different, carrying out the normalization and weighting of three categories is easier than doing so for 18 categories. In fact, ReCiPe allows the normalization of the three damage categories by converting the reference unit of each damage category into points. That makes it easier to interpret the global environment assessment of the bridge. Figure 4.2.11 shows the normalized value of each damage category of the whole life-cycle of the bridge, and Figure 4.2.12 displays the contribution of each phase considering that the different damage categories have the same importance. On one hand, Figure 11 shows that human health is the most important damage category, followed by resources and ecosystem. On the other hand, in Figure 4.2.12 the contribution of different phases using the endpoint approach can be seen. The manufacturing phase is the phase with the highest contribution to the bridge life-cycle, followed by the use and maintenance phase, and both the construction phase and the end-of-life phase make very low contributions compared to the other two phases.

Table 4.2.4. Endpoint approach

Damage category	Reference unit	Manufacturing		Construction		Use and Maintenance		EoL	
		m	cv (%)	m	cv (%)	m	cv (%)	m	cv (%)
HH	DALY	2.03E-05	11.69%	2.36E-06	11.68%	1.01E-05	4.89%	-8.86E-07	11.70%
R	$	1.19E+02	4.01%	8.78E+00	16.90%	6.91E+01	5.60%	1.88E+00	16.86%
E	species.yr	4.58E-03	13.53%	5.18E-04	9.75%	2.75E-03	6.26%	-1.33E-04	7.64%

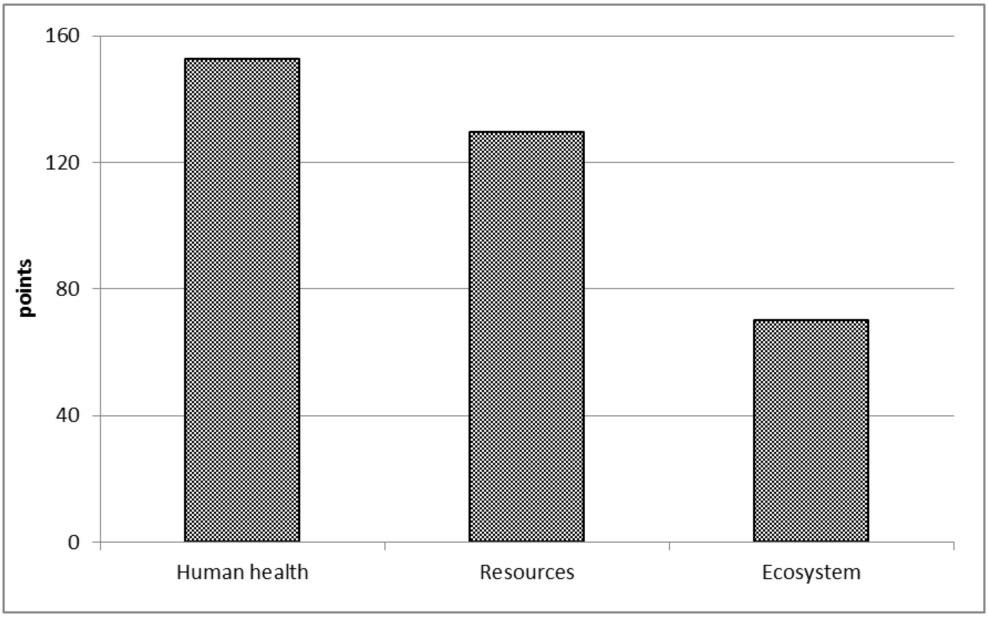

Figure 4.2.11. Damage categories

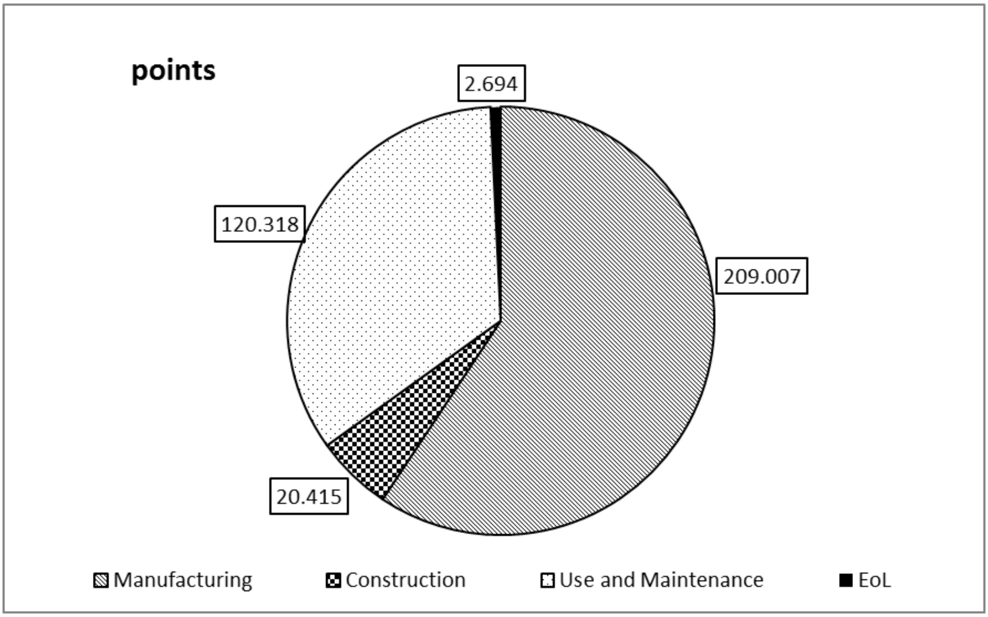

Figure 4.2.12. Contribution of bridge life-cycle phases

4.2.5. Conclusions

Reduction of the environmental impact is a trend that must be taken into account due to the environmental problems that exist nowadays. In this respect, the construction sector has a large margin for improvement. The design of structures or buildings must consider the aspects of three pillars of sustainability. The assessment of the environmental impact during the whole life is a factor that must be taken into account in the design of structures or buildings. Although CO_2 emissions are not the only indicator to be considered in the environmental assessment, due to the relationship of this indicator with the cost, it is used to obtain a bridge with the lowest cost and a low environmental impact. Once this bridge has been obtained, a complete environmental assessment is carried out. For this purpose, a heuristic optimization by means of a hybrid memetic algorithm is used to obtain a cost-optimized prestressed concrete precast bridge and thus a low amount of associated CO_2. Then, the midpoint and endpoint approaches of the ReCiPe method are used to obtain a complete environmental profile of the bridge. These different approaches make it possible to obtain complementary data that provide different information. While the midpoint approach provides detailed information, the endpoint approach provides more concentrated information so it is possible to obtain only one score to assess all the environmental impacts.

Regarding the results of the midpoint approach, the manufacturing phase and use and maintenance phase are the phases with the higher environmental impact. With this knowledge, it is interesting to determine the processes that make the biggest contributions in these phases to try to reduce the environmental impact. Cement production and steel production are the processes with the highest environmental impact in the manufacturing phase, while the maintenance activities have the most environmental impact in the use and maintenance phase. Therefore, the midpoint approach indicates the process with the highest contribution in each impact category, and in this way it is possible to know which process to modify depending on the impact category to be improved. The midpoint approach provides detailed information, but does not offer a single score that represents the global environmental impact of the bridge. For this purpose, the endpoint approach is used. As can be deduced, in the midpoint approach, the manufacturing phase and the use and maintenance phase are the ones with the higher environmental impact.

After studying both the midpoint and endpoint approaches, the results show the need for a complete environmental profile to evaluate the environmental impact of the bridge. The midpoint approach provides information that makes it possible to identify the processes in which improvements should be carried out to improve specific impact categories of the bridge, but the endpoint approach provides a single score that is able to evaluate the global environmental impact of the bridge. Furthermore, although CO_2 emissions are an important indicator in the environmental impact assessment, in some cases it is not sufficient to obtain an accurate environmental evaluation and it is necessary to take into account all the other impact categories.

Acknowledgments: The authors acknowledge the financial support of the Spanish Ministry of Economy and Competitiveness, along with FEDER funding (Project: BIA2017-85098-R).

References

[1] United Nations., World Commission on Environment and Development Our common future. New York, USA, 1987.

[2] T. Waas, J. Hugé, T. Block, T. Wright, F. Benitez-Capistros, and A. Verbruggen, "Sustainability Assessment and Indicators: Tools in a Decision-Making Strategy for Sustainable Development," Sustainability, vol. 6, no. 9, pp. 5512–5534, Aug. 2014.

[3] V. Penadés-Plà, T. García-Segura, J. Martí, and V. Yepes, "A review of multi-criteria decision-making methods applied to the sustainable bridge design," Sustainability, vol. 8, no. 12, p. 1295, 2016.

[4] D. Jato-Espino, E. Castillo-Lopez, J. Rodriguez-Hernandez, and J. C. Canteras-Jordana, "A review of application of multi-criteria decision making methods in construction," Automation in Construction, vol. 45, pp. 151–162, 2014.

[5] V. Yepes, J. V. Martí, and T. García-Segura, "Cost and CO2 emission optimization of precast-prestressed concrete U-beam road bridges by a hybrid glowworm swarm algorithm," Automation in Construction, vol. 49, no. PA, pp. 123–134, 2015.

[6] C. V. Camp and A. Assadollahi, "CO2 and cost optimization of reinforced concrete footings using a hybrid big bang-big crunch algorithm," Structural and Multidisciplinary Optimization, vol. 48, no. 2, pp. 411–426, 2013.

[7] J. V. Martí, V. Yepes, and F. González-Vidosa, "Memetic algorithm approach to designing precast-prestressed concrete road bridges with steel fiber reinforcement," Journal of Structural Engineering, vol. 141, no. 2, p. 4014114, 2015.

[8] T. García-Segura and V. Yepes, "Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety," Engineering Structures, vol. 125, pp. 325–336, 2016.

[9] T. García-Segura, V. Yepes, and D. M. Frangopol, "Multi-objective design of post-tensioned concrete road bridges using artificial neural networks," Structural and Multidisciplinary Optimization, vol. 56, no. 1, pp. 139–150, 2017.

[10] A. Laurent, S. I. Olsen, and M. Z. Hauschild, "Limitations of carbon

footprint as indicator of environmental sustainability," Environmental Science & Technology, vol. 46, no. 7, pp. 4100–4108, 2012.

[11] G. Du and R. Karoumi, "Life cycle assessment of a railway bridge: Comparison of two superstructure designs," Structure and Infrastructure Engineering, vol. 9, no. Iso14040 2006, pp. 1149–1160, 2012.

[12] G. Du, M. Safi, L. Pettersson, and R. Karoumi, "Life cycle assessment as a decision support tool for bridge procurement: Environmental impact comparison among five bridge designs," The International Journal of Life Cycle Assessment, vol. 19, no. 12, pp. 1948–1964, 2014.

[13] J. Hammervold, M. Reenaas, and H. Brattebø, "Environmental life cycle assessment of bridges," Journal of Bridge Engineering, vol. 18, no. 2, pp. 153–161, 2013.

[14] B. Pang, P. Yang, Y. Wang, A. Kendall, H. Xie, and Y. Zhang, "Life cycle environmental impact assessment of a bridge with different strengthening schemes," The International Journal of Life Cycle Assessment, vol. 20, no. 9, pp. 1300–1311, 2015.

[15] P. Zastrow, F. Molina-Moreno, T. García-Segura, J. V. Martí, and V. Yepes, "Life cycle assessment of cost-optimized buttress earth-retaining walls: A parametric study," Journal of Cleaner Production, vol. 140, pp. 1037–1048, 2017.

[16] V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, "Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges," Sustainability, vol. 9, no. 10, p. 1864, 2017.

[17] Ecoinvent Center, "Ecoinvent v3.3." Dübendorf, Switzerland, 2016.

[18] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, ReCiPe 2008. A life cycle impact assessment which comprises harmonised category indicators at midpoint and at the endpoint level. Netherlands, 2009.

[19] M. Z. Cohn and A. S. Dinovitzer, "Application of structural optimization," Journal of Structural Engineering, vol. 120, no. 2, pp. 617–650, 1994.

[20] C. Blum, J. Puchinger, G. R. Raidl, and A. Roli, "Hybrid metaheuristics in combinatorial optimization: A survey," Applied Soft Computing, vol. 11, no. 6, pp. 4135–4151, 2011.

[21] J. V. Martí, T. García-Segura, and V. Yepes, "Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy," Journal of Cleaner Production, vol. 120, pp. 231–240, Feb. 2016.

[22] International Organization for Standardization (ISO), Environmental managment - life cycle assessment - principles and framework. Geneva, Switzerland, 2006.

[23] S. Yi, K. H. Kurisu, K. Hanaki, and K. Hanaki, "Life cycle impact assessment and interpretation of municipal solid waste management scenarios based on the midpoint and endpoint approaches," The

International Journal of Life Cycle Assessment, vol. 16, no. 7, pp. 652–668, 2011.
[24] European Committee for Standardization, EN 206-1 Concrete - Part1: Specification, performance, production and conformity. Brussels, Belgium, 2000.
[25] Ministerio de Fomento, EHE-08: Code on structural concrete. Madrid, Spain, 2008.
[26] Ministerio de Fomento, IAP-11: Code on the actions for the design of road bridges. Madrid, Spain, 2011.
[27] P. Moscato, “On evolution, search, optimization, genetic algorithms and martial arts - Towards memetic algorithms,” Pasadena, California, 1989.
[28] R. Dawkins, The selfish gene. Oxford, UK: Claarendon Press, 1976.
[29] Catalonia Institute of Construction Technology, “BEDEC PR/PCT ITEC material database.” Barcelona, Spain, 2016.
[30] T. García-Segura, V. Yepes, D. M. Frangopol, and D. Y. Yang, “Lifetime reliability-based optimization of post-tensioned box-girder bridges,” Engineering Structures, vol. 145, pp. 381–391, 2017.
[31] B. Lagerblad, Carbon dioxide uptake during concrete life cycle - State of the art, no. 2. Stockholm, Sweeden, 2005.
[32] T. García-Segura, V. Yepes, and J. Alcalá, “Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability,” The International Journal of Life Cycle Assessment, vol. 19, no. 1, pp. 3–12, 2014.
[33] R. Frischknecht, N. Jungbluth, H.-J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, and M. Spielmann, “The Ecoinvent database: Overview and methodological framework,” vol. 10, no. 1, pp. 3–9, 2005.
[34] A. Ciroth, S. Muller, B. Weidema, and P. Lesage, “Empirically based uncertainty factors for the pedigree matrix in Ecoinvent,” The International Journal of Life Cycle Assessment, vol. 21, pp. 1339–1348, 2016.
[35] Y. Itoh and T. Kitagawa, “Using CO2 emission quantities in bridge lifecycle analysis,” Engineering Structures, vol. 25, no. 5, pp. 565–577, 2003.
[36] L. Bouhaya, R. Le Roy, and A. Feraille-Fresnet, “Simplified environmental study on innovative bridge structure,” Environmental Science & Technology, vol. 43, no. February, pp. 2066–2071, 2009.

4.3. Life-Cycle Assessment: A Comparison between Two Optimal Post-Tensioned Concrete Box-Girder Road Bridges[2]

[2] V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, "Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges," *Sustainability*, vol. 9, no. 10, p. 1864, 2017.

Vicent Penadés-Plà[a], José V. Martí[b], Tatiana García-Segura[c], Víctor Yepes[d*]

[a] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: vipepl2@cam.upv.es

[b] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain E-mail: jvmartia@upv.es

[c] Dept. of Construction Engineering and Civil Engineering Projects, Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: tagarse@upv.es

[d] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. Corresponding author. E-mail: vyepesp@cst.upv.es

Abstract: The goal of sustainability involves a consensus among economic, environmental and social factors. Due to climate change, environmental concerns have increased in society. The construction sector is one of the most active sectors which have a high environmental impact. This paper proposes new features to consider a more detailed life-cycle assessment (LCA) of reinforced or pre-stressed concrete structures. Besides, this study carries out a comparison between two optimal post-tensioned concrete box-girder road bridges with different maintenance scenarios. ReCiPe method is used to carry out the life-cycle assessment. The midpoint approach shows a complete environmental profile with 18 impact categories. In practice, all the impact categories make their highest contribution in the manufacturing and use and maintenance stages. Afterwards, these two stages are analyzed to identify the process that makes the greatest contribution. In addition, the contribution of CO_2 fixation is taking into account, reducing the environmental impact in use, maintenance, and end of life stage. The endpoint approach shows more interpretable results, enabling an easier comparison between different stages and solutions. The results show the importance of considering the whole life-cycle, since a better design reduces the global environmental impact despite the higher environmental impact in the manufacturing stage.

Keywords: Sustainability; Environmental impact; Life-cycle assessment; Construction LCA; Bridge LCA; ReCiPe; Sustainable construction.

4.3.1. Introduction

The term ‘sustainable development’ appeared for the first time in the Our Common Future report by The World Commission on Environment and Development [1], and can be defined as “development that meets the needs of the present generation without compromising the needs of the future generation”. This report already considers that to achieve sustainable development it is necessary to take into account economic, environmental and social factors. Later, many other definitions have been developed, most of them considering this intergeneracional balance of these three aspects. Thus, economic, environmental and social factors are the basic aspects to consider in order to achieve sustainability. This implies integrating different ratings in a final assessment that can be carried out by a decision-making process.

The construction sector is one of the most important and active sectors, and therefore achieving sustainability is crucial. A sustainable construction can be defined as one that achieves a consensus among economic, environmental and social aspects throughout its whole life. Some authors [2], [3] conducted a review of the decision-making methods used to achieve sustainability in the construction sector. Waas et al. [4] stated that sustainable development must be considered as a decision-making strategy. Thus, it is first necessary to assess these three pillars of sustainability throughout the whole life of a construction, and then apply the decision-making process to obtain a single evaluation of its sustainability.

It is a fact that we are facing an environmental problem, and that human influence is a vital factor in this problem. For this reason, concern with environmental issues has been increasing in society. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change [5] shows that since 1950 greenhouse gas (GHG) emissions have increased. This increment of the GHG concentration in the atmosphere has caused changes in the environmental system, the most famous of which is global warming. In addition, the Fifth Assessment Report includes estimates of the evolution of the GHG concentration in the atmosphere along the XXI century. In these scenarios, there is one path along which no policy changes are made to reduce the emissions (RCP 8.5), two intermediate paths (RC 6 and RC 4.5), and one more path along which major changes are made to reduce the emissions (RC 2.6). Of these four scenarios, the only one that manages to reduce the GHG concentration by the end of the XXI century is path RC 2.6. Thus, to achieve sustainable development it is crucial to carry out major changes and give more importance to environmental issues.

The construction sector is responsible for a major part of these GHG emissions [6], [7]. The materials most used in the construction sector are steel, wood, and concrete. Steel has the advantage that is a recyclable material and wood has the advantage that is a renewable material. Although these two materials have their own environmental impacts, concrete is the material that has the greatest impact on climate change, with the disadvantage that it is neither recyclable nor renewable. Nowadays, concrete production accounts for more than 5% of anthropogenic GHG emissions per year, mostly attributable to the production of cement clinker, where 1 ton of cement production amounts on average to 0.87 ton of CO_2 emission [7]. Some authors [8] indicate that the current annual production of cement is about 3 Gton, and that it will increase until reaching about 5.5 Gton in the year 2050. The environmental impact of concrete production has been studied by several authors [9]–[11] highlighting the influence of the components concrete matrix on the final impact. All of this implies that environmental assessment in the construction sector is essential. However, despite the importance of GHG emissions, there are other environmental impacts that should be taken into account to achieve a complete environmental assessment [12].

For all of this, the correct environmental assessment must be complete, considering all the life-cycle stages and providing a full environmental impact. This can be achieved through life-cycle assessment (LCA). LCA is a strong and versatile tool to quantify the environmental impact and energy consumption over the whole life of a construction. LCA can evaluate the environmental impact of a product, service or process through a compilation and evaluation of the inflows and outflows of a system. ISO 14040 [13] stated that LCA involves 4 phases: (a) goal and scope definition, (b) inventory, (c) impact assessment, and (d) interpretation. In the first phase it is necessary to define the objective, goal, and functional unit, among others. In the second phase, data should be collected by means of direct measurement, background information or databases. In the third phase, the data are transformed into various categories. Finally, in the fourth phase, the information should be interpreted. Thus, LCA allows the environmental assessment of civil constructions, becoming an excellent tool to achieve sustainability in civil design.

From a review of LCA works, it is clear that only a few studies apply LCA for bridges. The first studies were carried out by Horvath and Hendrickson [14] and Widman [15]. After that, some other authors assessed the environmental impact of bridges, but most of them did not make this assessment for all stages of the life-cycle and focused on just one [16], [17] or took into account a small number of environmental indicators, normally CO_2 and energy [18], [19]. It was not until Steele et al. [20] that the first complete LCA was carried out, and most of the complete LCA studies are much more recent. On the one hand, Du and Karoumi [21], Du et al. [22] and Hammervold et al. [23] compare different bridge designs, and on the other hand Pang et al. [24] focus on comparing different maintenance activities. All of them divided the life-cycle of the bridge into four stages: manufacturing, construction, use and maintenance, and end of life. In some works [21]–[23], the manufacturing stage is the one with the highest environmental impact, but in Pang et al. [24] it is maintenance that has the greatest environmental impact. This work takes the best suggestions of these papers, and incorporates the CO_2 fixation and the disaggregation of the main products into its components to have more control and accuracy in the LCA.

This paper presents a methodology to carry out the LCA of reinforced concrete structures, focusing on bridges. The different phases considered for ISO 14040 are explained for a reinforced concrete structure discussing some features considered in the complete LCA studies reviewed. After that, a comparison between two optimal post-tensioned concrete box-girder road bridges is carried out considering these recent developments. The aim of this study is to show the importance of considering the whole life-cycle. Thus, this paper compares the environmental impact of the different stages of a bridge life-cycle in order to find out if a good design reduces the global environmental impact due to the reduced impact of maintenance activities.

4.3.2. LCA method

LCA is a method to obtain the environmental impact of a product along its whole life, assessing the inputs and outputs of a system. LCA has become one of the most important and accepted methods to evaluate, reduce or improve the environmental impacts of a product, process or activity. Therefore, LCA is a useful tool to assess the environmental part of a sustainability study of structures. In this respect, ISO 14040:2006 [13] will be followed to define a methodology to carry out the LCA of bridges, displaying schemes of the process considered in each life-cycle stage.

4.3.2.1. Goal and scope definition

The first step defines the features of the study, mainly the goal, the functional unit and the boundaries of the system. The main goal is to obtain a quantitative assessment of the environmental impacts of the bridge that can be used to carry out comparisons. Pang et al. [24] stated that there are three main reasons to carry out an LCA on bridges: comparison of different alternatives, comparison of different bridge component alternatives, and comparison of new material with conventional material. In order to make a comparison between bridges at the same location, it is necessary to satisfy three conditions: similar deck dimensions, similar load capacities, and similar life-span. In case that the bridges are at different places, it is necessary to take into account external conditions, such as the geological and geotechnical characteristics, seismic parameters, among others. The external conditions have an effect in the bridge behavior, and therefore, the bridge dimensions.

Once the bridges are defined it is necessary to consider the same functional unit. The functional unit is the unit to which all the inputs and outputs will be referred. Although it is possible to compare the whole bridge, two kinds of functional unit are usually used: 1 m length of the bridge and 1 m^2 of the bridge. The use of 1 m unit length as a functional unit is only possible if the bridges have the same width, otherwise 1 m^2 must be used as the functional unit. Steele et al. [25] suggest that the service life should be defined in terms of the functional unit.

Finally, the boundary of the system defines the inputs and outputs that should be quantified. A complete LCA covers the whole life-span of the bridge. This implies defining the boundaries of each different stage of the bridge's life-cycle. In order to delimit the system boundaries, it is necessary to know the information provided for the databases. In this way, it is possible to define a system that represents the process or product that one wants to create in a specific location. After reviewing LCA studies on bridges, it can be proposed that the Ecoinvent database [26] is the most suitable database for the construction sector. In the next two sections, a brief account of how to use the information from the Ecoinvent database will be presented. After that, a general system of each life-cycle stage of the bridge will be proposed.

4.3.2.1.1. Ecoinvent

Ecoinvent [26] is one of the most representative databases for life-cycle inventories. Ecoinvent is certified worldwide for its reliability and permanent updating, in which construction processes and products are one of the most important areas. The first version of the Ecoinvent database appeared around 2004 through the efforts of several Swiss Federal Offices and research institutes of the ETH to harmonize and update a life-cycle inventory (LCI) for use in life-cycle assessment (LCA). Therefore, it must be understood as a database of different life-cycle inventories [27]. In this first version, the processes were obtained based on Swiss information (CH), but there were also processes that were valid for the Rest of Europe (RER). In later versions, new information on different geographical locations was added, mainly from Canada (CA-QC), Germany (DE), Rest of World (RoW), and Global (GLO). Apart from the geographical scope outlined above, other considerations must be taken into account, such as temporal or technical scope.

All of this means that obtaining the environmental impacts will be more reliable in one place, time and with one technology than in another. This is an important detail to consider when an LCA is to be carried out. For example, the assessment of 1 m^3 of concrete in Spain is different from the assessment of 1 m^3 of concrete in Switzerland or the average for Europe, because the distances between quarries and concrete plants are not the same, and the transport, technical and other aspects may not be the same. Therefore, obviously, the data on Switzerland allows a more reliable assessment of environmental impacts for Switzerland than for Spain. This can be mitigated by separating the components of the main process and taking into account the associated uncertainty.

4.3.2.1.2. Uncertainty

Uncertainty considerations must be taken into account in two stages. First are basic uncertainty factors, which are used depending on the kind of input and output considered [27]. Second are uncertainty factors that consider the aspects discussed in the point above. This can be solved by using the pedigree matrix [28], which can help to obtain an uncertainty factor according to five indicators: Reliability, Completeness, Temporal correlation, Geographical correlation, and Further technological correlation. Thus, at the moment of using a process from the Ecoinvent database, it is necessary to use the basic uncertainty factor depending on the kind of data, and then to consider the origin of this information so as to obtain the uncertainty from the pedigree matrix.

4.3.2.1.3. Stages

The stages to consider along the bridge's life-cycle are manufacturing, construction, maintenance and use, and end of life. The processes implied in these stages must be taken into account in the planning and design. Therefore, the classification of the processes and impacts (inputs and outputs) into different stages depends on the moment at which they take place and not when they are considered. Then, the system for each stage will be explained and the advantages of the separation of the main materials and processes will be discussed. In this paper we focus on post-tensioned concrete box-girder road bridges, but this methodology can be used for all reinforced concrete structures with minor modifications.

MANUFACTURING

The manufacturing phase includes the upstream process of the materials used in the bridge, from the extraction of raw materials to materials that are ready to be used. The materials most used in bridges currently are concrete and steel. The Ecoinvent database has several products that represent these main materials, considering all the upstream activities. Despite the convenience of using these general products, they do not normally represent the specific features that we want to take into account. As stated above, the separation of the existing general processes or products into several sub-processes or products has some advantages that are even greater in the manufacturing phase. Then, the manufacturing processes of the materials are described, showing the advantages of disaggregating the main products and processes. Figure 4.3.1 shows the general scheme to obtain 1 m^3 of concrete, and Figure 4.3.2 shows the general scheme to obtain 1 kg of reinforced steel.

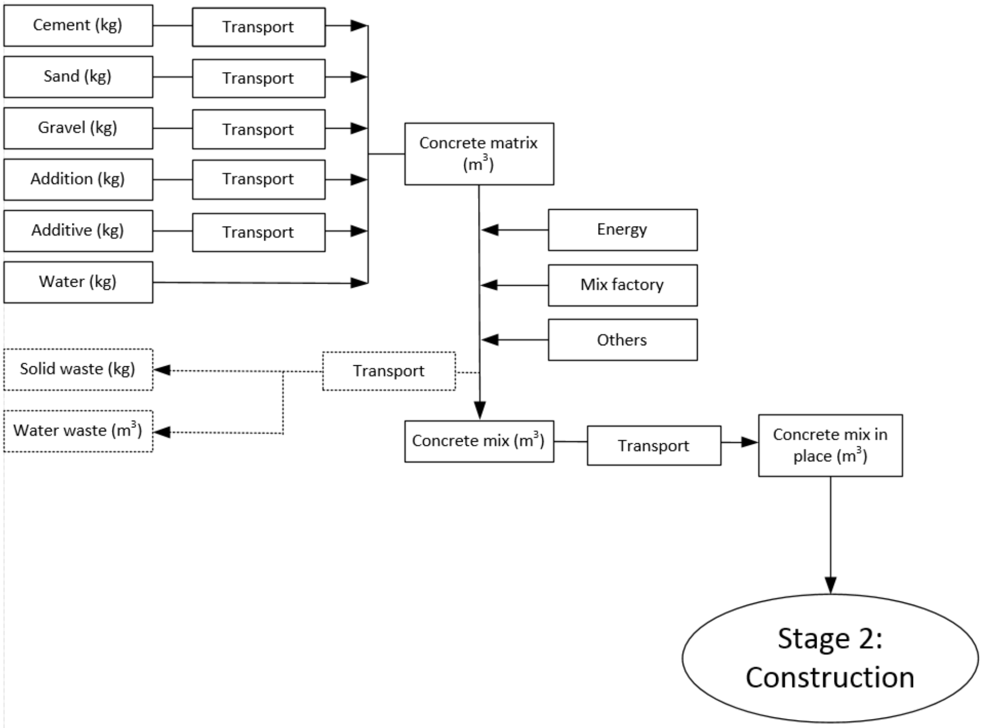

Figure 4.3.1. Concrete manufacturing

The matrix concrete product is separated into basic components. This separation has two main advantages: controlling the dosage of the concrete, and controlling the distance and mode of transportation of the materials. The created concrete products from Ecoinvent only represent specified dosages and the mode and distance of transportation are averaged for the area where the information is obtained. This separation allows one to consider the real dosage, distances, and mode of transportation for one concrete study, and thus to be more accurate for a specific study. Once the matrix concrete product is determined, it needs to be processed in a mixing factory to obtain the concrete mix product. Another advantage of the separation of the created concrete products from Ecoinvent is the control of the type and amount of energy. Ecoinvent has energy information from several different countries, but in the created concrete products the process of energy used is based on the place where the concrete product was created. This separation allows one to use the energy information for the area in which the study will be carried out. In addition, Kellenberg et al. [29] and Marceau et al. [30] define a general process to take into account in the mixing for each 1 m^3 of concrete production.

Sometimes, by-products such as fly ash or silica fume are used replacing some original products. In these cases, it is considered that these products do not have environmental impact, except for post-process and transport, since they are by-products from other materials [31]. Furthermore, the waste products of concrete must be considered. Therefore, the real amount of the primary material must be the mass to obtain 1 m^3 of concrete plus the mass of waste materials. Marceau et al. [30] state that for 1 m^3 of concrete production, the solid waste consisting of concrete and small amounts of paste totals 24.5 kg and the wastewater from concrete production accounts for 0.0348 m^3. Thus, the real amount of the primary material can be calculated according to Eq. 4.3.1 to 4.3.5. Finally, the distance and mode of transportation of the concrete mix between the factory and the construction zone can be defined exactly.

$$Primary\ Water = Water + Waste\ water \tag{4.3.1}$$

$$Total\ solid = Cement + Gravel + Sand \tag{4.3.2}$$

$$Primary\ Cement = Cement + \left(\frac{Cement}{Total\ solid}\right) \cdot Waste\ concrete \tag{4.3.3}$$

$$Primary\ Gravel = Gravel + \left(\frac{Gravel}{Total\ solid}\right) \cdot Waste\ concrete \tag{4.3.4}$$

$$Primary\ Sand = Sand + \left(\frac{Sand}{Total\ solid}\right) \cdot Waste\ concrete \tag{4.3.5}$$

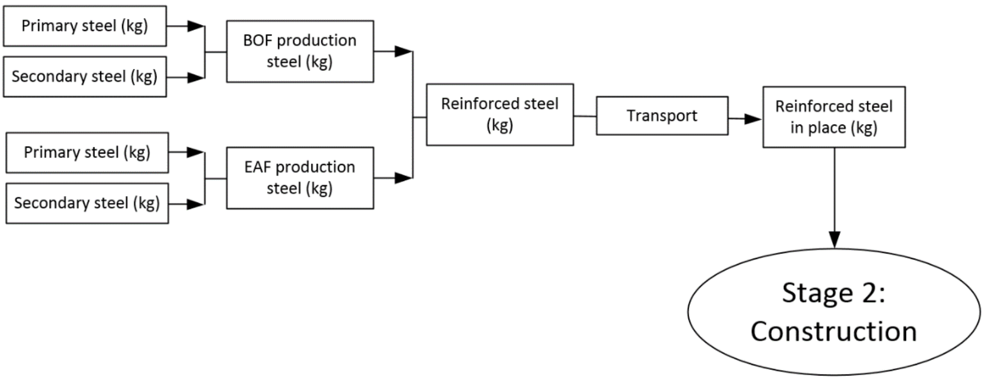

Figure 4.3.2. Steel manufacturing

Reinforced steel is separated into two main production methods: Basic Oygen Furncace (BOF) and Electric Arc Furnace (EAF). In BOF the iron is combined with less than 30% of steel scrap (recycled steel), and in EAF around 90–100% of steel scrap (recycled steel) is used. BOF and EAF have different environmental impacts, so control of the production method depending on the area of the study is crucial. The Ecoinvent database considers a ratio of around 19% of recycled scrap in the steel produced by BOF and 100% of steel recycled in the EAF; therefore, the ration of recycled steel can be controlled. This database takes into account all the by-products and wastes involved in the product manufacture

Some steel products from Ecoinvent already consider a steel production ratio to obtain reinforced steel, for example, reinforcing steel considering 37% of steel obtained by EAF and other steel obtained by BOF, which corresponds to the average for Europe [22]. Nevertheless, the separation of steel into different production methods allows direct control of the ratio of steel obtained by each production method and indirect control of the recycled steel ratio, which can differ depending on the area considered such as in Zastrow et al. [32]. In addition, as well as the concrete, the distance and mode of its transportation can be controlled more exactly.

CONSTRUCTION

The construction phase includes all the materials and construction machinery associated with the erection of the bridge. According to the type and location of the bridge, the construction method must be defined. The principal material used in this phase is the formwork, and the construction machinery considered includes all the different kinds of machinery, such as cranes, dumpers, scaffolding, compactors, etc. Most authors who have studied the LCA of bridges [21]–[24] stated that this phase is much less significant than the others. However, once the construction method is determined, the amount of energy and diesel consumed by construction machinery must also be determined according to the literature, data from machinery companies or other databases. Figure 4.3.3 shows a general scheme to take this phase into account.

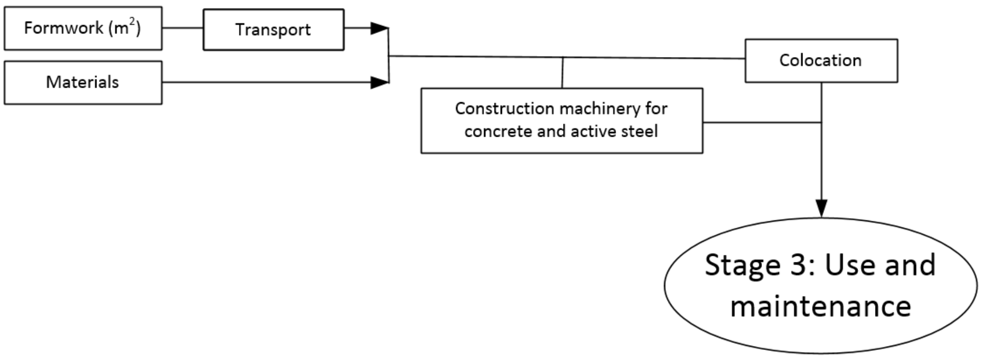

Figure 4.3.3. Construction diagram

MAINTENANCE AND USE

The maintenance and use phase includes all the activities and processes in the whole service life of the bridge considered in the design and planning phase. These activities and processes can be divided into three categories: maintenance activities, traffic detour, and fixed CO_2. Maintenance activities can cause partial or total closure of the bridge. If the closure of the bridge is total, traffic must change its habitual route, increasing the distance traveled, and thus increasing the environmental impact. This traffic detour is considered as an extra distance travelled by cars and trucks. Thus, the location and the traffic characteristics are the main factors affecting the traffic detour. The average daily traffic, the percentage of trucks and the detour distance are the variables that should be known to evaluate a particular case.

On the one hand, some authors use a literature review to consider the recommended maintenance activities in order to evaluate the environmental impact [21]–[23], and others suggest different scenarios to assess which one has the least environmental impact [24]. In addition, if the closure of the bridge is total, depending on the features of the bridge design, materials and the ambient environment, it is possible to determine the number of maintenance periods required. Once that is determined, the energy and diesel consumption of maintenance machinery and pollutant emissions related to traffic disturbance during maintenance activities must be taken into account.

On the other hand, some studies [31], [33]–[36] stated that concrete can fix carbon through carbonation. Carbonation is the crucial decay of reinforced concrete bridges, and depends on three main factors [31]: the w/b ratio, the concentration of CO_2 in the surrounding air and the specific climate conditions, and the depth of embedded steel. Despite the structural problems that result from carbonation, the carbonation of the concrete reduces the environmental impact of the bridge in this stage, and consequently in its life-cycle. Lagerblad [37] studied the CO_2 uptake of the concrete during its life-cycle based on Fick's first law. Fixed CO_2 can be calculated according to Eq. 4.3.6, in which k is the carbonation coefficient, t is the service life, A is the exposed area of concrete, r is the ratio of CaO that is going to become carbonated, C is the content of cement in 1 m^3 of concrete, k is the content of clinker in the cement, L is the content of CaO in the clinker, and ε is the molecular weight ratio of CO_2/CaO. This equation can be simplified by grouping the constants. In this way, Lagerblad [37] assumed that r is 0.75, L can be considered 0.65 and ε is 0.7857. Taking into account these constants, Eq. 4.3.6 can be reduced to Eq. 4.3.7. Some studies [31] showed that the ratio of CO_2 generated for concrete structures can be fixed along its service life. Figure 4.3.4 shows a maintenance and use scheme in which fixed CO_2 is considered.

$$CO_2 fixed\ (kg) = \frac{k\left(\frac{mm}{\sqrt{year}}\right)\cdot\sqrt{t(year)}}{1000} \cdot A(m^2) \cdot r \cdot C\left(\frac{kg}{m^3}\right) \cdot k(\%) \cdot L(\%) \cdot \varepsilon \qquad (4.3.6)$$

$$CO_2 fixed\ (kg) = 0.383 \cdot \frac{k\left(\frac{mm}{\sqrt{year}}\right)\cdot\sqrt{t(year)}}{1000} \cdot A(m^2) \cdot C\left(\frac{kg}{m^3}\right) \cdot k(\%) \qquad (4.3.7)$$

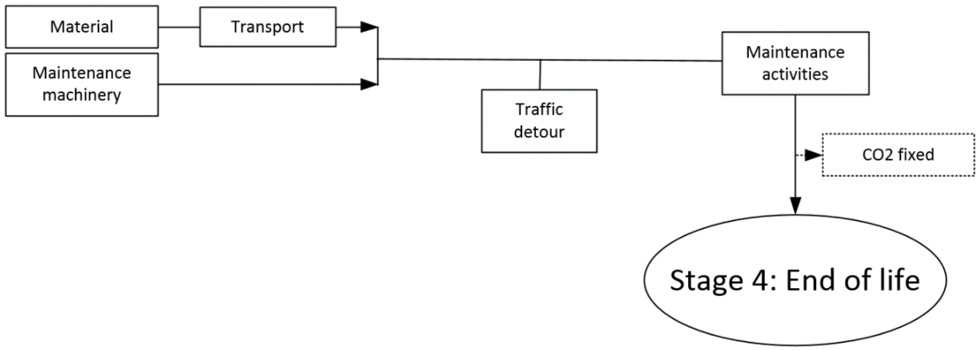

Figure 4.3.4. Maintenance and use diagram

END OF LIFE

The end of life phase includes all the activities and processes after the service life of the bridge concludes. In this stage, two general points should be defined and taken into account: the treatment of generated wastes (reuse, recycling, or disposal in landfill), and the machinery needed for the demolition of the bridge, transport and treatment of wastes. Therefore, it is first necessary to define in the planning and the design the destination of the materials after its service life. Note that, depending on the material and the treatment of the waste of this material, the environmental impact differs. Considering steel and concrete as common materials in bridge structures, there are several ways to treat it depending on the needs, technology and society of the region of the study. Figure 4.3.5 shows a general scheme of the end of life phase.

Most studies consider the ratio of steel to be recycled, but there are varying points of view on the percentage of the steel recycled. Some authors consider a high steel recycling ratio: Hettinger et al. [38] and Du et al. [21] consider a large steel recycling ratio, and Hammervold et al. [23] consider a 100% steel recycling ratio based on the increasingly strict requirements that the construction sector is expected to fulfill when it comes to waste treatment. Other authors consider the average for a larger area of study, for example, the average steel recycling ratio in Europe [22]. As has been pointed out above, the steel recycling ratio differs depending on the location. For this reason, controlling this ratio is essential to give a more accurate environmental assessment. In addition, the steel recycled can be used for bridges, so the steel that will be recycled in the end of life phase will be the recycled steel used in a subsequent manufacturing phase. Therefore, in the end of life phase, the unique process that must be considered as concerns the steel recycled is its transport to the treatment location.

Concrete is more difficult to reuse or recycle, the contribution of recycled concrete on bridges being practically zero. Even so, recycled or reused concrete can be used in other areas. The ratio of recycled or reused concrete, as for steel, depends on the features of the area of study. Du and Karoumi [21] stated that all the concrete is crushed and then transported to landfill, while Hettinger et al. [38] consider that only 15% of the concrete is recycled. Other works consider that all the concrete is crushed and then reused [22]. As stated above, concrete is a material that fixes CO_2 due to carbonation. This process continues even after the service life is finished. The area exposed to the environment is a variable that influence the fixed CO_2. Therefore, the CO_2 fixed by concrete that can be considered in the end of life phase differs according to whether the concrete has been treated or not. We assumed that all the concrete is crushed and carbonated [31]. Lagerblad [37] provide the coefficient of carbonation according to the concrete strength and exposure environment. Taking into account a concrete with a strength greater than 35 MPa, the coefficient of carbonation (k) takes 0.5mm/year0.5, 0.75mm/year0.5, 1mm/year0.5, 2.5mm/year0.5 and 3.5mm/year0.5 depending on whether concrete is exposed, sheltered, indoor , wet or buried, respectively. In those cases, the complete concrete carbonation takes 100, 44.4, 25, 4 and 2.04 years, respectively, assuming that after the crushed concrete aggregate is 10-mm diameter. The results show the importance of the exposure environment.

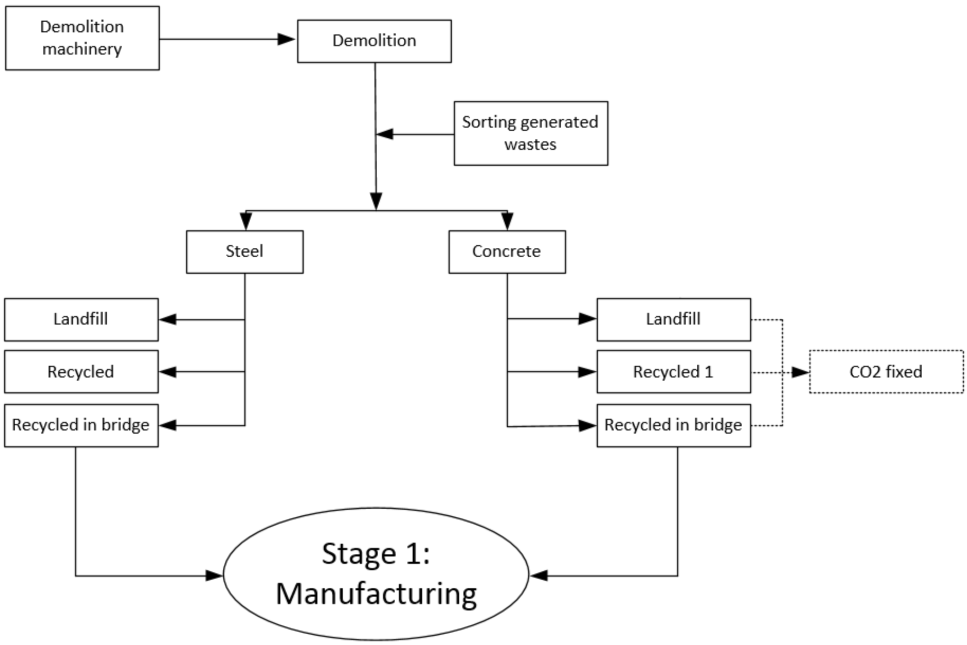

Figure 4.3.5. End of life diagram

4.3.2.2. Inventory analysis

Inventory analysis comprises the collection of data and processes to quantify the inflows and outflows of the studied system. The information that forms the life-cycle inventory originates from direct measurements, literature or electronic sources such as databases. Databases are the most commonly used sources to form the life-cycle inventory due to the greater facility of operating with such information. Ecoinvent is one of the most complete databases, with many processes that cover extensively construction materials, energy, transport and treatment of wastes. Therefore, Ecoinvent is a useful database for this sector and is widely used in the complete LCA of bridges, although others databases are considered too, such as the Steel and Energy Fact Sheet for steel information [39], and European Reference Life Cycle for energy information [40]. In some cases, although the process or material used to evaluate the environmental impact pertains to the main databases, the specific amount is obtained from more regional databases or direct measurements.

