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

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Abstract

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

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

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

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

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1. Introduction

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

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

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

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

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

2. Materials and methods

2.1. Preventive designs and problem definition

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

A unit length of a real concrete bridge deck exposed to marine chlorides is considered here to compare the environmental performance of alternative designs based on the aforementioned measures. The bridge of Illa de Arosa, in Galicia - Spain is considered as a case study. A cross section of the bridge deck is shown in Figure 1. The input data regarding the durability and geometry characterization of this structure has been obtained from the literature (León et al., 2013; Pérez-Fadón, 1985; Pérez-Fadón, 1986). The original concrete mix of the bridge deck has a cement content of 485 kg/m^3, and a water/cement ratio w/c=0.45. The concrete cover of the deck is 30 mm. The steel amount considered in this study is 100 kg/m^3 of concrete, in accordance with Pérez-Fadón (1985). This quantity does not include the steel of the prestressing tendons. The deck has a width of 13 m and a section depth of 2.3 m. The deck is located 9.6 m over the high tide sea water level. It is worth noting that according to the Spanish regulations for marine environments the deck is designed for no cracking of concrete, i.e. concrete remains uncracked.

The present study takes as a starting point the described design (reference design or REF henceforth) to evaluate alternative designs based on the preventive strategies presented above. The particular preventive designs evaluated in the present study are as follows. Firstly, it has been considered an increase in the reinforcement concrete cover to 35 mm, 45 mm, and to 50 mm (measures CC35, CC40 and CC50 respectively henceforth). It shall be noted that, when large concrete covers are used, the cracks width in tensile zones can increase significantly. This can be avoided using fiber-reinforcement (Martí et al., 2015). Fibers will affect the durability performance of this first type of measure and, consequently, the maintenance and the associated environmental impact of the alternative. This study aims to evaluate the impacts derived from single, uncombined solutions. For this reason, fibers have not been considered in the impact evaluation. A second group of measures consists in the addition to the existing concrete mixture of fly ash, silica fume or polymers. The resulting concrete mixes have been assumed to be applied to the whole deck, although only the properties of the cover will affect the durability performance of the design alternative. Additions of 10% and 20% of fly ash (measures FA10 and FA20) have been considered. Regarding silica fume, additions of 5% and 10% (measures SF5 and SF10) have been studied. Regarding polymers, additions of 10% and 20% (measures PMC10 and PMC20) have been assumed. The mentioned percentages are meant to be a percentage of the cement content of the reference concrete mix design. In the cases where fly ash or silica fume are added, the amount of cement is partially substituted by those components, as they contribute to the resistance development of the resulting concrete. On the other hand, it is worth noting that the addition of silica fume shall reduce the critical chloride threshold as a consequence of the reduced chloride binding capacity of the resulting concrete (Manera et al., 2008). This effect has been taken into account in the present study. Thirdly, it has been considered a decrement in the water/cement ratio to w/c=0.40 and to w/c=0.35 (measures W/C40 and W/C35). Again, the resulting concrete mix has been applied to the whole bridge deck. When the water/cement ratio is reduced, it is common practice to add special additives in order to increase concrete workability. As these products may increase the environmental impact of the measure, the addition of superplasticizers has been considered in the definition of measures W/C40 and W/C35. The concrete mixes corresponding to the design alternatives presented above are shown in Table 1. It shall be noted that, in order to make alternatives comparable, the resulting strength and deformability of the resulting designs should be at least the same as the ones of the reference design. According to the mix proportions reported by León et al. (2013), the reference design has a mean compressive strength f_{cm} equal to 40 MPa, with a modulus of elasticity E_c equal to 29 GPa. Some alternatives result in greater resistances or modulus of elasticity, as observed in Table 1. In order to make the alternatives comparable, in such cases the depth of the deck has been slightly decreased so as to make the resulting designs have the same bending strength and deformability as the original deck. As a consequence, both alternatives W/C35 and those including polymers in the concrete mix have resulted in section depths of 2.1m and 2.23m respectively.

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

2.2. Service life predictions

A criterion is needed to decide when maintenance is required during the service life of the analyzed bridge deck. This varies for the different preventive designs considered. Regarding structures located in chloride laden environments, it is common practice to consider the initiation period in the Tuutti model in Figure 2 (Mosquera-Rey, 2015). The initiation period is the time needed for the chloride ions to travel through the concrete cover and reach the critical chloride content at the embedded reinforcing steel bars. The critical chloride content is the chloride concentration needed to start corrosion. It mainly depends on the chemical composition of the steel. This means that no corrosion is developed during the initiation time. The initiation period is the time after which maintenance operations shall be held. Assuming this criterion, it is guaranteed that the reinforcing steel is not corroded when maintenance operations are held, thus leading to less cost demanding solutions.

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

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

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

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

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

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

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

Table 2 presents the values of the reference diffusion coefficient D_o and of the critical chloride C_{crit} content computed for the different preventive measures, as well as the expected durability associated to each of them for the different concrete covers r_x. The values of these parameters for the zero-alternative, i.e. the non-preventive design, are also shown. On the basis of the distance between the structure and the sea water surface, a surface chloride content of $C_{s,0}$=3.34% is assumed for the evaluation of the bridge deck.

Considering these parameters, the expected service life for each of the analyzed measures has been calculated taking into account Fick's equation. In Table 2, the expected service life of the alternative INOX is not shown, meaning that the service life of this alternative is long enough to meet durability requirements without maintenance needs. This is due to the fact that the assumed surface chloride content is below the chloride threshold value assigned to stainless steel. It shall be noted that, in severe environments, carbonation of the concrete cover may influence the diffusive process of chlorides and reduce the time to corrosion initiation. However, for the present study the influence of the carbonated concrete on the corrosive process of the reinforcement has not been taken into account, as the conditions that favor a rapid carbonation and chloride penetration rarely coexist (Sirivivatnanon et al., 1999).

2.3. Life cycle assessment (LCA)

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

2.3.1. Definition of goal and scope

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

The life cycle of the analyzed bridge deck is divided into five phases. The first phase is the production of the construction materials. The second is their transport from the production facilities to the installation point. The third is the installation. The fourth is the maintenance needed during the structure service life. And the fifth is the end of life phase. The life cycle stages considered in the analysis, together with the different concepts taken into account in the definition of each of them are shown in Figure 3. For this study, the functional unit considered for the LCA is 1 m length of a bridge deck connecting Arosa Isle to the mainland, including the production, transport, installation, and maintenance for a service life of 100 years.

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

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

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

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

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

where x_c is the carbonation depth (mm), t is the time of evaluation (years), $W(t)$ is a weather function and k is the carbon rate coefficient (mm/year$^{0.5}$). The carbonation rate coefficient depends on the concrete properties. Table 3 includes the values of k assumed for each type of concrete analyzed in the present study as obtained from the Fib Bulletin 34 (Fib, 2006). The weather function is defined as:

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

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

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

It is also important to note that the LCA includes the impacts derived for an analysis period of the first 100 years of bridge life. This is the required service life for bridge structures according to European Committee for Standardization (2002). Taking into account the durability criterion described in Table 2, the number of maintenance operations to be held during the analysis period is obtained dividing the 100 year period of analysis of the service life expected for each alternative computed in Table 2. Finally, note that unit processes were considered in the definition of the different analyzed concepts in order to make it possible to develop an uncertainty analysis of the resulting environmental indicators. A probabilistic uncertainty analysis of the obtained environmental indicators is performed using Monte Carlo simulations.

2.3.2. Inventory analysis

Life cycle inventory (LCI) data for the reinforcement steel, cement, aggregate, zinc, and polymer production were collected from the Ecoinvent database 3.2. The data on energy demand for the production of the different concrete alternatives assumed in this study, the energy consumed in the galvanizing process of the reinforcement associated to the alternative GALV and the fuel consumed during the maintenance sandblasting operation were obtained from the existing literature (Blakey and Beck, 2004; Millman and Giancaspro, 2012; Zastrow et al., 2017). LCI data for the rest of the machinery consumptions involved in the maintenance operations, as well as the energy needed for the production of the hydrophobic emulsion, were calculated based on the information about technology processes obtained from the machinery manufacturers. These data are shown in Table 4.

