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Life-Cycle Assessment: A Comparison between Two Optimal Post-Tensioned Concrete Box-Girder Road Bridges

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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 among the most active high environmental impact sectors. 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 which makes the greatest contribution. In addition, the contribution of CO_2 fixation is taken into account, reducing the environmental impact in the use and maintenance and end of life stages. 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 a higher environmental impact in the manufacturing stage.

Keywords: sustainability; environmental impact; life-cycle assessment; construction LCA; bridge LCA; ReCiPe; sustainable construction

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 intergenerational 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. Sustainable construction can be defined as construction 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 project, and then apply the decision-making process to obtain a single evaluation of its sustainability.

It is clear that we are facing environmental problems, and that human influence is a vital factor in these problems. 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 throughout the 21st 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 sorted 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., 2015 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 for 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.

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.

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 the 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.

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 (Eidgenössische Technische Hochschule) 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 and time, and more with one technology than 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.

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.

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.

2.1.4. 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 1 shows the general scheme to obtain 1 m^3 of concrete, and Figure 2 shows the general scheme to obtain 1 kg of reinforced steel.

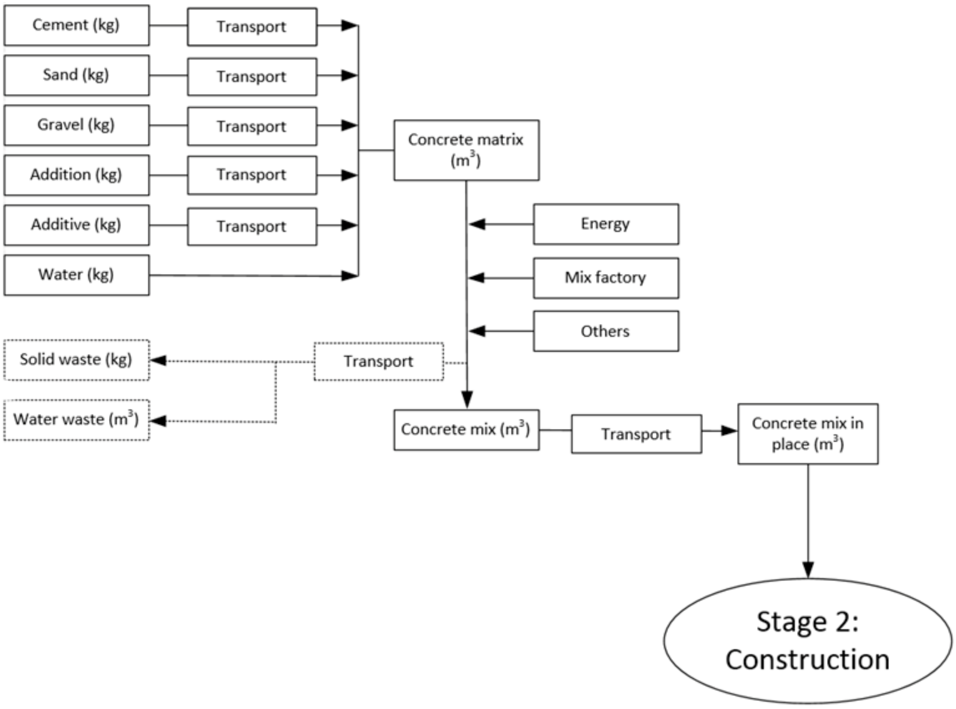

Figure 1. Concrete manufacturing.