4.3.2.3. Impact assessment

The purpose of the impact assessment is the evaluation of the inventory results, analyzing and quantifying the environmental impacts, to finally convert them into environmental indicators. Selecting the method by which to carry out the desired impact assessment is an important choice in the LCA. For this reason, it is necessary to give a brief review of the different types of impact assessment approaches: midpoint and endpoint assessment. On the one hand, the midpoint approach defines a complete environmental profile represented by means of a set of indicators, but although the midpoint approach shows a complete environmental profile, it is difficult to interpret [41]. On the other hand, the endpoint approach converts the indicators of the impact categories into just three damage categories (human health, ecosystem, and resources). The endpoint approach does not provide the detailed environmental profile provided by the midpoint approach, but is easier to interpret.

The LCA methods used by the authors to study the complete LCA of the bridges are Eco-Indicator, CML and ReciPe. CML is a midpoint LCA method, while Eco-Indicator is an endpoint LCA method. ReciPe can provide both the midpoint and endpoint assessment [42]. The midpoint approach is more reliable than the endpoint approach, and it is useful when the assessor wants to assess only the environmental impact, focusing more on a specific process. However, the endpoint approach is easier to understand than the midpoint approach, and it is useful when the assessor is going to operate with a lot of information, for example, to evaluate the sustainability (environmental, social and economic factors). The midpoint and endpoint provide the assessment at different levels, both of them helpful for different aspects. For this reason, the ReCiPe method is suggested to provide both midpoint and endpoint assessment [43].

4.3.2.4. Interpretation

Interpretation is the last stage of LCA. The main objective of LCA can vary. The information obtained can be used to compare the environmental impact of different alternatives, options for the same alternative (different construction methods, materials, maintenance alternatives), or to obtain a single value that can be used to obtain the sustainability. For this reason, to better interpret the results of the LCA, the use of both midpoint and endpoint approaches is recommended. In this way, it is possible to study or compare impact categories individually using the midpoint approach, as well as obtaining a single score through normalizing the damage categories using the endpoint. In addition, uncertainty must be taken into account for correct implementation of LCA.

4.3.3. Case of study

At this point, a general scheme that summarizes all the information explained above will be displayed. Then, the LCA of two optimal post-tensioned concrete box-girder road bridges located in an eastern coastal region of Spain will be carried out.

4.3.3.1. General scheme

Figure 4.3.6 shows the general scheme used in the case study. The final goal of the LCA is to obtain the necessary data to evaluate the environmental aspects of the bridge, and finally to assess its sustainability. In this case, only the environmental aspect is assessed and the steps followed were those indicated in the box with the dashed line. Figures 4.3.1, 4.3.2, 4.3.3, 4.3.4 and 4.3.5 define the scope of each stage of the bridge life-cycle. Once the scope of LCA of the bridge is determined, the Ecoinvent database is used to define the process and products needed. Uncertainty is considered depending on the type of flow and its features according to the pedigree matrix. Finally, the ReCiPe method is used to consider the midpoint and endpoint approaches. Next, two points describe the definition of the processes of each stage of the bridge life-cycle, taking into account the uncertainty and the results obtained.

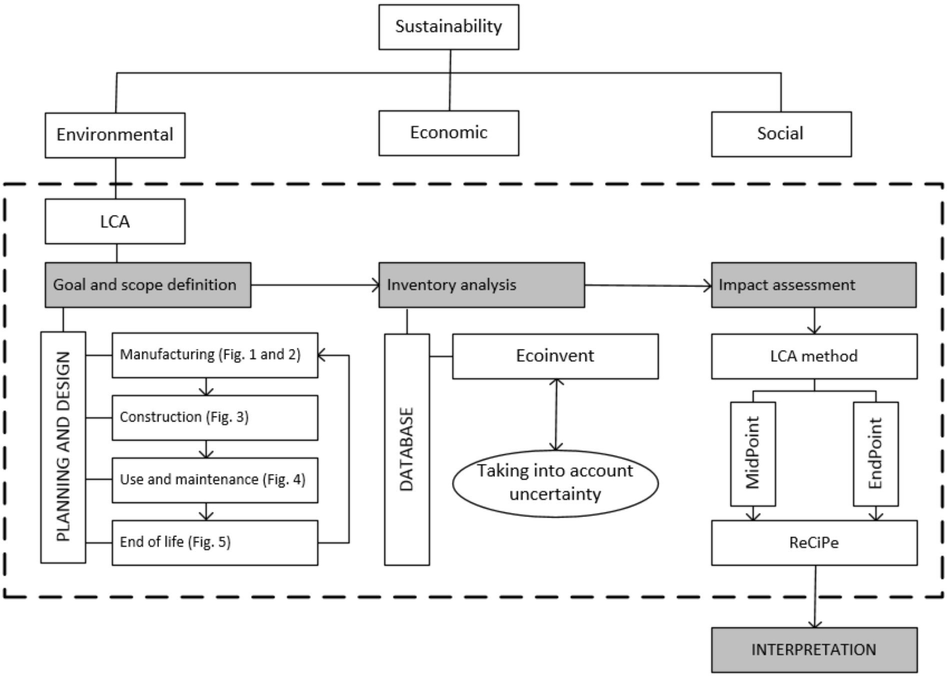

Figure 4.3.6. General scheme

4.3.3.2. Bridge studied

As an example, two optimal post-tensioned concrete box-girder road bridges located in an eastern coastal region of Spain were assessed. The bridges have three continuous spans of 35.2, 44 and 35.2 meters and a width of 11.8 meters. These bridges were selected from a Pareto front [44], [45], in which 34 variables were selected to simultaneously minimize the initial cost of material production and construction, maximize the overall safety factor with respect to the ultimate limit state, and maximize the corrosion initiation time. In addition, maintenance was optimized to ensure that the bridge complied with all the performance requirements during its life-span of 150 years. The bridges selected for the LCA were of two contrasting designs, and the functional unit used was 1 meter length. The first solution was built with concrete of 35 MPa and the initial corrosion time was 10.45 years, which means that two maintenance operations were necessary. The second solution was built with concrete of 50 MPa and the initial corrosion time was 65.68 years. Figure 4.3.7 shows the general view of the bridge.

Some general features to consider that are the same for both bridges are the distance and mode of transportation. These two characteristics of the transport depend very much on the region of the study, because they are really influenced by the properties on the ground. In this case, the study was carried out in the eastern coastal area of Spain and the distances considered were: 20 km to transport the aggregates to the mixing factory, 10 km to transport the cement to the mixing factory, 20 km to transport the concrete to the site, and 100 km to transport the steel to the site.

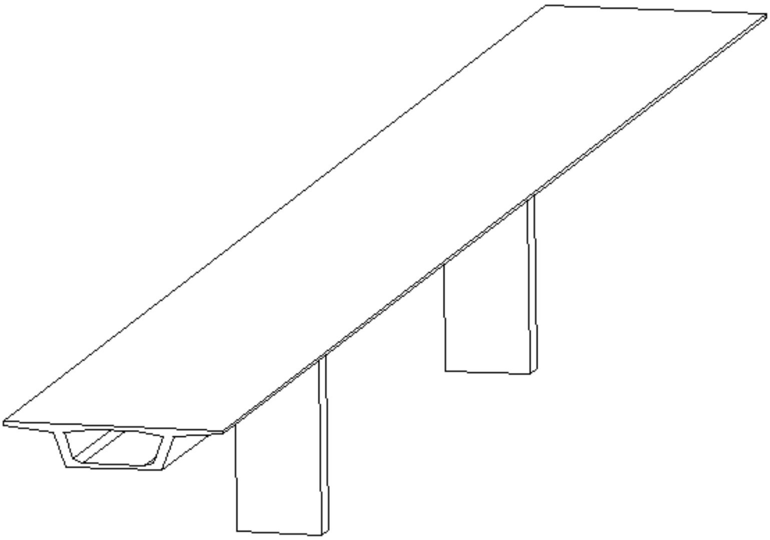

Figure 4.3.7. General view of the bridges

4.3.3.2.1. Manufacturing

The dosage of concrete matrix for each solution is obtained according to the XC-4 environmental ambient from EN 206-1 [46]. Table 4.3.1 shows the amount of general material per 1 m^2 of bridge and the dosage needed to make 1 m^3 of concrete depending on the required strength. The wastes from concrete production are those suggested by Marceau et al. [30] and described in Section 2.1.3.

Table 4.3.1. Amounts of materials

	Solution 1	Solution 2
Strength (MPa)	35	50
Passive steel (kg/m^2)	66.89	74.67
Active steel (kg/m^2)	21.98	19.8
Concrete (m^3/m^2)	0.674	0.67
Cement (kg/m^3)	300	400
Gravel (kg/m^3)	848	726
Sand (kg/m^3)	1088	1136
Water (kg/m^3)	160	160
Superplasticizer (kg/m^3)	4	7

Reinforced steel is obtained as a combination of the production methods according to the area of the study. In Spain, around 67% of steel is produced by the EAF method, while the remaining 23% of steel is produced by the BOF method. Assuming the same steel recycling ratio for each production method as in Ecoinvent (19% of recycled steel in BOF and 100% of steel recycled in EAF), the recycling ratio considered is around 71%.

4.3.3.2.2. Construction

The construction was considered to be cast in place. The construction machinery considered in this section was divided into the machinery needed for the concrete handling and the active reinforcement handling. For each kind of machinery, the amount of energy and CO_2 emissions was obtained from the Bedec database [47]. On the one hand, the handling of concrete requires machinery that consumes 123.42 MJ of energy and emits 32.24 kg of CO_2 per m^3 of concrete. On the other hand, the handling of active reinforcement requires machinery that consumes 10.2 MJ of energy and emits 2.62 kg of CO_2 per kg of active steel. In addition, the formwork considered is a wood formwork that can be reused 3 times.

4.3.3.2.3. Maintenance and use

Maintenance activities and traffic detours were considered to be the same for each maintenance period. Therefore, the difference between the solutions was the number of maintenance periods required. Accordingly, for the same service life, Solution 1 needed two maintenance periods and Solution 2 only needed one maintenance period. One period of maintenance operation required the closure of the bridge for 7 days to remove the old concrete cover and replace it with repair mortar. In addition, the traffic detour was considered, taking into account the average daily traffic (8500 vehicle/day), the percentage of trucks (12%), and the detour distance (2.9 km). For concrete repair, water blasting was required to remove the old concrete cover. In addition, an adhesion coating was applied to prepare a suitable surface for the new concrete cover. Finally, repair mortar was cast to form the new cover. All of these activities could only be carried out by a truck-mounted platform. As above, the energy and CO_2 emission due to the machinery were obtained from the Bedec database [47] amounting to 584.28 MJ and 46.58 CO_2 per m^2 repaired for each maintenance period. Finally, fixed CO_2 during the whole service life is considered.

4.3.3.2.4. End of life

End of life considers the machinery used to carry out the demolition and the treatment of the wastes. In this case, 71% of steel is recycled, and all the concrete is crushed and left to landfill. On the one hand, the ratio of recycled steel matches the ratio of recycled steel used in the manufacturing phase, so the steel cycle is closed. On the other hand, it is assumed that the crushed concrete will be completely carbonated.

4.3.3.3. Results

The results were obtained proceeding with the description displayed in the points above. The ReCiPe method was used to carry out the analysis based on both the midpoint and endpoint approaches. In the midpoint approach, 18 impact categories are shown with the associated uncertainty. Also, the mean of these impact categories is displayed in bar charts for better comparison among stages. In the endpoint approach, three damage categories are studied. This allows a greater degree of interpretation.

4.3.3.3.1. Midpoint approach

The midpoint approach provides a complete environmental profile of each stage of the bridge life-cycle represented by 18 impact categories: Agricultural land occupation (ALO), Climate change (GWP), Fossil depletion (FD), Freshwater ecotoxicity (FEPT), Freshwater eutrophication (FEP), Human toxicity (HTP), Ionizing radiation (IRP), Marine ecotoxicity (MEPT), Marine eutrophication (MEP), Metal depletion (MD), Natural land transformation (NLT), Ozone depletion (OD), Particulate matter formation (PMFP), Photochemical oxidant formation (POFP), Terrestrial acidification (TAP), Terrestrial ecotoxicity (TEPT), Urban land occupation (ULO), and Water depletion (WD). Although these results are difficult to interpret, this allows one to obtain more reliable results. As stated above, the data obtained from the database does not correspond exactly with the features of the study. For this reason, the impact categories have an associated uncertainty.

Tables 4.3.2 and 4.3.3 show the mean and the coefficient of variation for each impact category for each stage of the life-cycle of the bridge. The uncertainty associated with the inputs causes an uncertainty in the outputs, which is represented in Tables 4.3.2 and 4.3.3 with the mean and the coefficient of variation of each impact category. In both solutions, although the mean is different, the coefficient of variation is very similar because the uncertainty used in both cases was the same. In the manufacturing stage, the impact category with the highest coefficient of variation is the GWP, followed by IRP and WD. In the construction stage, the ranking is ALO, ULO and MD. Regarding the use and manufacturing stage, this classification is formed by MEPT, ULO and HTP. Finally, in the end of life stage the impact category with the highest coefficient of variation is the NLT, followed by MD and MEP. Comparing the stages of production and use and maintenance, it is observed that the coefficient of variation in the use and maintenance stage is generally higher than the coefficient of variation in the manufacturing stage.

In addition, for a more compressed view of these results, Figures 4.3.8 and 4.3.9 show bar charts to allow easier comparison among stages for both solutions. In these figures, the contribution of each stage of the bridge life-cycle can be observed for each impact category. In both solutions, the most decisive stages are production and use and maintenance. These stages have the greatest contribution for each impact category except ALO. Besides, focusing on the two more significant stages (production and use and maintenance), Figure 4.3.8 shows that the impact of maintenance and use stage is higher than one of production stage in FD, MEP, NLT, ODP, PMFP, POFP, and TAP. However, Figure 4.3.9 shows that maintenance and use stage just have higher impact in NLT, ODP, and POFP. This is explained by the fact that Solution 1 requires one more maintenance action due to the lower initial durability.

Table 4.3.2. Impact categories for Solution 1

Acronym	Reference unit	Manufacturing		Construction		Use and Maintenance		EoL	
		m	cv (%)	m	cv (%)	m	cv (%)	m	cv (%)
ALO	m^2*a	155.34	4.13	576.41	33.43	22.23	24.51	3.84	4.89
GWP	kg CO_2 eq	3589.85	18.93	1453.67	3.17	2770.57	12.17	-807.73	-5.62
FD	kg oil eq	577.04	6.44	148.42	6.38	964.35	11.68	24.10	16.00
FEPT	kg 1,4-DB eq	70.02	2.79	4.15	7.78	42.92	33.56	0.41	6.57
FEP	kg P eq	1.51	4.50	0.15	7.07	0.27	24.77	0.01	5.51
HTP	kg 1,4-DB eq	2687.18	2.90	137.99	9.51	429.79	26.39	12.75	6.40
IRP	kg U235 eq	414.10	15.96	208.40	4.13	195.61	12.26	22.61	5.49
MEPT	kg 1,4-DB eq	69.40	2.75	3.90	8.05	38.01	33.13	0.38	6.67
MEP	kg N eq	0.54	9.87	0.11	8.46	1.02	5.62	0.02	21.83
MD	kg Fe eq	1685.92	2.50	10.20	14.13	157.81	21.68	1.67	22.48
NLT	m^2	0.45	7.85	0.08	9.32	1.02	11.04	0.02	23.64
ODP	kg CFC-11 eq	0.00	7.15	0.00	5.59	0.00	10.90	0.00	17.09
PMFP	kg PM10 eq	7.08	6.05	1.22	8.16	9.27	6.57	0.23	19.84
POFP	kg NMVOC	10.73	9.88	1.88	8.79	28.76	4.94	0.57	26.35
TAP	kg SO2 eq	9.93	9.88	3.23	6.15	17.96	6.56	0.54	16.41
TETP	kg 1,4-DB eq	0.84	2.62	0.04	21.79	0.23	21.41	0.00	15.19
ULO	m^2*a	41.60	6.68	14.72	28.80	31.52	28.10	0.37	7.79
WD	m^3	15361.74	10.46	3197.70	4.60	2077.07	22.44	323.72	4.92

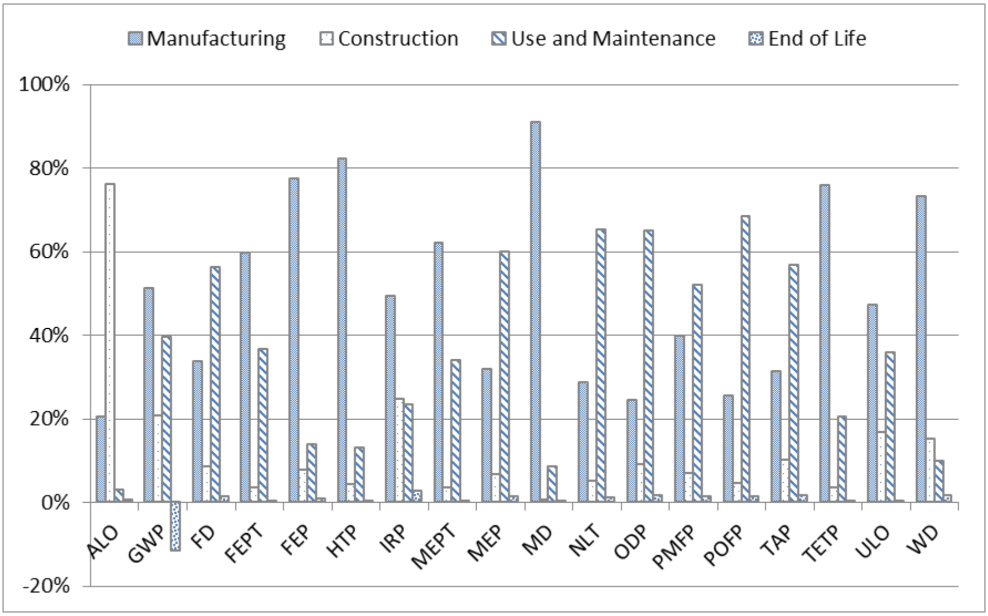

Figure 4.3.8. Impact categories for Solution 1

Regarding GWP, this impact category represents 51.24% in the manufacturing stage and 39.54% in the maintenance and use stage in Solution 1. Solution 2 presents a tendency toward a higher contribution in the manufacturing stage. For example, taking the previous example, GWP represents 73.4 % in the manufacturing stage and 22.37% in the use and maintenance stage. Even in this particular impact category, the construction stage has the same contribution as the use and maintenance stage, with 22.51%. In the other impact categories, the manufacturing stage and use and maintenance stage have the highest contributions. Also it is important to highlight the positive contribution of the end of life stage due to the fixation of CO_2 by the crushed concrete. This consideration reduces the global impact of the bridge. In addition, the end of life stage has a positive contribution that improves the global impact of the bridge along its life-cycle.

These results show that for the same bridge typology, the same bridge dimensions and, thus, the same construction method, the environmental impact along the life-cycle of the bridge differs considerably depending on the decisions made in the planning and design phase. The two bridges represent optimal bridges with different conditions. Solution 1 has a lower contribution in the manufacturing stage, but the features of the materials used and the exigent environmental ambient make two maintenance periods necessary to comply with the regulations along the 150 years of service life. Solution 2 has a higher contribution in the manufacturing stage due to the superior quality of materials, but this implies that only a single maintenance period will be necessary along its service life.

Table 4.3.3. Impact categories for Solution 2

Acronym	Reference unit	Manufacturing		Construction		Use and Maintenance		EoL	
		m	cv (%)	m	cv (%)	m	cv (%)	m	cv (%)
ALO	m^2*a	186.01	4.07	568.93	33.85	10.97	22.96	3.84	4.84
GWP	kg CO_2 eq	4413.77	21.13	1353.95	3.16	1345.10	11.51	-1099.2	-5.09
FD	kg oil eq	669.39	7.56	139.37	6.70	479.48	10.78	23.99	15.79
FEPT	kg 1,4-DB eq	78.01	3.19	3.91	8.21	21.08	31.55	0.41	6.62
FEP	kg P eq	1.71	5.27	0.14	7.45	0.13	23.15	0.01	5.55
HTP	kg 1,4-DB eq	3001.31	3.20	130.42	10.04	211.78	24.77	12.75	6.44
IRP	kg U235 eq	497.18	18.30	194.46	4.14	97.21	11.34	22.61	5.53
MEPT	kg 1,4-DB eq	77.27	3.13	3.67	8.50	18.67	31.15	0.38	6.71
MEP	kg N eq	0.63	11.64	0.11	8.93	0.51	5.18	0.02	21.47
MD	kg Fe eq	1864.44	2.73	9.73	14.84	78.03	20.20	1.66	22.11
NLT	m^2	0.48	7.64	0.07	9.84	0.51	10.19	0.02	23.25
ODP	kg CFC-11 eq	0.00	8.54	0.00	5.82	0.00	10.06	0.00	16.85
PMFP	kg PM10 eq	8.06	7.22	1.15	8.62	4.62	6.04	0.23	19.53
POFP	kg NMVOC	12.49	11.64	1.77	9.29	14.36	4.58	0.57	25.91
TAP	kg SO2 eq	11.56	11.58	3.04	6.45	8.96	6.03	0.54	16.19
TETP	kg 1,4-DB eq	0.84	2.52	0.04	22.55	0.11	20.36	0.00	15.00
ULO	m^2*a	44.99	6.54	14.41	29.41	15.48	26.67	0.37	7.81
WD	m^3	17948.35	12.29	2988.85	4.70	1026.25	20.95	324.08	4.89

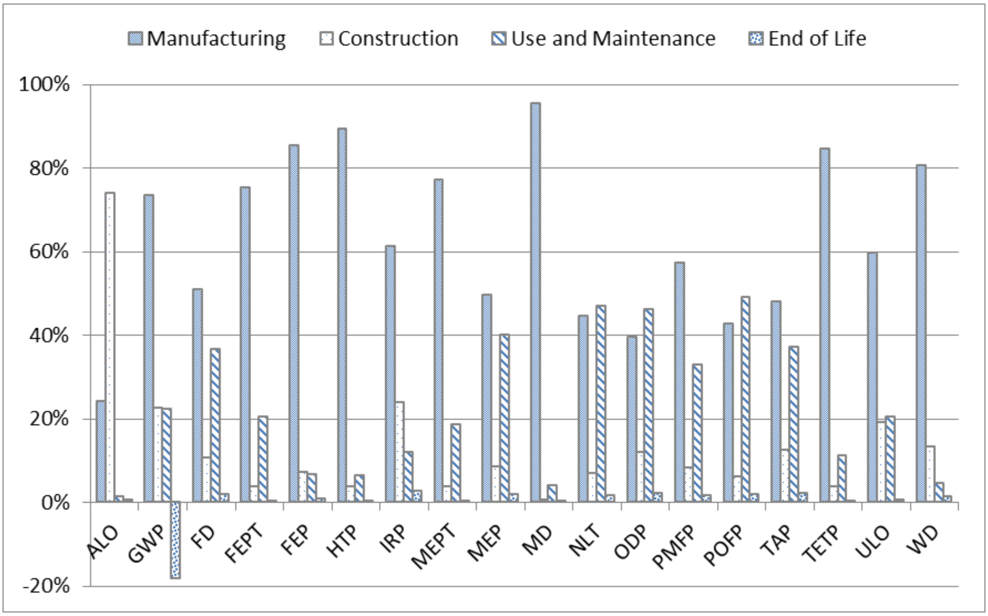

Figure 4.3.9. Impact categories for Solution 2

In both solutions, the contribution of the construction stage is very similar due to the fact that the bridge dimensions and construction methods are the same. As observed above, although the bridges have the same conditions, the decisions made in the planning and design phase have a major influence on the impact contribution of the other stages. Figures 4.3.10 and 4.3.11 show the contribution of the most important processes of the manufacturing and use and maintenance stages to GWP. In the manufacturing stage, cement production is the process with the highest contribution, followed by passive reinforcement and active reinforcement. The higher contribution of the passive reinforcement than active reinforcement is due to its greater amount in both solutions. The cement production is higher in Solution 2 than Solution 1 due to the need for greater strength of the concrete. This process is the most important in the manufacturing stage and is the reason why the environmental GWP impact in Solution 2 is higher than Solution 1. In the use and maintenance stage, there are no significant differences among the contributions of the processes for the two solutions. In this stage, it is important to highlight that the contribution of the emission of CO_2 from traffic detour depends on the detour distance and the average daily traffic. For this reason, if the bridge must be closed during its service life, an alternative route must be studied in the planning and design phase. The minor difference between both solutions in the higher fixation of CO_2 in Solution 2 is due to the greater amount of cement. Although the contributions of the processes in the use and maintenance stage are very similar in both solutions, as shown in Tables 4.3.2 and 4.3.3, the total impact of Solution 1 in the use and maintenance stage is two times the total impact of Solution 2. This is why Solution 1 needs two maintenance periods against the single one needed for Solution 2. Finally, Figure 4.3.12 shows a comparison of the global impact of each impact category for both solutions, taking into account the whole life-cycle of the bridge, in which it is possible to see the greater global impact of Solution 1 than Solution 2.

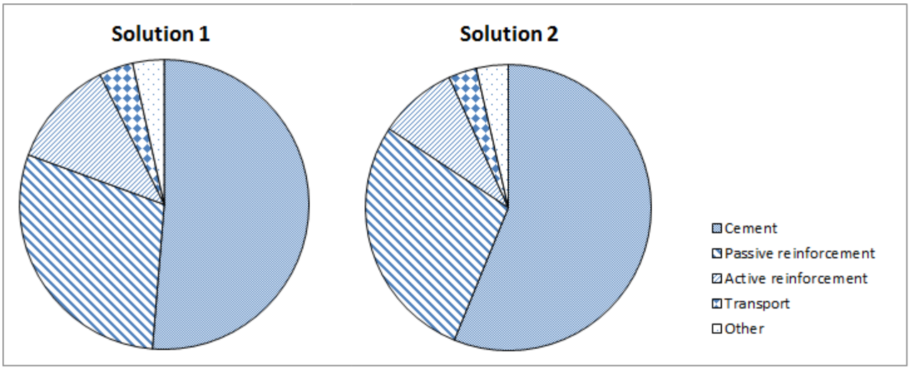

Figure 4.3.10. Contribution in % of manufacturing processes in GWP

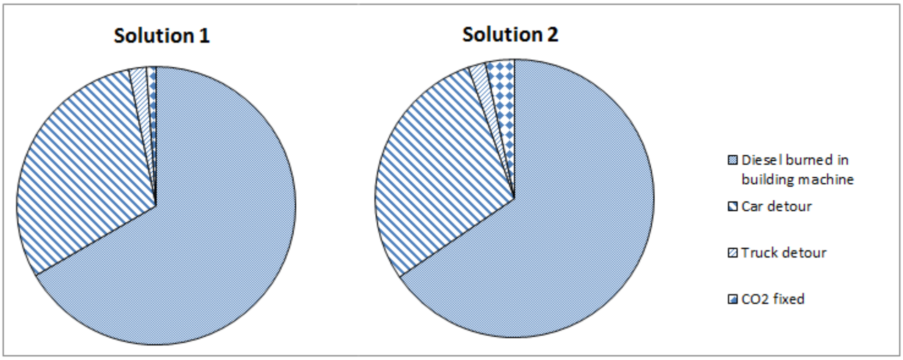

Figure 4.3.11. Contribution in % of use and maintenance processes in GWP

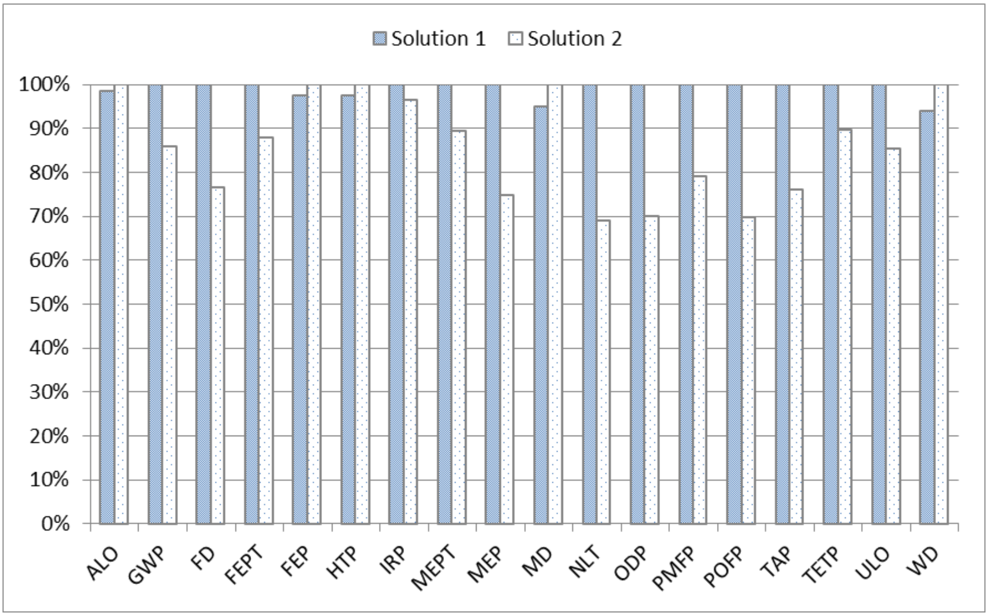

Figure 4.3.12. Comparison between Solution 1 and Solution 2

4.3.3.3.2. Endpoint approach

In the midpoint approach, the results provide a complete environmental profile with a lot of information that can help to identify specific problems or carry out a more particular assessment, but the global impact is difficult to interpret. This can be solved by using the endpoint approach. In the endpoint approach only three damage categories encompass the environmental impact: Human health, Resources and Ecosystem. In addition, these damage categories can be normalized, making it easier to compare the stages and solutions. Figure 4.3.13 represents the impacts for each damage category using the Europe ReCiPe H [person/year] normalization. As we stated for the midpoint approach, the manufacturing and use and maintenance stages make the highest contribution to the environmental impact. In the three damage categories there is the same pattern, where in the manufacturing stage the environmental impact of Solution 2 is higher than that of Solution 1, but in the use and maintenance stage, the opposite is the case. In the construction stage there are no significant differences among solutions. And in the end of life stage, Solution 2 has a greater positive contribution due to the greater amount of cement that will be carbonated.

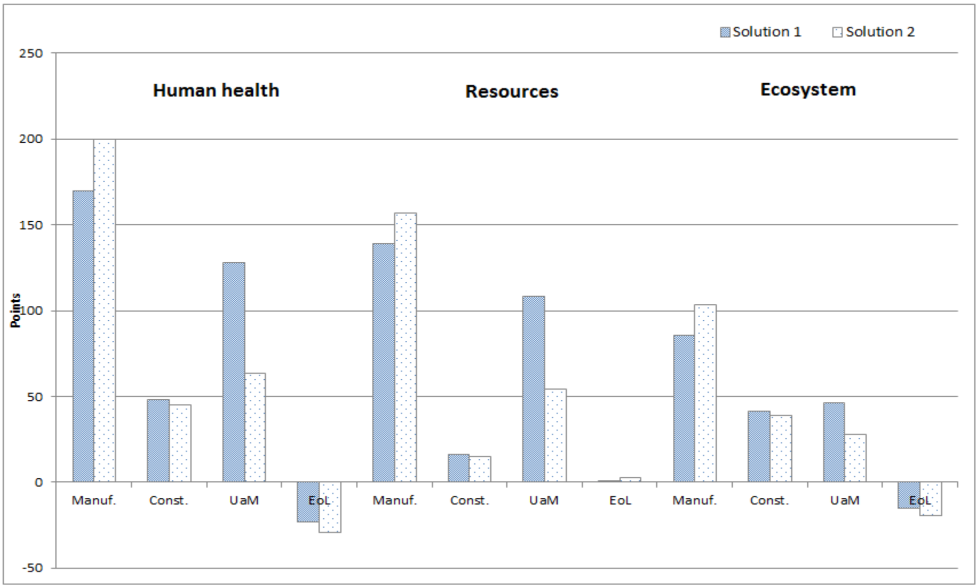

Figure 4.3.13. Comparison between damage categories

Having normalized the three damage categories in the point units, assuming that they have the same importance, the result of each damage category can be added. On the one hand, Solution 1 has a 394.79 point contribution in the manufacturing stage, 105.92 points in the construction stage, 283.32 points in the use and maintenance stage, and -36.71 points in the end of life stage, making a total of 747.32. On the other hand, Solution 2 has a 460.71 point contribution in the manufacturing stage, 99.52 points in the construction stage, 145.2 points in the use and maintenance stage, and -45.83 points in the end of life stage, making a total of 659.6. These results show the importance of decisions made in the planning and design phase, because, despite the lower environmental impact of Solution 1 in its early life, the lower quality of the materials used means that in the use and maintenance stage the environmental impact will be almost twice that of Solution 2. In this way, taking into account the whole life-cycle of the bridge, the global environmental impact is higher for Solution 1. This can be observed in Figure 4.3.14, in which almost 70% of the global environmental impact of Solution 2 is caused in the manufacturing phase, by contrast with Solution 1, where the contribution of the manufacturing stage and the use and maintenance stage is 52.8% and 37.9% respectively.

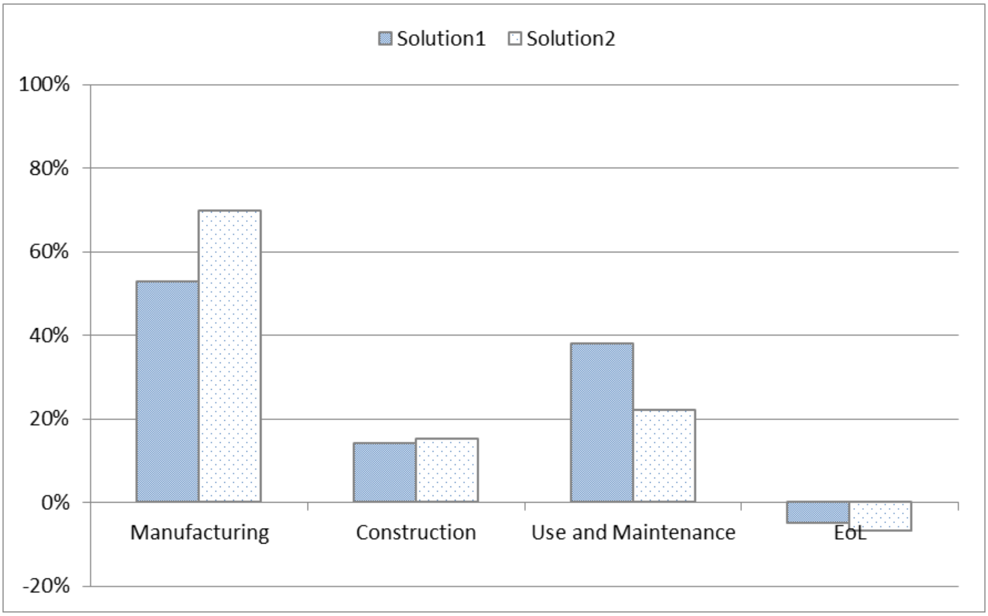

Figure 4.3.14. % of contribution of each stage

4.3.4. Conclusions

Climate change is now an established fact. For this reason, it is necessary take into account the environmental impacts generated by human activity. The construction sector is one of those with the greatest influence on climate change, and it is thus important to carry out an environmental assessment of this sector. For this purpose, a complete LCA is necessary to take into account all the stages of the life-cycle of structures and a complete environmental profile. A complete methodology is applied to assess the environmental impact of reinforced and pre-stressed concrete structures with specific features using the Ecoinvent database and uncertainties. The advantages of this methodology are discussed and a case study is then carried out.

A comparison between two optimal post-tensioned concrete box-girder road bridges in the eastern coastal area of Spain is carried out. The first solution uses concrete with 35 MPa and requires two maintenance periods, and the second solution uses concrete with 50 MPa and needs only one period of maintenance. The features considered in the life-cycle of the bridge are determined according to the site of the bridge. The distance between different locations, the machinery used, and the kind of transportation are controlled. The features of the concrete or steel are obtained, modifying the amounts of the basic products. In addition, the environmental impact caused by the traffic diversion required during the maintenance periods is considered. Finally, the CO_2 fixed by carbonation is taken into account.

With these conditions, the LCA of both solutions is carried out using ReCiPe. The midpoint approach shows that, in both solutions, practically all the impact categories make their greatest contribution in the manufacturing or use and maintenance stages. Solution 1 has a lower environmental impact in the manufacturing stage, but in the use and maintenance stage the environmental impact is almost two times that of Solution 2. Due to the importance of these two stages, the contribution of the most important process for each stage is obtained. On the one hand, in the manufacturing stage the most important contribution is the cement production, followed by steel. On the other hand, in the use and maintenance stage, the contribution of the machinery needed to repair the deteriorated concrete is the most significant. This ratio is very dependent on the features of the traffic detour, because in other conditions of ADT or detour distance the percentage can differ, even causing the traffic detour to make the higher contribution. In addition, the influence of the concrete carbonation generates a positive environmental impact in the last two stages, being higher in Solution 2 due to the greater amount of cement. The endpoint approach can summarize the midpoint approach results to allow a better interpretation. From this point of view, it is easier to see the general contribution of each stage and to make comparisons between solutions. Results show the importance of considering the whole life-cycle. Despite a higher environmental impact in manufacturing stage, a better design reduces the global environmental impact due to the lower environmental impact of maintenance activities. In addition, the global contribution is obtained and found to be 13.3% higher for Solution 1.

Acknowledgments

The authors acknowledge the financial support of the Spanish Ministry of Economy and Competitiveness, along with FEDER funding (BRIDLIFE Project: BIA2014-56574-R).

References

[1] United Nations., World Commission on Environment and Development Our common future. New York, USA, 1987.

[2] V. Penadés-Plà, T. García-Segura, J. Martí, and V. Yepes, “A review of multi-criteria decision-making methods applied to the sustainable bridge design,” Sustainability, vol. 8, no. 12, p. 1295, 2016.

[3] D. Jato-Espino, E. Castillo-Lopez, J. Rodriguez-Hernandez, and J. C. Canteras-Jordana, “A review of application of multi-criteria decision making methods in construction,” Automation in Construction, vol. 45, pp. 151–162, 2014.

[4] T. Waas, J. Hugé, T. Block, T. Wright, F. Benitez-Capistros, and A. Verbruggen, "Sustainability Assessment and Indicators: Tools in a Decision-Making Strategy for Sustainable Development," Sustainability, vol. 6, no. 9, pp. 5512–5534, Aug. 2014.

[5] Intergovernmental Panel On Climate Change, Climate change: Fifth assessment report. 2014.

[6] T. Ramesh, R. Prakash, and K. K. Shukla, "Life cycle energy analysis of buildings: An overview," Energy and Buildings, vol. 42, no. 10, pp. 1592–1600, 2010.

[7] A. Petek Gursel, E. Masanet, A. Horvath, and A. Stadel, "Life-cycle inventory analysis of concrete production: A critical review," Cement and Concrete Composites, vol. 51, pp. 38–48, 2014.

[8] M. Taylor, C. Tam, and D. Gielen, "Energy efficiency and CO2 emissions from the global cement industry," in International Energy Agency, 2006, p. 13.

[9] M. W. Tait and W. M. Cheung, "A comparative cradle-to-gate life cycle assessment of three concrete mix designs," The International Journal of Life Cycle Assessment, vol. 21, no. 6, pp. 847–860, Jun. 2016.

[10] D. K. Panesar, K. E. Seto, and C. J. Churchill, "Impact of the selection of functional unit on the life cycle assessment of green concrete," The International Journal of Life Cycle Assessment, vol. 22, no. 12, pp. 1969–1986, Dec. 2017.

[11] A. P. Gursel and C. Ostertag, "Comparative life-cycle impact assessment of concrete manufacturing in Singapore," The International Journal of Life Cycle Assessment, vol. 22, no. 2, pp. 237–255, 2017.

[12] A. Laurent, S. I. Olsen, and M. Z. Hauschild, "Limitations of carbon footprint as indicator of environmental sustainability," Environmental Science & Technology, vol. 46, no. 7, pp. 4100–4108, 2012.

[13] International Organization for Standardization (ISO), Environmental managment - life cycle assessment - principles and framework. Geneva, Switzerland, 2006.

[14] A. Horvath and C. Hendrickson, "Steel versus steel-reinforced concrete bridges: Environmental assessment," Journal of Infrastructure Systems, vol. 4, no. 3, pp. 111–117, 1998.

[15] J. Widman, "Environmental impact assessment of steel bridges," Journal of Construction Steel Research, vol. 46, no. 412, pp. 291–293, 1998.

[16] H. Gervasio and L. Simoes da Silva, "Comparative life-cycle analysis of steel-concrete composite bridges," Structure and Infrastructure Engineering, vol. 4, no. 4, pp. 251–269, 2008.

[17] T. Stengel and P. Schiessl, "Life cycle assessment of UHPC bridge constructions : Sherbrooke Footbridge , Kassel Gärtnerplatz Footbridge and Wapello Road Bridge," Architecture Civil Engineering Environment, vol. 1, pp. 109–118, 2009.

[18] Y. Itoh and T. Kitagawa, "Using CO2 emission quantities in bridge lifecycle analysis," Engineering Structures, vol. 25, no. 5, pp. 565–577, 2003.

[19] L. Bouhaya, R. Le Roy, and A. Feraille-Fresnet, "Simplified environmental study on innovative bridge structure," Environmental Science & Technology, vol. 43, no. February, pp. 2066–2071, 2009.

[20] K. N. P. Steele, G. Cole, and G. Parke, "Application of life cycle assessment technique in the investigation of brick arch highway bridges," in 6th International Masonry Conference, 2002, pp. 1–8.

[21] G. Du and R. Karoumi, "Life cycle assessment of a railway bridge: Comparison of two superstructure designs," Structure and Infrastructure Engineering, vol. 9, no. Iso14040 2006, pp. 1149–1160, 2012.

[22] G. Du, M. Safi, L. Pettersson, and R. Karoumi, "Life cycle assessment as a decision support tool for bridge procurement: Environmental impact comparison among five bridge designs," The International Journal of Life Cycle Assessment, vol. 19, no. 12, pp. 1948–1964, 2014.

[23] J. Hammervold, M. Reenaas, and H. Brattebø, "Environmental life cycle assessment of bridges," Journal of Bridge Engineering, vol. 18, no. 2, pp. 153–161, 2013.

[24] B. Pang, P. Yang, Y. Wang, A. Kendall, H. Xie, and Y. Zhang, "Life cycle environmental impact assessment of a bridge with different strengthening schemes," The International Journal of Life Cycle Assessment, vol. 20, no. 9, pp. 1300–1311, 2015.

[25] K. Steele, G. Cole, G. Parke, B. Clarke, J. Harding, and J. Harding, "Highway bridges and environment-sustainable perspectives," Proceedings of the Institution of Civil Engineers, vol. 156, no. 4, pp. 176–182, 2003.

[26] Ecoinvent Center, "Ecoinvent v3.3." Dübendorf, Switzerland, 2016.

[27] R. Frischknecht, N. Jungbluth, H.-J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, and M. Spielmann, "The Ecoinvent database: Overview and methodological framework," vol. 10, no. 1, pp. 3–9, 2005.

[28] A. Ciroth, S. Muller, B. Weidema, and P. Lesage, "Empirically based uncertainty factors for the pedigree matrix in Ecoinvent," The International Journal of Life Cycle Assessment, vol. 21, pp. 1339–1348, 2016.

[29] D. Kellenberger, H. J. Althaus, N. Jungbluth, and T. Künniger, Life cycle inventories of building products. 2007.

[30] M. L. Marceau, M. A. Nisbet, and M. G. Vangeem, Life cycle inventory of portland cement concrete. Skokie, Illinois, USA, 2007.

[31] T. García-Segura, V. Yepes, and J. Alcalá, "Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability," The International Journal of Life Cycle Assessment, vol. 19, no. 1, pp. 3–12, 2014.

[32] P. Zastrow, F. Molina-Moreno, T. García-Segura, J. V. Martí, and V. Yepes, "Life cycle assessment of cost-optimized buttress earth-retaining walls: A parametric study," Journal of Cleaner Production, vol. 140, pp. 1037–1048, 2017.

[33] A. Dodoo, L. Gustavsson, and R. Sathre, "Carbon implications of end-of-life management of building materials," Resources, Conservation and Recycling, vol. 53, no. 5, pp. 276–286, 2009.