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

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

The transport distances of the materials from the production facilities to the installation site have been taken from León et al. (2013). These distances take into account the specific geographical locations of the Arosa's bridge and the locations of the nearest construction material providers. The assumed transport distances are summarized in Table 5. The distance between the concrete plant and the installation site of the bridge is 17.5 km. All concrete components (aggregates, cement, plasticizers, as well as additives and additions when used) are transported from their respective factories to the concrete plant. Once the concrete is made, it is transported from the concrete plant to the building site. The reinforcing steel and the surface treatment products are transported directly to the construction site of the bridge. If the provider is located more than 100 km away from the site where the structure is built, it is then assumed that 80% of the transport is done by means of freight train and only 20% of the distance is travelled by lorry.

2.3.3. Impact analysis and interpretation

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

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

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

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

3. Results of the life cycle assessment

3.1. Environmental impact assessment

The environmental impacts for the different preventive designs against chloride corrosion in the Arosa's bridge are shown in Table 6, which presents the value of the Eco-indicator 99 for each of the damage groups described in section 2.3.3 above, namely human health, ecosystem quality, and resources. The impact of each measure is shown as a percentage of the impact caused by the zero-alternative. This reference measure, or *zero-alternative*, represents the actual design of the structure, without any further corrosion preventive measures.

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

Figure 4 shows the LCIA results summarized per damage categories. Regarding the impacts on the ecosystem quality, it is observed that using stainless steel is by far the most hazardous alternative. This high impact derives from its impact on ecotoxicity associated with the stainless steel production. The rest of the alternatives show impacts on this field at least 4 times lower than that of the measure INOX. Similar results have also been reported previously in the literature (Mistry et al., 2016). However, these high impact of stainless steel is not to be seen in the rest of impact categories. Regarding the impacts on human health, the reference alternative shows the greatest impacts, mainly derived from the energy consumed during the maintenance activities in terms of fuel and electricity. The main impacts on human health of the maintenance related to the alternative REF are associated with the emission of carcinogenic and its negative contribution to climate change. On the other hand, the alternatives which are more durable and less maintenance demanding, such as reducing the water/cement ratio (W/C35), adding silica fume to the concrete mix (SF10) or treating the deck surface (HYDRO, SEAL) show the lowest impacts on human health, approximately only a 30 - 40% of the impact of the reference design. It has been observed that the impacts derived from the addition of fly ash or silica fume to the concrete mix decrease the greater the addition ratio considered. This impact decrease is mainly due to its better performance against corrosion and its less need for repair. Additionally, it is worth noting that cement production is a main contributor to climate change. Consequently, those alternatives where cement is partially replaced by additions, such as fly ash or silica fume, allow to decrease the global warming potential of the considered preventive strategy and consequently its impact on human health (Van den Heede et al., 2017). However, in this case study, this negative impact of the cement industry is partially masked by the also great impacts on climate change of the steel production and the machinery involved in maintenance. Consequently, alternatives such as FA10 or FA20 find such positive contribution burdened with the damage caused by the activities mentioned above, due to the high requirement of maintenance if exposed to chlorides.

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

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

Of particular interest is the contribution of the CO_2 fixation in the climate change impact subcategory. Table 7 shows the total score derived from the evaluation of the climate change impact subcategory according to the Eco-indicator 99 methodology, as well as the contribution, both in total and in relative terms, of the CO_2 uptake derived from the maintenance life cycle stage, and from the End of Life stage. As can be seen, the contribution is negative in every case, meaning that CO_2 uptake reduces the resulting environmental impact on climate change.

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

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

System expansion has not been considered in the present study as it can lead to LCA inconsistencies derived from double counting of the avoided burdens and it does not guarantee global coherency between LCA studies (Chen et al., 2010; Pelletier et al., 2015). It also may lead to contradictory results when evaluating waste management systems (Heijungs and Guinée, 2007). However, and for the sake of transparency, the obtained results assuming economic allocation of co-products, namely fly ash and silica fume, are compared with the impacts resulting from adopting a system expansion approach. In this case, system expansion credits for the burdens avoided when using such products in concrete mixes by subtracting the impacts derived from transport of these industry co-products to landfills (Margallo et al., 2014; Babbitt and Lindner, 2008). In the particular context of the case study, the landfill lies 8.6 km away from the thermoelectric plant where fly ash is obtained, and 35.7 km away from the ferro-silicon production plant responsible for the silica fume. Figure 5 shows a comparison of the Eco-Indicator 99 results obtained adopting the economic allocation and the system expansion approach. Results show that, under a system expansion perspective, alternatives related to the use of these additions has lower impacts if compared to the ones presented here resulting from economic allocation. It is important to note that these results are highly dependent on the particular geographical context studied. In this case, the resulting impact reduction is greater for the solutions based on silica fume additions due to the really short distances to landfill in the case of fly ash. Under this new modeling hypothesis, the greatest impact difference is that of SF10, which turns to be the most preferable alternative in environmental terms, incurring in even lower impacts than the hydrophobic treatments.

3.2. Element contribution to the overall impacts

The elements considered are the different types of concrete and reinforcing steel used, the transport activities, and the maintenance operations needed for each alternative. Figure 6 shows the contribution of each life cycle element to the environmental effects for the different preventive measures. The environmental effects are the ecosystem quality, human health, and resources, together with the overall environmental effect. Maintenance operations include the activities of hydrodemolition of the concrete cover, cleaning of the outermost reinforcement and shotcreting with the corresponding concrete mixture to restore the original cover. The impact of the concrete used for the replacement is evaluated under the corresponding concrete concept in the mentioned tables. In the case of surface treatment, maintenance operations only involve the reapplication of the treatment.

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

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

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

3.3. Uncertainty analysis

An uncertainty analysis of the obtained environmental results is performed using Monte Carlo simulations. The model converges after 1000 Monte Carlo iterations. In this study, convergence is said to be achieved when the relative error associated with the mean value of the estimation of the total environmental impact falls below 0.25% with a confidence level of 99% for every alternative evaluated. The uncertainty associated with each unit is defined according to the Ecoinvent database, which assigns particular log-normal probability distributions to every unit process so as to take into consideration the geographic representativeness of the data, as well as the inaccuracies associated to data and measurement quality at the production locations (Frischknecht et al., 2005). Table 8 shows the uncertainty range for the impact results by applying a 95% confidence interval. Results are shown for the ecosystem, human health, and resources categories, as well as for the resulting final value of the eco-indicator. The uncertainty range in all the studied measures is less than 15% of their corresponding impact indicator results for the Eco-indicator resulting value. Slightly higher ranges can be seen in the subcategory human health, where for the reference measure the difference reaches 15.8%. The uncertainty associated with the considered Ecoinvent processes is, indeed, reduced. The coefficients of variation derived from the obtained results, which result from dividing the standard deviation by the mean, are below 5% for every of the results presented. The greatest variation is associated to impact categories Ecosystem Quality and Human Health.

Additionally, the differences between various LCIA methods can mean a great source of uncertainty. According to Hung and Ma (2009), the application of different LCIA methodologies can produce different rankings of the analyzed alternatives, thus leading to different decisions. Taking this into account, two other methods, namely EPS (acronym for Environmental Priority Strategies) and ReCiPe, are considered. These methods have been chosen due to the fact that they can estimate the environmental performance of an alternative in one single indicator, as Ecoindicator 99 does. In particular, the results of the EPS assessment method are damage costs derived from emissions and use of natural resources, and are expressed as Environmental Load Units (ELU), each ELU representing the externalities corresponding to one Euro environmental damage cost. On the other hand, the ReCiPe assessment integrates eighteen midpoint indicators into three impact categories in the endpoint level, related to environmental effects on human health, on biodiversity and on resource scarcity. The ranking resulting from the evaluation of the alternatives based on these three methods is shown in Table 9. It can be observed that the considered methods offer very slight differences for the case study considered.

