Navarro, I.; Martí Albiñana, JV.; Yepes, V. (2019). Reliability-based maintenance optimization of corrosion preventive designs under a life cycle perspective. Environmental Impact Assessment Review. 74:23-34. https://doi.org/10.1016/j.eiar.2018.10.001

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

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Abstract

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

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

1. Introduction

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

According to the long-term perspective on which the sustainability concept is based, life cycle assessment has become an internationally recognized method when dealing with the sustainable design of concrete bridges. Within this framework, the three pillars on which sustainability is based, namely society, environment and economy, have been covered to a greater or lesser extent. Hammervold et al. (2013) compare the life cycle environmental impacts of three bridges built in Norway, assuming routine repairs during the use phase. Zhang et al. (2016) include uncertainty in the evaluation of the environmental impacts.

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Du et al. (2014) and Penadés-Plà et al. (2017) compare alternative bridge designs from an environmental point of view. On the other hand, Eamon et al. (2012) compare the life cycle costs of reinforcement alternatives for concrete bridges. Navarro et al. (2018a) evaluate the costs associated with alternative bridge designs in coastal environments. A general conclusion is that the maintenance and use phase of a concrete bridge is the main source of impacts during its life cycle, both environmentally and economically. An adequate maintenance strategy is essential in order to reduce the life cycle impacts of the structure (Frangopol and Soliman, 2016). Studies have been carried out that optimize the maintenance costs of concrete bridges (Kendall et al., 2008; Safi et al., 2015; Frangopol, 2011). García-Segura et al. (2017) include environmental criteria in the maintenance optimization of bridge decks.

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

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

2. Materials and methods

LCA is a widespread methodology that in recent years has taken firm root and been standarized (ISO, 2006a; ISO, 2006b) in the international context. LCCA, on the contrary, although in a fairly advanced stage of development (Hunkeler et al., 2008), still lacks an ISO standard that helps the integration of both assessment methodologies. In order to provide a comparative analysis on a consistent basis, the present study applies the ISO 14040 methodological framework for the LCC assessment (Swarr et al., 2011). According to ISO 14040, the assessment should be carried out in four phases: the definition of goal and scope, the inventory analysis, the impact assessment and the interpretation of the results.

2.1. Goal and scope definition

The present study focuses on particular preventive design alternatives applied to a real concrete bridge deck in a coastal environment. The bridge of Ensenada do Engano in Spain is analyzed. A cross-section of the bridge deck is shown in Fig. 1. The bridge, which is 721 m long and has a span distribution of 41 m + 9 x 70 m + 50 m, crosses over an estuary, with the deck less than 9 m above the mean sea level. The bridge consists of a box girder deck, with a section height of 3.2 m and a total width of 11 m. The concrete cover of the deck is 30 mm. The concrete mix of the deck is assumed to consist of a cement content of 400 kg/m^3, and a water/cement ratio of 0.45. A passive reinforcing steel in the amount of 100 kg/m^3 of concrete is considered. It shall be noted that, according to the Spanish design codes for marine environments, the bridge is designed to remain uncracked. This will be assumed for the rest of the study.

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

The use of corrosion inhibitors is a usual way to extend the service lives of concrete structures in agressive environments. The present study considers two types of inhibitor, namely an organic inhibitor used as an additive to the original concrete mix (design OCI hereafter), and a migratory inhibitor, which is applied to the concrete surface and penetrates the concrete cover, thus reacting with the concrete and increasing its resistivity (alternative MIG). The study also evaluates the use of galvanized steel (design GALV) and stainless steel (design INOX) instead of the ordinary steel of the reference design in the bridge structure. The use of durable steels increases the amount of chlorides needed to start the corrosion process, thus extending the service life of the design. In addition, the application of a hydrophobic product to the exposed deck surface (alternative HYDRO) and the application of a sealant product (alternative SEAL) in order to prevent chloride ingress in the concrete cover have been considered. Finally, large structures in marine environments are also protected by means of impressed current cathodic protection (ICCP), where the reinforcing steel is forced to act as a cathode, thus preventing its oxidation. In summary, a total of 18 design alternatives, including the reference design, are taken into account in the performance evaluation. The resulting concrete mixes are shown in Table 1.

2.1.1. Goal and scope of the study

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

2.1.2. Functional unit

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

However, the analyzed solutions shall provide not only the same service life but the same structural behavior as well. The reference design has a modulus of elasticity E_c equal to 29 GPa, and a characteristic compressive strength f_{ck} equal to 32 Mpa. Some of the evaluated alternatives are based on concrete mixes that result in different structural properties, as observed in Table 1. In order to make the resulting alternative concrete decks display the same deformability and strength than the reference design, the depth of some of the alternatives has been modified. Assuming the vertical deflection of the bridge mid-span section under service loads to be a measure of the deformability, section depths of the stiffer designs have been reduced. In particular, the designs W/C40, PMC10 and PMC20 have resulted in 3.04 m deep box girder sections, while the alternative W/C35 has a depth of 2.89 m to make these designs equally deformable as the reference design. The reference bending strength is achieved in these modified sections by slightly increasing the pre-stress force.