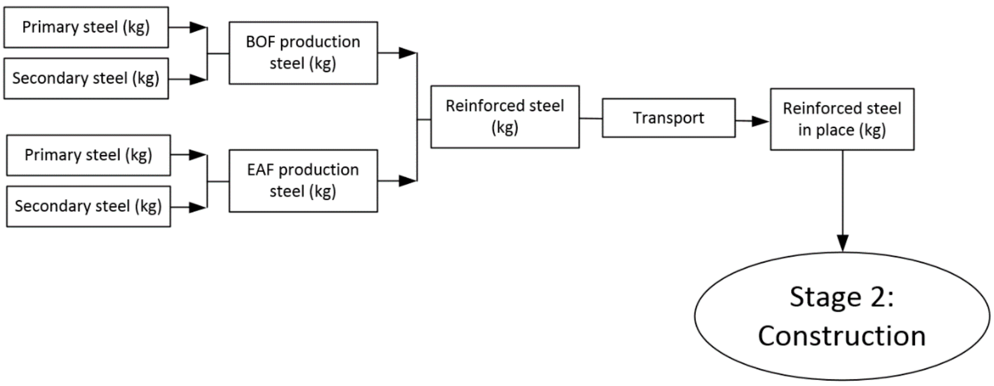

Figure 2. Steel manufacturing.

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 concrete products created with 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 concrete products created with Ecoinvent is the control of the type and amount of energy. Ecoinvent has energy information from several different countries, but in the concrete products created 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 (1)–(5). Finally, the distance and mode of transportation of the concrete mix between the factory and the construction zone can be defined exactly.

$$Primary\ Water = Water + Waste\ water \tag{1}$$

$$Total\ solid = Cement + Gravel + Sand \tag{2}$$

$$Primary\ Cement = Cement + \left(\frac{Cement}{Total\ solid}\right) \cdot Waste\ concrete \tag{3}$$

$$Primary\ Gravel = Gravel + \left(\frac{Gravel}{Total\ solid}\right) \cdot Waste\ concrete \tag{4}$$

$$Primary\ Sand = Sand + \left(\frac{Sand}{Total\ solid}\right) \cdot Waste\ concrete \tag{5}$$

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.

2.1.5. 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, and so on. 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 3 shows a general scheme to take this phase into account.

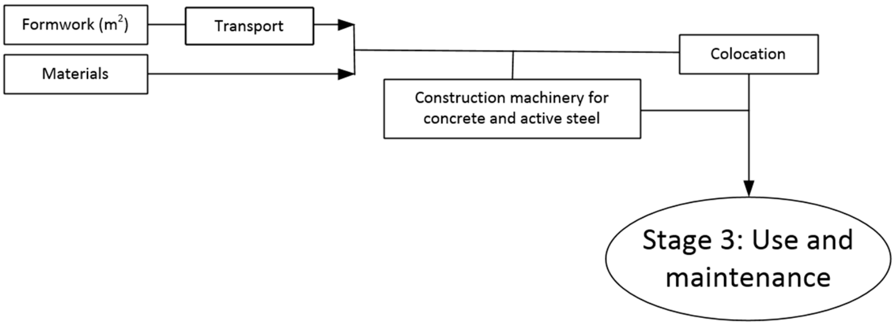

Figure 3. Construction diagram.

2.1.6. 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 detours, 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 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 through Equation (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, Equation (6) can be reduced to Equation (7). Some studies [31] showed that the ratio of CO_2 generated for concrete structures can be fixed along its service life. Figure 4 shows a maintenance and use scheme in which fixed CO_2 is considered.

$$CO_2 fixed\ (\mathrm{kg}) = \frac{k\left(\frac{\mathrm{mm}}{\sqrt{\mathrm{year}}}\right)\cdot\sqrt{t(\mathrm{year})}}{1000}\cdot A\left(\mathrm{m}^2\right)\cdot r\cdot C\left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)\cdot k(\%)\cdot L(\%)\cdot\varepsilon \quad (6)$$

$$CO_2 fixed\ (\mathrm{kg}) = 0.383\cdot\frac{k\left(\frac{\mathrm{mm}}{\sqrt{\mathrm{year}}}\right)\cdot\sqrt{t(\mathrm{year})}}{1000}\cdot A\left(\mathrm{m}^2\right)\cdot C\left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)\cdot k(\%) \quad (7)$$

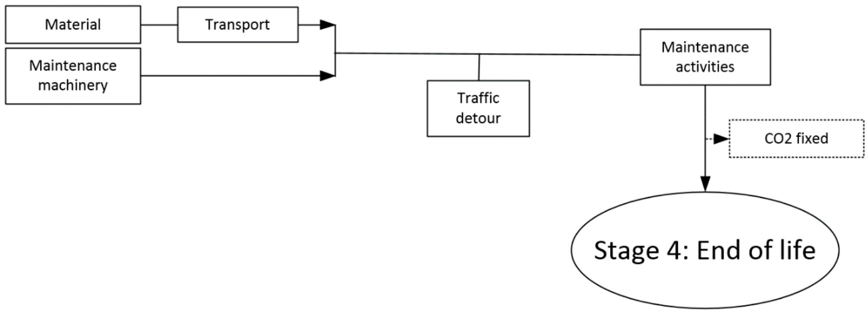

Figure 4. Maintenance and use diagram.