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

3.4. Design-oriented approach versus maintenance-oriented approach

The results of this study focus on the impacts derived from alternative deck designs with different durability and maintenance needs. However, it is interesting to compare such a design-based approach with the usual maintenance-oriented approach, i.e. an existing, unsustainable design with poor durability in which different maintenance strategies are held when needed. The question arises whether such an approach is preferable in environmental terms to a design in which sustainability is already considered at the project phase. The new scenario now considers that the reference design (REF) is maintained for the first time after 6.5 years, according to the expected service life of this design presented in Table 2. The concrete cover is then replaced by a new cover with alternative durability properties, namely those associated with the alternative designs evaluated in the present study. Assuming that the geometry of the deck remains unchanged along the time, and given that reinforcement is not to be substituted during maintenance activities, alternatives INOX, GALV, CC35, CC45 and CC50 are not considered in the current comparative analysis.

Figure 7 shows the Eco-indicator 99 results associated to both the design- and the just described maintenance-oriented approach. It can be observed that, considering this new scenario, the most preferable maintenance alternative consists in replacing the reference concrete cover by concrete with 10% silica fume addition (SF10). It is observed as well that some alternatives incur in lesser impacts than in the original approach. This is the case, for example, of alternatives based on polymer modified concrete. In the design-based approach, it is considered that the complete bridge deck is made of this material, while now, as the deck is constructed with the reference concrete, the impacts at the construction stage are lower for these alternatives and the LCA results are consequently reduced. Maintenance based on SF5 and FA20 concretes, although almost the same as in the design approach, show lower impacts. This is due to the fact that design alternatives based on silica fume and fly ash have slightly greater impacts at the construction stage derived from the transport processes associated with these additions. From the results presented in Figure 7, it is derived that the design-based approach is preferable in environmental terms than the maintenance-based one. The former perspective allows the designer to reduce the life cycle environmental impacts up to 10.8% when compared to the most preferable of the alternatives in the new maintenance-oriented scenario.

4. Discussion

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

Preventive designs based on hydrophobic and sealant surface treatments have proven to perform best from an environmental point of view. Although they require the greatest amount of maintenance interventions along the service life of the structure, they result in almost 70% lower impacts than the reference, non-preventive design. Similar results were already reported by Årskog et al. (2004) and Petcherdchoo (2015), where it is shown that such measures are far more preferable from an ecological perspective than designs where concrete cover has to be replaced periodically. These results result from the lower impacts associated with maintenance operations, as shown in Figure 6, in comparison to those associated to conventional repairs.

However, the present study also shows that there are designs based on special concrete mixes that are highly competitive in environmental terms. So, concrete with silica fume (SF10) has been shown to perform almost as well as surface treatments, due to its high durability and to the low impacts related to the material production. Such environmental benefits of concretes with high percentages of additions on human health, as well as on the ecosystem quality, have already been reported (Tait and Cheung, 2016), although not applied to a chloride exposed structure. On the contrary, other solutions with also great durability, such as those based on polymer modified concrete (expected service life of 73.9 years for PMC20), have shown to reduce environmental impacts only a 20% when compared to the reference design. The findings above assume that the alternative concrete mixes are applied to the complete concrete volume. In these cases, the high impacts related to material production burden their good durability performance, taking from 40% to 60% of the total environmental impact, as derived from Figure 6. From a maintenance-oriented perspective, replacing the original concrete cover with polymer modified concrete (PMC20) has shown to perform quite better, reducing the impacts of the design-based approach by approximately one half.

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

5. Concluding remarks

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

- Prevention strategies based on the application of surface treatments to prevent the chloride ingress on concrete show the lowest environmental impacts. This is mainly due to the use of less energy demanding machinery for the maintenance operations.
- Alternatives focused on reducing the density of the concrete cover, such as the reduction of water/cement ratios or the partial replacement of cement by silica fume, have also shown to be very competitive against

surface treatments in terms of environmental impacts. These alternatives perform better from the point of view of durability, and are less intensive in maintenance, reducing consequently the damage to the environment associated with these activities.

- Other additions, such as fly ash, although performing more than acceptably from the environmental point of view, have shown average impacts if compared to the rest of the considered strategies. Other additions, such as silica fume, have shown to perform better, thus leading to less maintenance demanding solutions.
- The use of polymeric additives in concrete mixes has great impacts on human health and resources depletion throughout the life cycle of the analysed bridge deck. Although this may seem contradictory, these negative impacts can be lessened by increasing the amount of addition used, as the durability performance of polymer modified concretes increases exponentially with the addition percentage.
- The environmental impacts of stainless steel rebars are greater than those alternatives with carbon steel rebars regarding the ecosystem quality and the resource depletion. Thus, despite the unnecessary maintenance for this alternative, the global environmental impact of such design results in the less environmental friendly alternative, leading to impacts almost 50% greater than the reference design.
- Increasing the concrete cover can reduce the environmental life cycle impacts of the deck if compared to the reference alternative up to 45%, performing similarly than using of galvanized reinforcement.

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References

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

Babbitt, C.W., Lindner, A.S., 2008. A life cycle comparison of disposal and beneficial use of coal combustion products in Florida. Part 1: methodology and inventory of materials, energy and emissions. Int. J. Life-cycle Assess. 13, 202–11. doi: 10.1065/lca2007.07.353

Bertolini, L., Bolzoni, F., Pastore, T., Pedeferri, P., 1996. Behaviour of stainless steel in simulated concrete pore solution. Br. Corros. J. 31, 218–22. doi:10.1179/000705996798114572.

Blakey, S.G., Beck, S.B.M., 2004. Energy consumption and capacity utilization of galvanizing furnaces. Proc. Inst. Mech. Eng. Part E J. Process. Mech. Eng. 218, 251–9. doi: 10.1243/0954408042466927.

Bolzoni, F., Brenna, A., Fumagalli, G., Goidanich, S., Lazzari, L., Ormellese, M., Pedeferri, M.P., 2014. Experiences on corrosion inhibitors for reinforced concrete. Int. J. Corros. Scale. Inhib. 3(4), 254-278.

Braga, A.M., Silvestre, J.D., de Brito, J., 2017. Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. J. Clean. Prod. 162, 529-543. doi: 10.1016/j.jclepro.2017.06.057

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

Cheewaket, T., Jaturapitakkul, C., Chalee, W., 2014. Concrete durability presented by acceptable chloride level and chloride diffusion coefficient in concrete: 10-year results in marine site. Mater. Struct. 47, 1501–11. doi: 10.1617/s11527-013-0131-4.

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

Chen, C., Habert, G., Bouzidi, Y., Jullien, A., Ventura, A., 2010. LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete. Resour. Conserv. Recycl. 54, 1231–1240. doi: 10.1016/j.resconrec.2010.04.001.

Collins, F., 2010. Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint. Int. J. Life-cycle Assess. 15(6), 549-556. doi: 10.1007/s11367-010-0191-4.

Cooper, J.S., 2003. Specifying functional units and reference flows for comparable alternatives. Int. J. Life-cycle Assess. 8, 337. doi: 10.1007/BF02978507

Costa, A., Appleton, J., 2001. Concrete carbonation and chloride penetration in marine environment. Concr. Sc. Eng. 3, 242-249.

De Schepper, M., Van den Heede, P., Van Driessche, I., De Belie, N., 2014. Life cycle assessment of completely recyclable concrete. Mater. 7, 6010-6027. doi: ,10.3390/ma7086010.

De Simone Souza, H.H., Lima, Â.M.F., Esquerre, K.O., Kiperstok, A., 2017. Life cycle assessment of the environmental influence of wooden and concrete utility poles based on service lifetime. Int. J. Life-cycle Assess. 1-12. doi: 10.1007/s11367-017-1293-z.

Darwin, D., Browning, J., O'Reilly, M., Xing, L., Ji, J., 2009. Critical Chloride Corrosion Threshold of Galvanized Reinforcing Bars. ACI Mater. J. 106, 176–83. doi:10.14359/56465.

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. Int. J. Life-cycle Assess. 19(12), 1948-1964. doi: 10.1007/s11367-014-0797-z.