[34] F. Collins, "Inclusion of carbonation during the life cycle of built and recycled concrete: Influence on their carbon footprint," The International Journal of Life Cycle Assessment, vol. 15, no. 6, pp. 549–556, 2010.

[35] T. García-Segura and V. Yepes, "Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety," Engineering Structures, vol. 125, pp. 325–336, 2016.

[36] T. García-Segura, V. Yepes, J. Alcalá, and E. Pérez-López, "Hybrid harmony search for sustainable design of post-tensioned concrete box-girder pedestrian bridges," Engineering Structures, vol. 92, pp. 112–122, 2015.

[37] B. Lagerblad, Carbon dioxide uptake during concrete life cycle - State of the art, no. 2. Stockholm, Sweeden, 2005.

[38] A. Hettinger, J. Birat, O. Hechler, and M. Braun, "Sustainable bridges - LCA for a composite and a concrete bridge," in Economical Bridge Solutions Based on Innovative Composite Dowels and Integrated Abutments, Springer., E. Petzek and R. Bancila, Eds. Wiesbaden, Germany, 2015, pp. 45–54.

[39] World Steel Association, "Steel and energy fact sheet." 2008.

[40] European Commission, "European reference life-cycle database," 2012.

[41] S. Yi, K. H. Kurisu, K. Hanaki, and K. Hanaki, "Life cycle impact assessment and interpretation of municipal solid waste management scenarios

based on the midpoint and endpoint approaches," The International Journal of Life Cycle Assessment, vol. 16, no. 7, pp. 652–668, 2011.

[42] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, ReCiPe 2008. A life cycle impact assessment which comprises harmonised category indicators at midpoint and at the endpoint level. Netherlands, 2009.

[43] Y. H. Dong and S. T. Ng, "Comparing the midpoint and endpoint approaches based on ReCiPe - A study of commercial buildings in Hong Kong," The International Journal of Life Cycle Assessment, vol. 19, no. 7, pp. 1409–1423, 2014.

[44] T. García-Segura, V. Yepes, and D. M. Frangopol, "Multi-objective design of post-tensioned concrete road bridges using artificial neural networks," Structural and Multidisciplinary Optimization, vol. 56, no. 1, pp. 139–150, 2017.

[45] T. García-Segura, V. Yepes, D. M. Frangopol, and D. Y. Yang, "Lifetime reliability-based optimization of post-tensioned box-girder bridges," Engineering Structures, vol. 145, pp. 381–391, 2017.

[46] European Committee for Standardization, EN 206-1 Concrete - Part1: Specification, performance, production and conformity. Brussels, Belgium, 2000.

[47] Catalonia Institute of Construction Technology, "BEDEC PR/PCT ITEC material database." Barcelona, Spain, 2016.

4.4. Environmental and social life cycle assessment of cost-optimized post-tensioned concrete road bridges[3]

[3] V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, "Environmental and social life cycle assessment of cost-optimized post-tensioned concrete road bridges," *Environmental impact assessment review (Submitted)*

Vicent Penadés-Plà[a*], David Martínez-Muñoz[b], Tatiana García-Segura[c], Víctor Yepes[d]
[a] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. Corresponding author. E-mail: vipepl2@cam.upv.es
[b] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain E-mail: jvmartia@upv.es
[c] Dept. of Construction Engineering and Civil Engineering Projects, Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: tagarse@upv.es
[d] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: vyepesp@cst.upv.es

Abstract

Most of the definitions of sustainability include three basic pillars: economic, environmental, and social. The economic pillar has always been considered and there is a growing trend of evaluating the environmental pillar. However, the social pillar has rarely been considered and assessment of it has been very confusing. Furthermore, in order to achieve a complete assessment of all these pillars, it is necessary to use methodologies that make it possible to obtain a global assessment of each one of the pillars, and not to use a few criteria to assess it. This article is divided into two parts. In the first part, a review of life cycle impact assessment methods, which allow a global assessment of the environmental and social pillars, is carried out. Next, the most appropriate methodology is discussed. In the second part, a complete sustainability assessment is made using the selected life cycle assessment methods and comparison of three cost-optimized bridges: two post-tensioned concrete box-girder road bridges with different initial and maintenance characteristics, and a pre-stressed concrete precast bridge. The results show the impact of each one of these pillars for each life cycle stage and show that there is a high interrelation between the different pillars of sustainability.

Keywords: Sustainability; LCA; S-LCA; Social assessment; Ecoinvent; SOCA

4.4.1. Introduction

The concept of sustainability emerged in the 1960s as a response to environmental degradation caused by bad natural resources management [1]. However, it was in 1987 when the first definition of sustainability or sustainable development was delineated in the Our Common Future report [2]. This report stated the bases of the three pillars of sustainability: economic, environmental, and social [3], [4]. The interaction between these three pillars has been emphasized in recent times [5], [6]; the United Nations defined 17 sustainable development goals aimed at establishing a global direction toward sustainable development [7] and to achieve this transition by 2030.

Despite social assessment being an important part in the sustainability definition, its evaluation is underestimated or relatively weak with respect to the other pillars of sustainability when sustainability assessments of products, processes, or services have been carried out [8], [9]. Vallance et al. [3] stated that this is due to the fact that the definition of social sustainability is quite chaotic, and Murphy [8] indicated that there are no clear criteria for assessing sustainability. However, social equity, education, basic health, and participatory democracy are important for sustainability development [10]. At present, there is a trend toward giving the social pillar the same importance as the economic and environmental pillars [11]–[13]. This is demonstrated by the fact that 6 of the 17 sustainable development goals proposed by the United Nations focus on social problems.

This abandonment of the social pillar is particularly important in the construction sector [14], due to the large number of stakeholders involved in construction projects. Valdes-Vasquez and Klotz [15] indicated that projects in the construction sector involve clients, employees, the community, and industry, and have the intention of satisfying current and future needs. Later, Almahmoud and Doloi [16] stated that the social aspect in the construction sector can be represented through the satisfaction of the different stakeholders involved in the projects, including industry, users, and the community. They also indicated that the importance of the impact of the project for future generations and the impact on present generations through health, safety, and conditions of workers must be taken into account.

Penadés-Plà et al. [4] reviewed the criteria considered to assess the different pillars of sustainability in bridges, as well as the multi-attribute decision-making methods used to obtain a global sustainability assessment. This review shows that the economic pillar is the most developed pillar. Although some early works only studied the initial cost of the bridge, a life cycle cost assessment (LCCA) is, nowadays, widely used. Conversely, a life cycle assessment (LCA) is less common. On the one hand, it is clear that only a few studies apply environmental life cycle assessment (E-LCA) to bridges. The first studies were carried out by Horvath and Hendrickson [17] and Widman [18]. After that, some other authors assessed the environmental impact of bridges, but most of them did not make this assessment for all stages of the life cycle and focused on just one [19], [20] or took into account a small number of environmental indicators—normally CO_2 and energy [21], [22]. It was not until the study of Steele et al. [23], that a complete E-LCA was carried out. Du and Karoumi [24], Du et al. [25], and Hammervold et al. [26] compared different bridge designs, and Pang et al. [27] focused on comparing different maintenance activities. On the other hand, the social pillar of sustainability is the most unclear. There is high disagreement with regard to defining the criteria that best represent social life cycle assessment (S-LCA). Criteria such as detour time, dust, and noise have been used in different works [5], [28], [29]. All of these tend to divide the life cycle of the bridge into four stages: manufacturing, construction, use and maintenance, and end of life.

In this paper, a bibliographic review of the LCA methods, both environmental and social, will first be conducted in Section 2. After that, Section 3 explains the methodology used, after discussing the best methods to assess the environmental and social pillars of bridges. In Section 4, these methods are used to carry out a sustainability assessment of three road bridges: two post-tensioned concrete box-girder road bridges with different initial and maintenance characteristics, and a pre-stressed concrete precast bridge. Section 5 shows the results of all the pillars of sustainability, focusing on social assessment. Finally, conclusions are presented in Section 6.

4.4.2. Life Cycle Assessment Methods

In order to carry out a complete sustainability assessment it is necessary to take into account the whole life cycle of a product, process or service. This is even more important in the construction sector, because structures are built to provide a service over a long time. For this purpose, life cycle cost assessment (for the economic pillar) and life cycle assessment (for the environmental and social pillars) are used. At this point, it is necessary to point out that despite the LCA techniques—which are used to assess both the environmental and social pillars—having the same central core, there are some differences between them. For this reason, in this study, the term LCA will be used when referring to the global technique and the terms E-LCA (environmental pillar) and S-LCA (social pillar) are going to be used for specific assessments.

Focusing on environmental and social assessment, the ISO 14040 [30] defines LCA as a technique for assessing the environmental and/or social aspects and impacts caused by a product, process, or service through a system of input flows (data) that cause output flows (impacts). ISO 14040 [30] divides the LCA into four phases:

- Goal and scope definition

- Inventory analysis
- Impact assessment
- Interpretation of results

The impact assessment step of the LCA is crucial. In this step, the information obtained from the life cycle inventory is transformed into a set of understandable indicators. Because of the complexity of this transformation, some methodologies have been developed to simplify this step, called life cycle impact assessment (LCIA) methods. In this way, the assessment and comparison between different cases becomes easier.

4.4.2.1. Environmental Life Cycle Impact Assessment

In the E-LCA, there are two approaches to transform the life cycle inventory into understandable indicators: the midpoint approach and the endpoint approach. The midpoint approach refers to environmental impact, while the endpoint approach refers to environmental damage. The midpoint approach provides more comprehensive information, and the endpoint approach provides more concise information (Figure 4.4.1).

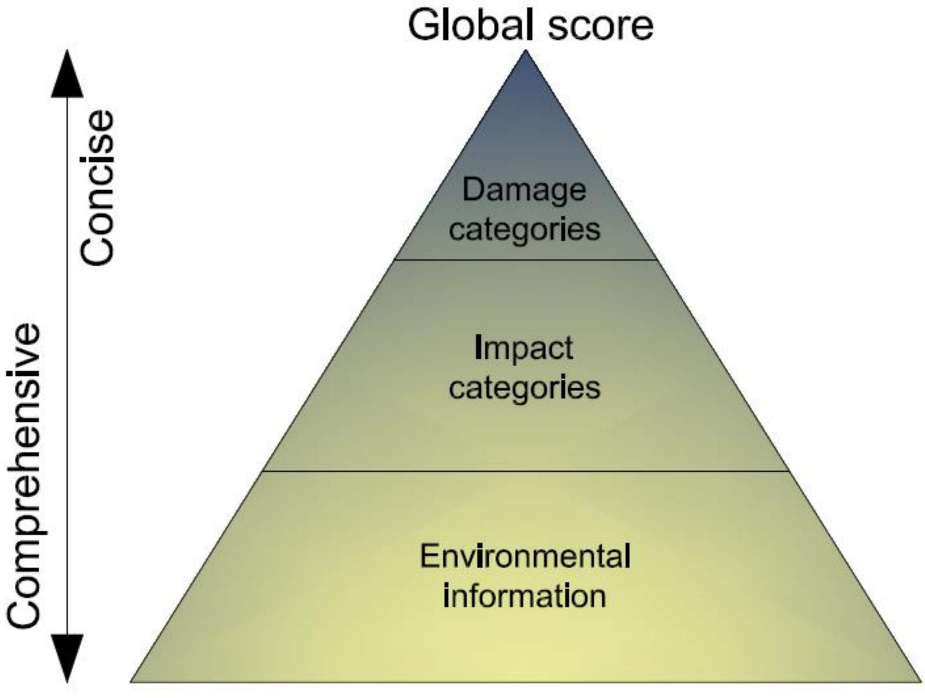

Figure 4.4.1. E-LCA approaches

Another way to understand the differences between these two approaches is to consider that the midpoint approach is the direct cause, while the endpoint approach is the long-term consequence. For example, any process, product, or service that affects climate change has gas emissions to the atmosphere that cause different environmental problems such as global warming or ozone depletion (midpoint approach); but in the long-term approach, these gas emissions will cause damage to the ecosystem, human health, or resources. In this example, ozone depletion can lead to increased skin cancer problems (endpoint approach).

Table 4.4.1 shows the most common methods for each category and the indicators (impact categories for the midpoint approach and damage categories for the endpoint approach) considered for each E-LCIA method. Each approach uses different methods to convert environmental information into untestable indicators. Within midpoint approach methods, the classical methods are the CML [31], EDIP 2003 [32], and TRACI [33]. These methods provide a set of impact categories that indicate the direct cause by a product, process, or service. The total number of these indicators is usually quite high, providing accurate information, but which is sometimes difficult to interpret. Endpoint approach methods are damage-oriented methods, such as the Eco-Indicator 99 [34], EPS [35], and Eco Scarcity [36]. These methods provide a set of damage categories that indicate the long-term consequences for a product, process, or service. The total number of these indicators is usually quite small, so the information is not as accurate as in the case of midpoint methods, but much easier to interpret. In addition, there is a set of new methods, which combines the methods of midpoint and endpoint approaches, such as the ReCiPe 2008 [37], LIME [38], and IMPACT 2008 [39].

Table 4.4.1. E-LCIA indicators

E-LCIA group	E-LCIA method	Impact categories	Damage categories
Midpoint approach	CML 2000	Obligatory impact categories: Depletion of abiotic resources, land competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, acidification and eutrophication. Optional impact categories: Loss of life support function, loss of biodiversity, freshwater sediment ecotoxicity, marine sediment ecotoxicity, impacts of ionizing radiation, malodorous air, noise, waste heat, casualties, lethal, non-lethal, depletion of biotic resources, desiccation and malodorous water	
	EDIP 2003	Global warming, ozone depletion, acidification, terrestrial eutrophication, aquatic eutrophication, photochemical ozone formation, human toxicity, ecotoxicity, and noise	
	TRACI	Ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health non cancer, human health criteria pollutants, eco-toxicity, and fossil fuel depletion	
Endpoint approach	EI99		Climate change, ozone layer depletion, acidification, eutrophication, carcinogenicity, respiratory effects, ionizing radiation, ecotoxicity, land use, mineral resources, fossil resources
	EPS		Life expectancy, severe morbidity and suffering, morbidity, severe nuisance, nuisance crop production capacity, wood production capacity, fish and meat production capacity, base cation capacity, production capacity for water, share of species extinction, depletion of element reserves, depletion of fossil reserves (gas), depletion of fossil reserves (coal), depletion of fossil reserves (oil), and depletion of mineral reserves
	Eco scarcity		Ozone depletion, photochemical oxidant formation, respiratory effects, air emissions, surface water emissions, radioactive emissions, cancer caused by radionuclides emitted to the sea, emissions to groundwater, emissions to soil, landfill municipal (reactive) wastes, hazardous wastes (stored underground), radioactive wastes , water consumption , gravel consumption , primary energy resources , endocrine disruptors, and biodiversity losses
Midpoint/Endpoint approach	ReCiPe	Climate change, ozone depletion, terrestrial acidification , freshwater eutrophication , marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation , terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation , urban land occupation, natural land transformation, water depletion, mineral resource depletion, fossil fuel depletion	Damage to human health, damage to ecosystem diversity, and damage to resource availability
	LIME	Ozone layer depletion, global warming, acidification, photochemical oxidant formation, regional air pollution, human-toxic chemicals, eco- toxic chemicals, eutrophication, land use, waste landfill, resources and consumption	Cataracts, skin cancer, other cancer, respiratory diseases, thermal stress, infectious diseases, hypoalimentation, disaster causality, agricultural production, forestry production, fishery production, loss of land-use, energy consumption, user cost, terrestrial ecosystem, aquatic ecosystem
	IMPACT 2000+	Human toxicity, respiratory effects, ionizing radiation, ozone depletion, photochemical oxidant formation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic eutrophication, terrestrial eutrophication and acidification, land occupation, global warming, non-renewable energy and mineral extraction	Damage to human health, damage to ecosystem quality, damage to climate change and damage to resources

4.4.2.2. Social Life Cycle Impact Assessment

The social pillar of sustainability is the least studied and probably the most diffuse and weakest pillar of sustainability. However, for a complete sustainability assessment, it is necessary to obtain a complete set of social indicators that can be used to carry out an accurate comparison and assessment of alternatives. Currently, there is only one S-LCA method that can transform the life cycle inventory into understandable indicators: the Social Impact Weighting Method. However, in contrast to E-LCA, when the S-LCA is studied, it is more common use the name of the database, and nowadays there are only two important social databases: PSILCA (Product Social Impact Life Cycle Assessment) [40] and SHDB (Social Hotspots Database) [41]. Both S-LCIA databases are inspired by UNEP/SETAC guidance [42] and use the activity variable “worker hour” in order to quantify the social impacts. Table 4.4.2 shows the topics of both methods grouped by stakeholders for the PSILCA database and impact categories for the SHDB database.

The PSILCA database was developed by GreenDelta and presented in 2013. This database provides information to carry out the assessment of the social pillar of products, processes, or services for their whole life cycle. The PSILCA covers 189 individual countries represented by around 15000 units classified by entities (i.e., industries and commodities). Currently, in the second version, there are 65 qualitative and quantitative indicators addressing 17 categories and five affected stakeholders groups, and it is expected to reach 88 qualitative and quantitative indicators, addressing 25 topics and 5 affected stakeholders [43].

The SHDB database is a project which was developed by New Earth in 2009 and published in 2013. The project seeks to provide detailed information on human rights and working conditions along supply chains, in order to assess risks and provide methods to calculate social footprints. This database covers 113 individual countries represented by around 6500 units classified by entities (i.e., industries and commodities). Currently, there are over 157 qualitative and quantitative indicators addressing 26 themes and 5 big groups [44].

Table 4.4.2. S-LCIA categories

S-LCIA database	CATEGORIES
PSILCA	WORKERS: Child labor, forced labor, fair salary, working time, discrimination, health and safety, social benefits and legal issues, workers' rights. VALUE CHAIN ACTORS: Fair competition, corruption, promoting social responsibility, supplier relationships. SOCIETY: Contribution to economic development, health and safety, prevention and mitigation of conflicts. LOCAL COMMUNITY: access to material resources, respect of indigenous rights, safe and healthy living conditions, local employment, migration. CONSUMERS: Health and safety, transparency, end of life responsibility.
SHDB	LABOR RIGHTS AND DECENT WORK: Forced labor, excessive working time, poverty, freedom of association, wage assessment, migrant labor, unemployment, child labor, labor laws, discrimination, social benefits HUMAN RIGHTS: Indigenous rights, human health issues, gender equity, high conflicts. HEALTH AND SAFETY: Injuries and fatalities, toxins and hazards. GOVERNANCE: Legal system, corruption. COMMUNITY: Hospital beds, drinking water, children out of school, sanitation, smallholder vs commercial farms.

4.4.3. Methodology

Section 2 reviews the most important methodologies used to carry out a complete E-LCA and S-LCA. Although E-LCA is a methodology that is increasingly being implemented, the bibliographic review shows that only few works have applied E-LCIA methods to evaluate the environmental pillar of sustainability. These works only use three different E-LCIA methods [23], [26], [45]: CML 2000 (midpoint approach), EI99 (endpoint approach), and ReCiPe (midpoint/endpoint approach). Because it is appropriate to have both midpoint/endpoint approaches in order to have both advantages, this work uses the ReCiPe method to carry out the E-LCA, which combines the CML and Eco-Indicator methods [37].

The midpoint approach of the ReCiPe method groups the results into 18 impact categories, measuring each according to its respective units: agricultural land occupation (ALO), climate change (GWP), fossil depletion (FD), freshwater ecotoxicity (FEPT), freshwater eutrophication (FEP), human toxicity (HTP), ionizing radiation (IRP), marine ecotoxicity (MEPT), marine eutrophication (MEP), metal depletion (MD), natural land transformation (NLT), ozone depletion (OD), particulate matter formation (PMF), photochemical oxidant formation (POFP), terrestrial acidification (TAP), terrestrial ecotoxicity (TEPT), urban land occupation (ULO), and water depletion (WD). These environmental impact categories have a high level of detail, providing accurate results, although they are more difficult to interpret. The endpoint approach of the ReCiPe method integrates several impact categories into three damage categories: human health (HH), ecosystems (E) and resource availability (R). These damage categories have the advantage of being easier to interpret and understand. However, the uncertainty of these results increases due to the high level of integration of them. In order to integrate all environmental impact categories into an overall score, the damage categories have been normalized using the standardization of Europe ReCiPe H/H [person/year] [37], [46]. In this way, a global score of the total environmental impact caused by the bridge throughout all of its life cycle can be obtained. This overall score is measured in points. In addition, in order to include the long-term perspective of environmental impacts, the hierarchical perspective was used, due to the inclusion of recycling and the subsequent use of concrete and steel for other purposes after the end of the useful life of the structure.

Regarding S-LCA, although some authors have stated that this methodology is important [8], it is rarely studied, and even less so in the construction sector. The bibliographic review shows that S-LCIA methods have not been used to assess the social pillar of sustainability in bridges. This work considers the PSILCA database because it is has the most updated available data source, transparent documentation of original data sources and risk assessment, and provides data quality assessment. In addition, this study uses SOCA [47], a database add-on for LCA developed by Green Delta, to integrate the social information from the PSILCA database with the processes of the Ecoinvent database, which was used to evaluate the environmental pillar. In this way, the social assessment can be carried out using the same processes as the environmental assessment. The SOCA database uses the first version of PSILCA, and provides 53 qualitative and quantitative indicators addressing 17 topics and 4 affected stakeholders groups [40].

Figure 4.4.2 shows the methodology used in this work. In order to reduce the number of outputs, the endpoint approach of ReCiPe is used to assess the environmental pillar of sustainability, and the indicators provided by the SOCA database are grouped into the four stakeholders represented.

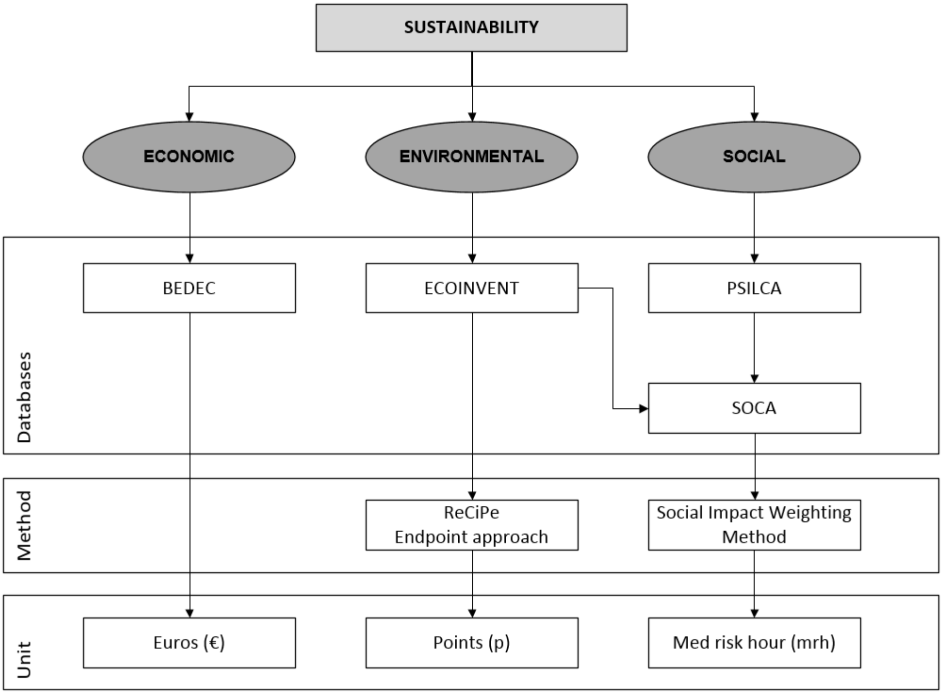

Figure 4.4.2. Methodology

4.4.4. Case study

Three cost-optimized bridges are analyzed: two post-tensioned concrete box-girder road bridges with different initial and maintenance characteristics, and a pre-stressed concrete precast bridge. These bridges have a width of 12 meters and are located in an eastern coastal region of Spain, and the environmental ambience corresponds to XC-4 according to EN 206-1 [48]. Thus, corrosion is mainly caused by carbonation and these bridges are subject to the same environmental and traffic conditions. In addition, they have the same width and similar lengths. Therefore, the bridges can be considered equivalent. The environmental pillar of the two post-tensioned concrete box-girder road bridges have already been assessed by Penadés-Plà et al. [49], and the pre-stressed concrete precast bridge was evaluated by Penadés-Plà et al. [50]. In this work, the economic and social pillars are also considered in order to obtain a complete sustainability assessment.

The post-tensioned concrete box-girder road bridges have three continuous spans of 35.2 m, 44 m and 35.2 m. The first bridge (or alternative A1) was built with concrete of 50 MPa and requires one maintenance period, while the second bridge (or alternative A2) was built with concrete of 35 MPa and requires two maintenance periods. These bridges are optimized to meet the codes during a service life of 150 years. The distances considered for these bridges are: 20 km to transport the aggregate to the mixing factory, 10 km to transport the cement to the mixing factory, 20 km to transport the concrete to the site, and 100 km to transport the steel to the site. The pre-stressed concrete precast bridge has three spans of 40 meters. This bridge (or alternative A3) was built with concrete of 35 MPa in the beams and 40 MPa in the slab, and requires one maintenance period. This bridge is optimized to meet the codes during a service life of 120 years. The distances considered are: 50 km to transport the aggregate to the precast concrete plant, 10 km to transport the cement to the mixing factory, 50 km to transport the precast concrete plant to the site, and 100 km to transport the steel to the site. Figure 4.4.3 shows the three alternatives considered. Due to the total length and service life being a bit different among the three alternatives, the functional unit considered is meter length*year [27], [51].

Figure 4.4.3. Alternatives

Table 4.4.3 shows the amount of general material per 1 m^2 of bridge and the dosage needed to make 1 m^3 of concrete depending on the required strength. The waste from concrete production is as suggested by Marceau et al. [52]. Reinforced steel is obtained as a combination of the production methods according to the area of the study. In Spain, around 67% of steel is produced by the EAF method, while the remaining 33% of steel is produced by the BOF method. Assuming the same steel recycling ratio for each production method as in Ecoinvent (19% of recycled steel in BOF and 100% of recycled steel in EAF), the recycling ratio considered is around 71%. These amounts of materials have been obtained from the design of the bridges which follow the Spanish regulations for this type of structure [53], [54], as well as the Eurocodes [55], [56]. The serviceability and ultimate limit states (SLS and ULS) of vertical shear, longitudinal shear, punching shear, bending, torsion, torsion combined with bending and shear, cracking, compression and tension stress, and vibration have been checked. In addition, the geometrical and constructability requirements have been verified.

Table 4.4.3. Amount of materials

	A1	A2	A3	
			Precast concrete beam	Concrete slab
Strength (MPa)	50	35	35	40
Passive steel (kg/m^2)	74.67	66.89	12.52	23.92
Active steel (kg/m^2)	19.8	21.98	10.53	–
Concrete (m^3/m^2)	0.67	0.674	0.1117	0.1797
Cement (kg/m^3)	400	300	300	320
Gravel (kg/m^3)	726	848	848	829
Sand (kg/m^3)	1136	1088	1088	1102
Water (kg/m^3)	160	160	160	162
Superplasticizer (kg/m^3)	7	4	4	5

With regard to construction, the post-tensioned concrete box-girder road bridges and the slab of the pre-stressed concrete precast bridge are considered to be cast in place, while the beams of the pre-stressed concrete precast bridge are transported and elevated using special transport and cranes. In addition, the construction machinery considered in this section was divided into the machinery needed for the concrete and pre-stressed steel handling. For each kind of machinery, the amount of energy and CO_2 emissions was obtained from the BEDEC database [57]. On the one hand, the handling of concrete requires machinery that consumes 123.42 MJ of energy and emits 32.24 kg of CO_2 per m^3 of concrete. On the other hand, the handling of active reinforcement requires machinery that consumes 10.2 MJ of energy and emits 2.62 kg of CO_2 per kg of active steel. In addition, the formwork considered is a wood formwork that can be reused three times.

Maintenance activities and traffic detours are considered to be the same for each maintenance period. Therefore, the difference between the solutions was the number of maintenance periods required. One period of maintenance operation required the closure of the bridge for 7 days to remove the old concrete cover and replace it with repair mortar. In addition, the traffic detour was considered, taking into account the average daily traffic (8500 vehicles/day), the percentage of trucks (12%), and the detour distance (2.9 km). For concrete repair, water blasting was required to remove the old concrete cover. In addition, an adhesion coating was applied to prepare a suitable surface for the new concrete cover. Finally, repair mortar was cast to form the new cover. All of these activities could only be carried out by a truck-mounted platform [58]. As above, the energy and CO_2 emissions due to the machinery were obtained from the BEDEC database [57], amounting to 584.28 MJ and 46.58 CO_2 per m^2 repaired for each maintenance period. Finally, fixed CO_2 during the whole service life is considered [59].

End of life considers the machinery used to carry out the demolition and treatment of the waste. In this case, 71% of the steel is recycled and all the concrete is crushed and left as landfill. On the one hand, the ratio of recycled steel matches the ratio of recycled steel used in the manufacturing phase, so the steel cycle is closed. On the other hand, it is assumed that the crushed concrete will be completely carbonated.

4.4.5. Results

The results were obtained as described in the previous sections. Three pillars of sustainability were considered to carry out a complete sustainability assessment: the economic pillar was evaluated by the life cycle cost, the environmental pillar was evaluated by the ReCiPe method and the Ecoinvent database, and the social pillar was evaluated by the Social Impact Weighting Method and the SOCA database. Using these methodologies, two post-tensioned concrete box-girder road bridges with different initial and maintenance characteristics (A1 requires one maintenance period, and A2 requires two maintenance periods) and a pre-stressed concrete precast bridge (A3) were compared. Due to the large number of indicators in the environmental and social pillars, this study aimed to obtain a smaller number of indicators so that results would be understandable and complete for the three pillars. For this purpose, the environmental assessment was made according to the damage categories of the endpoint approach of the ReCiPe method, and the social assessment was made by stakeholders.

On the one hand, the damage categories obtained by the endpoint approach of the ReCiPe method which represent the environmental pillar are: the ecosystems (E), resources (R), and human health (HH). On the other hand, the four obtained by the SOCA method that represent the social pillar are: workers (W), local communities (LC), society (S), and value chain actors (VCA). Tables 4.4.4, 4.4.5, and 4.4.6 show the impact of the three pillars of sustainability for the alternatives A1, A2, and A3, respectively.

Table 4.4.4. Sustainability assessment of A1

Assessment		Unit	Manufacturing	Construction	Use and Maintenance	EoL	Total
Environmental	HH	P	1.33	0.30	0.42	-0.20	1.86
	R	P	1.05	0.10	0.36	0.02	1.53
	E	P	0.69	0.26	0.18	-0.13	1.01
						Total	4.40
Social	W	MRH	227.17	20.27	57.87	2.25	307.56
	LC	MRH	273.58	22.03	71.49	2.54	369.65
	S	MRH	320.67	25.05	79.56	2.98	428.26
	VCA	MRH	199.67	14.09	56.44	1.90	272.11
						Total	1377.58
Economic	Cost	€				**Total**	26.05

*p=points, mrh= med risk hour

Table 4.4.5. Sustainability assessment of A2

Assessment		Unit	Manufacturing	Construction	Use and Maintenance	EoL	Total
Environmental	HH	P	1.13	0.32	0.86	-0.15	2.16
	R	P	0.93	0.11	0.72	0.01	1.77
	E	P	0.57	0.28	0.31	-0.10	1.06
						Total	4.98
Social	W	MRH	197.63	20.68	115.75	2.26	336.31
	LC	MRH	238.77	22.36	142.98	2.55	406.67
	S	MRH	285.49	25.42	159.12	3.00	473.02
	VCA	MRH	174.01	14.34	112.87	1.91	303.14
						Total	1519.14
Economic	Cost	€				**Total**	29.57

*p=points, mrh= med risk hour

Table 4.4.6. Sustainability assessment of A3

Assessment		Unit	Manufacturing	Construction	Use and Maintenance	EoL	Total
	HH	P	0.74	0.08	0.56	0.00	1.38
	R	P	0.64	0.05	0.46	0.03	1.17
Environmental	E	P	0.36	0.04	0.23	-0.01	0.63
						Total	3.19
	W	MRH	124.88	4.02	82.27	2.81	213.97
	LC	MRH	151.20	5.08	101.62	3.44	261.34
Social	S	MRH	182.92	5.93	113.08	4.05	305.98
	VCA	MRH	109.66	4.11	80.22	2.73	196.72
						Total	978.02
Economic	Cost	€				**Total**	22.56

*p=points, mrh= med risk hour

These tables show the impact of the three pillars of sustainability for each life cycle stage. In general, the manufacturing stage is the life cycle stage with the highest impact in every category. A3 has the lowest impact for all the categories. However, A1 has a lower impact in the use and maintenance and end-of-life stages. This is because A1 requires one maintenance period for 150 years of service life, while A2 requires two maintenance periods for the same service life and A3 requires one maintenance period for 120 years of service life. Therefore, A1 has the lowest ratio between maintenance days and service life.

In addition, Figure 4.4.4 compares the social and environmental impacts of the three alternatives for each life cycle stage. For this purpose, the upper vertical axis represents the social impact, and the lower vertical axis represents the environmental impact. It can be seen that there is symmetry between these two pillars of sustainability and that, proportionally, the construction stage is more important in the environmental pillar. A3 has the lowest global social and environmental impacts and also the lowest social and environmental impacts in the manufacturing and construction stages. However, A1 has the lowest social and environmental impacts in the use and maintenance and end-of-life stages. The manufacturing stage has the highest contribution for both impacts.

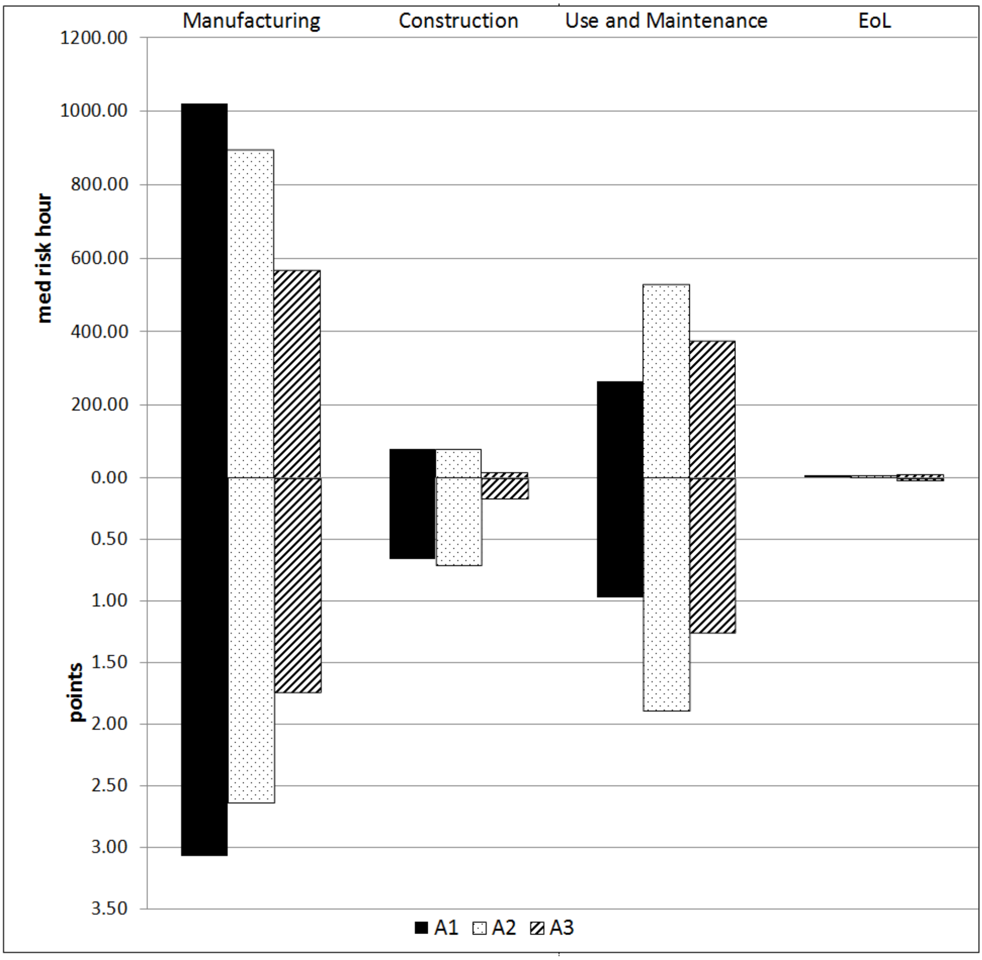

Figure 4.4.4. Total social and environmental impact

Table 4.4.7. Contribution of material in the social impact

	A1		A2		A3	
	Steel	**Concrete**	**Steel**	**Concrete**	**Steel**	**Concrete**
FL	57.93%	24.11%	53.04%	17.82%	54.82%	16.46%
FS	55.63%	29.60%	53.14%	22.73%	55.42%	21.10%
WH	49.90%	27.02%	43.92%	19.26%	45.12%	17.74%
GW	41.82%	42.58%	42.18%	34.56%	48.36%	34.60%
NFA	31.87%	49.36%	30.03%	37.22%	31.67%	34.12%
FA	35.70%	28.26%	28.27%	18.23%	28.64%	16.59%
SM	24.51%	49.95%	23.15%	36.30%	26.02%	36.09%
ND	51.76%	28.34%	46.35%	20.56%	47.38%	18.65%
SS	50.01%	27.31%	44.01%	19.49%	45.21%	17.88%
VL	53.19%	29.07%	49.35%	21.92%	51.51%	20.32%
ACB	58.06%	29.96%	57.53%	23.94%	62.05%	22.52%
TU	48.20%	29.57%	42.91%	21.32%	44.28%	19.64%
IMW	37.90%	22.07%	28.26%	13.29%	27.11%	11.98%

In addition, more detailed information can be obtained for each social indicator. As an example, 13 social indicators have been selected: association and bargaining rights (ACB), non-fatal accidents (NFA), fatal accidents (FA), pollution (P), gender wage gap (GW), violations of employment laws and regulations (VL), safety measures (SM), frequency of forced labor (FL), trade unionism (TU), fair salary (FS), workers affected by natural disasters (ND), weekly hours of work per employee (WH), social security expenditures (SS) and international migrant workers (IMW). Table 4.4.7 shows the contribution of the main materials used along the whole bridge life cycle for the selected social indicators. Both concrete production and steel production are the processes with the highest contributions. This table shows that steel production is the bridge process with the main social impact, followed by concrete production. However, there are two indicators for which diesel consumption has the highest contribution: FA and IMW. Figures 4.4.5 and 6 show the contribution of steel production, concrete production, and diesel consumption in these indicators. These figures show that the contribution of diesel consumption in A1 is relatively weak when compared with A2 and A3 because the importance of the materials is higher for A1. In A2 and A3, around half of the impact is due to diesel consumption.

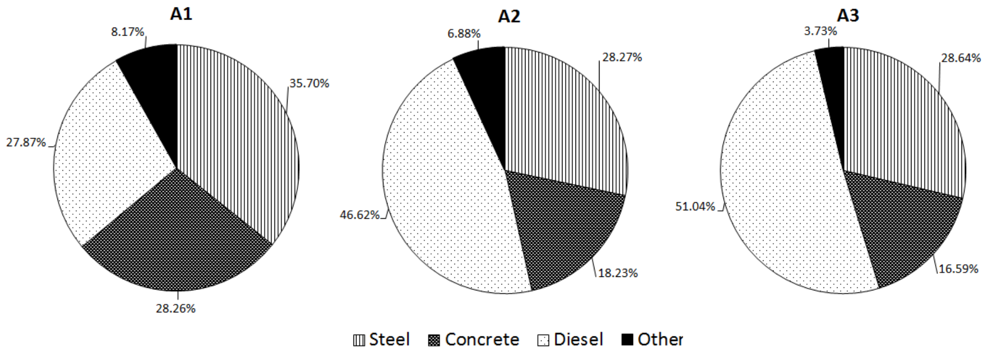

Figure 4.4.5. Contribution of processes to FA social impact

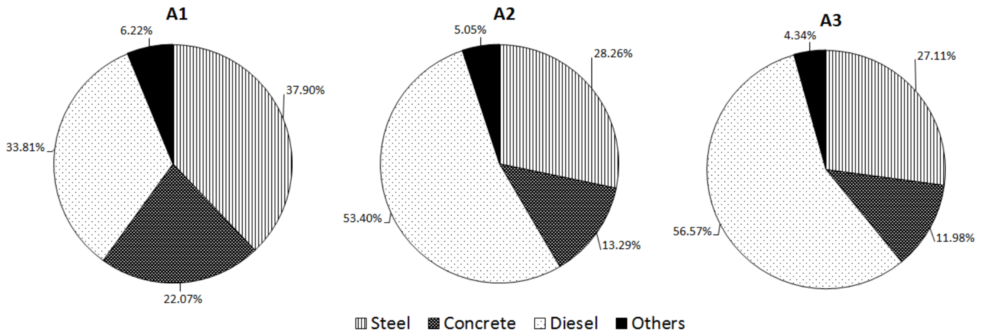

Figure 4.4.6. Contribution of processes to IMW social impact

4.4.6. Conclusion

This work carried out a complete sustainability assessment of three bridges: two post-tensioned concrete box-girder road bridges, with different initial and maintenance characteristics, and a pre-stressed concrete precast bridge. For this purpose, the economic pillar was evaluated by life cycle cost, and the environmental and social pillars were evaluated following the LCA methodology. After reviewing and discussing the different LCIA that best represent these pillars, a complete methodology was proposed. The ReCiPe method and Ecoinvent database were considered to carry out the environmental assessment, and the Social Impact Weighting Method and the PSILCA database with the SOCA add-on were considered to carry out the social assessment.

The comparison between the three bridges shows that the pre-stressed concrete precast bridge has the lowest impact in the three pillars of sustainability. Therefore, it can be considered the most sustainable bridge. In addition, the manufacturing stage is the stage with the highest environmental and social impact. The highest environmental impact is caused by concrete production, while the highest social impact is caused by steel production. Despite material production having a higher contribution to social impact, the FA and IMW indicators have direct impacts associated with diesel consumption. Because the alternatives A2 and A3 have a low ratio between material used and diesel consumption, the importance of these indicators becomes higher.

This work contributes to reaching the goal of sustainability assessment. The most important methods and databases used to carry out a complete environmental and social assessment are provided. In this way, future works can choose the most appropriate method or alternative to carry out an assessment of these pillars according to their objectives. In addition, the comparison made shows that a complete sustainability assessment can be used by engineers to compare different alternatives, for example, in a study of solutions. Currently, there is a trend toward sustainability and this work contributes to reaching this final goal in the construction sector. Regarding limitations, the social indicators obtained by the SOCA method use objective assessment, but in some cases it is necessary to consider other criteria such as aesthetics or cultural significance, which can be important depending on the place where the bridge is built.

Acknowledgements

The authors acknowledge the support for the Ministry of Economy and Company and FEDER funding (Project BIA2017-85098-R).

References

[1] S. McKenzie, "Social sustainability: Towards some definitions," Magil, 2004.

[2] United Nations., World Commission on Environment and Development Our common future. New York, USA, 1987.

[3] S. Vallance, H. C. Perkins, and J. E. Dixon, "What is social sustainability? A clarification of concepts," Geoforum, vol. 42, no. 3, pp. 342–348, Jun. 2011.

[4] V. Penadés-Plà, T. García-Segura, J. Martí, and V. Yepes, "A review of multi-criteria decision-making methods applied to the sustainable bridge design," Sustainability, vol. 8, no. 12, p. 1295, 2016.

[5] H. Gervásio and L. Simões Da Silva, "A probabilistic decision-making approach for the sustainable assessment of infrastructures," Expert Systems with Applications, vol. 39, no. 8, pp. 7121–7131, 2012.

[6] V. Balali, A. Mottaghi, O. Shoghli, and M. Golabchi, "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, vol. 2431, pp. 79–87, 2014.

[7] United Nations, "Indicators for sustainable development goals," 2014.

[8] K. Murphy, "The social pillar of sustainable development: a literature review and framework for policy analysis," Sustainability: Science, Practice and Policy, vol. 8, no. 1, pp. 15–29, Apr. 2012.

[9] L. Montalbán-Domingo, T. García-Segura, M. A. Sanz, and E. Pellicer, "Social sustainability criteria in public-work procurement: An international perspective," Journal of Cleaner Production, vol. 198, pp. 1355–1371, 2018.

[10] J. M. Harris, T. A. Wise, K. P. Gallagher, and N. R. Goodwine, A survey of sustainable development: Social and economic dimension. Washinton, 2001.

[11] L. A. Sierra, V. Yepes, and E. Pellicer, "Assessing the social sustainability contribution of an infrastructure project under conditions of uncertainty," Environmental Impact Assessment Review, vol. 67, pp. 61–72, Nov. 2017.