2.1.7. 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 waste generated (reuse, recycling, or disposal in landfill), and the machinery needed for bridge demolition, transport and treatment of wastes. Therefore, it is first necessary to define the destination of the materials after their service life in the planning and design phase. 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 5 shows a general scheme of the end of life phase.

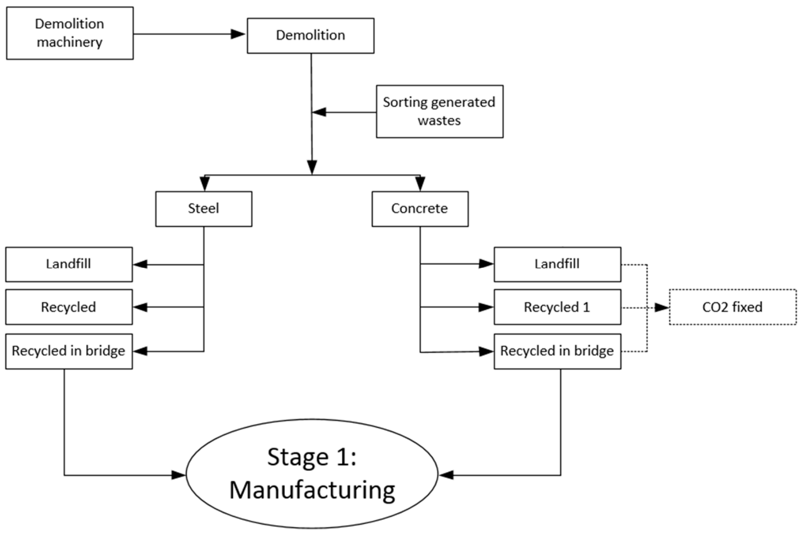

Figure 5. End of life diagram.

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 0.5 mm/year$^{0.5}$, 0.75mm/year$^{0.5}$, 1 mm/year$^{0.5}$, 2.5 mm/year$^{0.5}$ and 3.5 mm/year$^{0.5}$ depending on whether concrete is exposed, sheltered, indoor, wet or buried, respectively. In those cases, complete concrete carbonation takes 100, 44.4, 25, 4 and 2.04 years, respectively, assuming that the crushed concrete aggregate is 10-mm diameter. The results show the importance of the exposure environment.

2.2. Inventory Analysis

Inventory analysis comprises the collection of data and processes to quantify the inflows and outflows of the system under study. 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 other 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.

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].

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.

3. Case of Study

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

3.1. General Scheme

Figure 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 1–5 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.