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

Fib. Fib Bulletin 34, 2006. Model code for service life design. Lausanne: Fib

Flower, D.J.M., Sanjayan, J.G., 2007. Green house gas emissions due to concrete manufacture. Int. J. Life-cycle Assess. 12, 282. doi: 10.1065/lca2007.05.327.

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

Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2005. The ecoinvent database: overview and methodological framework. Int. J. Int. J. Life-cycle Assess. 10, 3-9. doi: 10.1065/lca2004.10.181.1.

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

García-Segura, T., Yepes, V., 2016. Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety. Eng. Struct. 125, 325-336. doi: 10.1016/j.engstruct.2016.07.012.

García-Segura, T., Yepes, V., Alcalá, J., 2014. Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. Int. J. Life-cycle Assess. 19(1), 3-12. doi: 10.1007/s11367-013-0614-0.

Gjørv, O., 2013. Durability design and quality assurance of major concrete infrastructure. Adv. Concrete. Constr. 1(1), 45-63. doi: 10.12989/csm.2013.1.1.045.

Gursel, A.P., Ostertag, C., 2016. Comparative life-cycle impact assessment of concrete manufacturing in Singapore. Int. J. Life-cycle Assess. 22(2), 237-255. doi: 10.1007/s11367-016-1149-y.

Heijungs, R., Guinée, J.B., 2007. Allocation and 'what-if' scenarios in life cycle assessment of waste management systems. Waste Manage. 27(8), 997–1005. doi: 10.1016/j.wasman.2007.02.013

Hung, M., Ma, H., 2009. Quantifying system uncertainty of life cycle assessment based on Monte Carlo simulation. Int. J. Life-Cycle Assess. 14, 19–27. doi 10.1007/s11367-008-0034-8.

Lagerblad, B., 2005. Carbon dioxide uptake during concrete life-cycle: State of the art. Swedish Cement and Concrete Research Institute, Stockholm.

León, J., Prieto, F., Rodríguez, F., 2013. Proyecto de rehabilitación del puente de la Isla de Arosa. Hormigón y Acero 270: 75-89.

Maes, M., Caspeele, R., Van den Heede, P., De Belie, N., 2012. Influence of sulphates on chloride diffusion and the effect of this on service life prediction of concrete in a submerged marine environment. IALCCE 2012: proceedings of the third international symposium on life-cycle civil engineering. 899-906. http://hdl.handle.net/1854/LU-3023500.

Manera, M., Vennesland, Ø., Bertolini, L., 2008. Chloride threshold for rebar corrosion in concrete with addition of silica fume. Corros. Sci. 50, 554–60. doi: 10.1016/j.corsci.2007.07.007.

Margallo, M., Aldaco, R., Irabien, Á., 2014. Environmental management of bottom ash from municipal solid waste incineration based on a life cycle assessment approach. Clean. Techn. Environ. Policy 16, 1319. doi: 10.1007/s10098-014-0761-4

Martí, J.V., Yepes, V., González-Vidosa, F., 2015. Memetic algorithm approach to designing of precast-prestressed concrete road bridges with steel fiber-reinforcement. J. Struct. Eng. 141(2), 04014114. doi: 10.1061/(ASCE)ST.1943-541X.0001058.

Martí, J.V., García-Segura, T., Yepes, V., 2016. Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy. J. Clean. Prod. 120, 231-240. doi: 10.1016/j.jclepro.2016.02.024.

Martínez-Martin, F., Gonzalez-Vidosa, F., Hospitaler, A., Yepes, V., 2012. Multi-objective optimization design of bridge piers with hybrid heuristic algorithms. J. Zhejiang Univ. Sci. A., 13(6), 420-432. doi: 10.1631/jzus.A1100304.

Meent, D., Klepper, O., 1997. Mapping the potential affected fraction (PAF) of species as an indicator of generic toxic stress. RIVM Report 607504001. RIVM, Bilthoven.

Medeiros, M., Castro-Borges, P., Aleixo, D., Quarcioni, V.A., Marcondes, C., Helene, P., 2012. Reducing water and chloride penetration through silicate treatments for concrete as a mean to control corrosion kinetics. Int. J. Electrochem. Sci. 7, 9682-9696. doi: 10.1016/S0950-0618(00)00043-X.

Millman, L.R., Giancaspro, J.W., 2012. Environmental Evaluation of Abrasive Blasting with Sand, Water, and Dry Ice. Int. J. Archit. Eng. Constr. 1, 174–82. doi: 10.7492/IJAEC.2012.019.

Mistry, M., Koffler, C., Wong, S., 2016. LCA and LCC of the world's longest pier: a case study on nickel-containing stainless steel rebar, Int. J. Life-Cycle Assess. 21, 1637–1644. doi: 10.1007/s11367-016-1080-2.

Miyazato, S., Otsuki, N., 2010. Steel corrosion induced by chloride or carbonation in mortar with bending cracks or joints. J. Adv. Concr. Technol. 8, 135–44. doi:10.3151/jact.8.135.

Molina-Moreno, F., Martí, J.V., Yepes, V., 2017. Carbon embodied optimization for buttressed earth-retaining walls: implications for low-carbon conceptual designs. J. Clean. Prod. 164, 872-884. doi: 10.1016/j.jclepro.2017.06.246

Mosquera-Rey, E.R., 2015. Revision of validity for the factor of safety (EHE-08) of the service life in structures under chlorides. Informes de la Construcción 67: e082. doi: 10.3989/ic.13.127.

Murray, C., Lopez, A., 1996. The global burden of disease. WHO World Bank and Harvard School of Public Health, Boston.

Nokken, M., Boddy, A., Hooton, R.D., Thomas, M.D.A., 2006. Time dependent diffusion in concrete—three laboratory studies. Cem. Concr. Res. 36, 200–7. doi: 10.1016/j.cemconres.2004.03.030.

Ohama, Y., 1995. Handbook of Polymer-Modified Concrete and Mortars. William Andrew.

Otsuki, N., Nishida, T., Yi, C., Nagata, T., Ohara, H., 2014. Effect of Blast Furnace Slag Powder and Fly Ash on Durability of Concrete Mixed with Seawater. Int. Conf. Durab. Concr. Struct. doi: 10.5703/1288284315406

Pang, B., Yang, P., Wang, Y., Kendall, A., Xie, H., Zhang, Y., 2015. Life cycle environmental impact assessment of a bridge with different strenghtening schemes. Int. J. Life-Cycle Assess. 20, 1300-1311. doi: 10.1007/s11367-015-0936-1.

Pelletier, N., Ardente, F., Brandão, M., De Camillis, C., Pennington, D., 2015. Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible? Int. J. Life-Cycle Assess. 20, 74–86. doi: 10.1007/s11367-014-0812-4.

Penadés-Plà, V., García-Segura, T., Martí, J.V., Yepes, V., 2016. A review of multi-criteria decision making methods applied to the sustainable bridge design. Sustainability 8(12), 1295. 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, 1864. doi: 10.3390/su9101864.

Pérez-Fadón, S., 1985. Puente a la Isla de Arosa. Hormigón y Acero 157: 197-218.

Pérez-Fadón, S., 1986. Puente sobre la Ría de Arosa. Revista de Obras Públicas. January 1986: 1-16.

Petcherdchoo, A., 2015. Environmental impacrts of combined repairs on marine concrete structures. J. Adv. Concr. Technol. 13, 205-213. doi: 10.3151/jact.13.205

Ramesh, T., Prakash, R., Shukla, K., 2010. Life cycle energy analysis of buildings: An overview. Energy and Buildings 42(10), 1592-1600. doi: 10.1016/j.enbuild.2010.05.007.

Sanjuan-Delmás, D., Hernando-Canovas, E., Pujadas, P., de la Fuente, A., Gabarrell, X., Rieradevall, J., Josa, A., 2015. Environmental and geometric optimisation of cylindrical drinking water storage tanks. Int. J. Life-cycle Assess. 20(12), 1612–1624. doi: 10.1007/s11367-015-0963-y.

Shen, L.Y., Lu, W.S., Yao, H., Wu, D.H., 2005. A computer-based scoring method for measuring the environmental performance of construction activities. Autom. Constr. 14, 297-309.