[12] I. J. Navarro, V. Yepes, and J. V. Martí, "Social life cycle assessment of concrete bridge decks exposed to aggressive environments," Environmental Impact Assessment Review, vol. 72, pp. 50–63, Sep. 2018.

[13] I. J. Navarro, J. V. Martí, and V. Yepes, "Reliability-based maintenance optimization of corrosion preventive designs under a life cycle perspective," Environmental Impact Assessment Review, vol. 74, pp. 23–34, Jan. 2019.

[14] L. Montalbán-Domingo, T. García-Segura, M. Amalia Sanz, and E. Pellicer, "Social Sustainability in Delivery and Procurement of Public Construction Contracts," Journal of Management in Engineering, vol. 35, no. 2, pp. 1–11, 2019.

[15] R. Valdes-Vasquez and L. E. Klotz, "Social sustainability considerations during planning and design: Framework of processes for construction projects," Journal of Construction Engineering and Management, vol. 139, no. 1, pp. 80–89, 2013.

[16] E. Almahmoud and H. K. Doloi, "Assessment of social sustainability in construction projects using social network analysis," Facilities, vol. 30, no. 3/4, pp. 152–176, 2015.

[17] A. Horvath and C. Hendrickson, "Steel versus steel-reinforced concrete bridges: Environmental assessment," Journal of Infrastructure Systems, vol. 4, no. 3, pp. 111–117, 1998.

[18] J. Widman, "Environmental impact assessment of steel bridges," Journal of Construction Steel Research, vol. 46, no. 412, pp. 291–293, 1998.

[19] T. Stengel and P. Schiessl, "Life cycle assessment of UHPC bridge constructions : Sherbrooke Footbridge , Kassel Gärtnerplatz Footbridge and

Wapello Road Bridge," Architecture Civil Engineering Environment, vol. 1, pp. 109–118, 2009.

[20] H. Gervasio and L. Simoes da Silva, "Comparative life-cycle analysis of steel-concrete composite bridges," Structure and Infrastructure Engineering, vol. 4, no. 4, pp. 251–269, 2008.

[21] Y. Itoh and T. Kitagawa, "Using CO2 emission quantities in bridge lifecycle analysis," Engineering Structures, vol. 25, no. 5, pp. 565–577, 2003.

[22] L. Bouhaya, R. Le Roy, and A. Feraille-Fresnet, "Simplified environmental study on innovative bridge structure," Environmental Science & Technology, vol. 43, no. February, pp. 2066–2071, 2009.

[23] K. N. P. Steele, G. Cole, and G. Parke, "Application of life cycle assessment technique in the investigation of brick arch highway bridges," in 6th International Masonry Conference, 2002, pp. 1–8.

[24] G. Du and R. Karoumi, "Life cycle assessment of a railway bridge: Comparison of two superstructure designs," Structure and Infrastructure Engineering, vol. 9, no. Iso14040 2006, pp. 1149–1160, 2012.

[25] G. Du, M. Safi, L. Pettersson, and R. Karoumi, "Life cycle assessment as a decision support tool for bridge procurement: Environmental impact comparison among five bridge designs," The International Journal of Life Cycle Assessment, vol. 19, no. 12, pp. 1948–1964, 2014.

[26] J. Hammervold, M. Reenaas, and H. Brattebø, "Environmental life cycle assessment of bridges," Journal of Bridge Engineering, vol. 18, no. 2, pp. 153–161, 2013.

[27] B. Pang, P. Yang, Y. Wang, A. Kendall, H. Xie, and Y. Zhang, "Life cycle environmental impact assessment of a bridge with different strengthening schemes," The International Journal of Life Cycle Assessment, vol. 20, no. 9, pp. 1300–1311, 2015.

[28] S. Sabatino, D. M. Frangopol, and Y. Dong, "Sustainability-informed maintenance optimization of highway bridges considering multi-attribute utility and risk attitude," Engineering Structures, vol. 102, pp. 310–321, 2015.

[29] Z. Chen, A. B. Abdullah, C. J. Anumba, and H. Li, "ANP experiment for demolition plan evaluation," Journal of Construction Engineering and Management, vol. 140, no. 2, pp. 51–60, 2013.

[30] International Organization for Standardization (ISO), Environmental managment - life cycle assessment - principles and framework. Geneva, Switzerland, 2006.

[31] J. B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. Wegener Sleeswijk, H. a. Udo De Haes, J. a. de Bruijn, R. van Duin, and M. a. J. Huijbregts, "Life cycle assessment: An operational guide to the ISO standards," III: Scientific background, no. May, p. 692, 2001.

[32] M. Hauschild and J. Potting, "Background for spatial differentiation in LCA impact assessment - The EDIP2003 methodology," Environmental news, no. 996, 2005.

[33] J. C. Bare, "The Tool for the reduction and assessment of chemical and other environmental impacts," Journal of Industrial Ecology, vol. 6, no. 3–4, pp. 49–78, Jun. 2002.

[34] M. Gocdkoop, P. Hofstetter, R. Müller-Wenk, and R. Spriemsma, "The Eco-Indicator 98 explained," International Journal of Life Cycle Assessment, vol. 3, no. 6, pp. 352–360, 1998.

[35] B. Steen, "A systematic approach to environmental priority strategies in product development (EPS)," 1999.

[36] R. Frischknecht, R. Steiner, and N. Jungbluth, "Methode der ökologischen Knappheit – Ökofaktoren 2006," p. 190, 2009.

[37] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, ReCiPe 2008. A life cycle impact assessment which comprises harmonised category indicators at midpoint and at the endpoint level. Netherlands, 2009.

[38] N. Itsubo, M. Sakagami, T. Washida, K. Kokubu, and A. Inaba, "Weighting across safeguard subjects for LCIA through the application of conjoint analysis," International Journal of Life Cycle Assessment, vol. 9, no. 3, pp. 196–205, 2004.

[39] O. Jolliet, M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer, and R. Rosenbaum, "IMPACT 2002+: A new Life Cycle Impact Assessment Methodology," International Journal of Life Cycle Assessment, vol. 8, no. 6, pp. 324–330, 2003.

[40] GreenDelta, "PSILCA v1.0 (Product Social Impact Life-Cycle Assessment)." 2013.

[41] New Earth, "SHDB v1.0 (Social Hotspot Database)." 2009.

[42] C. Benoît and B. Mazijn, Guidelines for Social Life Cycle Assessment of Products. UNEP/SETAC Life Cycle Initiative, Sustainable Product and Consumption Branch, vol. 15, no. 2. 2009.

[43] GreenDelta, “PSILCA database,” 2013. [Online]. Available: https://psilca.net/. [Accessed: 01-Oct-2019].

[44] New Earth, “SHDB database,” 2009. [Online]. Available: https://www.socialhotspot.org/for-more-information.html. [Accessed: 01-Oct-2019].

[45] G. Du and R. Karoumi, “Environmental life cycle assessment comparison between two bridge types : Reinforced concrete bridge and steel composite bridge,” in 3th International Conference on Sustainable Construction Materials and Technologies.

[46] J. J. Pons, V. Penadés-Plà, V. Yepes, and J. V. Martí, “Life cycle assessment of earth-retaining walls: An environmental comparison,” Journal of Cleaner Production, vol. 192, pp. 411–420, Aug. 2018.

[47] GreenDelta, “SOCA v1.0.” 2017.

[48] European Committee for Standardization, EN 206-1 Concrete - Part1: Specification, performance, production and conformity. Brussels, Belgium, 2000.

[49] V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, “Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges,” Sustainability, vol. 9, no. 10, p. 1864, 2017.

[50] V. Penadés-Plà, T. García-Segura, J. V. Martí, and V. Yepes, “An optimization-LCA of a prestressed concrete precast bridge,” Sustainability (Switzerland), vol. 10, no. 3, pp. 1–17, 2018.

[51] K. Steele, G. Cole, G. Parke, B. Clarke, J. Harding, and J. Harding, “Highway bridges and environment-sustainable perspectives,” Proceedings of the Institution of Civil Engineers, vol. 156, no. 4, pp. 176–182, 2003.

[52] M. L. Marceau, M. A. Nisbet, and M. G. Vangeem, Life cycle inventory of portland cement concrete. Skokie, Illinois, USA, 2007.

[53] Ministerio de Fomento, EHE-08: Code on structural concrete. Madrid, Spain, 2008.

[54] Ministerio de Fomento, IAP-11: Code on the actions for the design of road bridges. Madrid, Spain, 2011.

[55] European Committee for Standardization, EN 1001-2:2003. Eurocode 1: Actions on structures- Part 2: Traffic loads bridges. Brussels, Belgium, 2003.

[56] European Committee for Standardisation, “EN1992-2:2005. Eurocode 2: Design of concrete structures- Part 2: Concrete Bridge-Design and detailing rules.,” Brussels, 2005.

[57] Catalonia Institute of Construction Technology, "BEDEC PR/PCT ITEC material database." Barcelona, Spain, 2016.

[58] T. García-Segura, V. Yepes, D. M. Frangopol, and D. Y. Yang, "Lifetime reliability-based optimization of post-tensioned box-girder bridges," Engineering Structures, vol. 145, pp. 381–391, 2017.

[59] T. García-Segura, V. Yepes, and J. Alcalá, "Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability," The International Journal of Life Cycle Assessment, vol. 19, no. 1, pp. 3–12, 2014.

CHAPTER 5. OPTIMIZATION AND METAMODEL

5.1. Introduction

Optimization processes have been widely used in many scientific fields. But in the structural optimization, the heuristic optimization is the most common as the mathematical optimization is not feasible because of the complexity of the problems. However, when the variability is considered in the problem, the computational cost gets higher. To overcome this problem, metamodels are used. This Chapter provides the paper where a comparison between conventional heuristic optimization and kriging-based optimization is made. This paper shows the computational cost reduction achieved by using kriging in optimization processes.

5.2. Accelerated optimization method for low-embodied energy concrete box-girder bridge design[4]

[4] Penadés-Plà V, García-Segura T, Yepes V. Accelerated optimization method for low-embodied energy concrete box-girder bridge design. *Engineering Structures* 2019;179:556–65.

Vicent Penadés-Plà[a], Tatiana García-Segura[b], Víctor Yepes[c*]
[a] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: vipepl2@cam.upv.es
[b] Dept. of Construction Engineering and Civil Engineering Projects, Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: tagarse@upv.es
[c] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. Corresponding author. E-mail: vyepesp@cst.upv.es

Abstract

Structural optimization is normally carried out by means of conventional heuristic optimization due to the complexity of the structural problems. However, the conventional heuristic optimization still consumes a large amount of time. The use of metamodels helps to reduce the computational cost of the optimization and, along these lines, kriging-based heuristic optimization is presented as an alternative to carry out an accelerated optimization of complex problems. In this work, conventional heuristic optimization and kriging-based heuristic optimization will be applied to reach the optimal solution of a continuous box-girder pedestrian bridge of three spans with a low embodied energy. For this purpose, different penalizations and different initial sample sizes will be studied and compared. This work shows that kriging-based heuristic optimization provides results close to those of conventional heuristic optimization using less time. For the sample size of 50, the best solution differs about 2.54% compared to the conventional heuristic optimization, and reduces the computational cost by 99.06%. Therefore, the use of a kriging model in structural design problems offers a new means of solving certain structural problems that require a very high computational cost and reduces the difficulty of other problems.

Keywords: Low-embodied energy; Post-tensioned concrete; Box-girder bridge; Structural optimization; Metamodel; Kriging.

5.2.1. Introduction

The traditional main objective of structural engineering is to reach maximum safety with the minimum investment. However nowadays, due to the increased concern for sustainability, other aspects have also become important within the field of structural engineering. These aspects are usually grouped into the three main objectives (economic, environmental and social) of sustainability [1], [2]. In this way, the traditional structural engineering problem becomes a complex problem that should be solved by means of a decision-making process [3], [4]. Regarding the environmental goal, life-cycle assessment is an accepted process to obtain the complete environmental profile of a process, product or service [5]–[7]. However, a first approximation of the environmental assessment can be carried out using a single criterion that represents, in a reliable way, the environmental impact. The most representative criteria are the CO_2 emissions and the embodied energy, which also have a direct relationship with the cost [8], [9]. This indicates that the optimization of CO_2 emissions or embodied energy reduces at the same time the cost. There are several works that have analyzed structures with a lower CO_2 emission [10], [11], but the embodied energy has been less studied [12].

Bridges are one of the most important structures in civil engineering due to their importance in the area of communications. However, designing a sustainable bridge is not easy, due to the fact that the structural problem is characterized by a large number of design variables with multiple combinations. A heuristic optimization process is presented as an alternative to achieve a solution within the design space that reaches the objectives and guarantees the constraints imposed by the regulations. This method has been used to optimize many types of structures, such as reinforced concrete columns [13], [14], reinforced concrete frames [8], precast concrete floors [15], prestressed concrete precast road bridges [12] and post-tensioned concrete box-girder bridges [11], [16]. However, the structural optimization problem depends on a large number of design variables with several constraints. This results in excessive computational costs [17]. One effective solution to carry out the optimization with a lower computational cost is the use of approximate response surfaces obtained by surrogate models or metamodels. The most common metamodels are polynomial regression, neural networks and kriging [18], [19]. The kriging model is one of the most encouraging metamodels used in structural optimization [20] although despite this fact, only few works have been carried out using a kriging-based heuristic optimization to design real structures. This model provides an optimal interpolation based on regression against observed values of the surrounding data points, weighted according to spatial covariance values. This means that kriging considers both global and local approximations at the same time. Thus, the kriging model takes into account the local variations of the objective response. In this context, a methodology that allows optimal designs to be determined with adequate accuracy and at reduced time cost is highly desirable.

In this work, conventional heuristic optimization and kriging-based heuristic optimization will be applied to determine an optimized continuous box-girder pedestrian bridge of three spans with a low embodied energy. A comparison between both optimization techniques will be carried out to determine if the kriging-based heuristic optimization provides reasonable results compared with the conventional heuristic optimization. For this purpose, different coefficients of penalizations and sampling sizes will be considered to determine the characteristics of the kriging-based heuristic that performs better. After that, a set of parameters for the kriging model will be recommended. In section 2 both optimization processes will be described. In section 3, a general scheme of the process to construct a metamodel will be shown, focusing on the main methods used in this work, namely latin hypercube sampling and the kriging model. In section 4, the problem design will be described, and in section 5 the most important results will be shown. Finally, the most important conclusions will be detailed.

5.2.2. Optimization process

Optimization is a process that tries to find the best possible solution to a problem that may be defined by one (mono-objective) or several (multi-objective) objective functions, f, that satisfy some constraints, gj.

$$f(X) \tag{5.2.1}$$

$$g_j(X) \leq 0 \tag{5.2.2}$$

where X represents the vector with the design variables chosen for the formulation.

The optimization process is defined by the algorithm used and establishes a set of rules to be followed in solving operational problems. These algorithms can be divided into exact algorithms and heuristic algorithms. Exact algorithms reach the global optimum by using sequential techniques of mathematical programming. Heuristic algorithms were developed to solve complex and realistic structural optimization problems of discrete variables. These algorithms achieve good solutions without guaranteeing the global optimum, but with a lower computational cost. Complex optimization problems, such as structural optimization, are defined for a large number of design variables, and thus the heuristic algorithms have demonstrated the best behavior in solving this kind of problem.

Heuristic algorithms try to simulate simple events observed in nature. In general, the traditional heuristic algorithms look for a local optimum, while the metaheuristic algorithms have tools to avoid local optimums in order to find a better solution. Metaheuristic algorithms follow an iterative process in which a complete structural design (combination of design variables) is defined to carry out the structural analysis and to evaluate aptitude by an objective function (Figure 5.2.1). In recent years, some metaheurisitc algorithms have been applied to structural optimization including the variable neighborhood search [10], harmony search [21] , threshold function [22], memetic algorithm [23], glowworm swarm algorithm [9] and simulated annealing [24] among others.

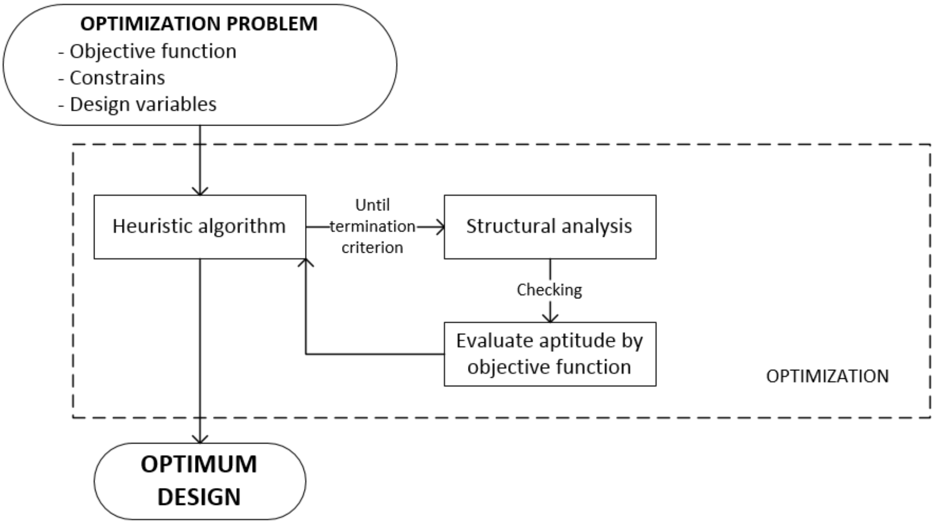

Figure 5.2.1. General flow chart of conventional heuristic optimization process

However, despite the advances in technology, the computational cost of structural heuristic optimization is still very high [25] due to the finite element structural analysis carried out during all iterations of the optimization process. This high computational cost can be reduced by means of metamodels (also called surrogate models or approximation models) [17]. These metamodels construct a mathematically approximate model of the objective function from a set of points in the design space (initial sampling) to predict the output without the need to carry out a full structural analysis. This means that the slowest part of the process of conventional heuristic optimization, which is the structural analysis and evaluation of the objective function part, is replaced by an evaluation of the metamodel. Therefore, the computational cost necessary for metamodel-based heuristic optimization (Figure 5.2.2) is lower than the computational cost necessary for conventional heuristic optimization.

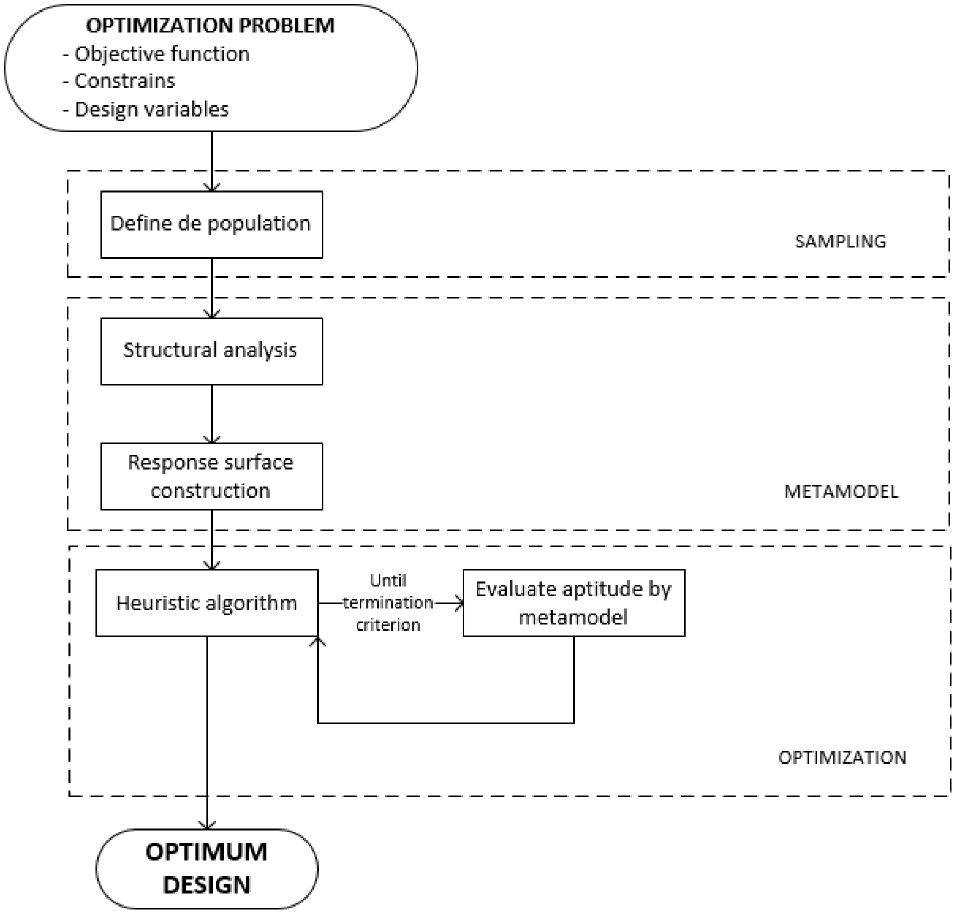

Figure 5.2.2. General flow chart of metamodel-based heuristic optimization.

5.2.3. Metamodel construction process

The basis of metamodels consists of constructing an approximate mathematical model of a detailed simulation model, which predicts the output data (objective response) from input data (design variables) in the whole design space, more efficiently than the detailed simulation models. It could, as such, be called a model of the model. The construction process of a metamodel focuses on three main parts: (a) obtaining the initial input dataset points inside the design space, (b) choosing the metamodel type to construct the approximate mathematical model and (c) choosing the fitting model. There are a large number of options for carrying out these steps [26]. Regardless of the choice for each step, the main objective of constructing a metamodel is to obtain a model with the best accuracy possible to predict the objective response.

The choice of the initial input dataset points or sampling inside the design space is defined by the sample size and the position of the points, because both aspects have an influence on the model construction. On the one hand, the sample size is fundamentally related to the number of design variables. The sample size must be higher with a larger number of design variables for the same accuracy of the metamodel, and therefore the computational cost necessary to construct the model will be higher. On the other hand, once the sample size has been defined, the position of the points must be placed within the design space in order to obtain the best possible information. This process is called Design Of Experiments (DoE).

The DoE can be divided into two different groups. The first group clusters the classic designs that include the factorial or fractional factorial designs, central composite designs, Box-Behnken designs, Plackett-Burman designs, Koshal designs and D-optimal designs [27]. These types of designs tend to spread the sample points around the border of the design space and only include a few points inside of it. The classic designs are mainly used to construct polynomial metamodels. When the initial input data points were used to construct more advanced metamodels, other designs, called space-filling designs, were preferred. These types of designs trend to spread the sample points all over the design space (often with a uniform distribution), so it is possible to take into account the local phenomena in any region of the design space. The most popular space-filling designs are the latin hypercube sampling [28], distance-based designs [29] and low-discrepancy sequences, which group Hammersley sequence sampling [30] and the uniform design [31].

In this work, to generate the sample, latin hypercube sampling (LHS) has been considered; its effectiveness in the estimation of the objective response of the metamodel has been proven in several works [32], [33]. LHS was proposed by McKay et al. in 1979 [28]. This method determines the N number of non-overlapping intervals for each variable (in this work these intervals are divided according to a uniform distribution) from a number of design variables (v) and a number of initial input dataset points (N). Therefore, the design space is divided into Nv regions. Each sample point will be located in one region in order that each point corresponds to a combination of different intervals of each design variable range. In this way, each interval of each design variable range will only be associated with one sample point. Consequently, the LHS guarantees that all of the design variables are represented along their respective ranges. Figure 5.2.3 shows an example with 2 design variables and 10 initial input dataset points.

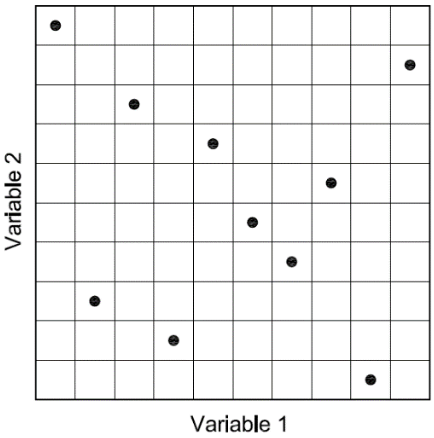

Figure 5.2.3. Latin hypercube sampling (v=2 and n=10)

Once the sample is defined, the objective response of the initial input dataset points is obtained. All of this initial information (inputs and outputs) is used to construct the metamodel over all of the design space. In this way, the metamodel predicts the objective response according to a mathematical function (Eq. 5.2.3):

$$y = f(x) = g(x) + \varepsilon \qquad (5.2.3)$$

where x are the input dataset points, f(x) corresponds to the real response (model), g(x) represents the approximate response (metamodel) and ε represents the approximation error. There are several mathematical formulations to construct metamodels with different characteristics [19], [26]. Although these metamodels have been compared [33]–[35], it is not possible to determine if one is better than the others as this depends on the problem posed. However, the most common metamodels are polynomial regression, neural networks and kriging [18], [19]. The polynomial-based response surface model is sometimes difficult to use in complex engineering problems, and the neural network-based model requires many sample points and much computational time for the training of the network [36]. The kriging model is a promising metamodel as it is more flexible than polynomial-based models and less time consuming than neural network-based techniques [34]. Thus, this work uses the kriging formulation to construct the metamodel.

Kriging is a metamodel that has its origins in geostatic applications involving spatially and temporally correlated data and was developed by the South African mining engineer called Danie Gerhardus Kirge. Later, many researches contributed to the problem of optimal spatial prediction, but the approach was formalized by Matheron in 1963 [37] who used the term kriging in honor of the contribution of Danie Gerhardus Kirge [20]. The idea behind kriging is that the deterministic response y(x) can be described as (Eq. 5.2.4):

$$y(x) = f(x) + Z(x) \tag{5.2.4}$$

where f(x) is the known approximation function, and Z(x) is a realization of a stochastic process with mean zero, variance σ^2 and non-zero covariance. The first term of the equation, f(x), is similar to a regression model that provides a global approximation of the design space (Eq. 5.2.5). The second term, Z(x), creates local deviations so that the kriging model interpolates the initial sample points (Eq. 5.2.6). In many cases, f(x) is simply a constant term and the method is then called ordinary kriging. If f(x) is set to 0, implying that the response y(x) has a mean of zero, the method is called simple kriging [38].

$$f(x) = \sum_{i=1}^{n} \beta_i \cdot f_i(x) \tag{5.2.5}$$

$$cov[Z(x_i), Z(x_j)] = \sigma^2 \cdot R(x_i, x_j) \tag{5.2.6}$$

where the process variance σ^2 scales the spatial correlation function $R(x_i,x_j)$ between two data points. In engineering design, the Gaussian correlation function (Eq. 5.2.7) is the most commonly used [38] function that can be defined with only one parameter (θ) that controls the area of influence of nearby points [36]. A low θ means that all the sample points have a high correlation, thus the term Z(x) will be similar all over the design space. As the value θ increases, the points with higher correlation will be closer, thus the term Z(x) will differ depending on the point in the design space:

$$R(x_i, x_j) = e^{-\sum_{k=1}^{m} \theta \left| x_k^i - x_k^j \right|^2} \tag{5.2.7}$$

Finally, each metamodel type has its associated fitting method. In this case, the kriging formulation uses the search for the Best Linear Unbiased Predictor (BLUP). Simpson et al. [19] gave a detailed review of the equations and fitting methods for common metamodel types.

5.2.4. Problem design

In this section, a comparison of conventional heuristic optimization and kriging-based heuristic optimization will be discussed. First of all, the structure considered (a continuous concrete box-girder pedestrian bridge) and all of the characteristics involved will be described. After that, the optimization problem associated with the bridge will be defined. Finally, both optimization processes will be explained. This final point includes the design variables considered in each case, as well as how each approach deals with the constraints.

5.2.4.1. Box-girder pedestrian bridge description

The bridge is a continuous concrete box-girder pedestrian bridge deck with three continuous spans of 40-50-40 meters length (the relationship between the external span and the central span follows the optimum of 80%). This type of bridge is commonly used due to its structural performance, low dead load and construction conditions. The pedestrian bridge deck has a constant width of 3 meters, and the remaining geometrical dimensions of the cross-section are defined by the seven variables of (Figure 5.2.4): depth (h), bottom slab width (b), web inclination width (d), top slab thickness (e_s), external cantilever section thickness (e_v), bottom slab thickness (e_i) and webs slab thickness (e_a). The value of these variables is limited for a range. The depth range is 1.25-2.5 meters, the bottom slab width range is 1.2-1.8 meters, the width of the web inclination range is 0-0.4 meters, the web slab thickens is 0.3-0.6 meters and the other slab thickness ranges are 0.15-0.4 meters. The haunch (t), is calculated from the values of other variables (Eq. 5.2.8) according to Schlaich and Scheff's [39] recommendation. In addition, the haunch must provide the space to contain the ducts in the high and low points.

$$t = max\left\{\frac{b-2\cdot ea}{5}, ei\right\} \quad . \tag{8}$$

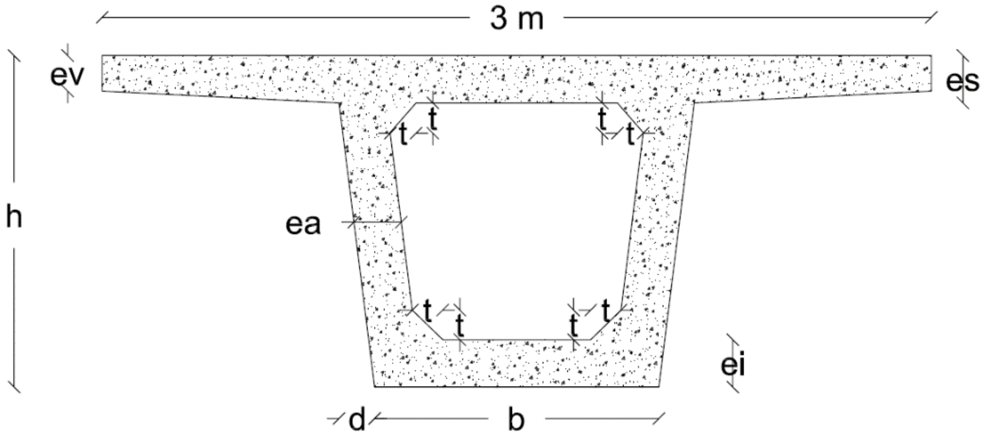

Figure 5.2.4. Box-girder cross-section

The strength of the concrete is defined by the variable f_{ck} that can take a value inside of the range 35-100 MPa. The post-tensioned steel formed by 0.6 inch strands is prestressed to 195.52 kN. The ducts are symmetrically distributed through the webs with a parabolic layout. The maximum eccentricity is present where the bending moment is the maximum or minimum (Figure 5.2.5). At these points, the distance considered between the duct and the surface is 0.2 meters. The distance from the piers to the point of inflection is defined by 5% of the length of each span. In addition, the position of the reinforced steel is defined according the Figure 5.2.6. Longitudinal reinforcement is defined by the number of bars per meter and their diameter, placed at the top slab (LRn1, LRØ1), the flange (LRn2, LRØ2, LRn3, LRØ3), the web (LRn4, LRØ4), the bottom slab (LRn5, LRØ5) and the core (LRn6, LRØ6). In addition, extra bending reinforcement is divided into two systems. One covers the top slab at the support zone (L/5 on both sides of the piers), with a diameter defined by LRØ7 and the same number of bars per meter as LRn1. The other is placed at the bottom slab throughout the rest of the external span (LRØ8) and the central span (LRØ9). The number of bars per meter is, for both locations, equal to LRn5. The diameter can change according to 0, 10, 12, 16, 20, 25 and 32 mm. Regarding transverse reinforcement, the diameter of the standard reinforcement (TRØ1, TRØ2, TRØ3, TRØ4, TRØ5, TRØ6, TRØ7) is set with the same spacing (TRS) for construction requirements.

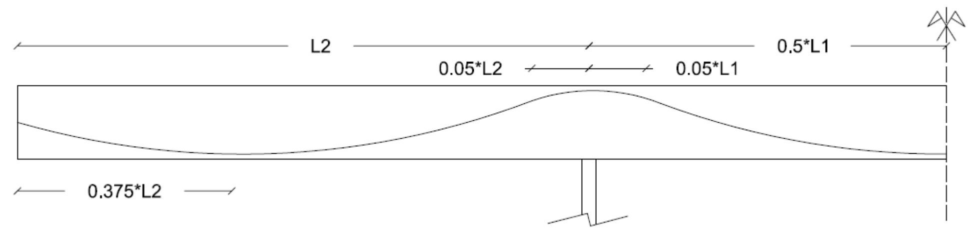

Figure 5.2.5. Pedestrian bridge and duct layout

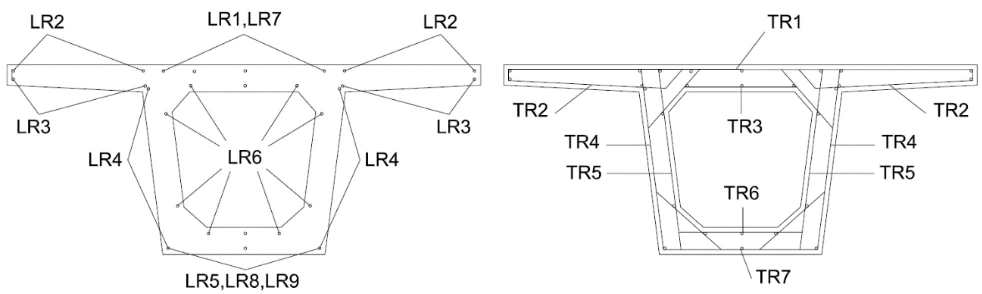

Figure 5.2.6. Longitudinal and transversal reinforcing steel disposition

Traditional scaffolding is used in the construction stage with a clearance of 5 meters. The formwork is disposed over the scaffolding to give the shape of the cross section of the bridge. In addition, lighting is used to lighten the self-weight of the bridge. Table 5.2.1 defines the other conditions employed in this study such as the materials, the load actions on the structure, the exposure class and the regulations used.

Table 5.2.1. Main parameters of the analysis

MATERIAL PARAMETERS	
Maximum aggregate size	20 mm
Reinforcing steel	B-500-S
Post-tensioned steel	Y1860-S7
Strand diameter	Φ_s = 0.6”
Tensioning time	7 days
GEOMETRICAL PARAMETERS	
Pedestrian bridge width	B = 3 m
Number of spans	3
Central span length	L1=50 m
External span length	L2=40 m
Clearance	5 m
Diaphragm thickness	1.2 m
EXPOSURE RELATED PARAMETERS	
External ambient conditions	IIb
REGULATION RELATED PARAMETERS	
Regulations	EHE-08/IAP-11/Eurocodes
Service working life	100 years
LOADING RELATED PARAMETERS	
Reinforced concrete self-weight	25 kN/m^3
Asphalt layer self-weight	24 kN/m^3
Mean asphalt thickness	47.5 mm
Bridge railing self-weight	1 kN/m
Live load	5 kN/m^2
Differential settling	5 mm

5.2.4.2. Optimization problem description

In this work, the problem of continuous concrete box-girder pedestrian bridge deck optimization involves a single-objective optimization of the embodied energy of the structure. Hence, this optimization aims to minimize the embodied energy (Eq. 5.2.9) and satisfy the constraints (Eq. 5.2.10).

$$Embodied\ energy = \sum_{i=1,n} e_i \times m_i(x_{1,}x_{2,} \ldots, x_n) \qquad (5.2.9)$$

$$g_j(x_1, x_2, x_3, \ldots, x_n) \leq 0 \qquad (5.2.10)$$

The objective function evaluates the embodied energy for the total number of construction units considering the material used and the placement embodied energy defined in equation 9. The embodied energy of each unit (e_i), shown in Table 5.2.2, were obtained from the BEDEC ITEC database [40]. The embodied energy of concrete is determined for each compressive strength grade according to the mix design, including the embodied energy of raw materials extraction, manufacture and transportation. The measurements (m_i) concerning the construction units are evaluated from the design defined using the design variables.

Table 5.2.2. Unit energy

UNIT MEASUREMENTS	Energy (kWh)
m^3 of scaffolding	20.4
m^2 of formwork	8.7
m^3 of lighting	1137.5
kg of steel (B-500-S)	10.44
kg of post-tensioned steel (Y1860-S7)	12.99
m^3 of concrete HP-35	612.22
m^3 of concrete HP-40	646.61
m^3 of concrete HP-45	681
m^3 of concrete HP-50	715.39
m^3 of concrete HP-55	749.77
m^3 of concrete HP-60	784.16
m^3 of concrete HP-70	852.94
m^3 of concrete HP-80	921.72
m^3 of concrete HP-90	990.49
m^3 of concrete HP-100	1059.27

The structural constraints represented by equation 10 check the serviceability and ultimate limit states (SLS and ULS) of Vertical shear, Longitudinal shear, Punching shear, Bending, Torsion, Torsion combined with bending and shear, Cracking, compression and tension stress, vibration. Note that the code [41] provides different equations for conventional and high-strength concrete (concrete with a characteristic compressive strength greater than 50 MPa). In addition, the geometrical and constructability requirements are verified, following the Spanish regulations for this type of structure [41], [42] as well as the Eurocodes [43], [44]. It is worth mentioning that the analysis and the verification of the limit states are coded in Matlab.

The algorithm used to carry out the optimization problem is simulated annealing (SA) [45] due to its versatile acceptance criterion. Many works use SA to carry out conventional heuristic optimization [8], [46]. In this work, the initial temperature is calibrated following Medina's [47] method, which proposes that the initial temperature is halved when the percentage of acceptances is greater than 40%, and doubled when it is less than 20%. After that, the temperature decreases according to a coefficient of cooling k following the equation T=k*T, when a Markov chain ends. In this work, the calibration revealed that a coefficient of cooling of 0.8 and a length of the Markov chain of 1000 are appropriate. The algorithm finishes after three Markov chains show no improvement.

5.2.4.3. Optimization process

As stated above, in this work, a comparison between conventional heuristic optimization and kriging-based optimization will be carried out. The main difference between these processes is that, while in conventional heuristic optimization, before obtaining the objective response, all of the constraints of the bridge are checked at each step of the optimization, in kriging-based heuristic optimization, the objective response is estimate throughout a mathematical approximation.

5.2.4.3.1. Conventional heuristic optimization

In conventional optimization, in addition to the seven geometrical variables and the concrete strength, the reinforced steel and the prestressed steel are also variables. Reinforced steel is defined by 23 variables, 15 for the longitudinal reinforcement and 8 for the transverse reinforcement (see Figure 5.2.6). Once the initial box-girder pedestrian bridge is completely defined, the SA algorithm carries out movements of the design variables to compare the objective response obtained after each movement until the energy-optimized box-girder pedestrian bridge is reached according to the process defined in the section 3.3. Each movement requires the complete verification of the SLS and ULS, entailing a high computational cost. Figure 5.2.2 shows a scheme of the conventional heuristic optimization considered.

5.2.4.3.2. Kriging-based heuristic optimization

In contrast to the conventional heuristic optimization in which the bridge is defined completely at the beginning of each iteration to later verify all of the constraint defined by the regulations, kriging-based heuristic optimization only defines the design variables that the engineers would take into account in their design (geometrical variables and the concrete strength) to later calculate the amount of the post-tensioned steel and the reinforced steel required according to the standards. Therefore, the post-tensioned and reinforced steel are not variables, and consequently, the design space is greatly reduced.

First of all, a specific sample size (N) over all the design space is obtained according to LHS, then, the embodied energy is calculated for each of these points. Due to the complexity of structural problems, there are regions of the design space for which certain combinations of the geometrical design variables are not possible (for example $h<es+ev+2*t$). This is because the embodied energy of the bridge cannot be obtained in some points of the LHS. To solve this constraint and attempt to conduct the optimization for feasible designs, two response surfaces will be constructed. The first one is determined by the feasible solutions of the LHS. With

this response surface, the objective response of the unfeasible solutions of the LHS will be estimated and a penalization is applied to those solutions. To prevent too much skewing of the response surface, the penalization is imposed depending on the case: if the total embodied energy is higher than the minimum embodied energy of the set of feasible solutions, the embodied energy is not modified (case 1). Otherwise, if the total embodied energy is lower than the minimum embodied energy of the set of feasible solutions, a penalization is imposed to avoid reaching unfeasible optimum solutions (case 2). A study of the penalization imposed will be carry out in the next section. Finally, on grouping all of the feasible and non-feasible solutions, a second response surface will be determined. This response surface is constructed considering all of the LHS points, and thus all of the design space will be represented. In addition, the penalization avoids the optimization tending towards to unfeasible solutions.

Once the final response surface is obtained, a validation process that compares the real embodied energy and the estimated embodied energy of nine random data points is carried out in order to determine the accuracy of the model. Then, heuristic optimization by means of the SA algorithm is carried out to determine the final energy-optimized continuous concrete box-girder pedestrian bridge. Finally, the estimated optimized solution will be checked. In the case that this solution is feasible, the process finishes, but if the solution is unfeasible, a new initial population by LHS will be generated and the entire process is repeated. This procedure aims to study the influence of the initial population (N) on the accuracy of the model, the optimization and the computational cost. Figure 5.2.7 shows the scheme followed in this kriging-based heuristic optimization.

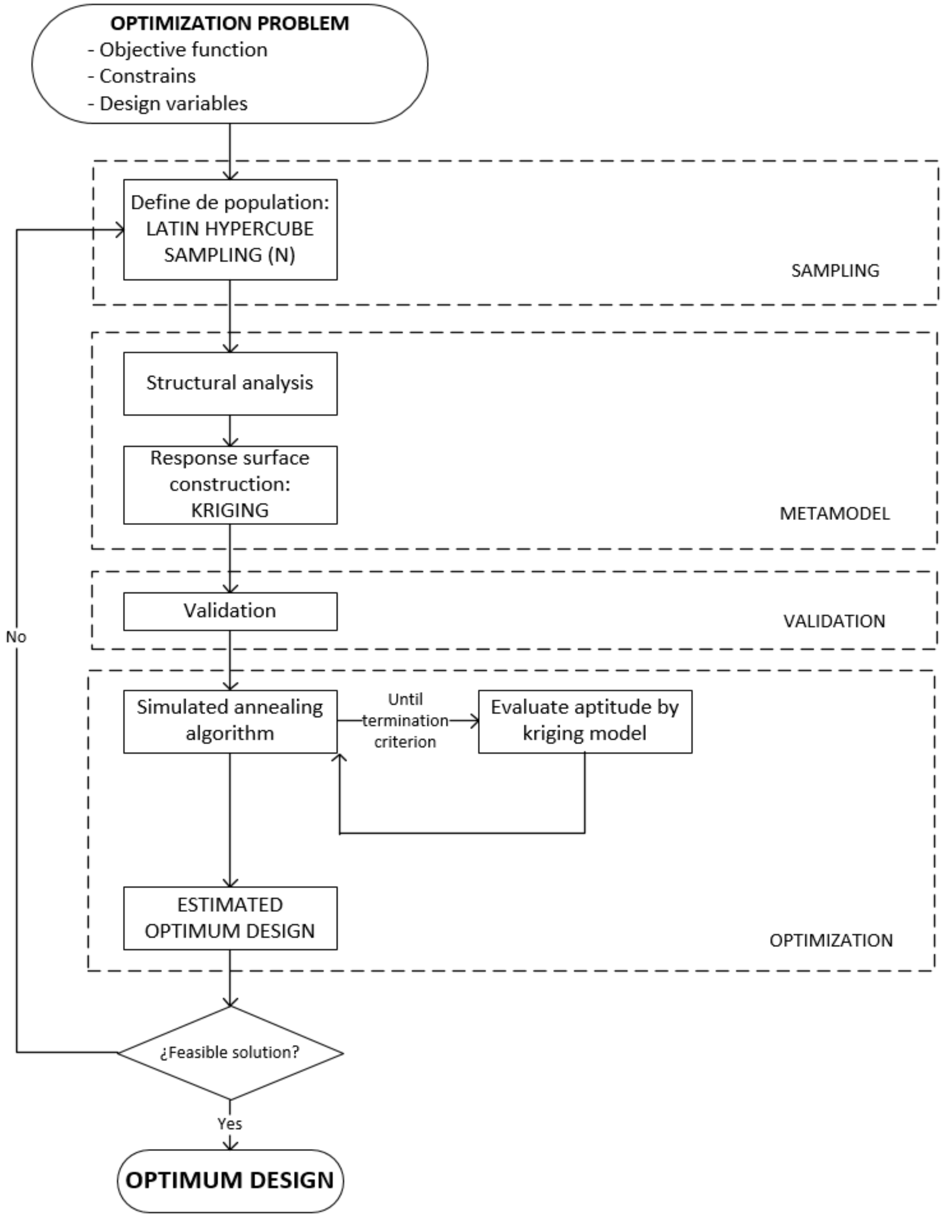

Figure 5.2.7. Kriging-based heuristic optimization

5.2.5. Results

In this section, the results of the comparison between conventional heuristic optimization and kriging-based heuristic optimization are shown. For this purpose two main objectives are proposed in this study: (1) to obtain the characteristics of the kriging model that provides good results of the optimization process, and (2) to study if the kriging-based heuristic optimization reaches acceptable results compared with the conventional heuristic optimization. The comparative study is carried out based on the mean results and best result of nine optimized solutions.