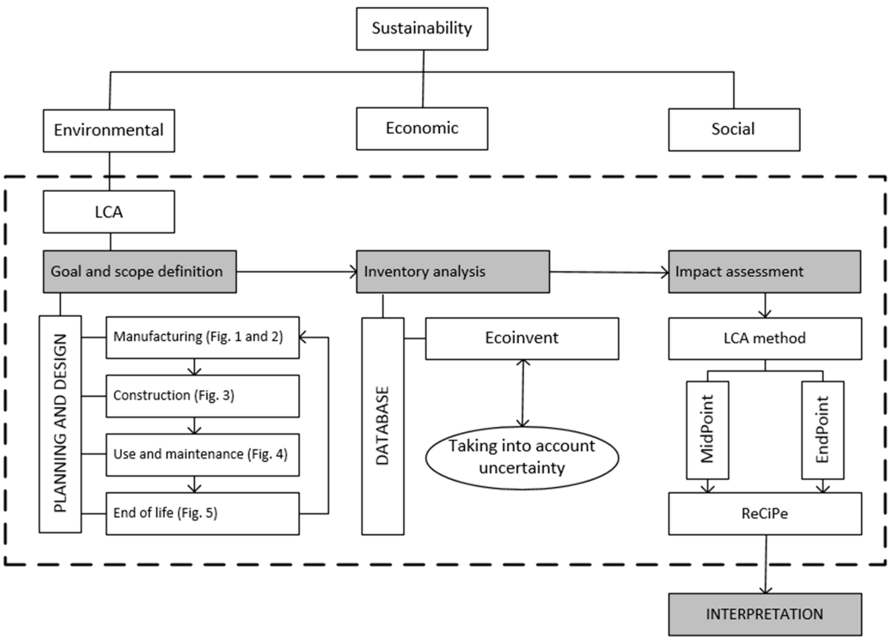

Figure 6. General scheme.

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 m and a width of 11.8 m. 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 7 shows the general view of the bridge.

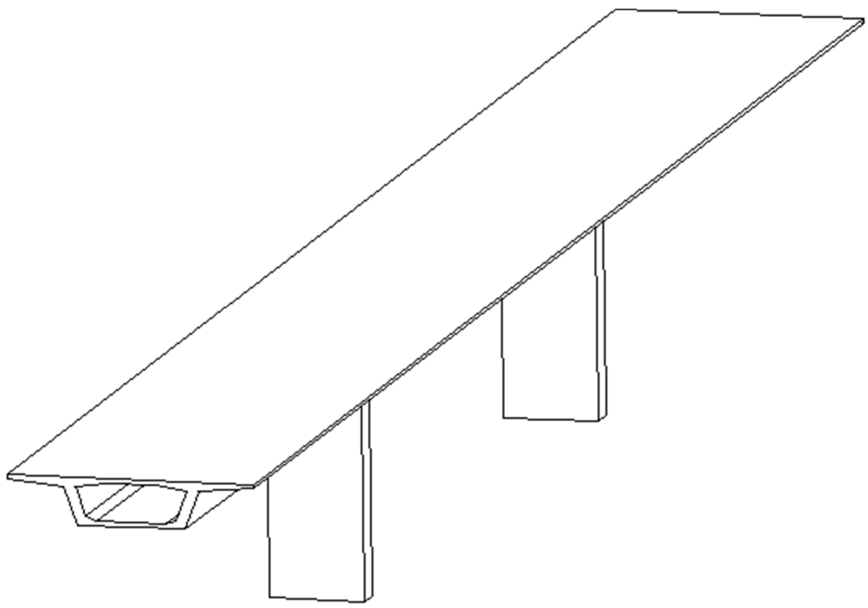

Figure 7. General view of the bridges.

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 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.

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 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 2.1.4.

Table 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%.

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.

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 (Institute of Construction Technology of Catalonia 2016), 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.

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.

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.

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 2 and 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 2 and 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.

Table 2. Impact categories for Solution 1.

Acronym	Reference Unit	Manufacturing		Construction		Use and Maintenance		EoL	
		m	**cv (%)**	**m**	**cv (%)**	**m**	**cv (%)**	**m**	**cv (%)**
ALO	$m^2 \times$ year	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 PM_{10} 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 SO_2 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	$m^2 \times$ year	41.60	6.68	14.72	28.80	31.52	28.10	0.37	7.79
WD	m^3	15,361.74	10.46	3197.70	4.60	2077.07	22.44	323.72	4.92

Table 3. Impact categories for Solution 2.

Acronym	Reference Unit	Manufacturing		Construction		Use and Maintenance		EoL	
		m	cv (%)	m	cv (%)	m	cv (%)	m	cv (%)
ALO	$m^2 \times$ year	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	−1099.20	−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 PM_{10} 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 SO_2 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	$m^2 \times$ year	44.99	6.54	14.41	29.41	15.48	26.67	0.37	7.81
WD	m^3	17,948.35	12.29	2988.85	4.70	1026.25	20.95	324.08	4.89

In addition, for a more compressed view of these results, Figures 8 and 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 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 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.