Shi, J., Sun, W., 2013. Effects of phosphate on the chloride-induced corrosion behavior of reinforcing steel in mortars. Cem. Concr. Compos. 45, 166-175. doi: 10.1016/j.cemconcomp.2013.10.002.

Sirivivatnanon, V., Khatri, R.P., Lacasse, M.A., Vanier, D.J., 1999. Characterising chloride penetration resistance of concrete: Chloride penetration resistance of concrete. Durab. Build. Mater. Comp. 8, 386-398.

Spanish Ministry of Public Works, 2008. EHE-08 Instrucción del Hormigón Estructural. ISBN: 978-84-498-0899-9.

Tait, M., Cheung, W., 2016. A comparative cradle-to-gate life cycle assessment of three concrete mix designs. Int. J. Life-cycle. Assess. 21(6), 847-860. doi: 10.1007/s11367-016-1045-5.

Texeira, E.R., Mateus, R., Camões, A.F., Bragança, L., 2016. Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. J. Clean. Prod. 112, 2221-2230. doi: 10.1016/j.jclepro.2015.09.124

Titi, A., Biondini, F., 2016. On the accuracy of diffusion models for life-cycle assessment of concrete structures. Struct. Infrastruct. Eng. 12, 1202–15. doi:10.1080/15732479.2015.1099110.

Van Den Heede, P., De Belie, N., 2012. Environmental impact and life cycle assessment (LCA) of traditional and "green" concretes: Literature review and theoretical calculations. Cem. Concr. Compos. 34, 431–442. doi: 10.1016/j.cemconcomp.2012.01.004.

Van den Heede, P., Maes, M., Gruyaert, E., De Belie, N., 2012. Full probabilistic service life prediction and life cycle assessment of concrete with fly ash and blast-furnace slag in a submerged marine environment: A parameter study. Int. J. Environ. Sustain. Dev. 11, 32–49. doi: 10.1504/IJESD.2012.049141.

Van den Heede, P., De Belie, N., 2014. A service life based global warming potential for high-volume fly ash concrete exposed to carbonation. Constr. Build. Mater. 55, 183–193. doi: 10.1016/j.conbuildmat.2014.01.033.

Van den Heede, P., De Keersmaecker, M., Elia, A., Adriaens, A., De Belie, N., 2017. Service life and global warming potential of chloride exposed concrete with high volumes of fly ash. Cem. Concr. Compos. 80, 210–23. doi:10.1016/j.cemconcomp.2017.03.020.

Vedalakshmi, R., Saraswathy, V., Song, H.W., Palaniswamy, N., 2009. Determination of diffusion coefficient of chloride in concrete using Warburg diffusion coefficient. Corros. Sci. 51 (6), 1299–1307 doi: 10.1016/j.corsci.2009.03.017.

Wang, T., Lee, I., Kendall, A., Harvey, J., Lee, E., Kim, C., 2012. Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. J. Clean. Prod. 33, 86-96. doi: 10.1016/j.jclepro.2012.05.001.

Wiertz, J., van Dijk & J.B. Latour, 1992. MOVE: Vegetatie-module; de kans op voorkomen van 700 plantensoorten als functie van vocht, pH, nutriënten en zout. RIVM report 711901006. RIVM, Bilthoven.

Xi, Y., Bažant, Z.P., 1999. Modeling Chloride Penetration in Saturated Concrete. J. Mater. Civ. Eng. 11, 58–65. doi:10.1061/(ASCE)0899-1561(1999)11:1(58)

Yang, Z., Shi, X., Creighton, A.T., Peterson, M.M., 2009. Effect of styrene–butadiene rubber latex on the chloride permeability and microstructure of Portland cement mortar. Constr. Build. Mater. 23, 2283–90. doi:10.1016/j.conbuildmat.2008.11.011.

Yepes, V., González-Vidosa, F., Alcalá, J., Villalba, P., 2012. CO2-Optimization Design of Reinforced Concrete Retaining Walls based on a VNS-Threshold Acceptance Strategy. J. Comput. Civ. Eng. 26(3), 378-386. doi: 10.1061/(ASCE)CP.1943-5487.0000140.

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. Autom. Constr. 49, 123-134. doi: 10.1016/j.autcon.2014.10.013.

Zastrow, P., Molina-Moreno, F., García-Segura, T., Martí, J., Yepes, V., 2017. Life cycle assessment of cost-optimized buttress earth-retaining walls: a parametric study. J. Clean. Prod. 140, 1037-1048. doi: 10.1016/j.jclepro.2016.10.085.

Zhang, J.Z., Buenfeld, N.R., 2000. Chloride profiles in surface-treated mortar specimens. Constr. Build. Mater. 14, 359–64. doi:10.1016/S0950-0618(00)00043-X.

Zhang, Y.R., Wu, W.J., Wang, Y.F., 2016. Bridge life cycle assessment with data uncertainty. Int. J. Life-Cycle Assess. 21, 569-576. doi: 10.1007/s11367-016-1035-7.

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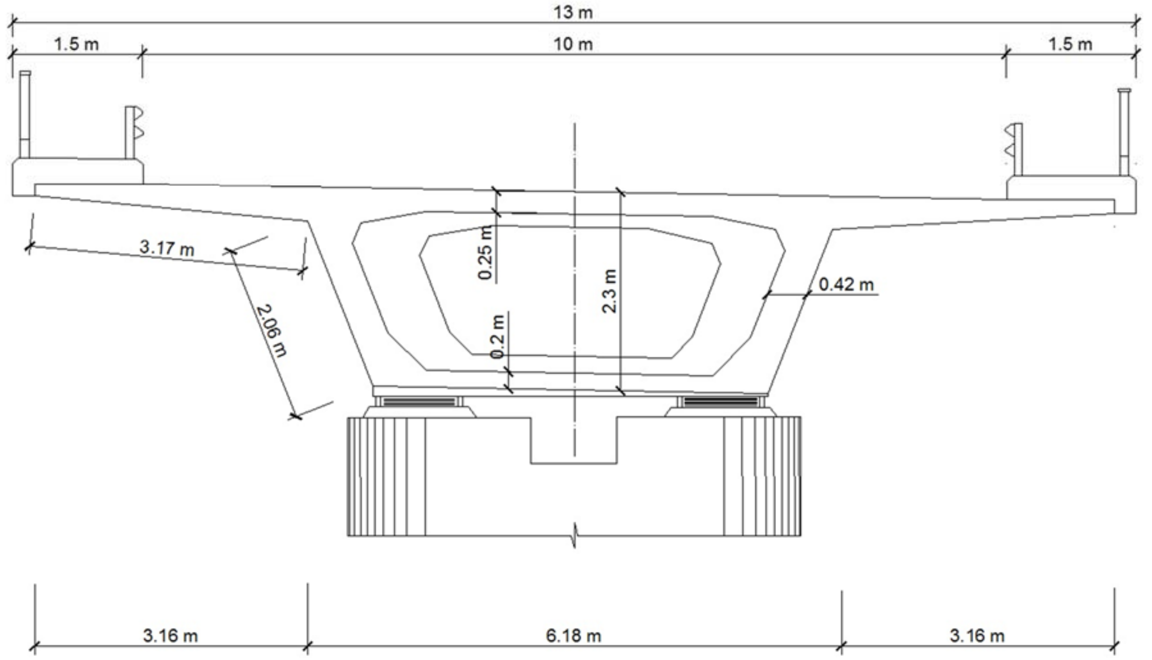
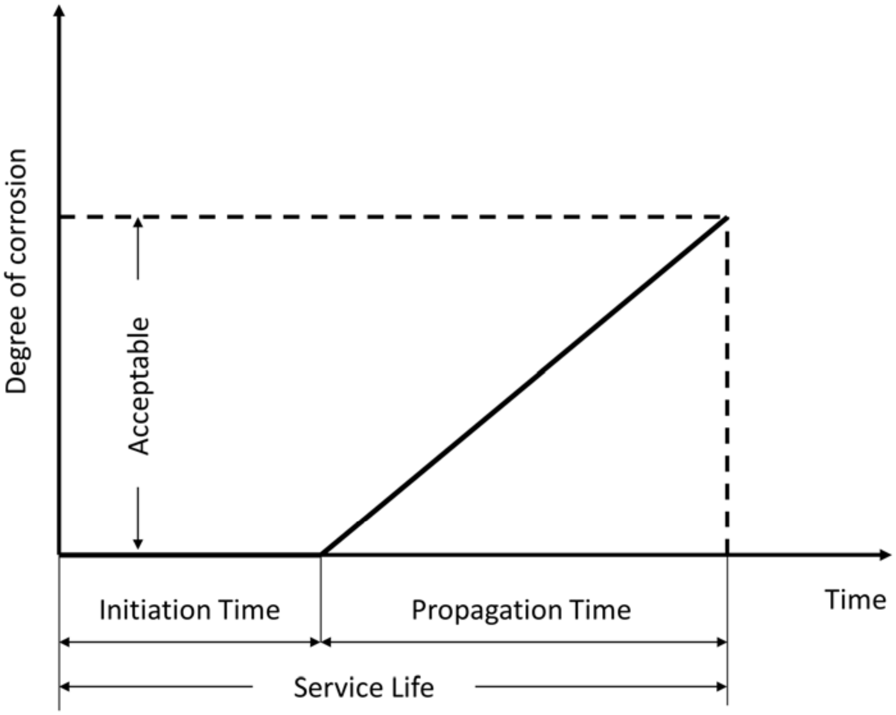