Before comparing the optimization methodologies, a sensitivity study is carried out to study the coefficient of penalization (p) applied to the unfeasible solutions of case 2. Different p values have been considered including 1, 1.25 and 1.5, and applied to the highest population considered (N=500) in order to determine the influence of this parameter on the kriging model. Table 5.2.3 shows the results of a group of nine solutions for each different coefficient of penalization. The first three columns refer to the mean results and the last one to the best result of each group. The first column shows the accuracy of the kriging model, evaluated as the mean difference of the real embodied energy and the estimated embodied energy of nine random points. The second and third columns show the mean embodied energy of nine optimized solutions in kWh and the accuracy of these nine optimized solutions. Finally, the last column shows the best optimized solution in kWh. Both the mean embodied energy and the best embodied energy improve when the coefficient of penalization decreases. For example, the mean embodied energy decreases from 771853 kWh to 744156 kWh when the coefficient of penalization decreases from 1.5 to 1. It shows that considering a coefficient of penalization of one improves the following optimization. This demonstrates that the kriging surface has a better behavior when there are smaller variations in its objective response. Thus, the coefficient of penalization considered to carry out this study will be p=1.

Table 5.2.3. Study of coefficient of penalization

	MEAN RESULTS			BEST RESULT
	Surface accuracy (%)	**Embodied energy (kWh)**	**Optimized-solutions accuracy (%)**	**Embodied energy (kWh)**
p=1	3.88%	744156	4.01%	701910
p=1.25	3.52%	750254	4.83%	704500
p=1.5	3.99%	771853	4.58%	731210

Once the coefficient of penalization is determined, nine kriging surfaces are obtained for each initial sample size (N=10, N=20, N=50, N=100, N=200, N=500) to evaluate the influence of the sample size on the accuracy of the results. The accuracy of this kriging surface is evaluated through the mean of the difference between the real embodied energy and the predicted embodied energy of a random sample of the design space. Figure 5.2.8 shows that the accuracy of the kriging surface increases with the number of initial samples but a horizontal convergence is observed from N=50, in which the accuracy of the surface is 4.04%. From N=10 to N=50 the accuracy of the kriging model improves from 11.11% to 4.04% (upgrading of 7.07%). However, the accuracy of the kriging model from N=50 to N=500 improves from 4.04% to 3.88% (upgrading of only 0.16%).

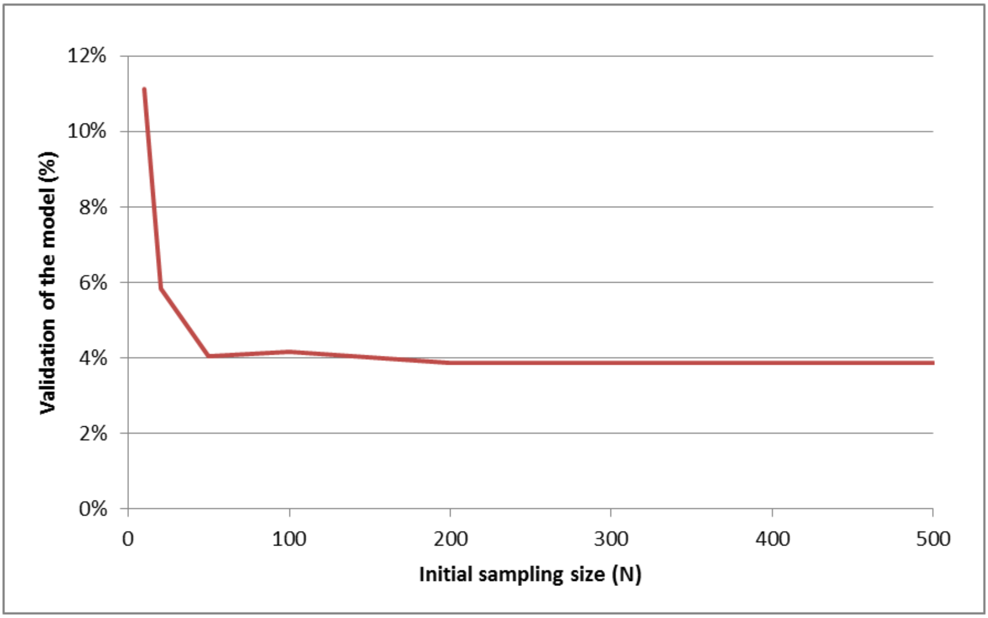

Figure 5.2.8. Validation of kriging response surface

Once the kriging surface is obtained, the optimization is carried out. For each initial sample size, different characteristics of the two optimizations have been compared. Figure 5.2.9 shows the mean embodied energy of nine optimized box-girder pedestrian bridges. The horizontal dashed line represents the mean embodied energy obtained by conventional heuristic optimization, while the solid line represents the mean embodied energy obtained by the kriging-based heuristic optimization according to the sample size. The mean embodied energy of the nine optimized bridges obtained by the conventional heuristic optimization is 713504 kWh. This result improves by 4.30% the best mean embodied energy of the nine optimized bridges obtained by the kriging-based heuristic optimization (corresponding to N=500). Furthermore, as can be seen in Table 5.2.4, the best solutions of each group of nine obtained by kriging-based heuristic optimization are close to the best solution of the conventional heuristic optimization. For example, the best solution obtained with N=50 differs only 2.54% with respect to the best solution of the conventional heuristic optimization. Besides, Figure 5.2.10 shows that the increment in the initial sample size reduces the coefficient of variance of the nine solutions, reaching a lower value than the coefficient of variance of the nine solutions obtained in the conventional heuristic optimization. While the coefficient of variance of the conventional heuristic optimization is 3.79%, the coefficient of variance of the kriging-based heuristic optimization is 3.67% when the sample size is N=500. These results show that a satisfactory solution can be obtained with an initial sample size of N=50, but a higher initial sample size improves the accuracy of the model and the mean embodied energy. Thus, it can be said that the kriging model is robust for optimization problems.

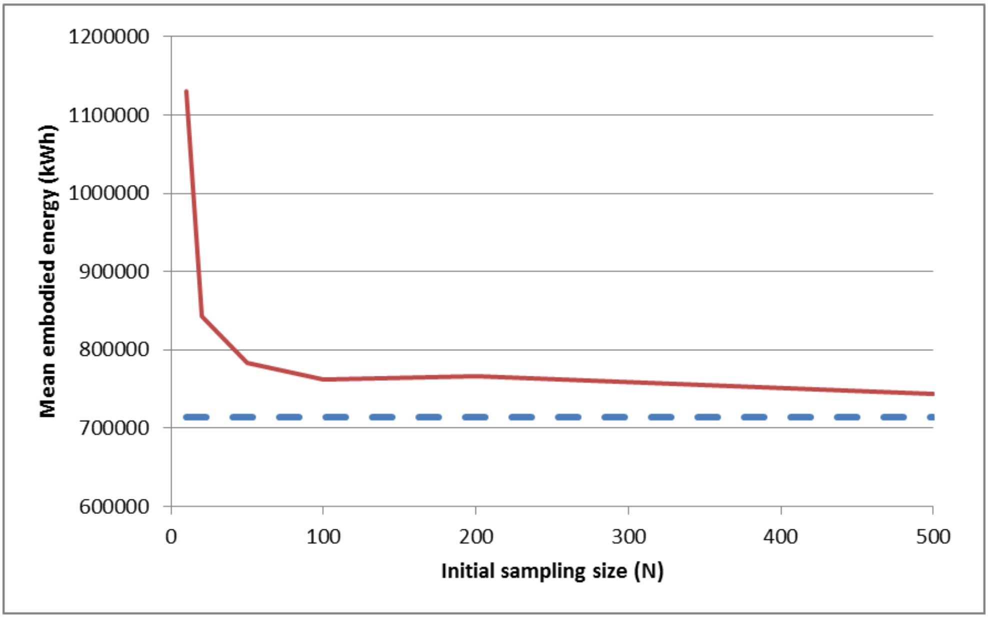

Figure 5.2.9. Comparison of the mean of embodied energy of bridges

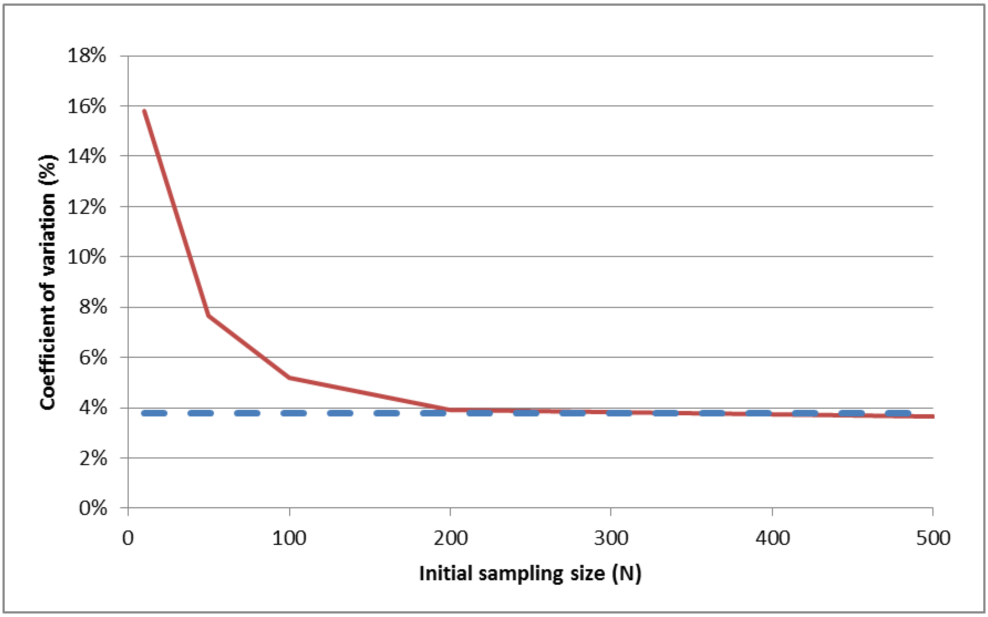

Figure 5.2.10. Comparison of the coefficient of validation

It must not be forgotten that the main advantage of the kriging-based heuristic optimization is the computational cost saving as the objective response of each iteration is directly obtained. The kriging-based heuristic optimization required 1804.11 seconds for an initial sample size of N=500, while the conventional heuristic optimization required 19617.14 seconds. This is a reduction of 90.80% in the computational cost. Note that the greater part of the computing time in the kriging-based heuristic optimization is due to the generation of the initial population. Regarding the conventional heuristic optimization, more than 80% of the computing time is spent in the analysis and the verification of the ultimate and serviceability limit states, as well as the geometrical and constructability requirements. Table 5.2.4 shows in more detail the time savings achieved for the other initial sample sizes.

Table 5.2.4 summarizes the most important results in comparing the optimization approaches. The first six rows represent the different initial sample sizes of the kriging-based heuristic optimizations, and the last row represents the conventional heuristic optimization. The columns represent the results of the different characteristics studied. The first six columns show the main results of the nine optimized bridges, and the last two columns show the best optimized bridges for each case. The first column shows the accuracy of the kriging model, evaluated as the mean difference of the real embodied energy and the estimated embodied energy of nine random points. The second and third columns show the mean computational time of nine optimized solutions in seconds and the percentage with respect to the conventional heuristic optimization. The fourth and fifth columns show the mean embodied energy of nine optimized solutions in kWh and the percentage with respect to the conventional heuristic optimization. The sixth column shows the coefficient of variance of the nine optimized solutions. Finally, the seventh and eighth columns show the best optimized solution of each group of nine in kWh and the percentage with respect to the conventional heuristic optimization. This table can be used as a reference for defining the initial sample size. Note that the design space of this work is formed by 8 variables. Depending on the preferred characteristics, one sample size will be adjusted more than the others. However, taking into account all of the characteristics, the initial sample size that shows the best behavior is N=50. This initial sample size provides a satisfying mean embodied energy (783726 kWh) with a low coefficient of variance (6.65 %) and gives the best solution (699240 kWh) whose cross section variables are b=1.2 m, h= 1.35 m, d=0 m, e_v=0.15 m, e_s=0.15 m, e_a=0.35 m, e_i=0.15 m, and f_{ck}=60 MPa. These results have been obtained with a 99.06% reduction in time spent with respect to the conventional heuristic optimization, whose cross section variables are b=1.35 m, h= 1.3 m, d=0 m, e_v=0.15 m, e_s=0.2 m, e_a=0.4 m, e_i=0.2 m, and f_{ck}=50 MPa. In addition, Figures 5.2.10, 5.2.11 and 5.2.12 show that the initial sample size of N=50 is close to the results of N=500, but saving 89.74% of the computational cost. However, as mentioned previously, the sample size of N=500 improves the coefficient of variance.

Table 5.2.4. Overview of results obtained

		MEAN RESULTS						BEST RESULT	
Method	N	Surface accuracy (%)	Time (s)	Time comparison with CH (%)	Embodied energy (kWh)	Energy comparison with CH (%)	Coefficient of variance (%)	Embodied energy (kWh)	Comparison with CH (%)
Kriging-based heuristic optimization (KH)	10	11.11%	26.73	99.86%	1130127	58.39%	15.81%	814840	19.49%
	20	5.83%	236.71	98.79%	844816	18.2%	13.67%	721400	5.79%
	50	4.04%	185.08	99.06%	783726	9.84%	6.65%	699240	2.54%
	100	4.16%	510.10	97.40%	762350	6.85%	5.20%	700800	2.77%
	200	3.88%	1497.33	92.37%	767034	7.50%	3.94%	701910	2.93%
	500	3.88%	1804.11	90.80%	744157	4.30%	3.67%	701910	2.93%
Conventional heuristic optimization (CH)			19617.14		713505		3.79%	681917	

5.2.6. Conclusions

In this work, a conventional heuristic optimization and a kriging-based heuristic optimization have been compared. The results show that the use of the kriging model provides a response surface with a goof accuracy that improves with an increase in the initial sample size. Therefore, the objective response of a problem can be obtained without any structural analysis and with a high accuracy. The results of kriging-based heuristic optimization are close to the solutions reached in the conventional heuristic optimization cases with a significantly high reduction of computational cost.

The sensitivity analysis of the penalization imposed on the unfeasible designs shows that the kriging model has a better behavior with the lowest penalization. In addition, the study of the optimization obtained according to the initial sample size shows that the best solutions obtained are similar for the different sample sizes, but that the mean and the coefficient of variance improve with the initial sample size. We can conclude that the initial sample size that performs best is N=50. For this case, the accuracy of the response surface is within 4.04% and the mean energy of the optimum solutions differ by 9.84% compared to the conventional heuristic optimization, but with a reduction in the computational cost of the 99.06%. Regarding the best solution, the comparison shows that the use of kriging increases the optimum energy by 2.54%. However, if the main objective is to reduce the coefficient of variance, the initial size that performs better is N=500. For this case, the solutions obtained have a coefficient of variance of 3.67%, even lower than the 3.79% that corresponds to the conventional heuristic optimization. Thus, structural engineers must consider an appropriate initial sample size depending on the characteristics of the problem.

In conclusion, the use of the kriging model in structural design offers a new way to solve a number of structural problems that require a very high computational cost and reduces the difficulty of other problems. On the one hand, due to the lower computational cost, kriging-based heuristic optimization can be used to obtain the best solution for problems involving several criteria and yields robust designs. On the other hand, kriging-based heuristic optimization can be used to optimize structural problems with a lower number of design variables by means of commercial software. In this way, structural engineers can obtain the response objective of a small sample size through commercial software without the necessity of writing code, and after that, achieve an optimized structure in simple terms. Thus, the use of the kriging model in structural design has a high potential in the research field as well as practical engineering.

Acknowledgments

The authors acknowledge the financial support of the Spanish Ministry of Economy and Competitiveness, along with FEDER funding (Project: BIA2017-85098-R).

References

[1] H. Gervásio and L. Simões Da Silva, "A probabilistic decision-making approach for the sustainable assessment of infrastructures," Expert Systems with Applications, vol. 39, no. 8, pp. 7121–7131, 2012.

[2] M. H. Aghdaie, S. H. Zolfani, and E. K. Zavadskas, "Prioritizing constructing projects of municipalities based on AHP and COPRAS-G: A case study about footbridges in Iran," The Baltic Journal of Road and Bridge Engineering, vol. 7, no. 2, pp. 145–153, 2012.

[3] E. Zavadskas, J. Antucheviciene, T. Vilutiene, and H. Adeli, "Sustainable decision-making in civil engineering, Construction and building technology," Sustainability, vol. 10, no. 2, p. 14, Dec. 2017.

[4] V. Penadés-Plà, T. García-Segura, J. Martí, and V. Yepes, "A review of multi-criteria decision-making methods applied to the sustainable bridge design," Sustainability, vol. 8, no. 12, p. 1295, 2016.

[5] J. Ferreiro-Cabello, E. Fraile-Garcia, E. Martinez-Camara, and M. Perez-de-la-Parte, "Sensitivity analysis of life cycle assessment to select reinforced concrete structures with one-way slabs," Engineering Structures, vol. 132, pp. 586–596, Feb. 2017.

[6] V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, "Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges," Sustainability, vol. 9, no. 10, p. 1864, 2017.

[7] H. Gervasio and L. Simoes da Silva, "Comparative life-cycle analysis of steel-concrete composite bridges," Structure and Infrastructure Engineering, vol. 4, no. 4, pp. 251–269, 2008.

[8] C. V. Camp and F. Huq, "CO2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm," Engineering Structures, vol. 48, pp. 363–372, Mar. 2013.

[9] V. Yepes, J. V. Martí, and T. García-Segura, "Cost and CO2 emission optimization of precast-prestressed concrete U-beam road bridges by a hybrid glowworm swarm algorithm," Automation in Construction, vol. 49, no. PA, pp. 123–134, 2015.

[10] F. Molina-Moreno, J. V. Martí, and V. Yepes, "Carbon embodied optimization for buttressed earth-retaining walls: Implications for low-carbon conceptual designs," Journal of Cleaner Production, vol. 164, pp. 872–884, 2017.

[11] T. García-Segura and V. Yepes, "Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety," Engineering Structures, vol. 125, pp. 325–336, 2016.

[12] J. V. Martí, T. García-Segura, and V. Yepes, "Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy," Journal of Cleaner Production, vol. 120, pp. 231–240, Feb. 2016.

[13] H. Park, B. Kwon, Y. Shin, Y. Kim, T. Hong, and S. Choi, "Cost and CO2 emission optimization of steel reinforced concrete columns in high-rise buildings," Energies, vol. 6, no. 12, pp. 5609–5624, Oct. 2013.

[14] S. M. Nigdeli, G. Bekdas, S. Kim, and Z. W. Geem, "A novel harmony search based optimization of reinforced concrete biaxially loaded columns," Structural Engineering and Mechanics, vol. 54, no. 6, pp. 1097–1109, 2015.

[15] A. T. de Albuquerque, M. K. El Debs, and A. M. C. Melo, "A cost optimization-based design of precast concrete floors using genetic algorithms," Automation in Construction, vol. 22, pp. 348–356, Mar. 2012.

[16] T. García-Segura, V. Yepes, J. Alcalá, and E. Pérez-López, "Hybrid harmony search for sustainable design of post-tensioned concrete box-girder pedestrian bridges," Engineering Structures, vol. 92, pp. 112–122, 2015.

[17] T. W. Simpson, A. J. Booker, D. Ghosh, A. A. Giunta, P. N. Koch, and R.-J. Yang, "Approximation methods in multidisciplinary analysis and optimization: A panel discussion," Structural and Multidisciplinary Optimization, vol. 27, no. 5, pp. 302–313, 2004.

[18] R. D. Bäckryd, A.-B. Ryberg, and L. Nilsson, "Multidisciplinary design optimisation methods for automotive structures," International Journal of Automotive and Mechanical EngineeringOnline, vol. 14, no. 1, pp. 2229–8649, 2017.

[19] T. W. Simpson, J. D. Poplinski, P. N. Koch, and J. K. Allen, "Metamodels for computer-based engineering design: Survey and recommendations," Engineering with Computers, vol. 17, no. 2, pp. 129–150, 2001.

[20] N. Cressie, "The origins of kriging," Mathematical Geology, vol. 22, no. 3, pp. 239–252, 1990.

[21] T. García-Segura, V. Yepes, D. M. Frangopol, and D. Y. Yang, "Lifetime reliability-based optimization of post-tensioned box-girder bridges," Engineering Structures, vol. 145, pp. 381–391, 2017.

[22] R. Kutylowski and B. Rasiak, "Application of topology optimization to bridge girder design," Structural Engineering and Mechanics, vol. 51, no. 1, pp. 39–66, Jul. 2014.

[23] J. V. Martí, V. Yepes, and F. González-Vidosa, "Memetic algorithm approach to designing precast-prestressed concrete road bridges with steel fiber

reinforcement," Journal of Structural Engineering, vol. 141, no. 2, p. 4014114, 2015.

[24] T. García-Segura and V. Yepes, "Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety," Engineering Structures, vol. 125, pp. 325–336, 2016.

[25] T. García-Segura, V. Yepes, and D. M. Frangopol, "Multi-objective design of post-tensioned concrete road bridges using artificial neural networks," Structural and Multidisciplinary Optimization, vol. 56, no. 1, pp. 139–150, 2017.

[26] R. R. Barton and M. Meckesheimer, "Metamodel-based simulation optimization," vol. 13, 2006.

[27] R. H. Myers, D. C. Montgomery, and C. M. Anderson-Cook, Response surface methodology: Process and product optimization using designed experiments. Toronto, Canada: Wiley, 1995.

[28] M. D. McKay, R. J. Beckman, and W. J. Conover, "Comparison of three methods for selecting values of input variables in the analysis of output from a computer code," Technometrics, vol. 21, no. 2, pp. 239–245, 1979.

[29] M. E. Johnson, L. M. Moore, and D. Ylvisaker, "Minimax and maximin distance designs," Journal of Statistical Planning and Inference, vol. 26, no. 2, pp. 131–148, 1990.

[30] J. R. Kalagnanam and U. M. Diwekar, "An efficient sampling technique for off-line quality control," Technometrics, vol. 39, no. 3, p. 308, Aug. 1997.

[31] K.-T. Fang, D. K. J. Lin, P. Winker, and Y. Zhang, "Uniform design: Theory and application," Technometrics, vol. 42, no. 3, p. 237, Aug. 2000.

[32] C. H. Chuang, R. J. Yang, G. Li, K. Mallela, and P. Pothuraju, "Multidisciplinary design optimization on vehicle tailor rolled blank design," Structural and Multidisciplinary Optimization, vol. 35, no. 6, pp. 551–560, Jun. 2008.

[33] R. Jin, W. Chen, and T. W. Simpson, "Comparative studies of metamodelling techniques under multiple modelling criteria," Structural and Multidisciplinary Optimization, vol. 23, no. 1, pp. 1–13, Dec. 2001.

[34] Y. F. Li, S. H. Ng, M. Xie, and T. N. Goh, "A systematic comparison of metamodeling techniques for simulation optimization in decision support systems," Applied Soft Computing, vol. 10, no. 4, pp. 1257–1273, 2010.

[35] B.-S. Kim, Y.-B. Lee, and D.-H. Choi, "Comparison study on the accuracy of metamodeling technique for non-convex functions," Journal of Mechanical Science and Technology, vol. 23, no. 4, pp. 1175–1181, Apr. 2009.

[36] A. I. J. Forrester and A. J. Keane, "Recent advances in surrogate-based optimization," Progress in Aerospace Sciences, vol. 45, no. 1–3, pp. 50–79, 2009.

[37] G. Matheron, "Principles of geostatistics," Economic Geology, vol. 58, no. 8, pp. 1246–1266, 1963.

[38] T. W. Simpson, T. M. Mauery, J. Korte, and F. Mistree, "Kriging models for global approximation in simulation-based multidisciplinary design optimization," AIAA Journal, vol. 39, no. December, pp. 2233–2241, 2001.

[39] J. Schlaich and H. Scheef, "Concrete box-girder bridges," in International Association for Bridge and Structural Engineering, 1982.

[40] Catalonia Institute of Construction Technology, "BEDEC PR/PCT ITEC material database." Barcelona, Spain, 2016.

[41] Ministerio de Fomento, EHE-08: Code on structural concrete. Madrid, Spain, 2008.

[42] Ministerio de Fomento, IAP-11: Code on the actions for the design of road bridges. Madrid, Spain, 2011.

[43] European Committee for Standardization, EN 1001-2:2003. Eurocode 1: Actions on structures- Part 2: Traffic loads bridges. Brussels, Belgium, 2003.

[44] European Committee for Standardisation, "EN1992-2:2005. Eurocode 2: Design of concrete structures- Part 2: Concrete Bridge-Design and detailing rules.," Brussels, 2005.

[45] S. Kirkpatrick, C. D. Gelatt, and M. P. Vecchi, "Optimization by simulated annealing.," Science (New York, N.Y.), vol. 220, no. 4598, pp. 671–80, May 1983.

[46] J. V. Martí, F. González-Vidosa, V. Yepes, and J. Alcalá, "Design of prestressed concrete precast road bridges with hybrid simulated annealing," Engineering Structures, vol. 48, pp. 342–352, 2013.

[47] J. R. Medina, "Estimation of incident and reflected waves using simulated annealing," Journal of Watery, Port, Coastal, and Ocean Engineering, vol. 127, no. 4, pp. 213–221, 2001.

CHAPTER 6. ROBUST DECISION-MAKING

6.1. Introduction

The sustainability assessment of bridges is a decision-making process in which different stakeholders with different points of view can intervene. Depending on the decision-maker's point of view, the relative weights associated with each of the criteria defined for sustainability assessment are will be different, and therefore the final design will change. This chapter seeks a bridge whose sustainability index is the best, and at the same time, the variability associated with the different points of view is the least. This bridge is defined as a robust sustainable bridge, since the design is the most sustainable regardless of the point of view of decision-makers.

6.2. Robust decision-making design for sustainable pedestrian concrete bridges[5]

[5] Penadés-Plà V, García-Segura T, Yepes V. Robust decision-making design for sustainable pedestrian concrete bridges. *Engineering Structures (Accepted, in press)*

Vicent Penadés-Plà[a], Tatiana García-Segura[b], Víctor Yepes[c*]

[a] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. Corresponding author. E-mail: vipepl2@cam.upv.es

[b] Dept. of Construction Engineering and Civil Engineering Projects, Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: tagarse@upv.es

[c] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: vyepesp@cst.upv.es

Abstract

In recent years, there is a trend toward the construction of sustainable structures. The goal of sustainability in structures involves several criteria that are normally opposed, leading to a decision-making process. In this process, there is a subjective portion that cannot be eliminated, such as qualitative criteria assessment of and assigning criteria importance. In these cases, decision-makers become part of the decision-making process, assessing it according to their preferences. In this work, a methodology to reduce the participation of decision-makers in achieving the goal of sustainability in structures is proposed. For this purpose, principal component analysis, kriging-based optimization, and the analytical hierarchy process are used. Principal component analysis is used to reduce the complexity of the problem according to the highly correlated criteria. Kriging-based optimization obtains sustainable solutions depending on all the perspectives of sustainability. Finally, the analytical hierarchy process is applied to reduce the optimized sustainable solutions according to the decision-maker's views. This methodology is applied a continuous concrete box-girder pedestrian bridge deck to reach sustainable designs. This methodology allows a reduction of the complexity of the decision-making problem and also obtains sustainable robust solutions.

Keywords: Post-tensioned concrete; Box-girder bridge; Sustainability assessment; Kriging; Principal Component Analysis; Decision-making; Robust design

6.2.1. Introduction

Traditionally, engineering projects seek to design structures for the lowest cost. But in recent years, the concern about the environmental and social aspects has caused a trend towards designing sustainable structures. This tendency has been supported by the work of several researchers [1–6], as they provide criteria for the development of the three main pillars of sustainability: economic, environmental and social [5,7]. Thus, the design of sustainable structures implies assessing the proper criteria to cover all the perspectives of sustainability, grouped in these three main pillars. After that, it is necessary to normalize and assign the relative importance of each criterion, which is a decision-making process [8,9]. Multi-attribute decision-making (MADM) methods have been widely used in the sustainability assessment of structural designs. Researchers have reviewed different MADM methods and criteria used in structure sustainability assessment problems [10]. These MADM methods have been applied to evaluate a sustainability index of different structures or choose the most sustainable structure among different alternatives [6,11]. Regardless of the criteria that the researchers considered to represent the sustainability of the structures, most of them point out that a complete sustainability assessment must cover the whole life-cycle of the structure (from cradle to grave) [12–14].

Summarizing, the main steps of the decision-making process are [15]: (a) choose the criteria that adequately represent the sustainable goal, (b) proposal of alternatives, (c) evaluation of the alternatives in term of criteria (which can be quantitative or qualitative criteria), normalize it, and assign it a relative importance, and finally (d) select the best alternative. Once the criteria and alternatives are proposed, evaluation of qualitative criteria and assigning relative importance of the different criteria involve subjective assessments. This implies that the sustainability assessment could be different depending on decision-making concerns. For this reason, an approach that reaches a sustainable structure that satisfies all the different interests of decision-makers would be of great value. Consequently, it is necessary to study how these different perspectives affect the design of structures. For this purpose, principal component analysis (PCA) [16], kriging-based optimization [17], and the AHP method [18] were used to seek sustainable solutions, abolishing the relationship between criteria and ensuring the sustainable robustness of the solutions against the different perspectives of the decision-maker. PCA is used to avoid assessing a cluster of criteria with a high correlation index. Instead, the criteria with a high correlation index are grouped into principal components, avoiding excessively (positively or negatively) valuing the sustainable valuation of the alternatives. Kriging-based optimization is used to obtain the most sustainable alternative according to each perspective. Due to the large number of optimizations that must be made to carry out this study, kriging-based optimization is the most appropriate because of its high calculation speed [19]. Finally, AHP is used to generate many consistent random relative importances to study the variability of each optimum alternative against all the different possible perspectives. Additionally, the problem of criteria dependence, highlighted by several researchers [20,21], is solved due to the linear independence of the principal components.

In this work, the first goal is to study the influence of uncertainty in decision-making problems and to obtain the sustainable alternatives that best represent the different interests of the decision-makers. The second goal is to determine the sustainable alternative that best satisfies all the different perspectives, regardless of the interests of the decision-makers. This solution could be called the sustainable robust solution. For this purpose, the sustainability assessment of a three-span continuous concrete box-girder pedestrian bridge was considered. This structure was chosen due to its structural performance, low dead load and construction conditions. To this end, a large set of criteria was considered to cover all the perspectives of sustainability of the bridge, taking into account its whole life-cycle. In this way, a complete sustainability assessment can be made.

6.2.2. Bridge description

The structure considered is a continuous concrete box-girder pedestrian bridge deck with three continuous spans of 40-50-40 meters length. The width of the pedestrian bridge deck (B) is 3 meters. The remaining geometrical dimensions that define the cross-section of the pedestrian bridge deck are variables (Figure 6.2.1): depth (h), width of bottom slab (b), width of web inclination (d), thickness of top slab (e_s), thickness of external cantilever section (e_v), thickness of bottom slab (e_i) and thickness of webs slab (e_a). The haunch (t) is obtained following Schlaich and Scheff's [22] recommendation (Eq. 6.2.1).

$$t = max\left\{\frac{b-2\cdot ea}{5}, ei\right\} \quad . \qquad (6.2.1)$$

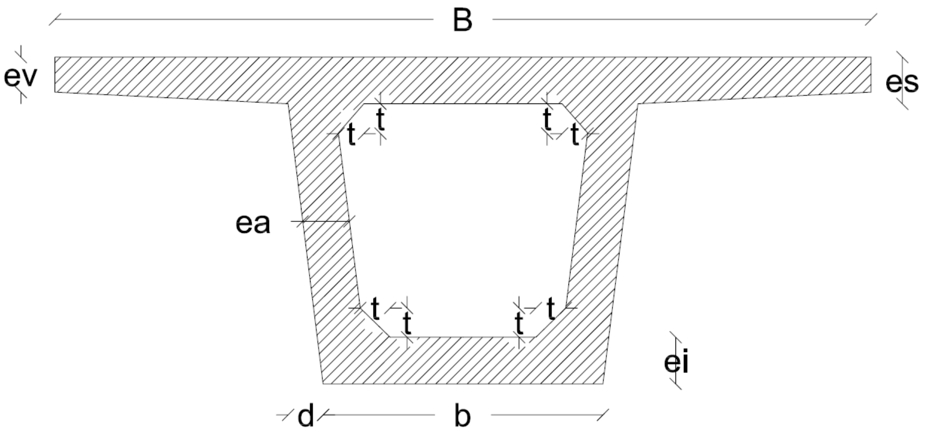

Figure 6.2.1. Box-girder cross-section

Furthermore, the concrete strength (f_{ck}) is considered as a variable. The post-tensioned steel is formed from 0.6 inch strands and is prestressed to 195.52 kN, and the ducts are symmetrically distributed through the webs with a parabolic layout. The maximum eccentricity is located where the bending moment is the minimum or maximum (Figure 6.2.2), where the distance of the ducts to the surface is 0.2 meters. In addition, the distance between the piers and the post-tensioned steel point of inflection is 5% of the length of each span.

The position of the reinforced steel is determined according to Figure 6.2.3. Longitudinal reinforcement is defined by the number of bars per meter and their diameter, placed at the top slab (LRn1, LRØ1), the flange (LRn2, LRØ2, LRn3, LRØ3), the web (LRn4, LRØ4), the bottom slab (LRn5, LRØ5) and the core (LRn6, LRØ6). Also, two extra bending reinforcements are considered. The first covers the top slab of the support area (LRØ7) with the same number of bars per meter as LRn1, and the other covers the bottom slab throughout the rest of the external span (LRØ8) and the central span (LRØ9) with the same number of bars per meter as LRn5. Transverse reinforcement is defined by the diameter of the standard reinforcement (TRØ1, TRØ2, TRØ3, TRØ4, TRØ5, TRØ6, TRØ7) and the spacing (TRS). Table 6.2.1 shows the other conditions employed in this study.

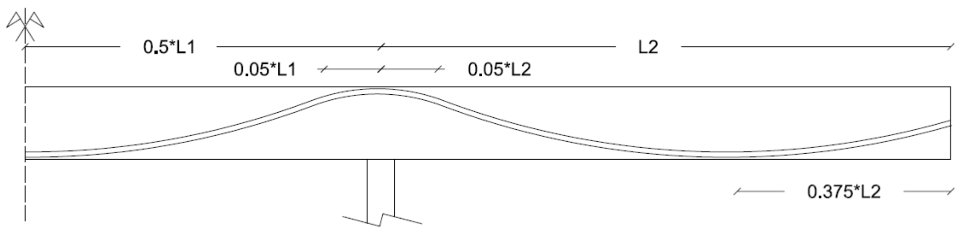

Figure 6.2.2. Pedestrian bridge and duct layout

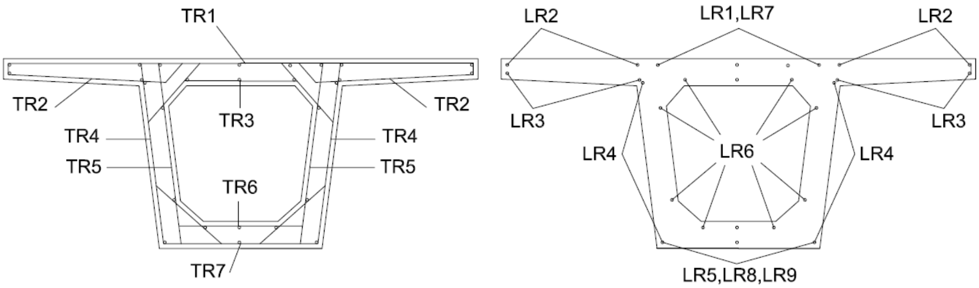

Figure 6.2.3. Transversal and longitudinal reinforcing steel disposition

Table 6.2.1. Parameters of the analysis

MATERIAL DESCRIPTION	
Maximum aggregate size	*20 mm*
Reinforcing steel	*B-500-S*
Post-tensioned steel	*Y1860-S7*
Strand diameter	$\Phi_s = 0.6''$
Tensioning time	*7 days*
GEOMETRICAL DESCRIPTION	
Pedestrian bridge width *(B)*	*3 m*
Number of spans	*3*
Central span length *(L1)*	*50 m*
External span length *(L2)*	*40 m*
Clearance	*5 m*
Diaphragm thickness	*1.2 m*
LOADING RELATED DESCRIPTION	
Reinforced concrete self-weight	*25* kN/m^3
Asphalt layer self-weight	*24* kN/m^3
Mean asphalt thickness	*47.5 mm*
Bridge railing self-weight	*1 kN/m*
Live load	*5* kN/m^2
Differential settling	*5 mm*
EXPOSURE RELATED DESCRIPTION	
External ambient conditions	*IIb*
REGULATION RELATED DESCRIPTION	
Codes	*Eurocodes / EHE-08 / IAP-11*
Service life	*100 years*

6.2.3. Methodology

This section explains the methodology used to carry out this work. Figure 6.2.4 shows a general diagram with specific information of this work. Each box represents the main steps of the methodology used, which corresponds to the different subsections of this section. The first box (Section 3.1) represents the process to select the criteria that best represent the sustainability for the case considered in this work. The second box (Section 3.2) represents the principal component analysis. In this section, an initial sample of 500 concrete box-girder pedestrian bridges is defined to carry out the principal component analysis. The principal component analysis is used to decrease the number of criteria defined in the previous section into a small set of linearly independent principal components. The third box (Section 3.3) represents the process to obtain the most sustainable bridge according to different perspectives of the sustainability. For this purpose, 1000 different random perspectives of sustainability are generated. Each one of these perspectives is defined by a set of relative weights that provides a different objective function (the sustainability index) for each one of the bridges of the initial sample. Therefore, 1000 different optimization problems are created according to the 1000 different random perspectives of sustainability, and 1000 different most sustainable bridges are obtained. Due to the high computational cost required for this purpose, the kriging-based optimization is applied. Finally, the fourth box (Section 3.4) represents the selection of one of these 1000 most sustainable bridges by means of the decision-making process. To reduce or avoid the participation of real decision-makers, 1000 hypothetic random decision-makers that cover all the possible preferences of real decision-makers are created. For this purpose, the AHP method is used. Each one of these 1000 hypothetic random decision-makers provides a sustainable index for each one of the 1000 most sustainable bridges obtained in the previous section. Finally, the results are interpreted and discussed (Section 4).

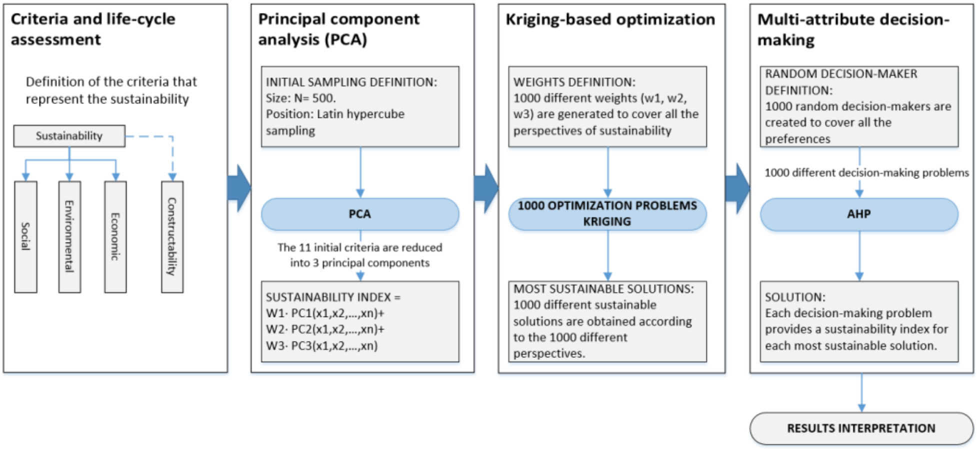

Figure 6.2.4. Overview of the methodology

6.2.3.1.Criteria and life-cycle assessment

In general, selecting the criteria that represent the decision-making problem depends on the characteristics of the goal. According to this goal, it is possible to define three different levels. The number of criteria necessary to cover the decision-making problem is different for each different level as the goal is more specific in each level, and therefore, some criteria have the same assessment for all the different alternatives. Thus, focusing on the construction sector, the (a) first level represents a decision-making problem in which the goal is to choose the best engineering project for a region/society/city; the (b) second level represents a decision-making problem in which the goal is to choose the best typology/methodology/process to carry out an already defined engineering project; and the (c) third level represents a decision-making problem in which the goal is to choose the best design. Obviously, to cover the first level of the decision-making problem, the criteria needed are higher since it concerns many aspects. Conversely, the criteria needed to cover the third level of the decision-making problem are those that are influenced by the design variables.

Figure 6.2.5 shows an overview of the three levels. Considering the decision-making performed in this work, an example of different levels is described. The criteria used in the first level must cover appropriately all the necessities of society, with alternatives being different projects (for example a road repair, construction of a pedestrian bridge, or construction of a public pool). If the project chosen is the construction of a pedestrian bridge, the criteria used in the second level must cover appropriately all the different bridge typologies (for example, a steel pedestrian bridge, a precast concrete beam pedestrian bridge, or a concrete box-girder pedestrian bridge). Finally, if the concrete box-girder pedestrian bridge is chosen, the criteria used in the third level must appropriately cover all the different designs (in this case, the designs are defined by the cross-section geometry and concrete strength).

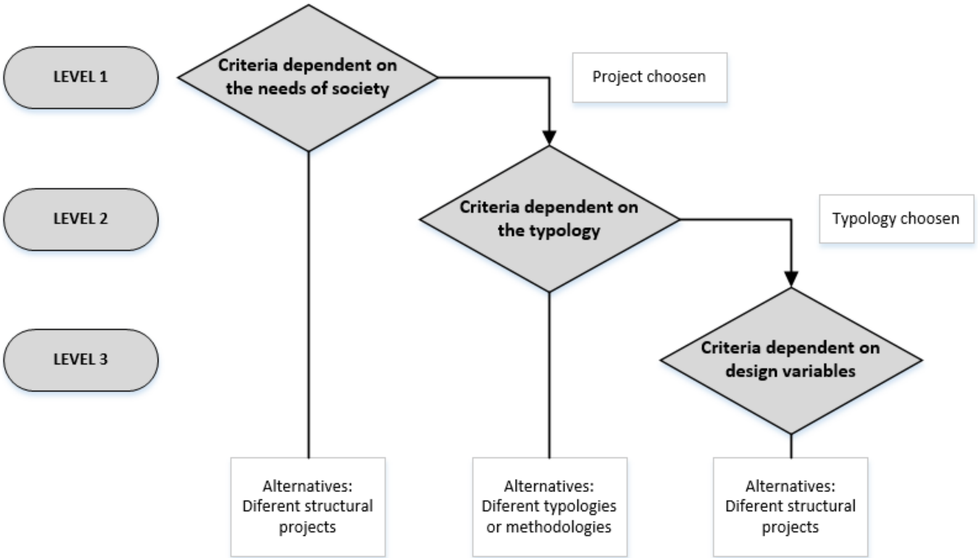

Figure 6.2.5. Decision-making problem levels

This work focuses on a third level decision-making problem. The goal was to reach the most sustainable design for a concrete box-girder pedestrian bridge according to eight variables (seven geometric variables that define the cross-section of the bridge and the concrete strength). For this purpose, the first step was to define all the criteria that cover all the perspectives of the sustainability assessment of a concrete box-girder pedestrian bridge along its whole life-cycle. Eleven criteria were considered, covering the three main pillars of sustainability and constructability of the bridge. This last group included evaluating the technical part. Figure 6.2.6 shows all the criteria considered.

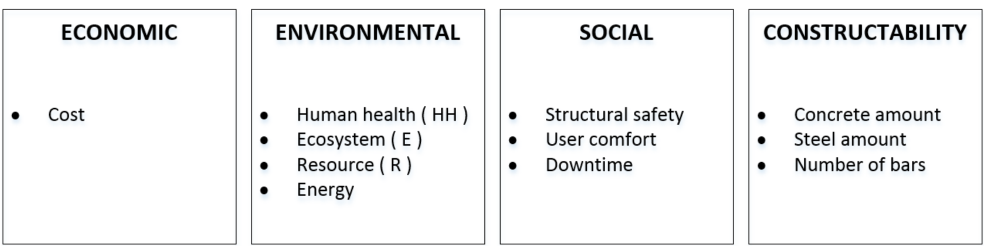

Figure 6.2.6. Sustainability criteria

A previous review of the criteria used for the sustainability assessment of bridges [10] was used as the basis for selection of the criteria considered in this work. The review shows a high consensus to assess the economic aspect, in which the total cost is the most-used criterion. This work assessed the economic aspect using information provided by the BEDEC database [23]. Review of the environmental aspect shows that it is common to use one or two criteria to define the environmental aspect (CO_2 and energy are the most-used criteria). However, to obtain a full environmental profile, it is necessary to consider a set of criteria that represent a complete environmental assessment [24]. For this purpose, this work used the endpoint approach of the life-cycle impact assessment method ReCiPe [25], using information provided by the Ecoinvent database [26] and processed using OpenLCA software. In this way, a complete environmental assessment was obtained and all the environmental impacts were considered [12,27]. Finally, the review shows that the social aspect is the most unclear. There is a high disagreement in defining the criteria that best represent the social aspect. Criteria such as detour time, dust, and noise have been used in different works [5,28,29]. Most of these criteria are associated with the different life-cycle activities on the bridge (construction and maintenance activities). For this reason, a single criterion that involves all the criteria that emerge during the work activities is considered, such as downtime. Additionally, structural safety and user comfort are included in the social aspect [1,9,11]. Furthermore, a last group of criteria has been defined to represent the technical aspect and the ease construction of the bridge. This group includes the amount of concrete, the amount of steel, and the number of bars [30].