2.1.3. System boundaries

The system boundary definition can substantially affect the results of LCCA and LCA. The same system has been considered for both assessments, covering from the production of the construction materials needed both for the construction and for the maintenance and use phase of the deck, to the end of the required service life, following a "gate-to-grave" approach. As usual for a comparison-oriented assessment, and according to the cut-off criteria established in ISO (2006b), processes that are considered as identical between alternatives are excluded from the analysis (Martínez-Blanco et al., 2014, Navarro et al., 2018b). Processes considered to be identical between alternatives include the execution of the road pavement, the wall parapets of the deck, the prestressing tendons, the installation of the adequate lighting spots or the painting works, as well as their respective maintenance needs throughout the required 100 years service life. The present study only takes into consideration those activities that are different between the alternatives, which are those related to both the different materials consumed in the construction and repair processes of the reinforced concrete deck shown in Fig. 1 and the number of maintenance activities resulting from the optimized strategy selected. Environmental impacts related to the demolition stage have also been considered, derived from the recycling treatments of waste concrete and steel, as well as from the secondary life of crushed concrete. Fig. 2 shows the system boundaries considered in both the LCCA and LCA.

2.2. Inventory analysis

The inventory data assumed in the environmental characterization of the production activities of the different construction materials, such as cement, aggregates, reinforcement steel or polymers, have been gathered from the environmental database Ecoinvent 3.2. Table 2 presents the Ecoinvent datasets to which the different construction materials related to the different alternative designs have been assimilated. This information has been complemented with data on specific concepts, such as machinery performance and fuel demand values. Table 3 shows the assumed values, which have been obtained from the existing literature and from machinery manufacturers. The impacts derived from the use of silica fume and fly ash additions, as by-products of industry, have been economically allocated as suggested by Chen (2009) and Chen et al. (2010). Consequently, the impact derived from the use of fly ash is 1% of the impact resulting from the electricity production that results in the generation of 1 kg fly ash, while for silica fume, an allocation of 4.8% of the impact derived from the production of the ferrosilicon needed to generate 1 kg silica fume is considered.

Transport distances between the different production facilities and the installation site have been estimated taking into consideration the location of the nearest material providers to the Engano Bridge. Table 4 shows the assumed transport distances. Materials are assumed to be transported between locations by lorry. However, when the production center is located more than 100 km away from the construction site, it is assumed that only 20% of the distance is travelled by lorry, while the rest of the transport is done by freight train.

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

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

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

where c is the cement content (kg/ m^3), CaO is a parameter assumed to be 0.65 (García-Segura et al., 2014), which represents the calcium oxide contained in Portland concrete, r is the amount of CaO that absorbs

CO_2 and is assumed to be 0.75 according to Lagerblad (2005), A is the concrete surface exposed to air, M is the molar fraction CO_2/CaO (assumed to be 0.79), t is the exposure time (years), t_0 is the time of reference in years (assumed to be 0.0767 years) and k is the carbon rate coefficient, which is material dependent. The assumed values for the carbon rate coefficients are shown in Table 5. In the present study, the duration of the secondary life of the recycled concrete is assumed to be 30 years.

Regarding the inventory data considered in the LCCA, the cost data have been gathered from the construction cost database developed by CYPE (CYPE Ingenieros S.L., Alicante, Spain). This database is constantly updated and considers the costs of materials, machinery and labour, as well as indirect costs for the different construction and maintenance activities that are usual in the Spanish construction sector. The present LCCA assumes the performance values adopted for machinery in the LCA. The assumed unit costs for each concept are shown in Table 6. As the analyzed system is located in Spain, the currency chosen for the assessment is the Euro (€).

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

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

2.3 Life cycle impact assessment

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

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

3. Reliability-based maintenance optimization

3.1. Service life prediction

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

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

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

The parameter values for the durability characterization of each design alternative have been obtained from the literature. Table 7 shows the mean and the standard deviation values assumed for both the critical chloride content and the diffusion coefficients considered for the different materials, as well as the resulting mean time to failure for each of the alternatives, in years. Parameters are assumed to follow a Gaussian distribution.