Fig. 1. Cross section of the Arosa's concrete bridge deck



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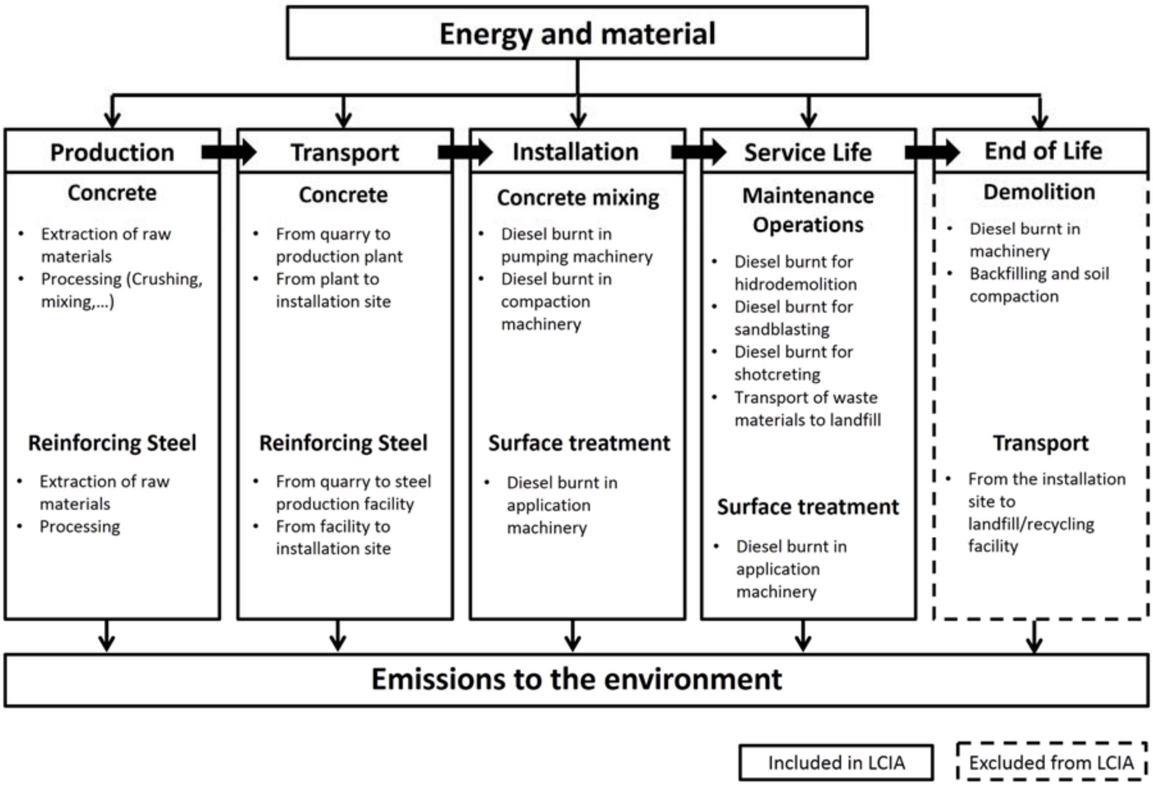

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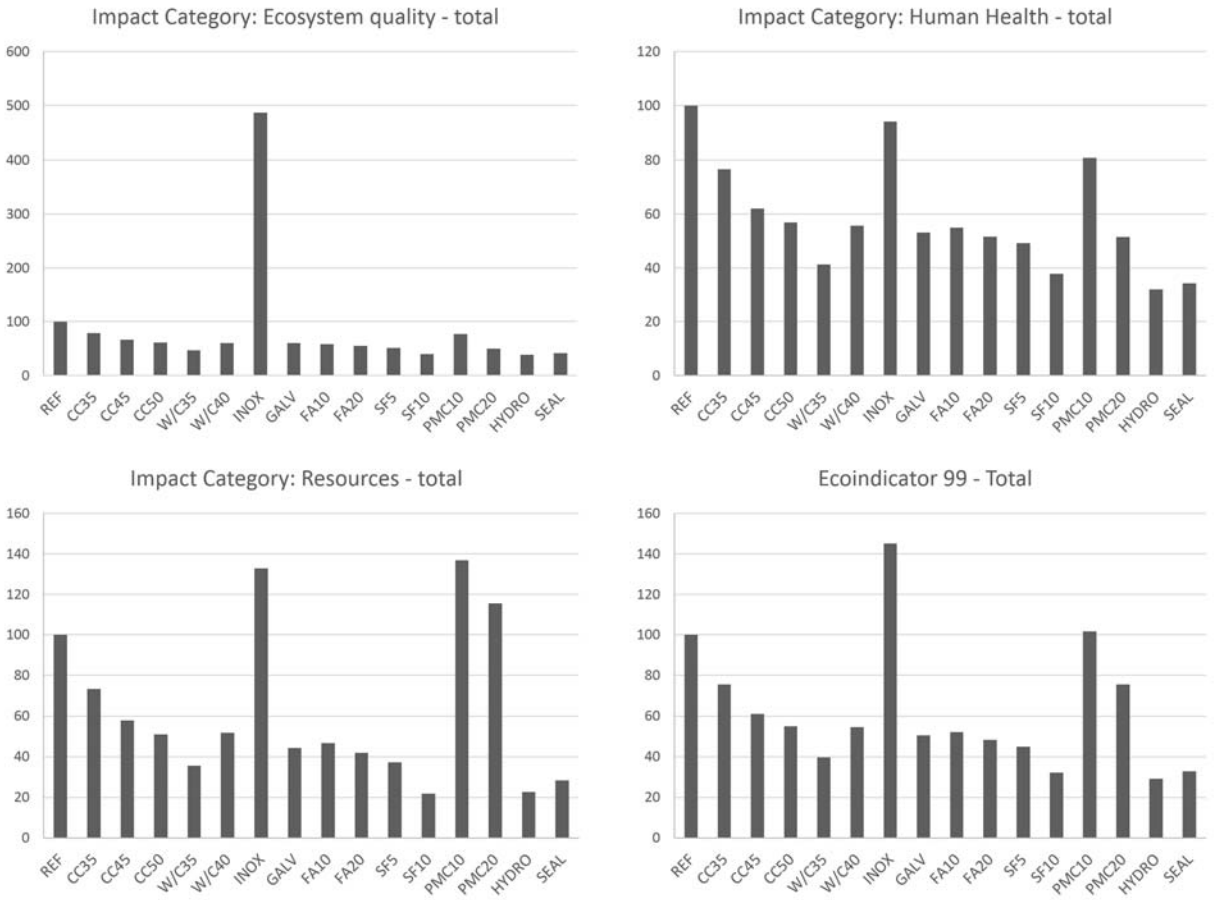