All these criteria were calculated along the whole life-cycle of the bridge. For this purpose, according to the initial bridge design, all the impacts were obtained for each stage of the bridge life-cycle: production, construction, use and maintenance, and end of life. The production stage covers all the products, processes, and services from the extraction of raw material to material disposal at the construction site. The construction stage refers to the products, processes, and services during bridge construction activities. The use and maintenance stage involves all the products, processes, and services along the service life of the bridge, including the maintenance activities. The end of life stage includes all the products, processes, and services after the service life of the bridge ends. A large description of all the products, processes, and services considered along the whole life-cycle of the bridge is explained in Penadés-Plà et al. [13].

Table 6.2.2 shows the unit prices and the unit environmental impacts of all the materials and processes considered in the life-cycle assessment. The BEDEC database [23] provides the unit prices and the ReCiPe method [25] provides the unit damage categories (Human health, Ecosystem, and Resources). The human health category includes the years of life lost and years of life disabled, the ecosystem category refers to the loss of species during a certain time in a certain area, and resources assesses how the use of mineral and fossil resources causes changes in the effort needed to extract future resources. The unit cost and the unit damage categories consider all the progress of the materials and processes defined. The other criteria (social and constructability) are calculated once the bridge design is defined. Structural safety is the lowest safety coefficient of the ultimate limit state (ULS), user comfort corresponds to the vibration service limit state (SLS), and downtime is the days that the bridge is not operational. The concrete amount is obtained once the geometric design is defined, and the steel amount and number of bars once the bridge is designed. The assessment of all these criteria throughout the life cycle given the initial bridge design has been carried out by means of a program coded in Matlab.

Table 6.2.2. Measurement units

UNIT MEASUREMENTS	COST (€)	RECIPE (points)		
		Human health	Ecosystem	Resources
Truck (t*km)	0.039	6.78E-03	3.74E-03	6.60E-03
Truck mixer (t*km)	0.095	1.63E-02	8.98E-03	1.58E-02
B-500-S steel (kg)	1.16	0.09	0.03	0.11
Y1860-S7 post-tensioned steel (kg)	2.56	0.09	0.03	0.11
HP-35 concrete (m^3)	104.57	7.71	5.68	2.06
HP-40 concrete (m^3)	109.33	8.26	6.07	2.28
HP-45 concrete (m^3)	114.1	8.98	6.59	2.42
HP-50 concrete (m^3)	118.87	10.26	7.5	2.78
HP-55 concrete (m^3)	123.64	11.7	8.54	3.18
HP-60 concrete (m^3)	128.41	12.51	9.11	3.58
HP-70 concrete (m^3)	137.95	12.7	9.25	3.61
HP-80 concrete (m^3)	147.49	12.86	9.36	3.77
HP-90 concrete (m^3)	157.02	13.34	9.7	3.86
HP-100 concrete (m^3)	166.56	14.09	10.23	4.13
Formwork (m^2)	33.81	0.23	0.17	0.99
Lighting (m^3)	104.57	0.04	0.24	0.06
Concrete placement (m^3)	30.06	3.85E-03	2.25E-03	2.34E-03
Steel placement (kg)	1.0847	3.20E-04	1.80E-04	1.90E-04
Repair mortar application	16.41	2.16E-04	2.16E-04	1.40E-04
Bonding coat application	43.28			
Truck-mounted platform	53.71	7.78E-03	3.07E-03	1.22E-03
Water blasting	11.5			
Demolition (m^3)	10.57	0.00047	0.00019	0.00073
Crushing (m^3)	5.88	0.00064	0.00032	0.00093

At the end of the bridge assessment, each criterion has different units. Therefore, for the sustainability assessment of the bridge, it is necessary to normalize these criteria for later aggregation. For this purpose, a linear normalization was applied to the different criteria. To facilitate the aggregation of the criteria to carry out the sustainability assessment, the best-normalized value of each criterion will be 0 and the worst will be 1. Therefore, in the case that the best value of the criteria is the lowest one, Eq. 6.2.2 is used. Otherwise, if the best value is the greatest one, Eq. 6.2.3 is used.

$$v_i = \frac{(x_i - x_{min})}{(x_{max} - x_{min})} \tag{6.2.2}$$

$$v_i = \frac{(x_{max} - x_i)}{(x_{max} - x_{min})} \tag{6.2.3}$$

6.2.3.2.Principal component analysis

Before the principal component analysis is carried out, an initial sample of pedestrian bridges should be defined. For this purpose, Latin hypercube sampling (LHS) was used according to Penadés-Plà et al. [19]. LHS was proposed by McKay et al. in 1979 [31]. This method determines N number of non-overlapping intervals for each variable, divided according to a uniform distribution, from a number of design variables (v) and a sample size (N). Therefore, the design space is divided into Nv regions. This method guarantees that each point of the sample is in one of these regions, so each interval of each design variable range is only taken for one point of the sample. Consequently, LHS guarantees that all the design variables are represented along with their respective ranges.

In this work, an initial sample size of 500 box-girder pedestrian bridges was considered according to to Penadés-Plà et al. [19]. These bridges have eight variables, concrete strength and seven geometric variables to define the cross-section of the bridge. The concrete strength (f_{ck}) ranged from 35–100 MPa. Depth (h) ranged from 1.25–2.5 meters, the bottom slab width (b) ranged from 1.2–1.8 meters, the web inclination width (d) ranged from 0–0.4 meters, the web slab thickness (e_a) ranged from 0.3–0.6 meters, and the other slab thicknesses (e_v, e_s, e_i) ranged from 0.15–0.4 meters.

Principal component analysis (PCA) is a statistical procedure that allows converting a set of possible correlated criteria into a set of linearly independent variables called principal components [16]. This work applied PCA to decrease the eleven original criteria into a set of principal components. This avoided excessively valuing (positively or negatively) some sustainable criteria due to their high correlation.

The first step in PCA is to obtain the total amount of variance in each original criterion that can be explained by the retained principal components (Table 6.2.3).

This is represented by the communalities after the extraction. Field [32,33] stated that for a sample size higher than 300 the communalities after extraction should be over 50%. The second column of Table 6.2.3 shows that all the criteria have communalities greater than 50%.

Table 6.2.3. Communalities

	Initial	Afer extraction
Cost	1	0.981
Human Health	1	0.949
Ecosystem	1	0.932
Resources	1	0.967
Downtime	1	0.981
Structural safety	1	0.521
User comfort	1	0.937
Concrete amount	1	0.919
Steel amount	1	0.885
Numer of bars	1	0.684

Table 6.2.4 shows the total amount of variance that can be explained by each principal component. The first principal component is the one that explains the greatest variability of the analysis. The second one has the second greatest variability explained, and so on. In this case, the first principal component explained 50.24% of the analysis, the second explained 22.73%, and the third one 14.58%, adding to a total of 87.55%. There are two different approaches to determine the number of principal components to consider. On the one hand, Kaiser [34] stated that all the principal components that have an eigenvalue higher than one should be considered. On the other hand, the number of principal components that should be considered are those that explains more than a specific portion of the analysis variability. In this case, the first three principal components have eigenvalues higher than one and explain almost 90% of the analysis variability.

Table 6.2.4. Total variance explained

Principal component	Initial eigenvalues			Addition of loads to the square of the extraction		
	Total	% of variance	% accumulated	Total	% of variance	% accumulated
1	5.024	50.236	50.236	5.024	50.236	50.236
2	2.273	22.734	72.970	2.273	22.734	72.970
3	1.458	14.577	87.547	1.458	14.577	87.547
4	0.600	6.001	93.548			
5	0.475	4.753	98.302			
6	0.115	1.146	99.448			
7	0.049	0.495	99.943			
8	0.005	0.049	99.991			
9	0.001	0.008	100.000			
10	0.000	0.000	100.000			

Finally, the correlation between the original criteria and the principal components was obtained. In this way, the value of the first three principal components can be calculated as a linear combination of the original criteria. Table 6.2.5 shows the principal component matrix, in which the correlations between all the original variables on each principal component are displayed. Authors [32] stated that significant loadings are those with a correlation higher than 0.4, and loadings smaller than 0.4 can be excluded.

Table 6.2.5. Principal component matrix

	Component		
	1	2	3
Cost		0.937	
Human Health	0.893		
Ecosystem	0.818		
Resources	0.960		
Downtime		0.927	
Structural safety	-0.602		
User comfort	-0.879		
Concrete amount	0.792		-0.531
Steel amount	0.811		
Numer of bars			0.690

6.2.3.3.Kriging-based optimization

The purpose of metamodels is to build an approximate mathematical model of a detailed simulated model, which predicts the objective response from the design variables in the design space. Once the approximate mathematical model is established, all the calculations made using metamodels are much more efficient than using the detailed simulated model. Penadés-Plà et al. [19] compare a conventional heuristic optimization against a kriging model-based heuristic optimization using a simulated annealing algorithm and show that the time reduction using the kriging-based heuristic optimization is greater than 90% compared to conventional heuristic optimization. In addition, most of the time consumed by the kriging-based heuristic optimization was due to the calculation of the initial sample size. All while reaching solutions similar to the conventional heuristic optimization. A longer description of the kriging metamodel can be found in Kleijnen [35], where the corresponding mathematical development is also explained.

The objective of this work is to study the influence of the uncertainty in the decision-making problems and to obtain the sustainable alternatives that best represent the different perspectives of sustainability. For this purpose, an optimization problem that represents the most sustainable bridge according to different perspectives of sustainability was proposed. The most sustainable bridge was defined as an aggregation index (sustainability index) in which different relative weights were assigned to each principal component (that is correlated to the original variables), as shown in Eq. 6.2.4. In this way, the most sustainable bridge according to each perspective can be obtained. In this work, 1000 different random perspectives of sustainability are generated. Each one of these perspectives is defined by a set of relative weights that provides a different objective function (sustainability index) for each one of the bridges of the initial sample. Therefore, 1000 different optimization problems are defined and a set of most sustainable bridge designs will obtained. Due to the high computational cost required to cover all these optimizations, the kriging model is the best option due to its high computational efficiency.

$$I = w_1.PC_1(x_{1,}x_{2,}\dots.,x_n) + w_2.PC_2(x_{1,}x_{2,}\dots.,x_n) + w_3.PC_3(x_{1,}x_{2,}\dots.,x_n) \quad (6.2.4)$$

$$g_j(x_1,x_2,x_3,\dots,x_n) \leq 0 \quad (6.2.5)$$

where x_1, x_2, x_3, .., x_n are the design variables.

A total of 1000 random relative weight sets (w_1, w_2, w_3) were generated. Each of these relative weight sets provided a different sustainability index for each bridge in the initial sample size (a different objective response for each bridge) according to Equation 4, and therefore a different kriging surface. Thus, the optimization of each of these relative weight sets gives the most sustainable bridge according to each relative weight set. Hence, this optimization aims to obtain the most sustainable bridge (Equation 6.2.4) satisfying the constraints (Equation 6.2.5) that guarantee the limit states of serviceability and ultimate limit states (SLS and ULS) of vertical shear, longitudinal shear, punching shear, bending, torsion, torsion combined with bending and shear, cracking, compression and tension stress, and vibration. In addition, the geometric and constructability requirements are verified, following the Spanish regulations for this type of structure [36,37] as well as the Eurocodes [38,39]. In this way, a total of 1000 optimization problems to obtain the most sustainable box-girder pedestrian bridge designs according to the 1000 different random perspectives are defined.

6.2.3.4. Multi-attribute decision-making

Once the set of most sustainable bridges are obtained, the decision-makers must choose one according to their preferences. Many MADM methods have been developed [8,10]. The pairwise comparison methods are popular because of their simplicity to convert subjective assessment into numerical values. In this group, the analytical hierarchy process (AHP) and the analytical network process (ANP), are the most used. The main difference between both MADM methods is that the ANP method considers the influence between criteria. In this case, due to the independence of the principal components, the use of the ANP method made no sense, and the AHP method was considered valid for the study. The AHP method was developed by Saaty in the 1970s [40], becoming one of the most popular decision-making methods due to its ease of use. Many works have used the AHP method for different decision-making problems [6,7,41]. To build the hierarchical structure, it is necessary to use a lower number of criteria since pairwise comparison can become difficult. Bahurmoz [42] stated that the maximum number of criteria must be seven, and Miller [43] stated that the number of criteria assimilable by people is 7±2. In this case, due to the reduction from 11 criteria to three principal components that represent all the criteria of sustainability the problem of excessive criteria is solved, so the AHP method is absolutely valid for this study. The relative weight of each principal component is obtained using the pairwise comparison. Saaty [18] proposed a fundamental scale to carry out the comparison among the different criteria (Table 6.2.6). After this scale, new scales were made by other authors.

Table 6.2.6. Saaty's fundamental scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	One activity is slightly favored over another
5	Strong importance	One activity is strongly favored over another
7	Very strong importance	One activity is very strongly favored over another
9	Extreme importance	One activity is the highest favoring over another

Once the decision-maker has made the pairwise comparisons, the consistency of the decision-making matrix is evaluated. This is made to spot contradictions in the decision-maker's assessment. The consistency is obtained by means of the Consistency Index, CI (Eq. 6.2.6), where λmax is the maximum eigenvector and N is the dimension of the decision-making matrix. A consistency index of 0 means a full consistency. After that, the Consistency Ratio, CR (Eq. 6.2.7) is calculated, with acceptable values under 10%.

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (6.2.6)$$

$$CR = \frac{CI}{RI} \qquad (6.2.7)$$

Once the consistency is verified, the weights for each criterion of this decision-making matrix are obtained (Eq. 6.2.8).

$$A \cdot w = \lambda_{max} \cdot w \qquad (6.2.8)$$

The pairwise comparison explained above refers to only one decision-maker's assessment. If different decision-makers take part in the same decision-making problem, each decision-maker will create a different decision-making matrix that generates different relative weights for the criteria, and consequently a different final sustainability index, which causes the selection of a different alternative. This work studies how this uncertainty affects different samples in the same decision-making problem. For this purpose, 1000 hypothetic random decision-makers are created to assess each one of the most sustainable box-girder pedestrian bridge designs obtained in the subsection 3.3, as long as the decision-making matrix will be consistent. In this way, the mean and the variability of the sustainability index of each bridge can be obtained. In addition, a set of set of sustainable solutions will be chosen independently of the preferences of the decision-makers.

6.2.4. Results

The procedure described in Section 3 leads to a set of solutions, which are chosen independently of the decision-maker preferences. These solutions are the most sustainable bridges according to the initial criteria considered. In this way, it is possible to reduce a large set of solutions to the most sustainable solutions, making the final selection by the decision-maker easy. In addition, independent of the final decision of the decision-maker, the bridge chosen will be a sustainable bridge. In this work, an initial set of 500 box-girder pedestrian bridges were generated by LHC. After that, a large set of most sustainable bridges that cover all the perspectives of sustainability was obtained using PCA and kriging-based optimization. Finally, 1000 random decisions were generated using the AHP method, and each of these decisions leads to one bridge according to the preferences. This process allows reducing the first 500 random box-girder pedestrian bridges to four solutions that are considered the most sustainable box-girder bridge independent of the preferences of the decision-maker (Tables 6.2.7 and 6.2.8). Therefore, these solutions are the bridges that represent the different points of view of decision-makers within the best sustainable bridges. So, within the set of the most sustainable solutions, Solution 3 is the bridge with the best safety security, comfort and lowest number of bars, Solution 4 is the bridge with the best cost and environmental impact. Solution 1 and Solution 2 are intermediate solutions between Solution 3 and Solution 4.

Table 6.2.7. Variables of sustainable solutions

	b (mm)	h (mm)	d (mm)	e_v (mm)	e_s (mm)	e_a (mm)	e_i (mm)	f_{ck} (MPa)	t (mm)
S1	1200	1400	25	150	150	350	150	70	150
S2	1200	1300	150	150	150	375	225	60	225
S3	1200	1350	25	175	175	350	150	70	150
S4	1200	1400	0	150	150	350	150	60	150

Table 6.2.8. Criteria of sustainable solutions

	Cost (€)	HH (points)	E (points)	R (points)	Downtown (days)	Structural safety	User comfort	Concrete amount (m^3)	Steel amount (kg)	Number of bars (unit)
S1	179501.5	6438.1	2656.9	8831.2	120	1.209	1.939	199.1	36857.1	54
S2	175467.7	5984.9	2484.4	8207.7	120	1.183	1.929	213.0	32587.3	53
S3	184497.3	6733.7	2743.1	9161.7	120	1.213	1.939	201.9	40197.1	52
S4	170393.6	5870.6	2463.3	8173.1	120	1.200	1.938	198.4	30925.4	64

In addition, each box-girder pedestrian bridge will have 1000 different sustainability indices according to the 1000 random decision-makers. Therefore, it is possible to obtain some statistical parameters (the mean, the standard deviation, and the coefficient of variation) of the sustainability index for each bridge according to the different perspectives of the decision-maker. These statistical parameters will provide useful information about the influence of the decision-maker's preferences on the final sustainability value. On the one hand, the mean sustainability index represents the mean sustainability assessment of all the decision-makers. Thus, a lower mean value means that the general satisfaction of the decision-makers is higher. On the other hand, the coefficient of variation represents the stability of the solution against the different perspective of decision-makers. Thus, a lower coefficient of variation means that there is a higher consensus on the sustainability index, which means that, regardless of the decision-maker's preferences, the sustainability index varies little.

In this way, it may be possible that one bridge has a good mean sustainability index but may not be the best for some decision-makers, while another bridge that has a higher mean sustainability index, may be chosen by some decision-makers. Tables 6.2.7 and 6.2.8 show the variables and criteria of the solutions that were chosen for at least one decision-maker and Table 6.2.9 shows their position according to the mean sustainability index. Solution 1 and Solution 2 also appear in the top four solutions according to the mean sustainability index. Conversely, Solution 3 and Solution 4, while preferred for some decision-makers, have a mean sustainability index higher than other solutions that were not chosen for any decision-maker. For example, Solution A has the third best mean sustainability index, but it has not been chosen by any decision-maker as the preferred solution. In addition, a low coefficient of variation shows that the sustainability assessment of that bridge design is less sensitive to a decision-maker's opinion. For example, Solution B has a high mean sustainable index, but its coefficient of variation is the lowest one.

Table 6.2.9. Statistical parameters of sustainable solutions

	General sustainable assessment		Stability of the sustainable assessment	
	Mean	**Position**	**σ**	**CV**
Solution 1	0.061	2	0.035	57.20%
Solution 2	0.048	1	0.018	37.66%
Solution 3	0.081	6	0.057	69.88%
Solution 4	0.072	5	0.040	56.53%
Solution A	0.066	3	0.023	34.69%
Solution B	0.681	69	0.137	20.17%

The box-girder pedestrian bridge that best satisfies the different preferences of the decision-makers is the bridge with the lowest sustainable index and the lowest coefficient of variation. The absolute positive ideal point is a sustainability index of 0 and a coefficient of variance of 0. However, the solutions with a lower mean sustainability index have a higher coefficient of variation and the solutions with a higher mean sustainability index have a lower coefficient of variation (Figure 6.2.7). Therefore, the most appropriate solution, taking into account the mean sustainable index and the coefficient of variation, will be the closest solution to the absolute positive ideal point. This solution will be called the most sustainable robust solution. This solution will have a low mean sustainable index and a low coefficient of variance, which means that stability against the different preferences of decision-makers will be strong. This indicates that the solution has a great sustainable assessment and its assessment is little influenced by the different preferences of the decision-maker. In this work, the most sustainable robust box-girder pedestrian bridge is Solution C, whose cross-section variables are b=1.2 m, h= 1.35 m, d=0.15 m, e_v=0.15 m, e_s=0.15 m, e_a=0.35 m, e_i=0.25 m, and f_{ck}=60 MPa. This solution is shown with an arrow in Figure 6.2.7 and its distance to the absolute positive ideal is 0.353 (Table 6.2.10).

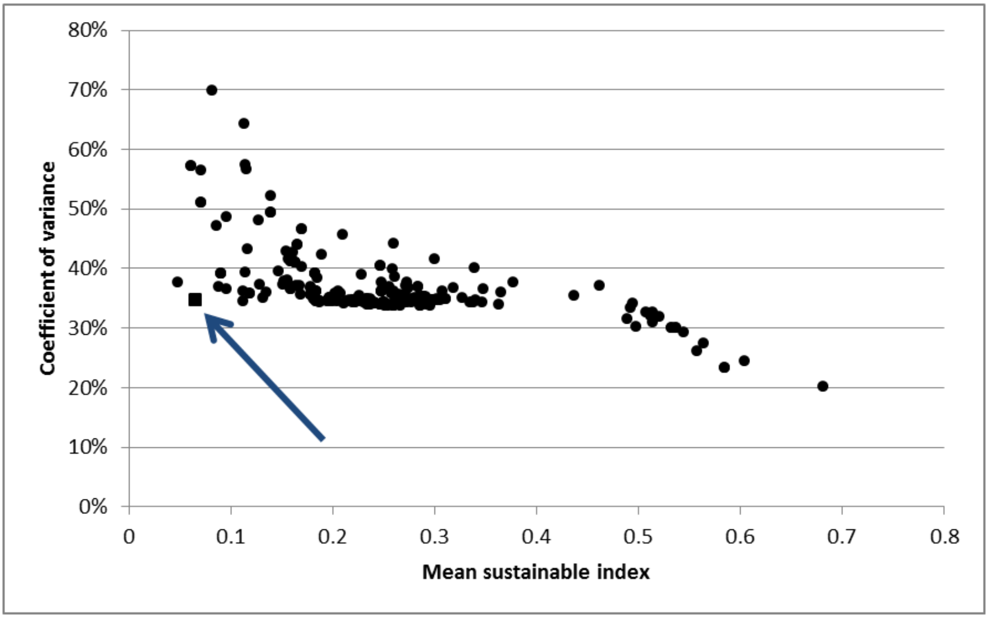

Figure 6.2.7. Pareto front of sustainable solutions

Table 6.2.10. Sustainable robustness assessment

	General sustainable assessment	Stability of the sustainable assessment		Distance	
	Mean	σ	CV	Distance	Position
Solution 1	0.061	0.035	57.20%	0.575	168
Solution 2	0.048	0.018	37.66%	0.380	7
Solution 3	0.081	0.057	69.88%	0.704	191
Solution 4	0.072	0.040	56.53%	0.570	167
Solution C	0.066	0.023	34.69%	0.353	1

6.2.5. Conclusions

In the construction sector, there is a current trend towards improving sustainability performance due to the great impact of structures in the economic, environmental and social context. However, sustainability assessment is a complex process that involves a large number of alternatives, criteria, and decision-makers who make a subjective assessment of the importance of the different criteria according to their perspective or interests. For this reason, this work shows a methodology that can reduce the participation of the decision-maker for the selection of the most sustainable alternative and reduces the sensitivity to the stakeholder’s opinion. In this way, the final alternative can be considered a sustainable solution regardless of the interests of the decision-maker.

This methodology has been applied for the selection of a box-girder concrete pedestrian bridge considering its entire life cycle assessment. To this end, a set of criteria representing the sustainability goal was first defined and a random set of bridges was calculated. In order to avoid the high correlation of some criteria, PCA was used. Then, kriging-based optimization was applied to reach the most sustainable bridge according to 1000 random relative weights. In this way, all the perspectives of sustainability are covered. Finally, 1000 random decision-makers were generated using the AHP method to select the preferred bridges according to the different preferences. Each of these random decision-makers chose the most sustainable bridge according to their interests, reducing the set of eligible alternatives.

After this process, the 500 alternatives of the initial sample were reduced to four sustainable alternatives. In this way, the participation of the decision-maker was reduced to a choice between four alternatives that will be always sustainable. These four alternatives were the safest and most comfortable alternative (Solution 3), most economical and environmentally friendly (Solution 4), and intermediate alternatives between the first two (Solution 1 and Solution 2). In addition, the results show the alternatives that have the best mean sustainability index and those that are more stable against the preferences of decision-makers, which mean that they are more robust. This turns the decision-making process into an objective process in which the final solution does not depend on the preference of a decision-maker. A solution can have a good mean assessment while it is not chosen by any decision-maker (Solution A) or it is very stable against the different assessments of the decision-makers (Solution B). Finally, the most robust solution was obtained (Solution C). Comparing this solution with the most economical solution, this solution is 3.37% more expensive than the most economical solution (Solution 2), and the environmental impact is also a little greater (2.85% for Human Health, 2.85% for Ecosystem and 1.83% for Resources) and similar comfort (0.19% better) and structural safety (0.12% worse). In addition, the number of bars used is 16.36%

lower, which improves workability. Therefore, the selected solution is optimal regarding the life-cycle sustainability criteria and it is robust against the stakeholder's opinion.

Acknowledgments

The authors acknowledge the financial support of the Spanish Ministry of Economy and Competitiveness, along with FEDER funding (Project: BIA2017-85098-R).

References

[1] García-Segura T, Yepes V. Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety. Engineering Structures 2016;125:325–36. doi:10.1016/j.engstruct.2016.07.012.

[2] Zastrow P, Molina-Moreno F, García-Segura T, Martí J V., Yepes V. Life cycle assessment of cost-optimized buttress earth-retaining walls: A parametric study. Journal of Cleaner Production 2017;140:1037–48. doi:10.1016/j.jclepro.2016.10.085.

[3] García-Segura T, Yepes V, Alcalá J, Pérez-López E. Hybrid harmony search for sustainable design of post-tensioned concrete box-girder pedestrian bridges. Engineering Structures 2015;92:112–22. doi:10.1016/j.engstruct.2015.03.015.

[4] Du G, Karoumi R. Life cycle assessment framework for railway bridges: Literature survey and critical issues. Structure and Infrastructure Engineering 2014;10:277–94. doi:10.1080/15732479.2012.749289.

[5] Gervásio H, Simões Da Silva L. A probabilistic decision-making approach for the sustainable assessment of infrastructures. Expert Systems with Applications 2012;39:7121–31. doi:10.1016/j.eswa.2012.01.032.

[6] Pan N-F. Fuzzy AHP approach for selecting the suitable bridge construction method. Automation in Construction 2008;17:958–65. doi:10.1016/j.autcon.2008.03.005.

[7] Aghdaie MH, Zolfani SH, Zavadskas EK. Prioritizing constructing projects of municipalities based on AHP and COPRAS-G: A case study about footbridges in Iran. The Baltic Journal of Road and Bridge Engineering 2012;7:145–53. doi:10.3846/bjrbe.2012.20.

[8] Hwang CL, Yoon K. Multiple attribute decision making: Methods and Applications. 1981.

[9] Zavadskas EK, Liias R, Turskis Z. Multi-attribute decision-making methods for assessment of quality in bridges and road construction: State-of-the-art

surveys. The Baltic Journal of Road and Bridge Engineering 2008;3:152–60. doi:10.3846/1822-427X.2008.3.152-160.

[10] Penadés-Plà V, García-Segura T, Martí J, Yepes V. A review of multi-criteria decision-making methods applied to the sustainable bridge design. Sustainability 2016;8:1295. doi:10.3390/su8121295.

[11] Yehia S, Abudayyeh O, Fazal I, Randolph D. A decision support system for concrete bridge deck maintenance. Advances in Engineering Software 2008;39:202–10. doi:10.1016/j.advengsoft.2007.02.002.

[12] Pons JJ, Penadés-Plà V, Yepes V, Martí J V. Life cycle assessment of earth-retaining walls: An environmental comparison. Journal of Cleaner Production 2018;192:411–20. doi:10.1016/j.jclepro.2018.04.268.

[13] Penadés-Plà V, Martí J V., García-Segura T, Yepes V. Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges. Sustainability 2017;9:1864. doi:10.3390/su9101864.

[14] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: An overview. Energy and Buildings 2010;42:1592–600. doi:10.1016/j.enbuild.2010.05.007.

[15] Opricovic S, Tzeng G-H. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. European Journal of Operational Research 2004;156:445–55. doi:10.1016/S0377-2217(03)00020-1.

[16] Hotelling H. Relations between two sets of variates. Biometrika 1936;28:321–77. doi:10.2307/2333955.

[17] Cressie N. The origins of kriging. Mathematical Geology 1990;22:239–52. doi:10.1007/BF00889887.

[18] Saaty RW. The analytic hierarchy process—what it is and how it is used. Mathematical Modelling 1987;9:161–76. doi:10.1016/0270-0255(87)90473-8.

[19] Penadés-Plà V, García-Segura T, Yepes V. Accelerated optimization method for low-embodied energy concrete box-girder bridge design. Engineering Structures 2019;179:556–65. doi:10.1016/J.ENGSTRUCT.2018.11.015.

[20] Begicevic N, Divjak B, Hunjak T. Comparison between AHP and ANP: Case Study of strategic planning of E-learning implementation. Development 2007;1:1–10.

[21] Görener A. Comparing AHP and ANP: An application of strategic decisions making in a manufacturing company. International Journal of Business and Social Science 2012;3:194–208.

[22] Schlaich J, Scheef H. Concrete box-girder bridges. International Association for Bridge and Structural Engineering, Zürich, Switzerland: 1982.

[23] Catalonia Institute of Construction Technology. BEDEC PR/PCT ITEC material database 2016.

[24] Laurent A, Olsen SI, Hauschild MZ. Limitations of carbon footprint as indicator of environmental sustainability. Environmental Science & Technology 2012;46:4100–8. doi:10.1021/es204163f.

[25] Goedkoop M, Heijungs R, Huijbregts M, Schryver A De, Struijs J, Zelm R Van. ReCiPe 2008. A life cycle impact assessment which comprises harmonised category indicators at midpoint and at the endpoint level. Netherlands: 2009. doi:10.029/2003JD004283.

[26] Ecoinvent Center. Ecoinvent v3.3 2016.

[27] Penadés-Plà V, Martí JV, García-Segura T, Yepes V. Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges. Sustainability (Switzerland) 2017;9:1864. doi:10.3390/su9101864.

[28] Sabatino S, Frangopol DM, Dong Y. Sustainability-informed maintenance optimization of highway bridges considering multi-attribute utility and risk attitude. Engineering Structures 2015;102:310–21. doi:10.1016/j.engstruct.2015.07.030.

[29] Chen Z, Abdullah AB, Anumba CJ, Li H. ANP experiment for demolition plan evaluation. Journal of Construction Engineering and Management 2013;140:51–60. doi:10.1061/(ASCE)CO.

[30] Martinez-Martin FJ, Gonzalez-Vidosa F, Hospitaler A, Yepes V. Multi-objective optimization design of bridge piers with hybrid heuristic algorithms. Journal of Zhejiang University: Science A 2012;13:420–32. doi:10.1631/jzus.A1100304.

[31] McKay MD, Beckman RJ, Conover WJ. Comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics 1979;21:239–45. doi:10.1080/00401706.1979.10489755.

[32] Field A. Discovering statistics using SPSS (2nd Edition). London, England: Sage; 2005.

[33] Kaiser HF. An index of factorial simplicity. Psychometrika 1974;39:31–6. doi:10.1007/BF02291575.

[34] Kaiser HF. The application of electronic computers to factor analysis. Educational and Psychological Measurement 1960;20:141–51. doi:10.1177/001316446002000116.

[35] Kleijnen JPC. Kriging metamodeling in simulation: A review. European Journal of Operational Research 2009;192:707–16. doi:10.1016/j.ejor.2007.10.013.

[36] Ministerio de Fomento. EHE-08: Code on structural concrete. Madrid, Spain: 2008.

[37] Ministerio de Fomento. IAP-11: Code on the actions for the design of road bridges. Madrid, Spain: 2011.

[38] European Committee for Standardization. EN 1001-2:2003. Eurocode 1: Actions on structures- Part 2: Traffic loads bridges. Brussels, Belgium: 2003.

[39] European Committee for Standardisation. EN1992-2:2005. Eurocode 2: Design of concrete structures- Part 2: Concrete Bridge-Design and detailing rules. Brussels: 2005.

[40] Saaty TL. The Analytic Hierarchy Process. New York: 1980.

[41] Chou J-S, Pham A-D, Wang H. Bidding strategy to support decision-making by integrating Fuzzy AHP and regression-based simulation. Automation in Construction 2013;35:517–27. doi:10.1016/j.autcon.2013.06.007.

[42] Bahurmoz AMA. The analytic hierarchy process: A methodology for win-win management. JKAU: Econ & Adm 2006;20:3–16.

[43] Miller GA. The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information n.d.

CHAPTER 7. ROBUST DESIGN OPTIMIZATION

7.1. Introduction

The optimization of bridges is a process that has been carried out in many works with different objective functions. Normally, when this optimization is carry out, the nominal values of different initial design variables and parameters are considered. Therefore, the bridge will perform well under the initially defined conditions, but the behavior can change when the conditions move away from those of the design. In this chapter, a cost-optimized bridge with a stable structural behavior against variation of the initial uncertain parameters is sought. This bridge is defined as an optimum robust bridge. The bridge will be optimum against the cost and robust against the structural behavior.

7.2. Robust design optimization for low-cost concrete box-girder bridge[6]

[6] Penadés-Plà V, García-Segura T, Yepes V. Robust design optimization for low-cost concrete box-girder bridge. *Engineering Structures (Submitted)*

Vicent Penadés-Plà[a], Tatiana García-Segura[b], Víctor Yepes[c*]
[a] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. Corresponding author. E-mail: vipepl2@cam.upv.es
[b] Dept. of Construction Engineering and Civil Engineering Projects, Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: tagarse@upv.es
[c] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain. E-mail: vyepesp@cst.upv.es

Abstract

The design of a structure is generally carried out according to a deterministic approach. However, all structural problems have associated initial uncertain parameters that can differ from the design value. This becomes important when the goal is to reach optimized structures, as a small variation of these initial uncertain parameters can have a big influence on the structural behavior. The objective of robust design optimization is to obtain an optimum design with the lowest possible variation of the objective functions. For this purpose, a probabilistic optimization is necessary to obtain the statistical parameters that represent the mean value and variation of the objective function considered. However, the main limitation of robust design optimization is the high computational cost required. In this paper, robust design optimization is applied to design a continuous prestressed concrete box-girder pedestrian bridge that is optimum in terms of its cost and robust in terms of structural stability. Furthermore, latin hypercube sampling and the kriging metamodel are used to deal with the high computational cost. Results show that the main variables that control the structural behavior are the depth and strength of the concrete, and that a compromise solution between the optimal cost and the robustness of the design can be reached.

Keywords: Robust design optimization; RDO; Post-tensioned concrete; Box-girder bridge, Structural optimization, Metamodel, Kriging.

7.2.1. Introduction

All structural problems have an associated variability or uncertainty [1,2]. In the design of a structure there are initial parameters, such as the dimensions of the structure, the mechanical characteristics of the materials, and the loads, which can differ from design value [3,4]. Nevertheless, the design of a structure is made using the nominal value, which has a low probability of occurring (for example, the resistance of concrete is the resistance that has a 5% of probability of failure). In addition, safety coefficients associated with a given probability of failure are assigned. However, a variation of these initial uncertain parameters can influence the variability of the structural behavior. Structural optimization usually uses a deterministic approach that does not consider the effects of the associated uncertainty [5–9]. This means that the structure has an optimum behavior only under the conditions initially defined, and the response can vary significantly when the values differ from the design values.

Unlike this approach, robust design has been studied to obtain designs in which the uncertainty of the initial parameters has the lowest possible influence on the objective response [10]. This robust design is reached by a probabilistic optimization. Nowadays, there are two approaches to the optimal probabilistic design of a structure: Reliability-Based Design Optimization, RBDO [11] and Robust Design Optimization, RDO [12]. In RBDO, the probability of failure is studied from the variations of the initial parameters. RDO studies a design that is less sensitive to variations of the initial parameters. The present paper focuses on the RDO. The concept of robust design was proposed by Taguchi in the 1940s, and applied to optimization problems in 1980 [1]. This approach uses the mean and standard deviation to study the variability of the objective response.

The main limitation of RDO is the high computational cost required due to the high number of optimizations that must be made to assess the sensitivity of the objective response of the problem [10,13]. For this reason, it is necessary to find methods that allow carrying out the optimization process more efficiently [4,10,14,15]. Metamodels allow the generation of a mathematical approximation of the objective response (an objective surface) from the assessment of points within the design space. Once the response surface has been generated, obtaining the value of the objective response given the inputs is much faster. These mathematical approximations or metamodels have already been used to solve RDO process problems [4,10]. Of all these metamodels, the kriging model has been demonstrated to be really useful to obtain great reliability in the assessment of the response due to its predictive accuracy in non-linear functions [16]. Penadés Plà et al. [17] made a comparison between conventional heuristic optimization and heuristic optimization based on kriging models, demonstrating that the solutions obtained through optimization based on kriging models are very close to the solutions obtained through conventional heuristic optimization, but with high computational cost savings.

In the present paper, the robust design methodology is applied to a continuous prestressed concrete box-girder pedestrian bridge to obtain a bridge that is optimal in terms of its cost objective function and also robust in terms of structural stability. Its structural stability is measured by the variability of the vertical displacement in the middle of the bridge [10,14]. For this purpose, latin hypercube sampling is used to obtain the initial sampling, the kriging model is used to obtain the mathematical approximation to the response, and then the simulated annealing optimization algorithm is used to obtain the robust optimum design. All this will be studied for different uncertain design parameters: the modulus of elasticity, the overload, and the prestressing force.

7.2.2. Robust design optimization

Robust design studies the variation of the objective response generated by the uncertain initial parameters. Therefore, the goal of robust design optimization (RDO) is to reach the best objective response with the lowest variation. It implies that the RDO problem is defined as a multi-objective optimization problem in which the mean and the standard deviation are the objective response (Eq. 7.2.1).

$$min\{\mu_{F(x,z)}(x_1, x_2, x_3, \dots, x_n), \sigma_{F(x,z)}(x_1, x_2, x_3, \dots, x_n)\} \quad (7.2.1)$$

where x_1, x_2, x_3,…,x_n are the deterministic values of the design variables or the probabilistic function of the uncertain initial parameters.

It is common that the two objective functions to be minimized in an RDO problem are in conflict. This situation leads to obtaining a set of solutions that represent a Pareto frontier. Figure 7.2.1 shows an example of the difference between the optimal solution and the robust optimal solution in a design space of one design variable. The solution A corresponds to the optimal solution, the point B corresponds to the most robust solution, and the point C corresponds to the robust optimal solution. It is possible to see that the same variation of the design variable (v) causes a higher variation in the objective function of the solution A (f_A) than it does in the solution C (f_C).

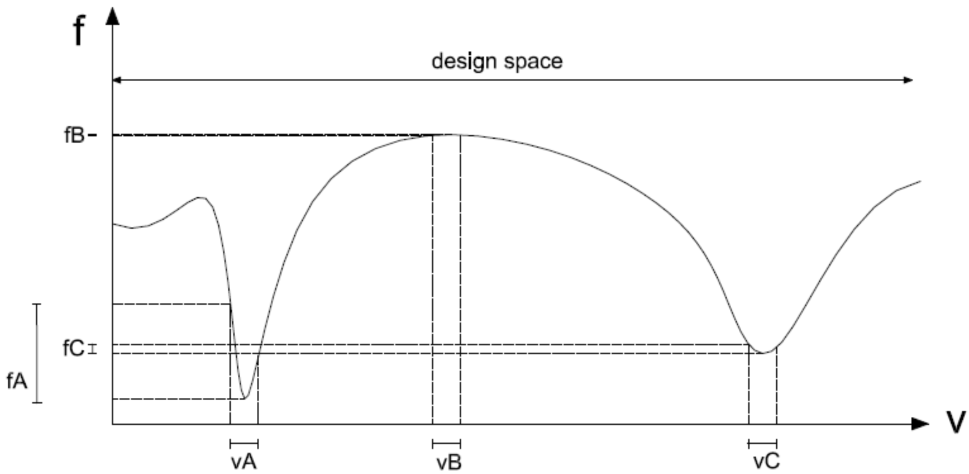

Figure 7.2.1. Robust design optimization

7.2.3. Robust design optimization using metamodels

The main goal of metamodels is to obtain results more efficiently by creating a mathematical approximate model of a detailed simulation model (model of a model). This makes it possible to predict output data (objective response) from input data (variables or design parameters) of the design space. There are three main steps to create a metamodel: (1) obtaining the initial points of the input or sampling data set within the design space (size and position), (2) choosing the method to create the approximate mathematical model, and (3) choosing the fitted model. Each of these three steps can be performed using many different options [18]. In this work, latin hypercube sampling is used to obtain the initial sampling, the kriging model is used to create the approximate mathematical model, and the search for the Best Linear Unbiased Predictor (BLUP) is use as the fitted model. Then, the mathematical approximation created is used to predict the objective functions according to the initial design variables and parameters. In this way, the optimization can be carried out more efficiently, saving a lot of computational cost, which is important in a probabilistic optimization. In addition, the simulated annealing algorithm is used to perform the optimization. Figure 7.2.2 shows a flowchart of the robust design optimization using these characteristics. A more detailed description of this approach can be seen in Penadés-Plà et al. [17].

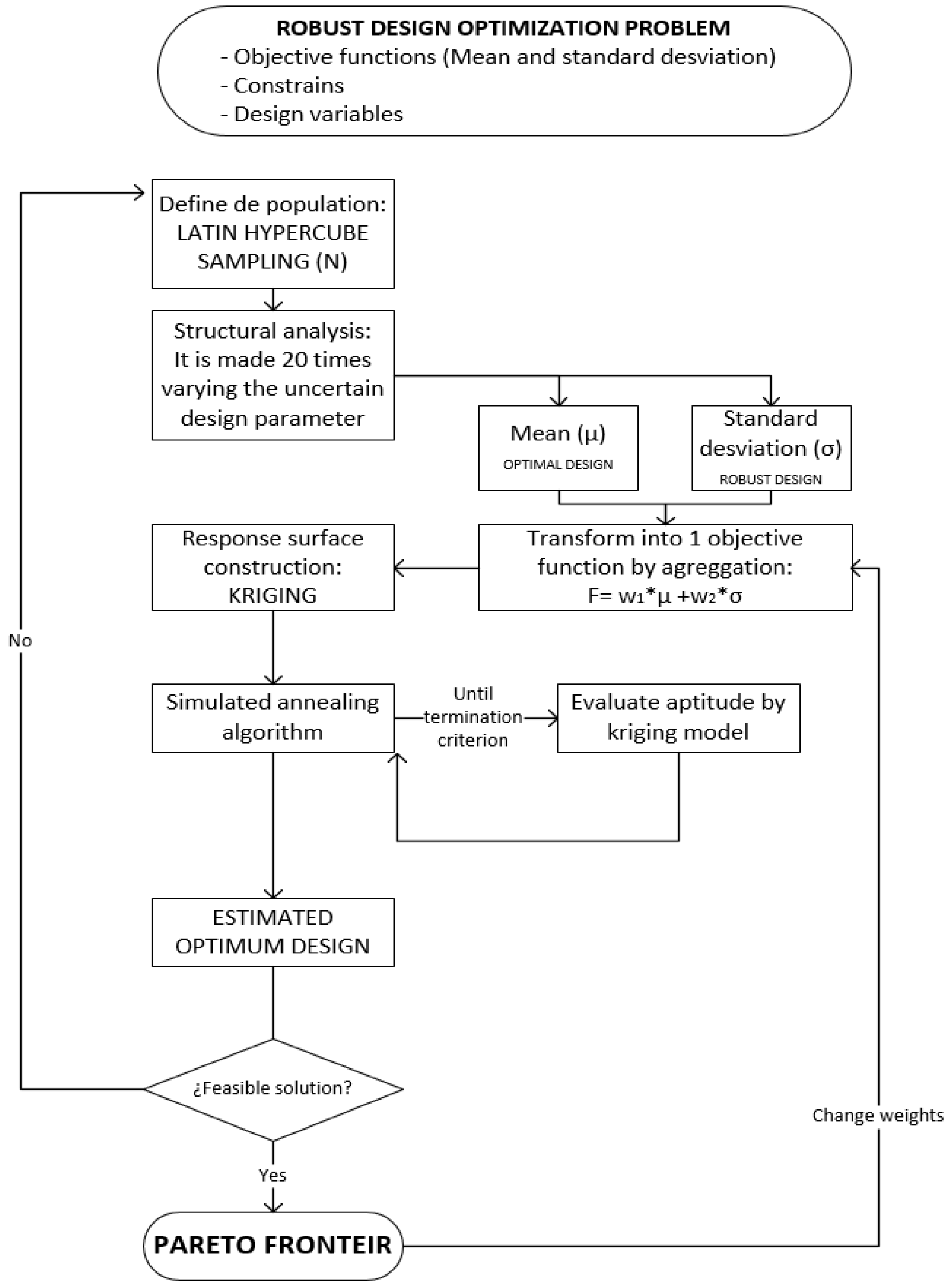

Figure 7.2.2. Flow diagram of robust design optimization

7.2.3.1. Latin hypercube sampling

Latin hypercube sampling (LHS) was proposed by McKay et al. in 1979 [19]. This method is a space-filling type of design of experiments. That means that this type of design of experiment trends to cover all of the design space by the positions of the initial sample points. In this way, a local deformation of any area of the design space can be taken into account. For this purpose, a number N of non-overlapping intervals must first be determined. These intervals divide each range of the design variables (v) into N sections, generating a mesh in the design space with N_v regions. Then, a combination of N random points is generated, so each point is placed in a combination of different intervals of each range of design variables. This guarantees that the initial sampling covers the entire range of each design variable. LHS has been used in several papers, showing its validity for the estimation of metamodel output data [15,20]. For this reason, in the present paper, a uniform distribution of the initial sample points by LHS is employed.