3.2. Maintenance optimization problem

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

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

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

Given

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

Goal

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

Subject to

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

$$\beta(T_{opt}) = -\phi^{-1}\left[p_f\,(T_{opt})\right] \leq \beta_{lim} \tag{3}$$

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

4. Results and discussion

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

4.1. Assessment results under economically optimized maintenance

Fig. 3 shows the assessment results of both LCCA and LCA considering the maintenance intervals for each alternative associated with minimum life cycle costs. The results presented are sorted from the most to the least expensive design, considering a period of analysis of 100 years. In accordance with the definition of the functional unit of the present assessment, the results are presented as mean impacts per longitudinal meter of deck.

It is observed that the most expensive prevention alternative is the reference measure (REF), namely the original deck design, followed by the alternatives PMC10 and GALV. It can be seen that, for the particular case evaluated, any of the analyzed preventive designs would allow us to reduce the life cycle costs significantly. The addition of 10% polymer to the original concrete mix (PMC10) or the substitution of ordinary steel reinforcement by galvanized bars (GALV) leads to designs which are between 16% and 36% lower in cost than the original design, respectively. From the results obtained, it is clear that, among the alternatives evaluated in this study, the optimal prevention alternative in terms of life cycle costs is SF10, which consists in the addition of 10% silica fume to the original concrete mix and the partial substitution of the cement content. The cost of this solution is 24% of the life cycle cost of the original design. This design is followed by the use of migrating inhibitors, which results, via LCCA, in 27% of the costs associated with the reference solution. The surface treatments (alternatives HYDRO and SEAL) are also very cost-efficient measures in the long term, generating life cycle costs of approximately 31 to 33% of the costs associated with the reference measure.

Table 8 shows the intermediate results related to the cost optimization calculation. It is common to undertake maintenance actions only when the end of the service life of the structure has been reached and not before, under the false assumption that less maintenance will lead to lower costs at the end of the life cycle. It is observed that, in general, it cannot be said that alternatives with shorter maintenance intervals show greater life cycle costs. Indeed, it is observed that surface treatments with hydrophobic products (HYDRO) and designs with polymers (PMC10), which have the same maintenance optimum interval, have completely different LCCA costs. So, although this statement is true for alternatives belonging to the same design family (CC45 and CC55, or W/C40 and W/C35), when comparing alternatives of a different nature, the costs associated with the different materials and repair processes play a major role. Table 8 presents the economic impacts due to installation and maintenance for the different designs. The economic impacts derived from demolition have not been included due to the reason that, when discounted, its effect can be neglected when compared to the impacts across the rest of the life cycle. It can be concluded that, in general, the economic impact of the maintenance and use phase is essential in the LCC assessment, taking up to 85% of the total life cycle costs in some cases. Similar results have been reported by Navarro et al. (2018a).

Table 8 shows for each alternative how much the resulting life cycle impact has been reduced by selecting the optimum interval for maintenance with respect to the impact resulting from performing maintenance only at the end of the service life for each design. It is observed that the optimization leads to a reduction of the life cycle costs that reaches up to 10 to 11% in some cases.

4.2. Assessment results under environmentally optimized maintenance

Fig. 4 shows the environmental and economic assessment results when the maintenance strategy is selected in order to minimize life cycle environmental impacts. Again, the results presented in Fig. 4 are sorted in descending order according to the resulting environmental impacts of each design throughout a period of analysis of 100 years. All the results are presented as mean impacts per longitudinal meter of deck.

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

Table 9 shows the intermediate results associated with the environmental maintenance optimization. It is observed that optimization in environmental terms leads to greater impact reductions, reaching a reduction of up to 23% of the impacts derived from performing maintenance actions only at the end of the service life of the design. As with LCC assessment results, it is observed that the relative importance of maintenance is essential for the minimization of the total impact of any preventive solution, as this impact is shown to be proportional to the number of maintenance operations required for the alternative evaluated. Exceptions to this are alternatives HYDRO and SEAL, which in fact require very intensive maintenance and generate very low environmental impacts. This result is based on the fact that the assumed maintenance operations for surface treatments imply less damage to the environment than the replacement of the concrete cover needed in the maintenance of the other alternatives. The impacts derived from demolition are also presented. Only those impacts derived from transport and recycling of waste materials are considered, neglecting those associated to machinery and energy consumption, which are considered identical between alternatives.

4.3. Analysis of the Pareto Front

Results have been presented considering those maintenance intervals that minimize either the environmental or the economic life cycle impacts of each alternative under study. However, it is possible to find other solutions that, not being the absolute optimum in either of the two impact areas considered, may provide an optimum in overall terms. Taking into consideration every feasible combination between alternatives and maintenance intervals, the Pareto principle is used to identify those optimal solutions. Fig. 5 shows the Pareto front of the alternatives under study. It is observed that the results present, in general, an almost linear behavior, which means that economic and environmental impacts are proportional. This can also be appreciated in Tables 8 and 9, where it is observed that the maintenance intervals that minimize impacts from an LCCA and LCA perspective are very close.