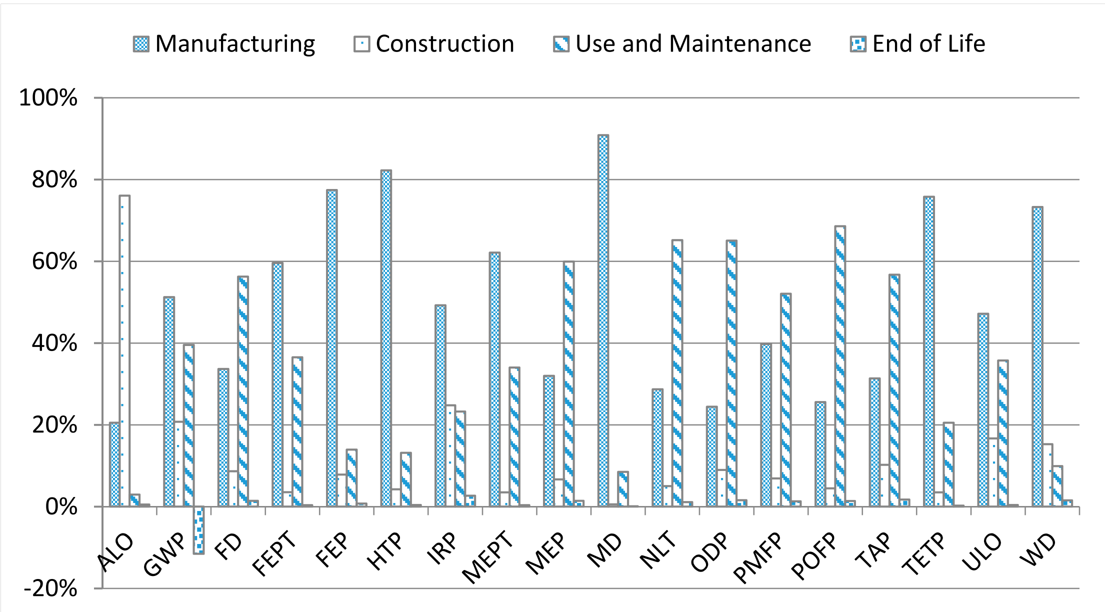

Figure 8. Impact categories for Solution 1.

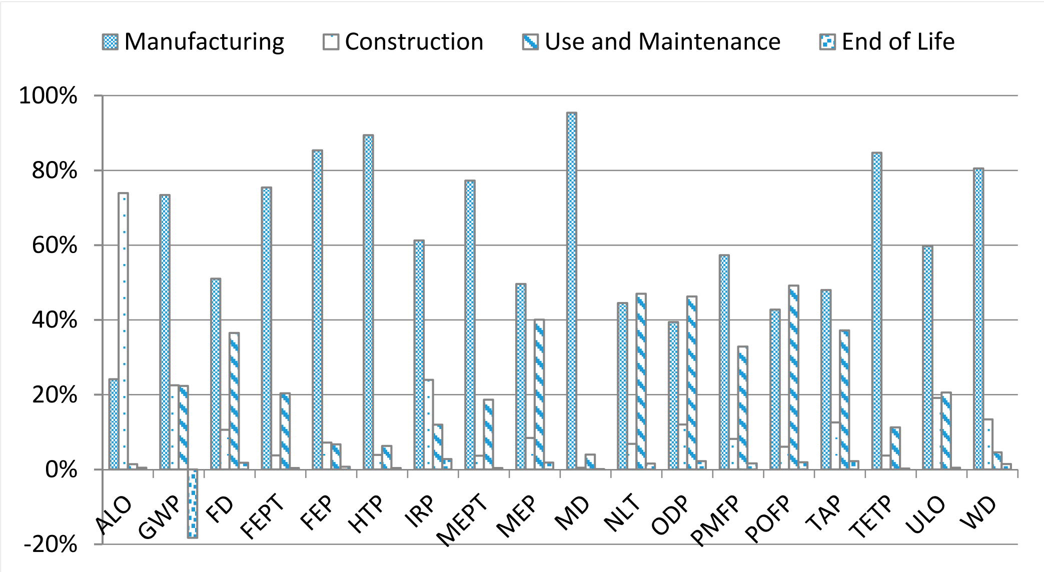

Figure 9. Impact categories for Solution 2.