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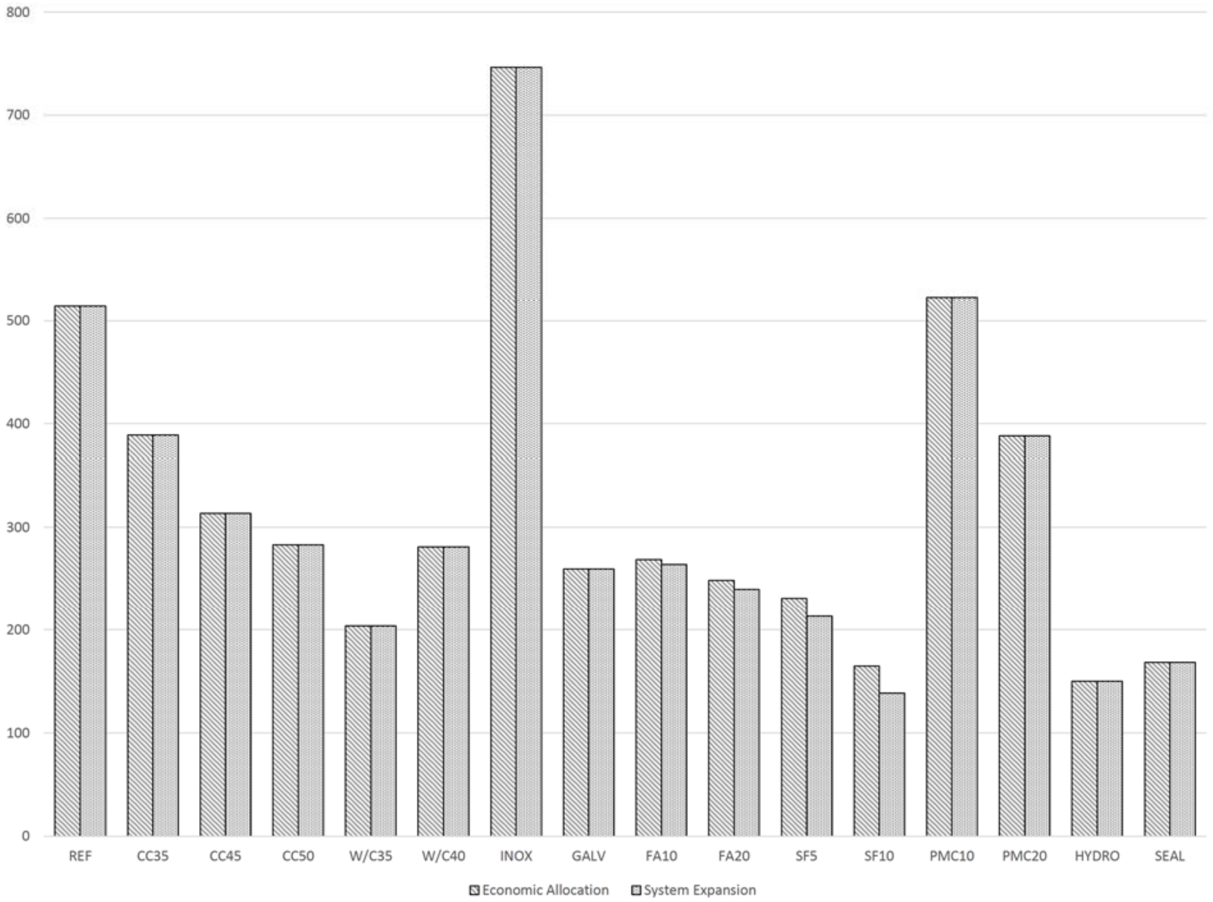

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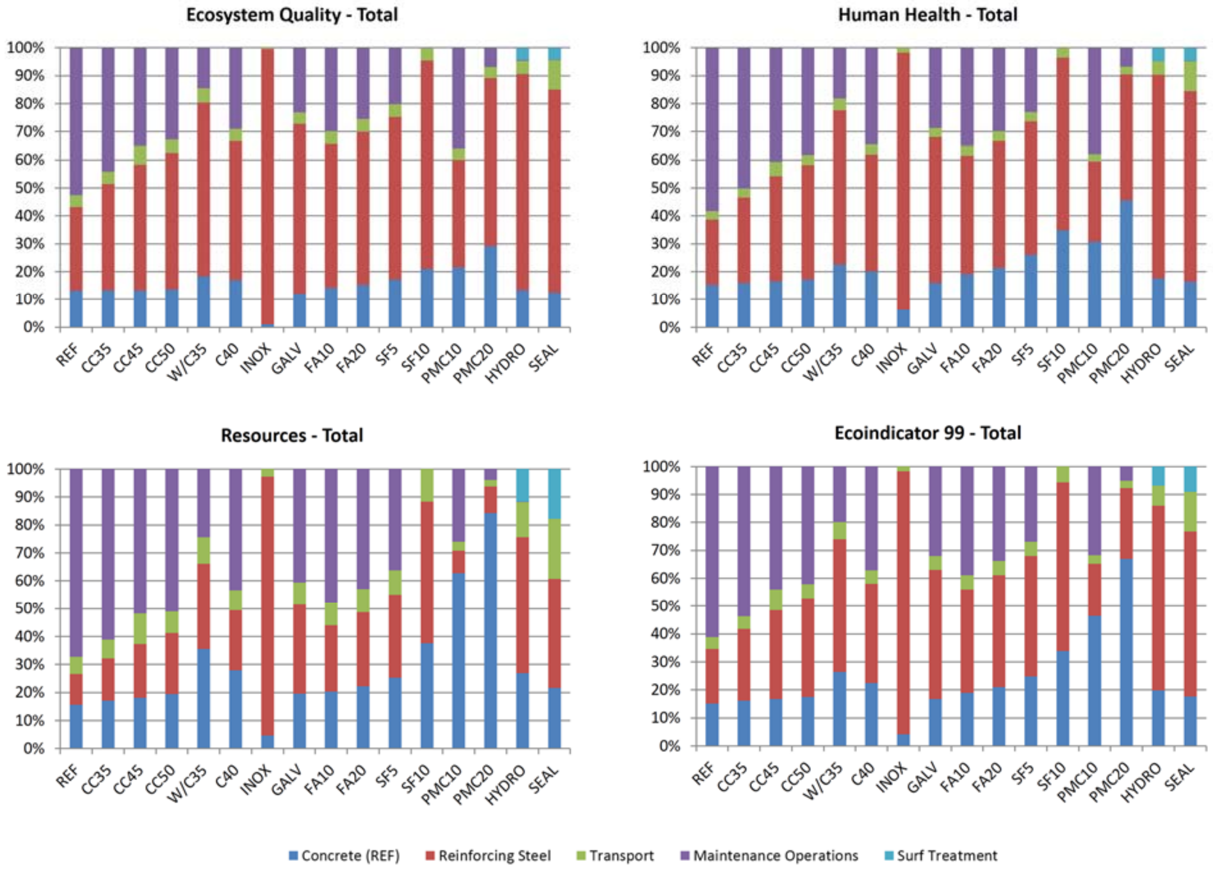