7.2.3.2. Kriging

The Kriging metamodel was originally created by Dannie Gerhrdus Krige, later much research contributed to its development and finally Matheron formalized the approach in 1963 [21]. The main idea of the kriging metamodel is that the deterministic response y(x) can be described by (Eq. 7.2.2):

$$y(x) = f(x) + Z(x) \qquad (7.2.2)$$

where f(x) is the known approximation function and Z(x) is a realization of a stochastic process with mean zero, variance σ^2 and non-zero covariance. The first term of the equation, f(x), is similar to a regression model that provides a global approximation of the design space (Eq. 7.2.3). The second term, Z(x), creates local deviations so that the kriging model interpolates the initial sample points (Eq. 7.2.4).

$$f(x) = \sum_{i=1}^{n} \beta_i \cdot f_i(x) \qquad (7.2.3)$$

$$cov\left[Z(x_i), Z(x_j)\right] = \sigma^2 \cdot R(x_i, x_j) \qquad (7.2.4)$$

where the process variance σ^2 scales the spatial correlation function $R(x_i,x_j)$ between two data points. In engineering design, the Gaussian correlation function (Eq. 7.2.5) is the most commonly used [22] function; it can be defined with only one parameter (θ) that controls the area of influence of nearby points [23]. A low θ means that all the sample points have a high correlation, thus Z(x) will be similar all over the design space. As the θ increases, points with higher correlations will be closer, thus Z(x) will differ depending on the point in the design space:

$$R(x_i, x_j) = e^{-\sum_{k=1}^{m} \theta \left|x_k^i - x_k^j\right|^2} \qquad (7.2.5)$$

7.2.3.3. The Fitted model

The formulation of kriging employs the search for the Best Linear Unbiased Predictor (BLUP). Simpson et al. [24] provides a review of the fitting methods for most common metamodels.

7.2.3.4. Mean and variance

The robust optimum design is measured by the mean (μ) and standard deviation (σ) of the responses of the objectives. These statistical parameters have been obtained for four different levels of uncertainty (10%, 20%, 30%, and 40%). The value of the uncertain initial parameter has been calculated according to a uniform distribution depending on the level of uncertainty. In this way, the mean refers to the optimum design, and the standard variation refers to the robust design.

7.2.3.5.Optimization

Simulated annealing (SA) is the heuristic algorithm used to carry out the RDO. This algorithm has been used in a lot of research to solve optimization problems [25,26]. In the present paper, the method of Medina [27] is used to calibrate the initial temperature. This method suggests that the initial temperature is reduced by half when the percentage of acceptances is higher than 40%, but doubled when it is less than 20%. After that, the temperature decreases according to a coefficient of cooling k following the equation T=k*T, when a Markov chain ends. In this work, the calibration showed that a coefficient of cooling of 0.8 and a length of the Markov chain of 1000 are appropriate. The algorithm ends after three unimproved Markov chains.

7.2.4. Problem design

In this section, the robust design optimization problems proposed are discussed. Section 4.1 describes the structure considered and Section 4.2 defines the characteristics of the problem. Section 4.2 includes the initial uncertain parameters considered and the objective functions studied.

7.2.4.1. Description of the box-girder pedestrian bridge

The structure is a continuous concrete box-girder pedestrian bridge deck with three continuous spans of 40-50-40 meters length. The deck of the bridge has a uniform width of 3 meters, and the remaining geometrical dimensions of the cross-section are defined by the seven variables (Figure 7.2.3): depth (h), bottom slab width (b), web inclination width (d), top slab thickness (e_s), external cantilever section thickness (e_v), bottom slab thickness (e_i) and webs slab thickness (e_a). The value of these variables is limited to a range according to Table 7.2.1. The haunch (t), is calculated from the values of the other variables (Eq. 7.2.6) according to the recommendation of Schlaich and Scheff [28]. In addition, the haunch must provide the space to contain the ducts in the high and low points. This structure was used to compare the conventional heuristic optimization and the kriging-based heuristic optimization. In this work, the kriging-based heuristic optimization and RDO are applied to the same structure. More detailed information about this structure can be found in Penadés-Plà et al. [17].

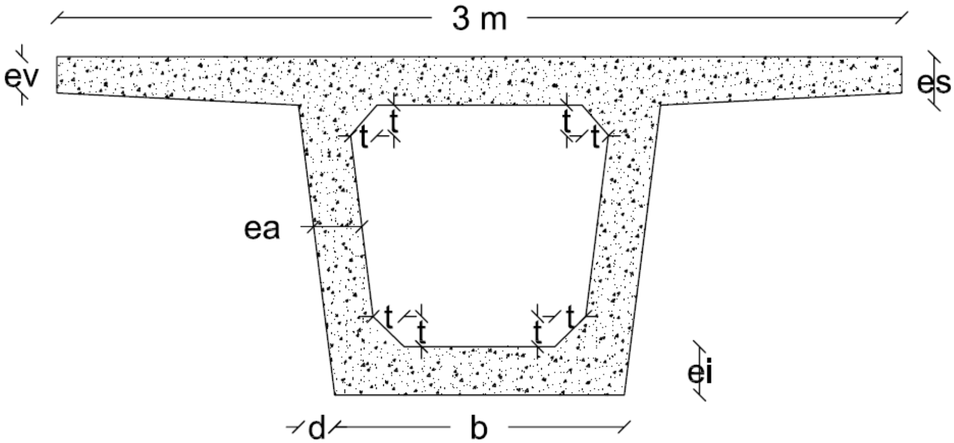

Figure 7.2.3. Box-girder cross-section

Table 7.2.1. Main parameters of the analysis

Design variable	Min. Value (m)	Max. Value (m)	Precision (m)
Depth *(h)*	1.25	2.5	0.05
Width *(b)*	1.2	1.8	0.05
Inclination width *(d)*	0	0.4	0.05
Top slab thickness *(e_s)*	0.15	0.04	0.05
External cantilever section thickness *(e_v)*	0.15	0.04	0.05
Bottom slab thickness *(e_i)*	0.15	0.04	0.05
Webs slab thickness *(e_a)*	0.3	0.6	0.05

$$t = max\left\{\frac{b-2\cdot ea}{5}, ei\right\} \quad . \qquad (7.2.6)$$

Spanish regulations [1,2] and the Eurocodes [31,32] are used to carry out the structural verification defined by the ultimate and service limit states: vertical shear, longitudinal shear, punching shear, bending, torsion, torsion combined with bending and shear, cracking, compression and tension stress, and vibration. In addition, the constructability and geometric requirements are also verified.

7.2.4.2. Description of the robust design optimization problem

The robust design optimization proposed in this paper is defined by two objective functions: the first one is the mean cost, and the second one is the structural stability represented by the vertical displacement in the middle of the bridge [10,14]. The statistical parameters for both objective functions are obtained varying the initial uncertain parameter (modulus of elasticity, overload, and prestressing force) according to a uniform distribution with three different levels of uncertainty (10%, 20%, and 30% for the modulus of elasticity and 10%, 20%, 30%, and 40% for the overload and prestressing force). These uncertain parameters were chosen after carrying out a sensitivity analysis of the vertical displacement and selecting the critical parameters.

In this way, the differences between the different Pareto frontiers obtained for each problem can be studied. Therefore, the goal is to obtain the design with the best cost that has the best structural stability for each RDO problem. Eq. 7.2.7 and 7.2.8 correspond to these objective functions assessed.

$$\mu_{COST} = \sum_{i=1,n} e_i \times m_i(x_{1,} x_{2,} \ldots., x_n) \qquad (7.2.7)$$

$$\sigma_{VERTICALDISPLACEMENT}(x_1, x_2, x_3, \ldots, x_n) \qquad (7.2.8)$$

where x_1, x_2, x_3, .., x_n are the design variables.

The conventional objective function evaluates the cost for the total number of construction units taking into account the placement and material used. The unit costs were obtained from the BEDEC ITEC database [29]. The cost of the concrete is determined according to the compressive strength grade. The measurements (m_i) concerning the construction units are evaluated from the design defined using the design variables. The variation of the vertical displacement in the middle of the bridge has been obtained according to the standard deviation of 20 different cases varying the initial uncertain parameter. Each one of these vertical displacements has been calculated following the Spanish regulations for this type of structure [41,42] as well as the Eurocodes [43,44].

Table 7.2.2. Unit cost

UNIT MEASUREMENTS	COST (€)
m^3 of scaffolding	10.2
m^2 of formwork	33.81
m^3 of lighting	104.57
kg of steel (B-500-S)	1.16
kg of post-tensioned steel (Y1860-S7)	3.40
m^3 of concrete HP-35	104.57
m^3 of concrete HP-40	109.33
m^3 of concrete HP-45	114.10
m^3 of concrete HP-50	118.87
m^3 of concrete HP-55	123.64
m^3 of concrete HP-60	128.41
m^3 of concrete HP-70	137.95
m^3 of concrete HP-80	147.49
m^3 of concrete HP-90	157.02
m^3 of concrete HP-100	166.56

It is common that a multi-objective optimization problem is transformed into to a mono-objective optimization where the objective function is an aggregation function [14] (Eq. 7.2.9).

$$Aggregationfunction = w_1 \cdot \mu_{COST} + w_2 \cdot \sigma_{VERTICALDISPLACEMENT} \qquad (7.2.9)$$

Here, the mean and the standard deviation are the normalized values of the objective functions, and w_1 and w_2 are weights with values in the range [0,1] such that $w_1+w_2 = 1$.

In this work, 200 different cases (N) are considered in such a way that w_1 runs from 0 to 1 with increasing 1/N and w_2 corresponds to 1-w_1. In this way, 200 different optimizations are made and all the possible solutions of the Pareto frontier are covered.

7.2.5. Results

The results are subdivided in two parts according to the initial uncertain design parameter considered: modulus of elasticity and loads (overload and prestressing force). Each one of these sections provides an initial validation of the kriging surfaces generated, the Pareto frontiers obtained, and some comparisons. For this purpose 200 points are created to verify the accuracy of the kriging surfaces (validation), and another 200 solutions are obtained from the robust design optimization problems carried out (Pareto frontier). After that, the results will be discussed.

7.2.5.1. Variation of modulus of elasticity

In this part, the uncertain design parameter studied is the modulus of elasticity. Three different RDO problems are studied. For this purpose, six kriging surfaces are generated depending on the objective function (μ_{cost} and $\sigma_{vertical\ displacement}$) and the variability considered of the modulus of elasticity (10%, 20%, and 30%). Table 7.2.3 shows the different validations of the different kriging surfaces obtained. The accuracy of the kriging surfaces that predict the mean cost are better than the kriging surfaces that predict the variability of the vertical displacement. The difference between the real and predicted mean value of the cost is lower than 2%, and the difference between the real and predicted standard deviation of the vertical displacement of the middle if the bridge is lower than 5% in all different uncertainties of the modulus of elasticity considered.

Table 7.2.3. Validation of the kriging surfaces while varying the modulus of elasticity

Uncertainty of E (%)	10	20	30
μ Cost discrepancy	1.21%	1.28%	1.07%
σ Displacement discrepancy	4.63%	4.75%	4.03%

Figure 7.2.4 shows the Pareto frontiers for the different uncertainties of the modulus of elasticity considered. This figure represents the mean of the cost against the standard deviation of the vertical displacement of the middle of the bridge. It shows that an increment of the uncertainty of the modulus of elasticity causes a displacement of the Pareto frontier, moving away from the positive ideal point (lowest μ_{cost} and lowest $\sigma_{vertical\ displacement}$). This is because the design of the structure should resist all the possible values of the uncertain parameter. Therefore, a higher variation of the initial uncertain parameter imposes greater requirements on the design and an increment of the cost.

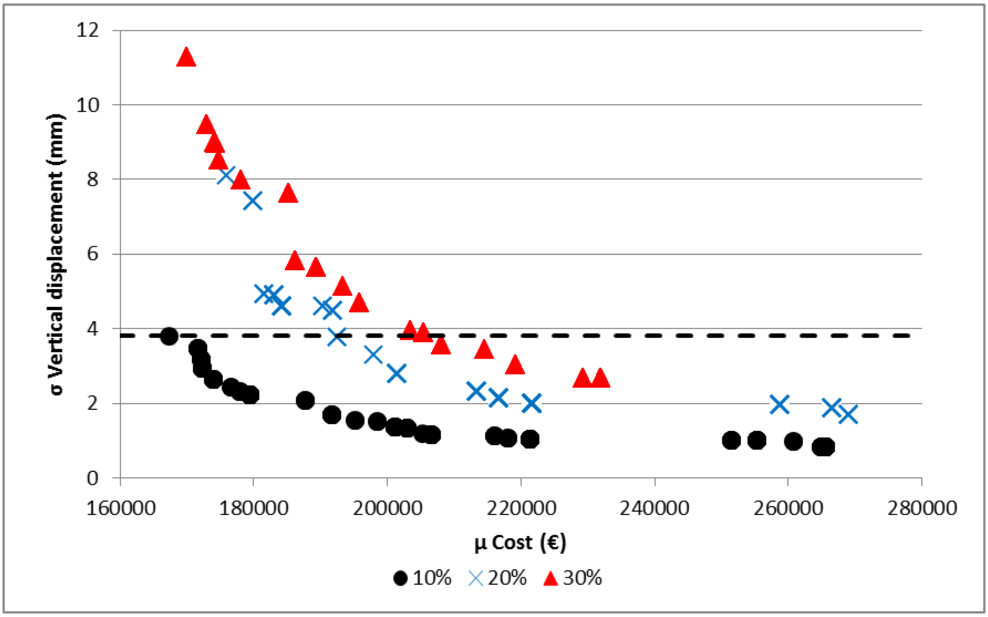

Figure 7.2.4. Pareto frontier of modulus of elasticity RDO problems

Table 7.2.4 shows a comparison between the designs of the different Pareto frontiers with the same structural behavior. In this case, the reference value taken into account is the standard deviation of the vertical displacement of the cheapest design of the Pareto frontier with the lowest variation of the modulus of elasticity studied. In this way, an imaginary horizontal line will intersect all the Pareto frontiers (dashed line of Figure 7.2.4). Solutions S10, S20 and S30 are selected, which correspond to a $\sigma_{\text{vertical displacement}}$ lower than 3.82 mm. It shows that to reach similar structural behavior, the price increases with an increment of the uncertainty of the modulus of elasticity, and that the design variables that cause this increment of the price are the depth and f_{ck}. Both are higher for each increment of the variability of the modulus of elasticity.

Table 7.2.4. Comparison of design with the same structural behavior in modulus of elasticity RDO problems

	b (mm)	h (mm)	d (mm)	e_v (mm)	e_s (mm)	e_a (mm)	e_i (mm)	f_{ck} (MPa)	t (mm)	μ_{cost} (€)	$\sigma_{v,displacement}$ (mm)
S10	1200	1450	0	150	150	350	225	45	225	167370.9	3.811
S20	1200	1800	125	150	150	350	250	60	250	192570.6	3.778
S30	1200	1950	0	150	150	350	225	80	225	208111.9	3.548

Furthermore, if just one Pareto frontier is studied and three key designs are considered: (A) the optimum or lowest μ_{cost}, (B) the robust optimum or shortest to the positive ideal point, and (C) the most robust or lowest $\sigma_{\text{vertical displacement}}$, the same design variables are affected. For example, Table 7.2.5 shows these designs for the Pareto frontier with a 20% variability of the modulus of elasticity. As shown in Table 7.2.4, the values of the depth and f_{ck} are higher when more robustness is required.

Table 7.2.5. Comparison of different designs of the Pareto Frontier with a 20% variation of the modulus of elasticity.

	b (mm)	h (mm)	d (mm)	e_v (mm)	e_s (mm)	e_a (mm)	e_i (mm)	f_{ck} (MPa)	t (mm)	μ_{cost} (€)	$\sigma_{v,displacement}$ (mm)
A	1200	1800	125	150	150	350	250	60	250	192570.6	3.778
B	1200	1900	50	150	150	350	150	80	150	201479.9	2.794
C	1800	2000	200	150	150	350	175	100	220	269128.5	1.684

7.2.5.2. Variation of loads: Overload and prestressing force

In this part, the uncertain design parameters studied are two loads. The first one is the overload due to its high uncertainty, and the second one is the prestressing force to know how the variability influences the behavior of the bridge. In this case, due to the higher uncertainty of these parameters, another increment of uncertainty in the loads is considered (40%). Therefore, four RDO problems are studied for each load. For this purpose, eight kriging surfaces are generated for each load depending on the objective function (μ_{cost} and $\sigma_{vertical\ displacement}$) and the variability considered of the modulus of elasticity (10%, 20%, 30%, and 40%). In these cases, the results discussed are the same as in the previous subsection. In this way, first, the validations of both loads are discussed (Tables 7.2.6 and 7.2.7) After that, the Pareto frontiers for each different uncertainty of the design parameter are shown (Figures 7.2.5 and 7.2.6), and finally some solutions are compared following the same rules as in the previous comparison: the overload (Tables 7.2.8 and 7.2.9), and the prestressing force (Tables 7.2.10 and 7.2.11).

Tables 7.2.6 and 7.2.7 show the different validations of the kriging surfaces obtained. As in the previous cases, the discrepancy of the mean value of the cost is lower than 2% in all cases. However, the discrepancy of the standard deviation of the vertical displacement of the middle of the bridge depends on the variability of the displacement, being higher when the vertical displacement variability is higher and lower when the vertical displacement variability is lower. The results show that when the variability of the overload is lower (10%), the kriging method cannot capture the variability of the displacement accurately. Thus, this uncertainty is not considered.

Table 7.2.6. Validation of the kriging surfaces varying the overload

Uncertainty of overload (%)	10	20	30	40
μ Cost discrepancy	1.32%	1.19%	1.17%	1.28%
σ Displacement discrepancy	38.61%	15.78%	11.53%	15.18%

Table 7.2.7. Validation of the kriging surfaces varying the prestressing force

Uncertainty of P0 (%)	10	20	30	40
μ Cost discrepancy	1.34%	1.09%	1.06%	1.21%
σ Displacement discrepancy	13.5%	7.16%	3.47%	4%

Figure 7.2.5 and 7.2.6 represent the Pareto frontiers for the different variations of the loads. In both cases, the Pareto frontiers have the same behavior as before, moving away from the positive ideal point according to the increment of the uncertainty of the loads. In addition, the comparisons made (Tables from 7.2.8 to 7.2.11) have similar behavior to the above.

Tables 7.2.8 and 7.2.10 show a comparison between different designs with the same structural behavior of the different Pareto frontiers. Table 7.2.8 corresponds to the RDO problems in which the overload is the uncertain parameter, and the $\sigma_{vertical\ displacement}$ of reference corresponds to 2.93 mm (dashed line of Figure 7.2.5). Table 7.2.9 corresponds to the RDO problems in which the prestressing force is the uncertain parameter, and the $\sigma_{vertical\ displacement}$ of reference corresponds to 11.06 mm (dashed line of Figure 7.2.6). In both cases, to reach a similar structural behavior the price increases with an increment of the uncertainty of the loads. As well as in the case of the RDO problems in which the modulus of elasticity is the uncertain parameter, the increment of the price is due to the increment of the depth and f_{ck}. The difference is that in the case (where the modulus of elasticity is the uncertain parameter) the depth and the value of f_{ck} increase in each increment of variability, and in the case where the uncertain parameter is the load, the increment of the depth and f_{ck} is not simultaneous. In these cases, a balance between these two design variables is achieved to reach a similar structural behavior. In addition, this increment of depth and f_{ck} is less significant in the case of the overload, due to the low differences among the different uncertainties. The same occurs when the comparison is made between the optimum or cheapest (A), the robust optimum or shortest to the positive ideal point (B), and the most robust or lowest variation of the vertical displacement (C) (Tables 7.2.9 and 7.2.11). As above, the key design variables to modify the structural behavior change are the depth and f_{ck}. These variables trend to be higher when a higher robustness is required.

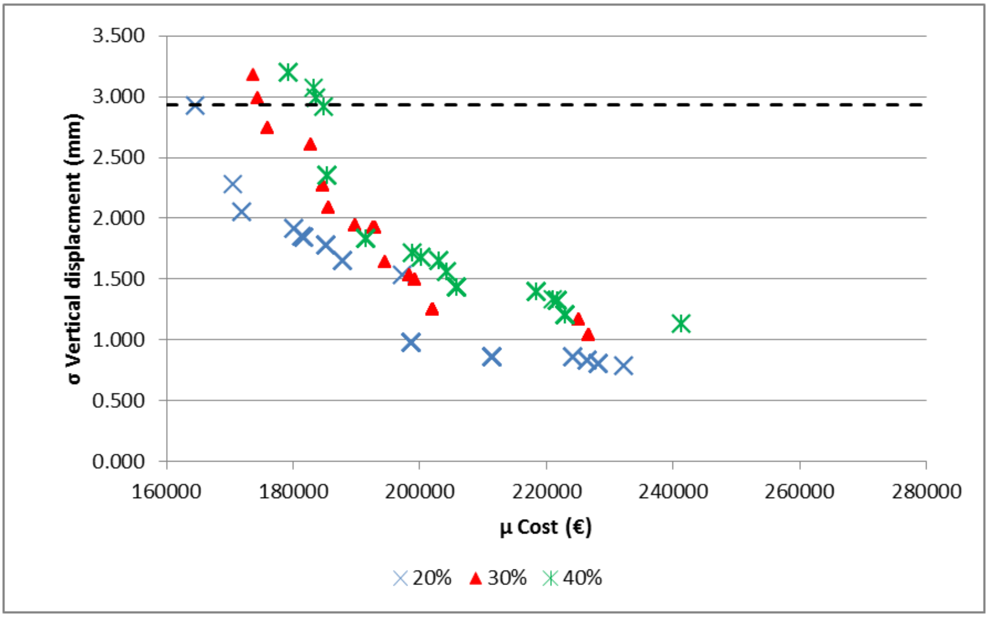

Figure 7.2.5. Pareto frontier of overload RDO problems

Table 7.2.8. Comparison of designs with the same structural behavior in overload RDO problems

	b (mm)	h (mm)	d (mm)	e_v (mm)	e_s (mm)	e_a (mm)	e_i (mm)	f_{ck} (MPa)	t (mm)	μ_{cost} (€)	$\sigma_{v,displacement}$ (mm)
S20	1200	1250	0	150	150	350	200	60	200	164594.2	2.924
S30	1200	1250	200	150	150	350	175	70	175	174467.1	2.991
S40	1200	1700	25	175	175	350	250	50	250	184821.6	2.917

Table 7.2.9. Comparison of different designs of the Pareto Frontier with a 20% of variation of the overload

	b (mm)	h (mm)	d (mm)	e_v (mm)	e_s (mm)	e_a (mm)	e_i (mm)	f_{ck} (MPa)	t (mm)	μ_{cost} (€)	$\sigma_{v,displacement}$ (mm)
A	1200	1350	100	150	150	350	175	80	175	180240.5	1.913
B	1200	1850	200	175	175	350	225	60	225	198687.3	0.971
C	1600	1800	150	275	275	350	225	70	225	238573.8	0.753

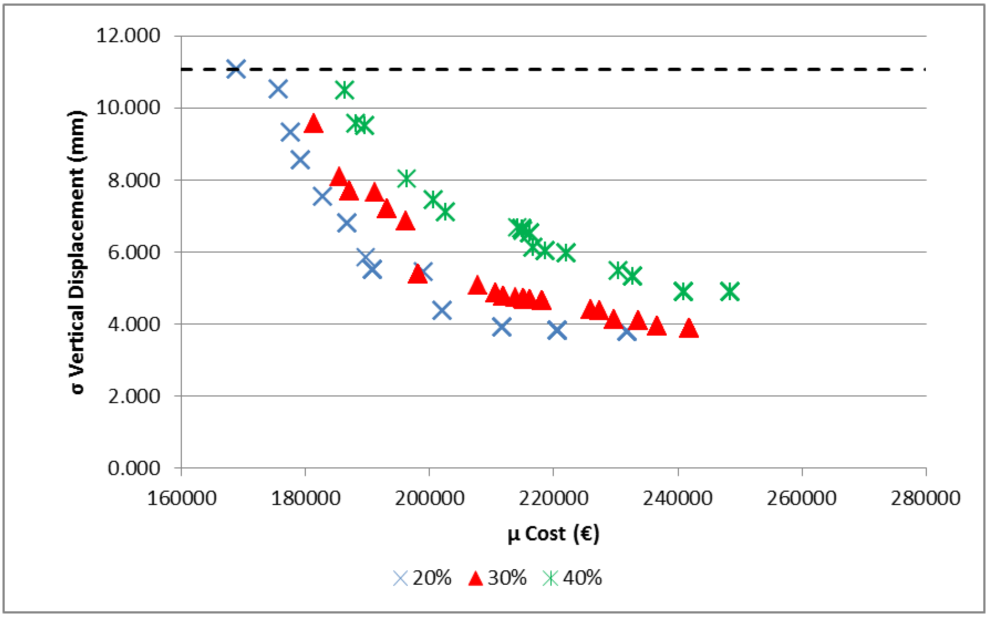

Figure 7.2.6. Pareto frontier of prestressing force RDO problems

Table 7.2.10. Comparison of designs with the same structural behavior in prestressing force RDO problems

	b (mm)	h (mm)	d (mm)	e_v (mm)	e_s (mm)	e_a (mm)	e_i (mm)	f_{ck} (MPa)	t (mm)	μ_{cost} (€)	$\sigma_{v,displacement}$ (mm)
S20	1200	1350	0	150	150	350	200	60	200	168833.9	11.058
S30	1200	1400	200	150	150	350	150	80	150	181276.4	9.552
S40	1200	1750	125	150	150	350	200	55	200	186380.7	10.497

Table 7.2.11. Comparison of different designs of the Pareto Frontier with a 20% variation of the prestressing force

	b (mm)	h (mm)	d (mm)	e_v (mm)	e_s (mm)	e_a (mm)	e_i (mm)	f_{ck} (MPa)	t (mm)	μ_{cost} (€)	$\sigma_{v,displacement}$ (mm)
A	1200	1350	0	150	150	350	200	60	200	168833.9	11.058
B	1200	1650	0	150	150	350	175	80	175	190734.7	5.510
C	1300	2000	0	225	300	350	275	80	275	231832.0	3.772

7.2.6. Conclusions

Currently, the design of structures is made according to a deterministic design. This approach has the result that when the design is optimized according to a conventional objective function, the behavior of the structure is really dependent on the initial values considered. This paper uses a probabilistic approach to consider the variation of the design parameters. In addition, to reduce the large computational cost of the probabilistic optimization, latin hypercube sampling and kriging metamodels are used. Each point of the latin hypercube sampling is calculated 20 times varying the initial uncertain parameters (modulus of elasticity, overload and prestressing force) obtaining the mean of the cost and the standard deviation of the vertical displacement in the middle of the bridge. These values are used to create the kriging surface that predicts the objective response depending on the initial design variables. These surfaces have an error lower than 2% in the mean of the cost for all cases, lower than 5% in the standard deviation of the vertical displacement when the modulus of elasticity is the uncertain parameter, and an accuracy dependent on the value of the vertical displacement when the loads are the uncertain parameters. After that, 200 solutions have been calculated for each case to obtain the different Pareto frontiers.

The Pareto frontiers show that, for all RDO problems, an increment of the uncertainty causes a displacement of the Pareto frontier, moving away from the positive ideal point. That means that to obtain a specific robustness when the uncertainty of the parameter is higher, the cost of the design will be higher. In addition, when just one Pareto frontier is taken into account, a more robust design implies an expensive design. In all cases, this increment of the price is due to an increment of two specific design variables: depth (h) and f_{ck}. Therefore, to obtain a robust design, it is necessary to increment the depth (h) and/or f_{ck}. However, these Pareto frontiers allow obtaining a compromise design between cost and robustness: the optimum robust design. This solution is the design closest to the positive ideal point.

This work shows that a probabilistic optimization can be carried out to obtain an optimum robust design. Nevertheless, the robust design optimization of complex problems requires a high computational cost. Therefore, the use of metamodels is necessary to carry out the probabilistic optimization. In previous works, the computational cost saved and the validity of kriging metamodels was proven. This work shows that the kriging metamodel has an appropriate behavior to carry out the robust design optimization, and therefore can be used to carry out optimization where there are uncertain information.

Acknowledgements

The authors acknowledge the support for the Ministry of Economy and Company and FEDER funding (Project BIA2017-85098-R).

References

[1] Taguchi G. Introduction to quality engineering. Tokio: Asian Productivity Organisation; 1986.

[2] Phadke MS, Shridhar M. Quality engineering using robust design. Prentice Hall; 1989.

[3] Fowlkes WY, Creveling CM. Engineering method for robust product design. Massachusetts: 1995.

[4] Lee K-H, Kang D-H. A robust optimization using the statistics based on kriging metamodel. Journal of Mechanical Science and Technology 2006;20:1169–82. doi:10.1007/BF02916016.

[5] Yepes V, Martí JV, García-Segura T, González-Vidosa F. Heuristics in optimal detailed design of precast road bridges. Archives of Civil and Mechanical Engineering 2017;17. doi:10.1016/j.acme.2017.02.006.

[6] Carbonell A, González-Vidosa F, Yepes V. Design of reinforced concrete road vaults by heuristic optimization. Advances in Engineering Software 2011;42:151–9. doi:10.1016/J.ADVENGSOFT.2011.01.002.

[7] García-Segura T, Yepes V. Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety. Engineering Structures 2016;125:325–36. doi:10.1016/j.engstruct.2016.07.012.

[8] García-Segura T, Yepes V, Martí J V., Alcalá J. Optimization of concrete I-beams using a new hybrid glowworm swarm algorithm. Latin American Journal of Solids and Structures 2014;11:1190–205. doi:10.1590/S1679-78252014000700007.

[9] Martí J V., García-Segura T, Yepes V. Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy. Journal of Cleaner Production 2016;120:231–40. doi:10.1016/J.JCLEPRO.2016.02.024.

[10] Jurecka F, Ganser M, Bletzinger K-U. Update scheme for sequential spatial correlation approximations in robust design optimisation. Computers & Structures 2007;85:606–14. doi:10.1016/J.COMPSTRUC.2006.08.075.

[11] Valdebenito MA, Schuëller GI. A survey on approaches for reliability-based optimization. Structural and Multidisciplinary Optimization 2010;42:645–63. doi:10.1007/s00158-010-0518-6.

[12] Doltsinis I, Kang Z. Robust design of structures using optimization methods. Computer Methods in Applied Mechanics and Engineering 2004;193:2221–37. doi:10.1016/J.CMA.2003.12.055.

[13] Simpson TW, Booker AJ, Ghosh D, Giunta AA, Koch PN, Yang R-J. Approximation methods in multidisciplinary analysis and optimization: A panel discussion. Structural and Multidisciplinary Optimization 2004;27:302–13. doi:10.1007/s00158-004-0389-9.

[14] Martínez-Frutos J, Martí P. Diseño óptimo robusto utilizando modelos Kriging: aplicación al diseño óptimo robusto de estructuras articuladas. Revista Internacional de Métodos Numéricos Para Cálculo Y Diseño En Ingeniería 2014;30:97–105. doi:10.1016/j.rimni.2013.01.003.

[15] Jin R, Chen W, Simpson TW. Comparative studies of metamodelling techniques under multiple modelling criteria. Structural and Multidisciplinary Optimization 2001;23:1–13. doi:10.1007/s00158-001-0160-4.

[16] Jin R, Du X, Chen W. The use of metamodeling techniques for optimization under uncertainty. Structural and Multidisciplinary Optimization 2003;25:99–116. doi:10.1007/s00158-002-0277-0.

[17] Penadés-Plà V, García-Segura T, Yepes V. Accelerated optimization method for low-embodied energy concrete box-girder bridge design. Engineering Structures 2019;179:556–65. doi:10.1016/J.ENGSTRUCT.2018.11.015.

[18] Barton RR, Meckesheimer M. Metamodel-based simulation optimization. vol. 13, 2006. doi:10.1016/S0927-0507(06)13018-2.

[19] McKay MD, Beckman RJ, Conover WJ. Comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics 1979;21:239–45. doi:10.1080/00401706.1979.10489755.

[20] Chuang CH, Yang RJ, Li G, Mallela K, Pothuraju P. Multidisciplinary design optimization on vehicle tailor rolled blank design. Structural and Multidisciplinary Optimization 2008;35:551–60. doi:10.1007/s00158-007-0152-0.

[21] Matheron G. Principles of geostatistics. Economic Geology 1963;58:1246–66.

[22] Simpson TW, Mauery TM, Korte J, Mistree F. Kriging models for global approximation in simulation-based multidisciplinary design optimization. AIAA Journal 2001;39:2233–41. doi:10.2514/3.15017.

[23] Forrester AIJ, Keane AJ. Recent advances in surrogate-based optimization. Progress in Aerospace Sciences 2009;45:50–79. doi:10.1016/J.PAEROSCI.2008.11.001.

[24] Simpson TW, Poplinski JD, Koch PN, Allen JK. Metamodels for computer-based engineering design: Survey and recommendations. Engineering with Computers 2001;17:129–50. doi:10.1007/PL00007198.

[25] Camp C V., Huq F. CO2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm. Engineering Structures 2013;48:363–72. doi:10.1016/j.engstruct.2012.09.004.

[26] Martí J V., González-Vidosa F, Yepes V, Alcalá J. Design of prestressed concrete precast road bridges with hybrid simulated annealing. Engineering Structures 2013;48:342–52. doi:10.1016/j.engstruct.2012.09.014.

[27] Medina JR. Estimation of incident and reflected waves using simulated annealing. Journal of Watery, Port, Coastal, and Ocean Engineering 2001;127:213–21.

[28] Schlaich J, Scheef H. Concrete box-girder bridges. International Association for Bridge and Structural Engineering, Zürich, Switzerland: 1982.

[29] Catalonia Institute of Construction Technology. BEDEC PR/PCT ITEC material database 2016.

CHAPTER 8. CONCLUSIONS

8.1. Introduction

This section is divided into general conclusions and specific conclusions. On the one hand, general conclusions encompass and unify all the work carried out in this dissertation. On the other hand, specific conclusions show the particular information obtained from each journal article. Finally, possible lines of future work are proposed.

8.2. General conclusions

This dissertation presents a compendium of publications that can be divided into two parts. The objective of the first part is to perform the sustainability assessment of a bridge over its whole life-cycle. For this purpose, several previous works have been carried out. The first two papers were conducted to carry out a complete environmental impact assessment through the Ecoinvent database and the ReCiPe method. The case studies considered are one precast-prestressed concrete U-beam road bridge and two different post-tensioned concrete box-girder road bridges. In the third paper, the social impact of these bridges is included using the SOCA add-on and the relative weighting method. The results of the sustainability assessment show that there is a strong relationship between the three pillars of sustainability and that the most important life-cycle stages are the manufacturing and the use and maintenance stage. In the manufacturing stage, the sustainability assessment is improved by a reduction in material consumption. In the use and maintenance stage, the sustainability assessment is improved by a reduction of the number of days of maintenance. However, when the whole life-cycle is studied, a greater impact on the manufacturing stage together with a reduction in the number of days of maintenance due to the higher quality of the materials is preferable.

In the second part, the main goal was study the influence of the variability of the uncertain initial parameters in order to obtain designs that are little influenced by uncertainty, called robust designs. For this purpose, a post-tensioned concrete box-girder pedestrian bridge has been coded and considered as a case study. This problem becomes a probabilistic approach problem, whose optimization has a high computational cost. In this dissertation, the use of metamodels to predict the objective response was proposed to reduce the computational cost. For this purpose, a post-tensioned concrete box-girder pedestrian bridge has been coded and considered as a case study and the kriging metamodel is considered. In this way, the kriging metamodel provides an approximate mathematical surface with a good accuracy that improves with an increase in the initial sample size. A comparison between conventional heuristic optimization and kriging-based heuristic optimization is made using a set of nine solutions. In this way, the best solutions obtained are similar for the different sample sizes, but the mean and coefficient of variance improve with icreases the initial sample size. The results show that the solutions reached in the kriging-based heuristic optimization are close to the solutions reached in the conventional heuristic optimization with a significantly large reduction of computational cost. With an initial sample size of N = 50, the error between the real objective value and the predicted objective response surface is within 4.04% and the objective response of the optimum solutions differs by 9.84% compared to the conventional heuristic optimization, but with a 99.06% reduction in the computational cost. Regarding the best solution, the comparison shows that the use of kriging increases the optimum objective response by 2.54%. However, if the main objective is to reduce the coefficient of variance, the initial size that performs better is N = 500. For this case, the solutions obtained have a coefficient of variance of 3.67%, even lower than the value of 3.79% corresponding to the conventional heuristic optimization.

This reduction of computational cost through the use of kriging-based heuristic optimization makes it possible to study the influence of the variability of some initial uncertain parameters to obtain solutions that are not very sensitive to initial uncertainty. Thus, using the same post-tensioned concrete box-girder pedestrian bridge, the variability of the preferences of decision-makers in the sustainability assessment is considered to study the influence on the sustainable design, and the variability of some uncertain parameters is considered to study the influence on the structural design. This first approach is carried out to obtain a sustainable design that is little influenced by the preferences of the decision-makers. For this purpose, several random decision-makers have been generated to cover all the different preferences. These random decision-makers provide a different index of sustainability for each bridge design according to their points of view. The life-cycle sustainability is assessed according to a set of criteria that covers the three pillars of sustainability, and principal component analysis is used to obtain a small set of linearly independent components. This makes it possible to obtain the most sustainable bridge according to different perspectives on sustainability. In this way, the initial large number of different designs is reduced to four sustainable designs. In addition, the variability of the decisions of the different random decision-makers can be evaluated and the design that has the best mean sustainability index and those that are more stable with respect to the preferences of decision-makers, and are therefore robust with respect to the preferences of stakeholders, are obtained.

The second approach is carried out to obtain the structural design that is least influenced by the initial uncertainty. This process is called RDO. For this purpose, each point is calculated several times while varying the initial uncertain parameters (modulus of elasticity, overload, and prestressing force) and the mean of the cost and the standard deviation of the vertical displacement in the middle of the bridge are obtained. The objective is to obtain the structural design with the lowest mean cost (optimum) and lowest vertical displacement in the middle of the bridge (robust). For this purpose, several solutions have been calculated for each case to obtain the different Pareto frontiers. The Pareto frontiers show that, for all RDO problems, an increment of the uncertainty causes a displacement of the Pareto frontier, moving away from the positive ideal point. That means that obtaining a specific robustness when the uncertainty of the parameter is higher will lead to a higher design cost. In addition, when just one Pareto frontier is taken into account, a more robust design implies an expensive design. In all cases, this increment of the price is due to increments of two specific design variables: depth (h) and f_{ck}. Therefore, to obtain a robust design, it is necessary to increment the depth (h) and/or f_{ck}. However, these Pareto frontiers make it possible to obtain a design that provides a compromise between cost and robustness: the optimum robust design. This solution is the design closest to the positive ideal point.

8.3. Specific conclusions

- The sustainability assessment should be done by the broad evaluation of each sustainability pillar, as the consideration of a small number of criteria can lead to erroneous sustainability assessments.
- For structures that only use common building materials (concrete, steel, prestressed steel), there is a relationship between the three pillars of sustainability: economic, environmental, and social.
- The production stage and the use and maintenance stage have the greatest impacts unless the construction process is very complex. In the production stage, the use of less material improves the impact of the three pillars, and in the use and maintenance stage, the use of fewer maintenance periods also improves the impact of the three pillars.
- When the whole life-cycle is assessed, a small increase in the initial impact is preferable due to the use of higher quality concrete, which allows a reduction of the impact in the use and maintenance stage and therefore a reduction of the global impact.
- The prediction of the objective response using metamodels provides results with a low level of error. Using a kriging model, an initial sample size of N = 10 provides a surface with an error of 11.11%, an initial sample size of N = 50 provides a surface with an error of 4.04%, and an initial sample size of N = 500 provides a surface with an error of 3.88%.
- The use of metamodels in the optimization process allows a reduction of the computational cost. Actually, the optimization process is practically instantaneous and it is the generation of the initial sample that has a greater

time consumption. Using the kriging-based heuristic optimization, an initial sample size of N = 10 reduces the time consumption by 99.86% compared with a conventional heuristic optimization, an initial sample size of N = 50 reduces the time consumption by 99.06%, and an initial sample size of N = 500 reduces it by 90.80%.

- The use of metamodels in the optimization process makes it possible to achieve good optimum designs. The kriging-based heuristic optimization with an initial sample size of N = 500 leads to a design only 4.3% worse than the design reached by the conventional heuristic optimization.
- The kriging-based optimization makes it possible to obtain the most sustainable bridge from each of the different perspectives of the decision-makers, covering all the stakeholders' preferences. In this sense, the variability of each bridge design can be studied, and the bridge with the best mean index of sustainability or the bridge with the most stable sustainability index can be selected.
- The kriging-based optimization makes it possible to obtain robust optimum designs. In this case, three uncertain initial parameters were selected (modulus of elasticity, overload, and prestressing force) and a Pareto frontier was obtained. In this way, it is possible to choose the optimal design, the robust design, and a compromise solution called robust optimum design.
- In all cases, this increment of the price is due to an increment of two specific design variables: depth (h) and f_{ck}. Therefore, to obtain a robust design, it is necessary to increment the depth (h) and/or f_{ck}.
- A solution can have a good mean assessment even though it is not chosen by any decision-maker (Solution A) or can be very stable with respect to the different assessments of the decision-makers (Solution B). Finally, the most robust solution is obtained (Solution C). Comparing this solution with the most economical solution (Solution 2), this solution is 3.37% more expensive and its environmental impact is also a little greater (2.85% for human health, 2.85% for ecosystem, and 1.83% for resources) with similar comfort (0.19% better) and structural safety (0.12% worse). In addition, the number of bars used is 16.36% lower, which improves workability. Therefore, the selected solution is optimal regarding the life-cycle sustainability criteria and is robust with respect to stakeholders' opinions.

8.4. Future work

The assessment of sustainability of structures in general, and of bridges in particular, must be carried out broadly and must cover each of the pillars of sustainability widely. In this sense, this paper shows a way of broadly encompassing the environmental and social pillars. Many works consider different criteria to assess sustainability. In this way, the creation of a methodology or framework that makes it possible to standardize and define the criteria to be considered for each of the structures would be of great utility for the evaluation of sustainability and a real comparison.

In addition, this dissertation carries out sustainability assessments of concrete bridges. Therefore, in order to better understand the sustainability of bridges, the methodology proposed in this dissertation could be applied to other types of bridges: mixed bridges and steel bridges. Also, other concrete designs that have varying depths, different phases of prestressing, multiple-cell box-girders, and transverse prestressing can be studied.

On the other hand, this dissertation has shown that the application of metamodel-based optimization to structures gives good results in an efficient way. This makes it possible to reduce the computational cost in the optimization processes and therefore to take into account uncertain initial parameters. This opens up the possibility to study robust optimal design further, so that optimal and stable solutions can be obtained, as well as robust sustainable design, so that solutions that are sustainable and better accepted by all the different stakeholders can be obtained.

LIST OF PUBLICATIONS

[1] V. Penadés-Plà, T. García-Segura, J. V. Martí, and V. Yepes, "An optimization-LCA of a prestressed concrete precast bridge," *Sustainability*, vol. 10, no. 3, pp. 1–17, 2018.

[2] V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, "Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges," *Sustainability*, vol. 9, no. 10, p. 1864, 2017.