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.

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 10 and 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 2 and 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 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.

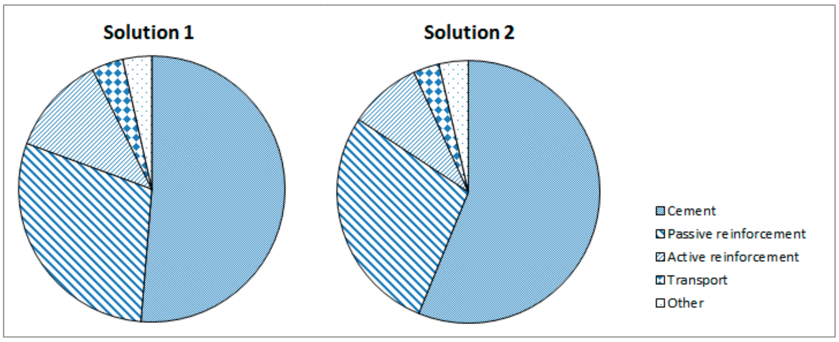

Figure 10. Contribution in % of manufacturing processes in climate change (GWP).

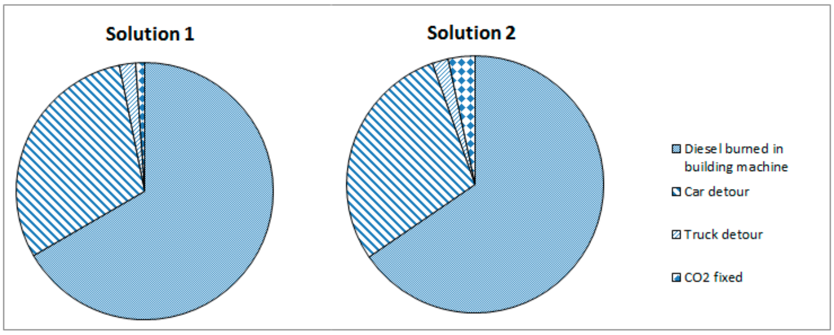

Figure 11. Contribution in % of use and maintenance processes in GWP.

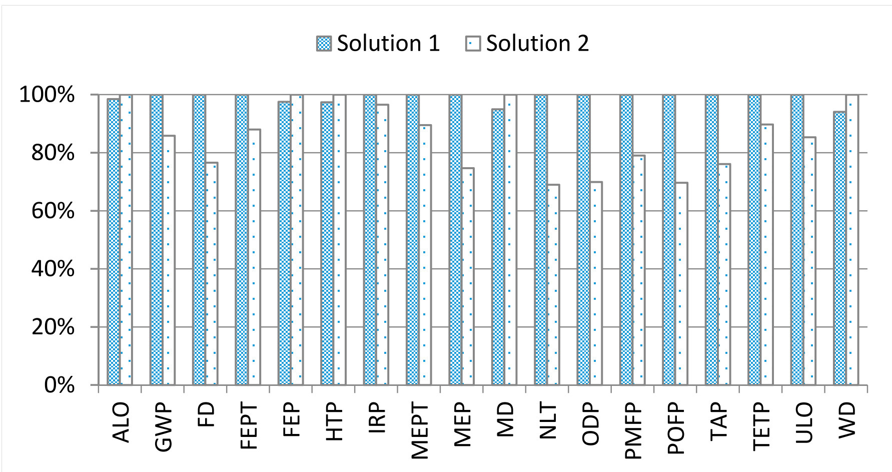

Figure 12. Comparison between Solution 1 and Solution 2.

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 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.