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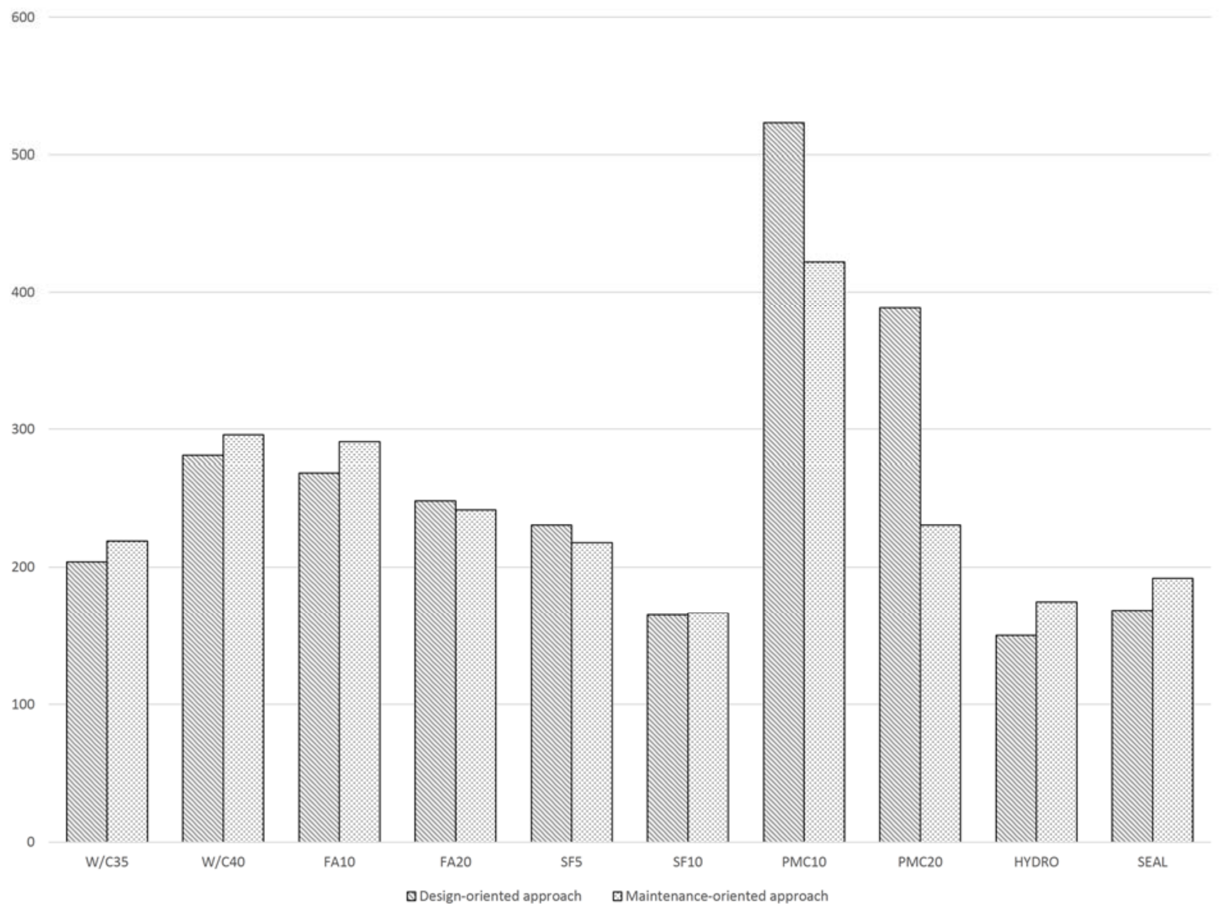

Fig. 7. Eco-Indicator 99 results for the design- and the maintenance-based approaches

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Table 1
Concrete mixes and mechanical properties

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

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

Table 2
Durability characterization of the analysed preventive strategies

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

* According to manufacturer's specifications

Table 3
Carbonation rate coefficients for the different types of concrete

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

Table 4
Assumed parameter values in relation to energy consumption

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

* According to manufacturer's specifications

Table 5
Assumed transport distances

Cement materials - from production facility to concrete plant

	Lorry (km)	Rail (km)	Total (km)
Aggregates	14		
Portland Cement	12		
Fly Ash	96		
Silica Fume	96		
Polymer	129.8	519.2	649
Plastiziser	129.8	519.2	649

Cement products - from concrete plant to installation site

	Lorry (km)	Rail (km)	Total (km)
Reference concrete	17.5		17.5
Polymer modified concrete	17.5		17.5
Fly ash concrete	17.5		17.5
Silica fume concrete	17.5		17.5

Steel products - from production facility to installation site

	Lorry (km)	Rail (km)	Total (km)
Carbon steel reinf.	31	124	155
Stainless steel reinf.	128.4	513.6	642
Galvanized steel reinf.	31	124	155

Surface treatment - from production facility to installation site

	Lorry (km)	Rail (km)	Total (km)
Hidrophobic	143.4	573.6	717
Sealant	143.4	573.6	717

Table 6
Eco-indicator 99 values for the analysed preventive measures

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

Table 7
Contribution of CO$_2$ uptake on climate change impact

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

Table 8. Results of the uncertainty analysis

	Ecosystem Quality - total			Human Health - total			Resources - total			Total - total		
	Mean	CV (%)	5 - 95 Percentile range	Mean	CV (%)	5 - 95 Percentile range	Mean	CV (%)	5 - 95 Percentile range	Mean	CV (%)	5 - 95 Percentile range
REF	47.9	4.43	6.9	274.1	4.80	43.4	194.8	2.07	13.2	516.8	3.19	52.7
CC35	37.9	4.22	5.3	210.4	4.09	27.2	143.2	1.82	8.7	391.4	2.73	34.3
CC45	32.1	4.36	4.8	171.4	3.21	18.1	113.1	1.68	6.3	316.5	2.27	23.5
CC50	29.5	4.07	4.1	156.6	3.06	15.7	99.3	1.61	5.3	285.4	2.24	20.7
W/C35	22.7	4.41	3.2	113.4	2.03	7.4	70.0	3.86	8.9	206.0	2.28	15.3
W/C40	29.0	4.14	4.0	153.8	2.99	14.8	101.5	2.76	8.7	284.3	2.32	20.9
INOX	232.3	0.34	2.4	257.3	0.39	3.1	259.1	0.19	1.6	748.8	0.27	6.0
GALV	29.1	4.46	4.3	147.3	2.78	12.7	86.6	1.50	4.4	263.1	2.05	17.4
FA10	28.0	3.92	3.6	151.4	2.91	14.7	91.4	1.53	4.4	270.9	2.10	18.6
FA20	26.4	3.79	3.3	142.0	2.54	11.9	81.8	1.47	3.7	250.2	1.88	15.2
SF5	24.9	4.02	3.2	135.6	1.92	8.3	72.8	1.24	3.0	233.2	1.54	11.8
SF10	19.3	3.93	2.5	104.6	0.77	2.5	43.0	0.93	1.3	166.9	0.96	5.4
PMC10	37.0	3.78	4.7	221.8	3.25	22.9	266.8	0.82	7.2	525.6	1.73	29.1
PMC20	23.8	3.36	2.7	141.8	0.92	4.1	224.9	0.22	1.6	390.5	0.54	6.7
HYDRO	18.7	4.28	2.5	89.0	1.12	3.0	44.7	0.89	1.5	152.4	1.18	5.7
SEAL	20.1	4.49	2.9	95.4	1.36	4.0	55.8	1.97	3.4	171.3	1.58	8.4

Table 9
Ranking results under different LCIA methods

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

Nomenclature

AE	- Eco-Indicator 99 impact category “Eutrophication”
CC	- Eco-Indicator 99 impact category “Climate change”
CCx	- Design alternative where the concrete cover is *x* mm
CE	- Eco-Indicator 99 impact category “Carcinogenic effects”
DALY	- Disability adjusted life years
ET	- Eco-Indicator 99 impact category “Ecotoxicity”
FAx	- Design alternative where *x%* fly ash is added
FFE	- Eco-Indicator 99 impact category “Fossil fuels extraction”
GALV	- Design alternative where galvanized reinforcing steel is used
HYDRO	- Design alternative where the concrete surface is hydrophobically treated
INOX	- Design alternative where stainless reinforcing steel is used
IR	- Eco-Indicator 99 impact category “Ionizing radiation”
LCA	- Life Cycle Assessment
LCI	- Life cycle inventory
LO	- Eco-Indicator 99 impact category “Land use”
ME	- Eco-Indicator 99 impact category “Mineral extraction”
OLD	- Eco-Indicator 99 impact category “Ozone layer depletion”
PAF	- Potentially affected fraction
PDF	- Potentially disappeared fraction impact
PMCx	- Design alternative where *x%* polymer is added
RE	- Eco-Indicator 99 impact category “Respiratory effects”
REF	- Reference design that serves as the basis to develop the case study presented
SEAL	- Design alternative where the concrete surface is sealed
SFx	- Design alternative where *x%* silica fume is added
W/Cx	- Design alternative where the water to cement ratio is set to *x*