[3] V. Penadés-Plà, J. V. Martí, T. García-Segura, and V. Yepes, "Environmental and social life cycle assessment of cost-optimized post-tensioned concrete road bridges," *Environmental impact assessment review (Submitted)*

[4] Penadés-Plà V, García-Segura T, Yepes V. Accelerated optimization method for low-embodied energy concrete box-girder bridge design. *Engineering Structures* 2019;179:556–65.

[5] Penadés-Plà V, García-Segura T, Yepes V. Robust decision-making design for sustainable pedestrian concrete bridges. *Engineering Structu*res *(Accepted, in press).*

[6] Penadés-Plà V, García-Segura T, Yepes V. Robust design optimization for low-cost concrete box-girder bridge. *Engineering* Structures *(Submitted)*

BIBLIOGRAPHY

Abu Dabous, S., Alkass, S., 2010. A multi-attribute ranking method for bridge management. Engineering, Construction and Architectural Management 17, 282–291. doi:10.1108/09699981011038079

Abu Dabous, S., Alkass, S., 2008. Decision support method for multi-criteria selection of bridge rehabilitation strategy. Construction Management and Economics 26, 883–893. doi:10.1080/01446190802071190

Aghdaie, M.H., Zolfani, S.H., Zavadskas, E.K., 2012. Prioritizing constructing projects of municipalities based on AHP and COPRAS-G: A case study about footbridges in Iran. The Baltic Journal of Road and Bridge Engineering 7, 145–153. doi:10.3846/bjrbe.2012.20

Almahmoud, E., Doloi, H.K., 2015. Assessment of social sustainability in construction projects using social network analysis. Facilities 30, 152–176.

Ardeshir, A., Mohseni, N., Behzadian, K., Errington, M., 2014. Selection of a bridge construction site using Fuzzy Analytical Hierarchy Process in Geographic Information System. Arabian Journal for Science and Engineering 39, 4405–4420. doi:10.1007/s13369-014-1070-2

Bäckryd, R.D., Ryberg, A.-B., Nilsson, L., 2017. Multidisciplinary design optimisation methods for automotive structures. International Journal of Automotive and Mechanical EngineeringOnline 14, 2229–8649. doi:10.15282/ijame.14.1.2017.17.0327

Bahurmoz, A.M.A., 2006. The analytic hierarchy process: A methodology for win-win management. JKAU: Econ. & Adm 20, 3–16.

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. doi:10.3141/2431-11

Ballestero, E., 2007. Compromise programming: A utility-based linear-quadratic composite metric from the trade-off between achievement and balanced (non-corner) solutions. European Journal of Operational Research 182, 1369–1382. doi:10.1016/j.ejor.2006.09.049

Bana e Costa, C.A., Vansnick, J., 1994. MACBETH-An interactive path towards the construction fo cardinal value functions. International Transactions in Operational research 1, 489–500. doi:10.1016/0969-6016(94)90010-8

Bare, J.C., 2002. The Tool for the reduction and assessment of chemical and other environmental impacts. Journal of Industrial Ecology 6, 49–78. doi:10.1162/108819802766269539

Barr, A.S., Sarin, S. c., G.Bishara, A., 1989. Procedure for structural optimization. ACI Structural Journal 86, 524–531. doi:10.14359/3268

Barton, R.R., Meckesheimer, M., 2006. Metamodel-based simulation optimization. doi:10.1016/S0927-0507(06)13018-2

Begicevic, N., Divjak, B., Hunjak, T., 2007. Comparison between AHP and ANP: Case Study of strategic planning of E-learning implementation. Development 1, 1–10.

Behzadian, M., Kazemzadeh, R.B., Albadvi, A., Aghdasi, M., 2010. PROMETHEE: A comprehensive literature review on methodologies and applications. European Journal of Operational Research 200, 198–215. doi:10.1016/j.ejor.2009.01.021

Benoît, C., Mazijn, B., 2009. Guidelines for Social Life Cycle Assessment of Products. UNEP/SETAC Life Cycle Initiative, Sustainable Product and Consumption Branch.

Blum, C., Puchinger, J., Raidl, G.R., Roli, A., 2011. Hybrid metaheuristics in combinatorial optimization: A survey. Applied Soft Computing 11, 4135–4151. doi:10.1016/J.ASOC.2011.02.032

Bond, D., 1975. An examination of the automated design of prestressed concrete bridge deck by computer. Proceedings of the Institution of Civil Engineers 59, 669–697. doi:10.1680/iicep.1975.3634

Bouhaya, L., Roy, R. Le, Feraille-Fresnet, A., 2009. Simplified environmental study on innovative bridge structure. Environmental Science & Technology 43, 2066–2071. doi:10.1021/es801351g

Boustead, I., Hancock, G.F., 1979. Handbook of industrial energy analysis, John Wiley.

Brans, J.P., Mareschal, B., Vincke, P., 1984. PROMETHEE: A new family of outranking methods in multicriteria analysis. Operational Research 408–421.

Brans, J.P., Vincke, P., Mareschal, B., 1986. How to select and how to rank projects: The Promethee method. European Journal of Operational Research 24, 228–238. doi:10.1016/0377-2217(86)90044-5

Camp, C. V., Assadollahi, A., 2013. CO2 and cost optimization of reinforced concrete footings using a hybrid big bang-big crunch algorithm. Structural and Multidisciplinary Optimization 48, 411–426. doi:10.1007/s00158-013-0897-6

Camp, C. V., Huq, F., 2013. CO2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm. Engineering Structures 48, 363–372. doi:10.1016/j.engstruct.2012.09.004

Carbonell, A., González-Vidosa, F., Yepes, V., 2011. Design of reinforced concrete road vaults by heuristic optimization. Advances in Engineering Software 42, 151–159. doi:10.1016/J.ADVENGSOFT.2011.01.002

Catalonia Institute of Construction Technology, 2016. BEDEC PR/PCT ITEC material database.

Chang, D.-S., Chen, S.-H., Hsu, C.-W., Hu, A., Tzeng, G.-H., 2015. Evaluation framework for a alternative fuel vehicles: sustainable development perspective. Sustainability 7, 11570–11594. doi:10.3390/su70911570

Chen, S.J., Hwang, C.L., n.d. Fuzzy multiple attribute decision making: Methods and applications, Springer-V. ed. Berlin.

Chen, Y., Okudan, G.E., Riley, D.R., 2010. Decision support for construction method selection in concrete buildings: Prefabrication adoption and optimization. Automation in Construction 19, 665–675. doi:10.1016/j.autcon.2010.02.011

Chen, Z., Abdullah, A.B., Anumba, C.J., Li, H., 2013. ANP experiment for demolition plan evaluation. Journal of Construction Engineering and Management 140, 51–60. doi:10.1061/(ASCE)CO

Chou, J.-S., Pham, A.-D., Wang, H., 2013. Bidding strategy to support decision-making by integrating Fuzzy AHP and regression-based simulation. Automation in Construction 35, 517–527. doi:10.1016/j.autcon.2013.06.007

Chuang, C.H., Yang, R.J., Li, G., Mallela, K., Pothuraju, P., 2008. Multidisciplinary design optimization on vehicle tailor rolled blank design. Structural and Multidisciplinary Optimization 35, 551–560. doi:10.1007/s00158-007-0152-0

Cinelli, M., Coles, M., Kirwan, K., 2014. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecological indicators 46, 138–148.

Ciroth, A., Muller, S., Weidema, B., Lesage, P., 2016. Empirically based uncertainty factors for the pedigree matrix in Ecoinvent. The International Journal of Life Cycle Assessment 21, 1339–1348. doi:10.1007/s11367-013-0670-5

Coello, C., 1994. Uso de algoritmos genéticos para el diseño óptimo de armaduras, in: Congreso Nacional de Informática: Herramientas Estratégicas Para Los Mercados Globales. pp. 290–305.

Cohn, M.Z., Dinovitzer, A.S., 1994. Application of structural optimization. Journal of Structural Engineering 120, 617–650. doi:10.1061/(ASCE)0733-9445(1994)120:2(617)

Collins, F., 2010. Inclusion of carbonation during the life cycle of built and recycled concrete: Influence on their carbon footprint. The International Journal of Life Cycle Assessment 15, 549–556. doi:10.1007/s11367-010-0191-4

Cressie, N., 1990. The origins of kriging. Mathematical Geology 22, 239–252. doi:10.1007/BF00889887

Curran, M.A., 1996. Environmental Life-Cycle Assessment, McGraw-Hill.

Dalkey, N., Helmer, O., 1963. An experimental application of the Delphi method to the use of experts. Managment Science 9, 458–467.

Dawkins, R., 1976. The selfish gene. Claarendon Press, Oxford, UK.

de Albuquerque, A.T., El Debs, M.K., Melo, A.M.C., 2012. A cost optimization-based design of precast concrete floors using genetic algorithms. Automation in Construction 22, 348–356. doi:10.1016/J.AUTCON.2011.09.013

De Brito, M.M., Evers, M., 2016. Multi-criteria decision-making for flood risk management: A survey of the current state of the art. Natural Hazards and Earth System Sciences 16, 1019–1033. doi:10.5194/nhess-16-1019-2016

Deng, J.L., 1989. Introduction to grey system theory. The Journal of Grey Theory 1, 1–24.

Dodoo, A., Gustavsson, L., Sathre, R., 2009. Carbon implications of end-of-life management of building materials. Resources, Conservation and Recycling 53, 276–286. doi:10.1016/j.resconrec.2008.12.007

Doltsinis, I., Kang, Z., 2004. Robust design of structures using optimization methods. Computer Methods in Applied Mechanics and Engineering 193, 2221–2237. doi:10.1016/J.CMA.2003.12.055

Dong, Y.H., Ng, S.T., 2014. Comparing the midpoint and endpoint approaches based on ReCiPe - A study of commercial buildings in Hong Kong. The International Journal of Life Cycle Assessment 19, 1409–1423. doi:10.1007/s11367-014-0743-0

Du, G., Karoumi, R., 2014. Life cycle assessment framework for railway bridges: Literature survey and critical issues. Structure and Infrastructure Engineering 10, 277–294. doi:10.1080/15732479.2012.749289

Du, G., Karoumi, R., 2012. Life cycle assessment of a railway bridge: Comparison of two superstructure designs. Structure and Infrastructure Engineering 9, 1149–1160. doi:10.1080/15732479.2012.670250

Du, G., Karoumi, R., n.d. Environmental life cycle assessment comparison between two bridge types : Reinforced concrete bridge and steel composite bridge, in: 3th International Conference on Sustainable Construction Materials and Technologies.

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. The International Journal of Life Cycle Assessment 19, 1948–1964. doi:10.1007/s11367-014-0797-z

Dutta, R., Ganguli, R., Mani, V., 2011. Swarm intelligence algorithms for integrated optimization of piezoelectric actuator and sensor placement and feedback gains. Smart Materials and Structures 20, 105018.

Ecoinvent Center, 2016. Ecoinvent v3.3.

Edwards, W., 1977. How to use multiattribute utility measurement for social decisionmaking. IEEE Transactions on Systems, Man, and Cybernetics 7, 326–340. doi:10.1109/TSMC.1977.4309720

Ei-Mikawi, M., Mosallam, A.S., 1996. A methodology for evaluation of the use of advanced composites in structural civil engineering applications. Composites Part B: Engineering 27, 203–215. doi:10.1016/1359-8368(95)00030-5

European Commission, 2012. European reference life-cycle database.

European Committee for Standardisation, 2005. EN1992-2:2005. Eurocode 2: Design of concrete structures- Part 2: Concrete Bridge-Design and detailing rules. Brussels.

European Committee for Standardization, 2003. EN 1001-2:2003. Eurocode 1: Actions on structures- Part 2: Traffic loads bridges. Brussels, Belgium.

European Committee for Standardization, 2000. EN 206-1 Concrete - Part1: Specification, performance, production and conformity. Brussels, Belgium.

Fang, K.-T., Lin, D.K.J., Winker, P., Zhang, Y., 2000. Uniform design: Theory and application. Technometrics 42, 237. doi:10.2307/1271079

Farkas, A., 2011. Multi-criteria comparison of bridge designs. Acta Polytechnica Hungarica 8, 173–191.

Ferreiro-Cabello, J., Fraile-Garcia, E., Martinez-Camara, E., Perez-de-la-Parte, M., 2017. Sensitivity analysis of life cycle assessment to select reinforced concrete structures with one-way slabs. Engineering Structures 132, 586–596. doi:10.1016/J.ENGSTRUCT.2016.11.059

Field, A., 2005. Discovering statistics using SPSS (2nd Edition). Sage, London, England.

Flanagan, R., Kendell, A., Norman, G., Robinson, G.D., 1987. Life cycle costing and risk management. Construction Management and Economics 5, S53–S71. doi:10.1080/01446193.1987.10462093

Forrester, A.I.J., Keane, A.J., 2009. Recent advances in surrogate-based optimization. Progress in Aerospace Sciences 45, 50–79. doi:10.1016/J.PAEROSCI.2008.11.001

Fowlkes, W.Y., Creveling, C.M., 1995. Engineering method for robust product design, Addison-Wesley[1] W.Y. Fowlkes, C.M. Creveling, Engineering method for robust product design, Massachusetts, 1995. Massachusetts.

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 10, 3–9. doi:10.1065/lca2004.10.181.1

Frischknecht, R., Steiner, R., Jungbluth, N., 2009. Methode der ökologischen Knappheit – Ökofaktoren 2006 190.

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. doi:10.1016/j.engstruct.2016.07.012

García-Segura, T., Yepes, V., Alcalá, J., 2014a. Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. The International Journal of Life Cycle Assessment 19, 3–12. doi: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, 112–122. doi:10.1016/j.engstruct.2015.03.015

García-Segura, T., Yepes, V., Frangopol, D.M., 2017a. Multi-objective design of post-tensioned concrete road bridges using artificial neural networks. Structural and Multidisciplinary Optimization 56, 139–150. doi:10.1007/s00158-017-1653-0

García-Segura, T., Yepes, V., Frangopol, D.M., Yang, D.Y., 2017. Lifetime reliability-based optimization of post-tensioned box-girder bridges. Engineering Structures 145. doi:10.1016/j.engstruct.2017.05.013

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

Gervasio, H., Simoes da Silva, L., 2008. Comparative life-cycle analysis of steel-concrete composite bridges. Structure and Infrastructure Engineering 4, 251–269. doi:10.1080/15732470600627325

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

Goedkoop, M., Hofstetter, P., Müller-Wenk, R., Spriemsma, R., 1998. The Eco-Indicator 98 explained. International Journal of Life Cycle Assessment 3, 352–360.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., Zelm, R. Van, 2009. ReCiPe 2008. A life cycle impact assessment which comprises harmonised category indicators at midpoint and at the endpoint level. Netherlands. doi:10.029/2003JD004283

Görener, A., 2012. Comparing AHP and ANP: An application of strategic decisions making in a manufacturing company. International Journal of Business and Social Science 3, 194–208.

Govindan, K., Jepsen, M.B., 2016. ELECTRE: A comprehensive literature review on methodologies and applications. European Journal of Operational Research 250, 1–29. doi:10.1016/j.ejor.2015.07.019

Grant, E., Ireson, W., 1960. Principles of engineering economy, New York: Ronald Press.

GreenDelta, 2017. SOCA v1.0.

GreenDelta, 2013a. PSILCA database [WWW Document]. URL https://psilca.net/ (accessed 10.1.19).

GreenDelta, 2013b. PSILCA v1.0 (Product Social Impact Life-Cycle Assessment).

GreenDelta, n.d. Open LCA.

Gu, X., Wang, Y., Yang, B., 2011. Method for selecting the suitable bridge construction projects with interval-valued intuitionistic Fuzzy information. International Journal of Digital Content Technology and its Applications 5, 201–206. doi:10.4156/jdcta.vol5.issue7.25

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Wegener Sleeswijk, A., Udo

De Haes, H. a., de Bruijn, J. a., van Duin, R., Huijbregts, M. a. J., 2001. Life cycle assessment: An operational guide to the ISO standards. III: Scientific background 692. doi:10.1300/J082v38n04_05

Gursel, A.P., Ostertag, C., 2017. Comparative life-cycle impact assessment of concrete manufacturing in Singapore. The International Journal of Life Cycle Assessment 22, 237–255. doi:10.1007/s11367-016-1149-y

Hajkowicz, S., Collins, K., 2007. A review of multiple criteria analysis for water resource planning and management. Water Resources Management 21, 1553–1566. doi:10.1007/s11269-006-9112-5

Hammervold, J., Reenaas, M., Brattebø, H., 2013. Environmental life cycle assessment of bridges. Journal of Bridge Engineering 18, 153–161. doi:10.1061/(ASCE)BE.1943-5592.0000328.

Harris, J.M., Wise, T.A., Gallagher, K.P., Goodwine, N.R., 2001. A survey of sustainable development: Social and economic dimension, Island Press. Washinton.

Hauschild, M., Potting, J., 2005. Background for spatial differentiation in LCA impact assessment - The EDIP2003 methodology. Environmental news.

Hettinger, A., Birat, J., Hechler, O., Braun, M., 2015. Sustainable bridges - LCA for a composite and a concrete bridge, in: Petzek, E., Bancila, R. (Eds.), Economical Bridge Solutions Based on Innovative Composite Dowels and Integrated Abutments,. Wiesbaden, Germany, pp. 45–54. doi:10.1007/978-3-658-06417-4

Hill, R.C., Bowen, P.A., 1997. Sustainable construction: principles and a framework for attainment. Construction Management and Economics 15, 223–239. doi:10.1080/014461997372971

Holland, J.H., 1975. Adaptation in natural and artificial systems, Ann Arbor: University of Michigan Press.

Horvath, A., Hendrickson, C., 1998. Steel versus steel-reinforced concrete bridges: Environmental assessment. Journal of Infrastructure Systems 4, 111–117. doi:10.1061/(ASCE)1076-0342(1998)4:3(111)

Hotelling, H., 1936. Relations between two sets of variates. Biometrika 28, 321–377. doi:10.2307/2333955

Hwang, C.L., Yoon, K., 1981. Multiple attribute decision making: Methods and Applications, Springer-Verlag.

Intergovernmental Panel On Climate Change, 2014. Climate change: Fifth assessment report. doi:10.1017/CBO9781107415324

International Organization for Standardization (ISO), 2006a. ISO 14040: Environmental managment - life cycle assessment - principles and framework. Geneva, Switzerland.

International Organization for Standardization (ISO), 2006b. ISO 14044: Environmental managment - life cycle assessment - requirments and guidelines. Geneva.

Itoh, Y., Kitagawa, T., 2003. Using CO2 emission quantities in bridge lifecycle analysis. Engineering Structures 25, 565–577. doi:10.1016/S0141-0296(02)00167-0

Itoh, Y., Sunuwar, L., Hirano, T., Hammad, A., Nishido, T., 2000. Bridge type selection system incorporating environmental impacts. Journal of Global Environment Engineering 6, 81–101.

Itsubo, N., Sakagami, M., Washida, T., Kokubu, K., Inaba, A., 2004. Weighting across safeguard subjects for LCIA through the application of conjoint analysis. International Journal of Life Cycle Assessment 9, 196–205. doi:10.1007/BF02994194

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. doi:10.1016/j.eswa.2014.12.039

Jato-Espino, D., Castillo-Lopez, E., Rodriguez-Hernandez, J., Canteras-Jordana, J.C., 2014. A review of application of multi-criteria decision making methods in construction. Automation in Construction 45, 151–162. doi:10.1016/j.autcon.2014.05.013

Jin, R., Chen, W., Simpson, T.W., 2001. Comparative studies of metamodelling techniques under multiple modelling criteria. Structural and Multidisciplinary Optimization 23, 1–13. doi:10.1007/s00158-001-0160-4

Jin, R., Du, X., Chen, W., 2003. The use of metamodeling techniques for optimization under uncertainty. Structural and Multidisciplinary Optimization 25, 99–116. doi:10.1007/s00158-002-0277-0

Johnson, M.E., Moore, L.M., Ylvisaker, D., 1990. Minimax and maximin distance designs. Journal of Statistical Planning and Inference 26, 131–148. doi:10.1016/0378-3758(90)90122-B

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., 2003. IMPACT 2002+: A new Life Cycle Impact Assessment Methodology. International Journal of Life Cycle Assessment 8, 324–330. doi:10.1007/BF02978505

Jurecka, F., Ganser, M., Bletzinger, K.-U., 2007. Update scheme for sequential spatial correlation approximations in robust design optimisation. Computers & Structures 85, 606–614. doi:10.1016/J.COMPSTRUC.2006.08.075

Kaiser, H.F., 1974. An index of factorial simplicity. Psychometrika 39, 31–36. doi:10.1007/BF02291575

Kaiser, H.F., 1960. The application of electronic computers to factor analysis. Educational and Psychological Measurement 20, 141–151. doi:10.1177/001316446002000116

Kalagnanam, J.R., Diwekar, U.M., 1997. An efficient sampling technique for off-line quality control. Technometrics 39, 308. doi:10.2307/1271135

Keeney, R.L., Raiffa, H., 1976. Decisions with multiple objective: Preferences and value tradeoffs, Wiley. ed. New York.

Kellenberger, D., Althaus, H.J., Jungbluth, N., Künniger, T., 2007. Life cycle inventories of building products, Swiss Centre for Life Cycle Inventories.

Kennedy, J., Eberhart, R., 1995. Particle swarm optimization, in: Proceedings of ICNN'95 - International Conference on Neural Networks. IEEE, pp. 1942–1948. doi:10.1109/ICNN.1995.488968

Kim, B.-S., Lee, Y.-B., Choi, D.-H., 2009. Comparison study on the accuracy of metamodeling technique for non-convex functions. Journal of Mechanical Science and Technology 23, 1175–1181. doi:10.1007/s12206-008-1201-3

Kirkpatrick, S., Gelatt, C.D., Vecchi, M.P., 1983. Optimization by simulated annealing. Science (New York, N.Y.) 220, 671–80. doi:10.1126/science.220.4598.671

Kleijnen, J.P.C., 2009. Kriging metamodeling in simulation: A review. European Journal of Operational Research 192, 707–716. doi:10.1016/j.ejor.2007.10.013

Korpela, J., Lehmusvaara, A., Tuominen, M., 2001. An analytic approach to supply chain development. International Journal of Production Economics 71, 145–155. doi:10.1016/S0925-5273(00)00114-6

Krishnanand, K.N., Ghose, D., 2009. Glowworm swarm optimisation: A new method for optimising multi-modal functions. International Journal of Computational Intelligence Studies 1, 93–119. doi:10.1504/IJCISTUDIES.2009.025340

Kutylowski, R., Rasiak, B., 2014. Application of topology optimization to bridge girder design. Structural Engineering and Mechanics 51, 39–66. doi:10.12989/sem.2014.51.1.039

Lagerblad, B., 2005. Carbon dioxide uptake during concrete life cycle - State of the art, The Swedish Cement and Concrete Research Institute. Stockholm, Sweeden.

Laurent, A., Olsen, S.I., Hauschild, M.Z., 2012. Limitations of carbon footprint as indicator of environmental sustainability. Environmental Science & Technology 46, 4100–4108. doi:10.1021/es204163f

Lee, K.-H., Kang, D.-H., 2006. A robust optimization using the statistics based on kriging metamodel. Journal of Mechanical Science and Technology 20, 1169–1182. doi:10.1007/BF02916016

Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013. Building Eora: A global multi-regional Input-Output Database at high country and sector resolution. Economic Systems Research 25, 20–49. doi:10.1080/09535314.2013.769938

Li, Y.F., Ng, S.H., Xie, M., Goh, T.N., 2010. A systematic comparison of metamodeling techniques for simulation optimization in decision support systems. Applied Soft Computing 10, 1257–1273. doi:10.1016/J.ASOC.2009.11.034

Lin, Y., Chen, M., Liu, S., 2004. Theory of grey systems: capturing uncertainties of grey information. Kybernetes 33, 196–218. doi:10.1108/03684920410514139

Lounis, Z., Cohn, M.Z., 1993. Optimization of precast prestressed concrete bridge girder systems. PCO Journal 38, 60–78.

Malekly, H., Meysam Mousavi, S., Hashemi, H., 2010. A fuzzy integrated methodology for evaluating conceptual bridge design. Expert Systems with Applications 37, 4910–

4920. doi:10.1016/j.eswa.2009.12.024

Marceau, M.L., Nisbet, M.A., Vangeem, M.G., 2007. Life cycle inventory of portland cement concrete, Portland Cement Association. Skokie, Illinois, USA.

Marshall, H.E., 1987. Building economics in the United States. Construction Management and Economics 5, S43–S52. doi:10.1080/01446193.1987.10462092

Martí, J. V., García-Segura, T., Yepes, V., 2016a. Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy. Journal of Cleaner Production 120, 231–240. doi:10.1016/J.JCLEPRO.2016.02.024

Martí, J. V., García-Segura, T., Yepes, V., 2016b. Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy. Journal of Cleaner Production 120, 231–240. doi: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, 342–352. doi:10.1016/j.engstruct.2012.09.014

Martí, J. V., Yepes, V., González-Vidosa, F., 2015. Memetic algorithm approach to designing precast-prestressed concrete road bridges with steel fiber reinforcement. Journal of Structural Engineering 141, 4014114. doi:10.1061/(ASCE)ST.1943-541X.0001058

Martínez-Frutos, J., Martí, P., 2014. Diseño óptimo robusto utilizando modelos Kriging: aplicación al diseño óptimo robusto de estructuras articuladas. Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería 30, 97–105. doi:10.1016/j.rimni.2013.01.003

Martinez-Martin, F.J., 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, 420–432. doi:10.1631/jzus.A1100304

Matheron, G., 1963. Principles of geostatistics. Economic Geology 58, 1246–1266.

McKay, M.D., Beckman, R.J., Conover, W.J., 1979. Comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics 21, 239–245. doi:10.1080/00401706.1979.10489755

McKenzie, S., 2004. Social sustainability: Towards some definitions. Magil.

Medina, J.R., 2001. Estimation of incident and reflected waves using simulated annealing. Journal of Watery, Port, Coastal, and Ocean Engineering 127, 213–221.

Miller, G.A., n.d. The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information.

Ministerio de Fomento, 2011. IAP-11: Code on the actions for the design of road bridges. Madrid, Spain.

Ministerio de Fomento, 2008. EHE-08: Code on structural concrete. Madrid, Spain.

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. doi:10.1016/j.jclepro.2017.06.246

Montalbán-Domingo, L., García-Segura, T., Amalia Sanz, M., Pellicer, E., 2019. Social Sustainability in Delivery and Procurement of Public Construction Contracts. Journal of Management in Engineering 35, 1–11. doi:10.1061/(ASCE)ME.1943-5479.0000674

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. doi:10.1016/j.jclepro.2018.07.083

Moscato, P., 1989. On evolution, search, optimization, genetic algorithms and martial arts - Towards memetic algorithms. Pasadena, California.

Mousavi, S.M., Gitinavard, H., Siadat, A., 2014. A new hesitant fuzzy Analytical Hierarchy Process method for decision-making problems under uncertainty, in: IEEE International Conference on Industrial Engineering and Engineering Management. pp. 622–626.

Murphy, K., 2012. The social pillar of sustainable development: a literature review and framework for policy analysis. Sustainability: Science, Practice and Policy 8, 15–29. doi:10.1080/15487733.2012.11908081

Myers, R.H., Montgomery, D.C., Anderson-Cook, C.M., 1995. Response surface methodology: Process and product optimization using designed experiments, Wiley. Wiley, Toronto, Canada.

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. doi:10.1016/J.EIAR.2018.10.001

Navarro, I.J., Yepes, V., Martí, J. V., 2018a. Social life cycle assessment of concrete bridge decks exposed to aggressive environments. Environmental Impact Assessment Review 72, 50–63. doi:10.1016/J.EIAR.2018.05.003

Navarro, I.J., Yepes, V., Martí, J. V., González-Vidosa, F., 2018b. Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks. Journal of Cleaner Production 196, 698–713. doi:10.1016/J.JCLEPRO.2018.06.110

New Earth, 2009a. SHDB database [WWW Document]. URL https://www.socialhotspot.org/for-more-information.html (accessed 10.1.19).

New Earth, 2009b. SHDB v1.0 (Social Hotspot Database).

Nigdeli, S.M., Bekdas, G., Kim, S., Geem, Z.W., 2015. A novel harmony search based optimization of reinforced concrete biaxially loaded columns. Structural Engineering and Mechanics 54, 1097–1109. doi:10.12989/sem.2015.54.6.1097

Ohkubo, S., Dissanayake, P.B.R., Taniwaki, K., 1998. An approach to multicriteria fuzzy optimization of a prestressed concrete bridge system considering cost and aesthetic feeling. Structural Optimization 15, 132–140. doi:10.1007/BF01278499

Omann, I., Spangenberg, J.H., 2002. Assessing social sustainability: The social dimension of sustainability in a socio-economic scenario.

Opricovic, S., 1998. Multicriteria optimization of civil engineering systems. Faculty of civil engineering, Belgrade.

Opricovic, S., Tzeng, G.-H., 2004. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. European Journal of Operational Research 156, 445–455. doi:10.1016/S0377-2217(03)00020-1

Pan, N.-F., 2008. Fuzzy AHP approach for selecting the suitable bridge construction method. Automation in Construction 17, 958–965. doi:10.1016/j.autcon.2008.03.005

Panesar, D.K., Seto, K.E., Churchill, C.J., 2017. Impact of the selection of functional unit on the life cycle assessment of green concrete. The International Journal of Life Cycle Assessment 22, 1969–1986. doi:10.1007/s11367-017-1284-0

Pang, B., Yang, P., Wang, Y., Kendall, A., Xie, H., Zhang, Y., 2015. Life cycle environmental impact assessment of a bridge with different strengthening schemes. The International Journal of Life Cycle Assessment 20, 1300–1311. doi:10.1007/s11367-015-0936-1

Park, H., Kwon, B., Shin, Y., Kim, Y., Hong, T., Choi, S., 2013. Cost and CO2 emission optimization of steel reinforced concrete columns in high-rise buildings. Energies 6, 5609–5624. doi:10.3390/en6115609

Paya, I., Yepes, V., González-Vidosa, F., Hospitaler, A., 2008. Multiobjective optimization of concrete frames by simulated annealing. Computer-Aided Civil and Infrastructure Engineering 23, 596–610. doi:10.1111/j.1467-8667.2008.00561.x

Penadés-Plà, V., García-Segura, T., Martí, J., Yepes, V., 2016. A review of multi-criteria decision-making methods applied to the sustainable bridge design. Sustainability 8, 1295. doi: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, 1–17. doi:10.3390/su10030685

Penadés-Plà, V., García-Segura, T., Yepes, V., 2019. Accelerated optimization method for low-embodied energy concrete box-girder bridge design. Engineering Structures 179, 556–565. doi:10.1016/J.ENGSTRUCT.2018.11.015

Penadés-Plà, V., Martí, J. V., García-Segura, T., Yepes, V., 2017a. Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges. Sustainability 9, 1864. doi:10.3390/su9101864

Penadés-Plà, V., Martí, J. V., García-Segura, T., Yepes, V., Penadés-Plà, V., Martí, J. V., García-Segura, T., Yepes, V., 2017b. Life-Cycle Assessment: A Comparison between Two Optimal Post-Tensioned Concrete Box-Girder Road Bridges. Sustainability 9, 1864. doi:10.3390/su9101864

Petek Gursel, A., Masanet, E., Horvath, A., Stadel, A., 2014. Life-cycle inventory analysis of concrete production: A critical review. Cement and Concrete Composites 51, 38–48. doi:10.1016/j.cemconcomp.2014.03.005

Phadke, M.S., Shridhar, M., 1989. Quality engineering using robust design. Prentice Hall.

Podvezko, V., 2011. The Comparative Analysis of MCDA methods SAW and COPRAS. Engineering Economics 22, 134–146. doi:10.5755/j01.ee.22.2.310

Pons, J.J., Penadés-Plà, V., Yepes, V., Martí, J. V., 2018. Life cycle assessment of earth-retaining walls: An environmental comparison. Journal of Cleaner Production 192, 411–420. doi:10.1016/j.jclepro.2018.04.268

Pons, O., De La Fuente, A., 2013. Integrated sustainability assessment method applied to structural concrete columns. doi:10.1016/j.conbuildmat.2013.09.009

Purdue University, 2013. Global trade analysis project. West Lafayette, Indiana.

Ramesh, T., Prakash, R., Shukla, K.K., 2010. Life cycle energy analysis of buildings: An overview. Energy and Buildings 42, 1592–1600. doi:10.1016/j.enbuild.2010.05.007

Rosenblatt, F., 1958. The perceptron: A probabilistic model for information storage and organization in the brain. Psychological Review 65, 386–408. doi:10.1037/h0042519

Roy, B., 1968. Classement et choix en présence de points de vue multiples (le méthode ELECTRE). Revue Francaise D Informatique de Recherche Operationnelle 8, 57–75.

Saaty, R.W., 1987. The analytic hierarchy process—what it is and how it is used. Mathematical Modelling 9, 161–176. doi:10.1016/0270-0255(87)90473-8

Saaty, T.L., 1996. Decision making with dependence and feedback: The analytic network process, Ellsworth. ed. Pittsburgh.

Saaty, T.L., 1980. The Analytic Hierarchy Process, McGraw-Hill. New York.

Sabatino, S., Frangopol, D.M., Dong, Y., 2015. Sustainability-informed maintenance optimization of highway bridges considering multi-attribute utility and risk attitude. Engineering Structures 102, 310–321. doi:10.1016/j.engstruct.2015.07.030

Sarabando, P., Dias, L.C., 2010. Simple procedures of choice in multicriteria problems without precise information about the alternatives' values. Computers and Operations Research 37, 2239–2247. doi:10.1016/j.cor.2010.03.014

Sarma, K.C., Adeli, H., 1998. Cost optimization of concrete structures. Journal of Structural Engineering 124, 570–578. doi:10.1061/(ASCE)0733-9445(1998)124:5(570)

Schlaich, J., Scheef, H., 1982. Concrete box-girder bridges, in: International Association for Bridge and Structural Engineering. Zürich, Switzerland.

Sierra, L.A., Yepes, V., Pellicer, E., 2017. Assessing the social sustainability contribution of an infrastructure project under conditions of uncertainty. Environmental Impact Assessment Review 67, 61–72. doi:10.1016/J.EIAR.2017.08.003

Simpson, T.W., Booker, A.J., Ghosh, D., Giunta, A.A., Koch, P.N., Yang, R.-J., 2004. Approximation methods in multidisciplinary analysis and optimization: A panel discussion. Structural and Multidisciplinary Optimization 27, 302–313. doi:10.1007/s00158-004-0389-9

Simpson, T.W., Mauery, T.M., Korte, J., Mistree, F., 2001. Kriging models for global approximation in simulation-based multidisciplinary design optimization. AIAA Journal 39, 2233–2241. doi:10.2514/3.15017

Simpson, T.W., Poplinski, J.D., Koch, P.N., Allen, J.K., 2001. Metamodels for computer-based engineering design: Survey and recommendations. Engineering with Computers 17, 129–150. doi:10.1007/PL00007198

Sobanjo, J.O., Stukhart, G., James, R.W., 1994. Evaluation of projects for rehabilitation of highway bridges. Journal of Structural Engineering 120, 81–99.

Steele, K., Cole, G., Parke, G., Clarke, B., Harding, J., Harding, J., 2003. Highway bridges and environment-sustainable perspectives. Proceedings of the Institution of Civil Engineers 156, 176–182. doi:10.1680/cien.156.4.176.36764

Steele, K.N.P., Cole, G., Parke, G., 2002. Application of life cycle assessment technique in the investigation of brick arch highway bridges, in: 6th International Masonry Conference. pp. 1–8.

Steen, B., 1999. A systematic approach to environmental priority strategies in product development (EPS).

Stengel, T., Schiessl, P., 2009. Life cycle assessment of UHPC bridge constructions : Sherbrooke Footbridge , Kassel Gärtnerplatz Footbridge and Wapello Road Bridge. Architecture Civil Engineering Environment 1, 109–118.

Sterner, E., 2002. Green procurement of building: Estimation of life cycle cost and environmental impact.

Taguchi, G., 1986. Introduction to quality engineering. Asian Productivity Organisation, Tokio.

Tait, M.W., Cheung, W.M., 2016. A comparative cradle-to-gate life cycle assessment of three concrete mix designs. The International Journal of Life Cycle Assessment 21, 847–860. doi:10.1007/s11367-016-1045-5

Tamiz, M., Jones, D., Romero, C., 1998. Goal programming for decision making : An overview of the current state-of-the-art. European Journal of Operational Research 111, 569–581. doi:10.1016/S0377-2217(97)00317-2

Taylor, M., Tam, C., Gielen, D., 2006. Energy efficiency and CO2 emissions from the global cement industry, in: International Energy Agency. Paris, Francia, p. 13.

Ugwu, O.O., Kumaraswamy, M.M., Wong, A., Ng, S.T., 2006. Sustainability appraisal in infrastructure projects (SUSAIP): Part 2: A case study in bridge design. Automation in Construction 15, 229–238. doi:10.1016/j.autcon.2005.05.005

United Nations, 2014. Indicators for sustainable development goals.

United Nations., 1987. World Commission on Environment and Development Our common future. New York, USA.

Utomo, C., Idrus, A., 2010. Value – based Group Decision on Support Bridge Selection. World Academy of Science, Engineering and Technology 4, 188–193.

Valdebenito, M.A., Schuëller, G.I., 2010. A survey on approaches for reliability-based optimization. Structural and Multidisciplinary Optimization 42, 645–663. doi:10.1007/s00158-010-0518-6

Valdes-Vasquez, R., Klotz, L.E., 2013. Social sustainability considerations during planning and design: Framework of processes for construction projects. Journal of Construction Engineering and Management 139, 80–89. doi:10.1061/(ASCE)CO.1943-7862.0000566

Vallance, S., Perkins, H.C., Dixon, J.E., 2011. What is social sustainability? A clarification of concepts. Geoforum 42, 342–348. doi:10.1016/j.geoforum.2011.01.002

Waas, T., Hugé, J., Block, T., Wright, T., Benitez-Capistros, F., Verbruggen, A., 2014. Sustainability Assessment and Indicators: Tools in a Decision-Making Strategy for Sustainable Development. Sustainability 6, 5512–5534. doi:10.3390/su6095512

Wang, H.-L., Zhang, Z., Qin, S.-F., Huang, C.-L., 2001. Fuzzy optimum model of semi-structural decision for lectotype. China Ocean Engineering 15, 453–466.

Widman, J., 1998. Environmental impact assessment of steel bridges. Journal of Construction Steel Research 46, 291–293.

Wills, J., 1973. A mathematical optimization procedure and its application to the design of bridge structures. Wokingham, United Kingdom.

World Steel Association, 2008. Steel and energy fact sheet.

Yehia, S., Abudayyeh, O., Fazal, I., Randolph, D., 2008. A decision support system for concrete bridge deck maintenance. Advances in Engineering Software 39, 202–210. doi:10.1016/j.advengsoft.2007.02.002

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. doi:10.1016/j.acme.2017.02.006

Yepes, V., Martí, J. V., García-Segura, T., 2015. 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. doi:10.1016/j.autcon.2014.10.013

Yi, S., Kurisu, K.H., Hanaki, K., Hanaki, K., 2011. Life cycle impact assessment and interpretation of municipal solid waste management scenarios based on the midpoint and endpoint approaches. The International Journal of Life Cycle Assessment 16, 652–668. doi:10.1007/s11367-011-0297-3

Yu, C., Gupta, H., Das, N.C., Paul, H., 1986. Optimization of prestressed concrete bridge girders. Engineering Optimization 10, 13–24. doi:10.1080/03052158608902524

Yu, P.L., 1973. A class of solutions for group decision problems. Management Science 19, 936–946.

Zadeh, L.A., 1965. Fuzzy sets. Information and Control 8, 338–353.

Zastrow, P., Molina-Moreno, F., García-Segura, T., Martí, J. V., Yepes, V., 2017. Life cycle assessment of cost-optimized buttress earth-retaining walls: A parametric study. Journal of Cleaner Production 140, 1037–1048. doi:10.1016/j.jclepro.2016.10.085

Zavadskas, E., Antucheviciene, J., Vilutiene, T., Adeli, H., 2017. Sustainable decision-making in civil engineering, Construction and building technology. Sustainability 10, 14. doi:10.3390/su10010014

Zavadskas, E.K., Kaklauskas, A., 1996. Determination of an efficient contractor by using the new method of multicriteria assessment. Assessment, in International Symposium for the Organization and Management of Construction: Shaping Theory and Practice; vol. 2; Managing the Construction Project and Managing Risk 94–104.

Zavadskas, E.K., Liias, R., Turskis, Z., 2008. Multi-attribute decision-making methods for assessment of quality in bridges and road construction: State-of-the-art surveys. The Baltic Journal of Road and Bridge Engineering 3, 152–160. doi:10.3846/1822-427X.2008.3.152-160

Zavadskas, E.K., Turkis, Z., 2012. Multiple criteria decision making (MCDM) methods in economics: An overview. Technological and Economic Development of Economy 18, 672–695. doi:10.3846/20294913.2012.753489

Zeleny, M., 1982. Multiple criteria decision making, McGraw-Hil. ed. New York.

ANNEX I. AUTHOR CONTRIBUTIONS

JCR Journal articles

- 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. DOI:10.3390/su8121295
- 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(10):1864. DOI:10.3390/su9101864
- PENADÉS-PLÀ, V.; GARCÍA-SEGURA, T.; MARTÍ, J.V.; YEPES, V. (2018). **An optimization-LCA of a prestressed concrete precast bridge.** *Sustainability*, 10(3):685. DOI:3390/su10030685
- PONS, J.J.; PENADÉS-PLÀ, V.; YEPES, V.; MARTÍ, J.V. (2018). **Life cycle assessment of earth-retaining walls: An environmental comparison.** *Journal of Cleaner Production*, 192:411-420. DOI:1016/j.jclepro.2018.04.268
- 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. DOI:1016/j.jclepro.2018.08.177
- PENADÉS-PLÀ, V.; GARCÍA-SEGURA, T.; YEPES, V. (2019). **Accelerated optimization method for low-embodied energy concrete box-girder bridge design.** *Engineering Structures*, 179:556-565. DOI:10.1016/j.engstruct.2018.11.015
- PENADÉS-PLÀ, V.; YEPES, V.; GARCÍA-SEGURA, T. (2020). **Robust decision-making design for sustainable pedestrian concrete bridges.** *Engineering Structures*, (accepted, in press). DOI:10.1016/j.engstruct.2019.109968
- PENADÉS-PLÀ, V.; GARCÍA-SEGURA, T.; YEPES, V. **Robust decision-making design for sustainable pedestrian concrete bridges.** *Engineering Structures* (Submitted)
- PENADÉS-PLÀ, V.; GARCÍA-SEGURA, T.; YEPES, V. **Environmental and social life cycle assessment of cost-optimized post-tensioned**

concrete road bridges. *Environmental impact assessment review* (Submitted)

- ATA-ALI, N.; PENADÉS-PLÀ, V.; YEPES, V. **Life-cycle assessment of ventilated facade with different insulation materials for different climatic conditions.** *Journal of cleaner production* (Submitted).

Conferences papers

- PENADÉS-PLÀ, V.; YEPES, V.; GARCÍA-SEGURA, T.; MARTÍ, J. (2017). **Study of criteria used to obtain a sustainable bridge.** International Structural Engineering and Construction Society ISEC-09, Valencia, Spain • Jul 24-Jul 29, 2017, 6 pp.
- PENADÉS-PLÀ, V.; YEPES, V.; GARCÍA-SEGURA, T. MARTÍ, J.V. (2017). **Estudio de la aplicación de los métodos de decisión multicriterio al ciclo de vida de los puentes.** VII Congreso de ACHE, A Coruña, junio.
- PENADÉS-PLÀ, V.; GARCÍA-SEGURA, T.; YEPES, V.; MARTÍ, J.V. (2018). **Kriging-based heuristic optimization of a continuous concrete box-girger pedestrian bridge.** Sixth International Symposium on Life-Cycle Civil Engineering (IALCCE 2018), Ganth (Belgium), October 2018, pp. 2753-2759. ISBN: 9781138626331
- PENADÉS-PLÀ, V.; YEPES, V.; GARCÍA-SEGURA, T. (2019). **Metodología para valorar la sostenibilidad con baja influencia de los decisores.** 5th International Conference on Mechanical Models in Structural Engineering, CMMoST 2019, 23-25 oct 2019, Alicante, Spain.
- YEPES, V.; PENADÉS-PLÀ, V.; GARCÍA-SEGURA, T. (2019). **Aplicación de optimización Kriging para la búsqueda de estructuras óptimas robustas.** 5th International Conference on Mechanical Models in Structural Engineering, CMMoST 2019, 23-25 oct 2019, Alicante, Spain.
- YEPES, V.; PENADÉS-PLÀ, V.; GARCÍA-SEGURA, T. (2020). **Application of robust design optimization in a continuous box-girder pedestrian bridge.** 7th International Symposium on Life-Cycle Civil Engineering IALCCE 2020, 27-30 October 2020, Shanghai, China (abstract accepted).