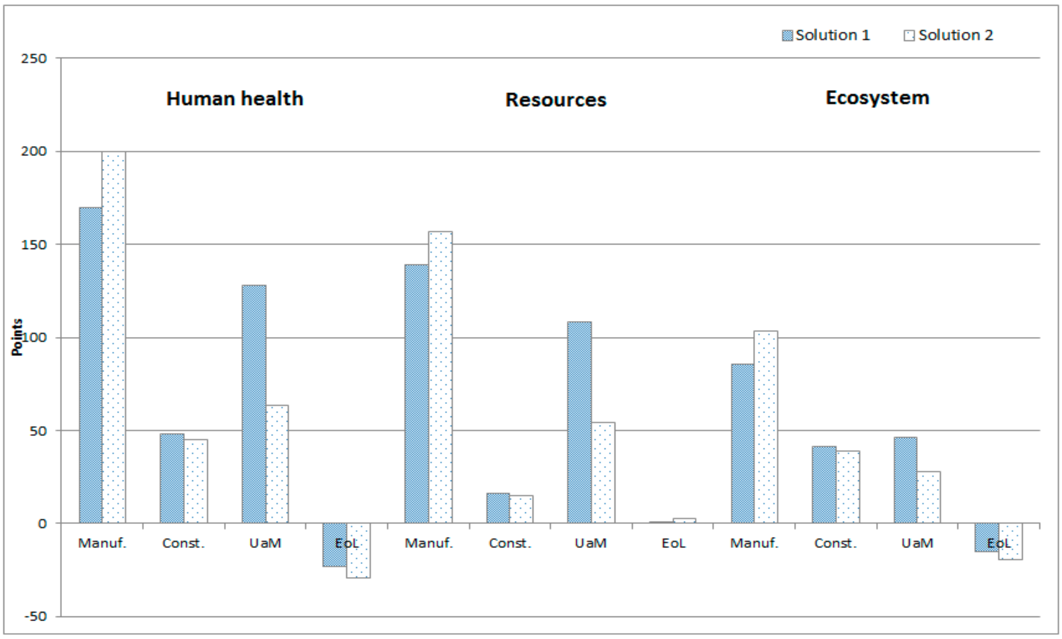

Figure 13. Comparison between damage categories.

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 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.

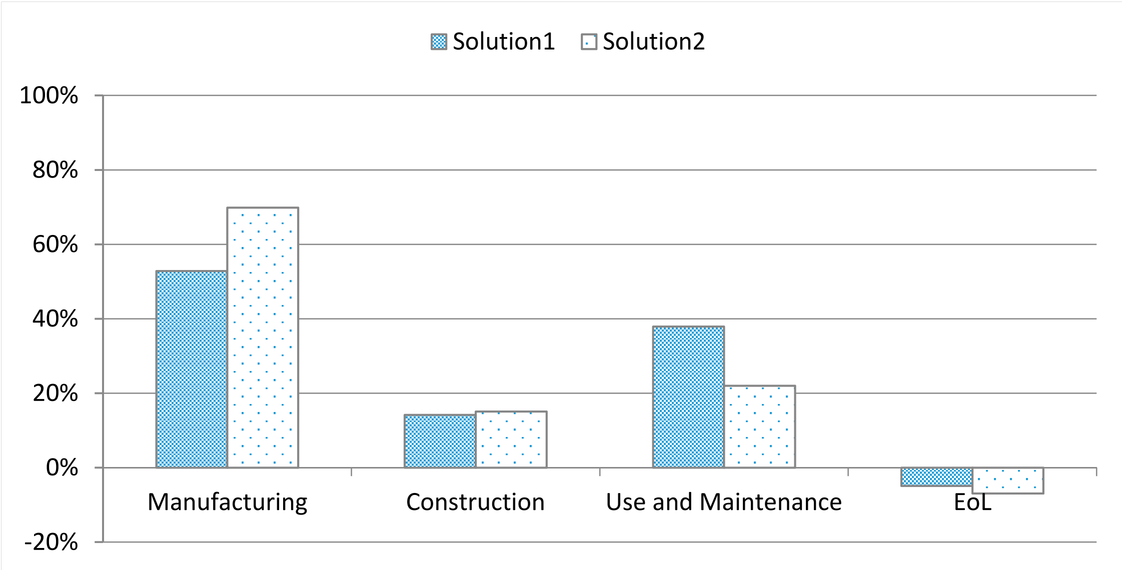

Figure 14. % of contribution of each stage.

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 (Average Daily Traffic) 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 the 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.

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