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

4.4. Uncertainty analysis of the results

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

With respect to the environmental results, the uncertainty associated with each of the considered datasets is defined in accordance with Ecoinvent database, which takes into consideration different aspects that might influence the input values, such as geographic representativeness or measurement inaccuracies at production locations. From the results presented in Table 9 it is derived that the estimations of the environmental impacts have coefficients of variation (COV) that fall below 5% for every alternative under evaluation. Regarding the economic assessment, the considered costs have been assigned a normal probability distribution with a variance of 0.15. As a consequence, economic results have slightly greater uncertainty, as their COV reach up to 12% for the worst case (REF), due to the reduced maintenance interval and the consequently greater number of repair activities to be considered in the evaluation.

In addition, two main sources of uncertainty are evaluated here: the considered LCA methodology chosen for the environmental assessment and the discount rate assumed for the LCCA. The discount rate chosen for LCCA is one of the main contributors on the assessment results, and therefore a critical source of uncertainty (Lee et al., 2011; Harvey et al., 2012). A sensitivity analysis of this parameter is performed to evaluate its effect on the Pareto set of optimal solutions obtained for the assumed discount rate of 2%. Two new discount rates are chosen within the usual range of European infrastructures, namely 3% and 4%. For these two new scenarios, the Pareto sets have been recalculated and are shown in Table 10. Results show that, regardless of the discount rate considered, the set of optimal solutions consists of the same alternative designs, namely SF10, MIG, SEAL and HYDRO. Slight differences are to be found, however, in the optimal maintenance interval: it can be observed that for a discount rate of 4%, the Pareto set consists of 7 solutions, with maintenance intervals that tend to be longer than when considering reduced discount rates. This is due to the fact that the greater the chosen discount rate, the less importance is given to future costs, thus promoting solutions with costs distant in time.

The LCA methodology chosen in the impact assessment is considered to be a great source of uncertainty as well (Cellura et al., 2011; Hung and Ma, 2009). Taking this into consideration, two different impact assessment methods are evaluated, namely EPS (which stands for Environmental Priority Strategies) and the Eco-Indicator 99. These methods have been chosen in this sensitivity study due to the fact that they allow the estimation of the environmental performance of a system in one single endpoint indicator. The Pareto sets resulting from the use of these methodologies are shown in Table 11. From the results it is concluded that the solutions conforming the Pareto set are not significantly sensitive to the environmental impact assessment methodology chosen. It shall be observed, however, that the sealant surface treatment is discarded from the Pareto set when using Eco-Indicator 99 method.

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

5. Conclusions

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

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

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

Acknowledgements

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

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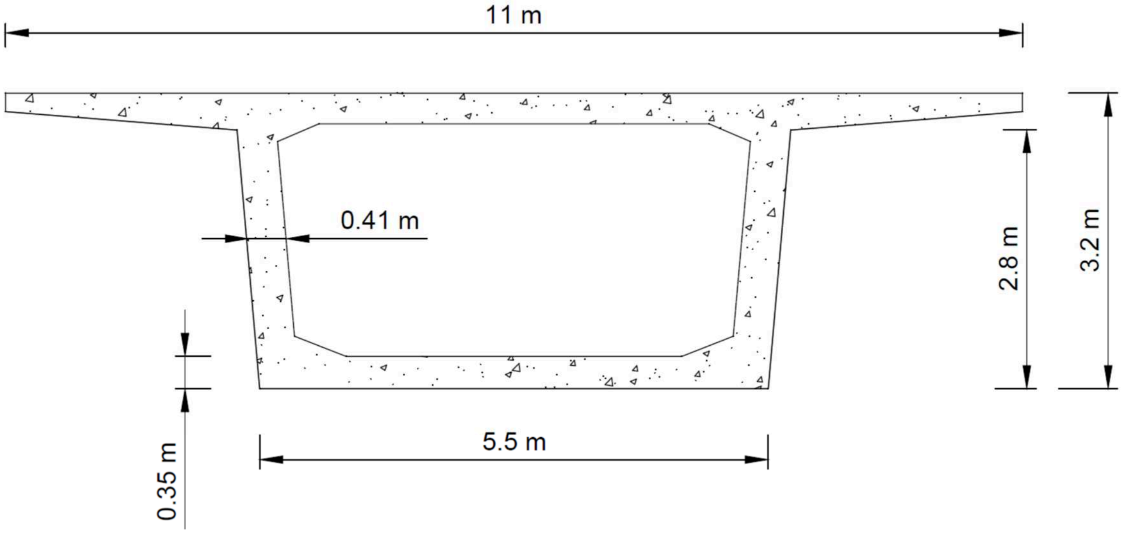

Fig. 1. Cross-section of the concrete bridge deck at Ensenada do Engano (dimensions in m)

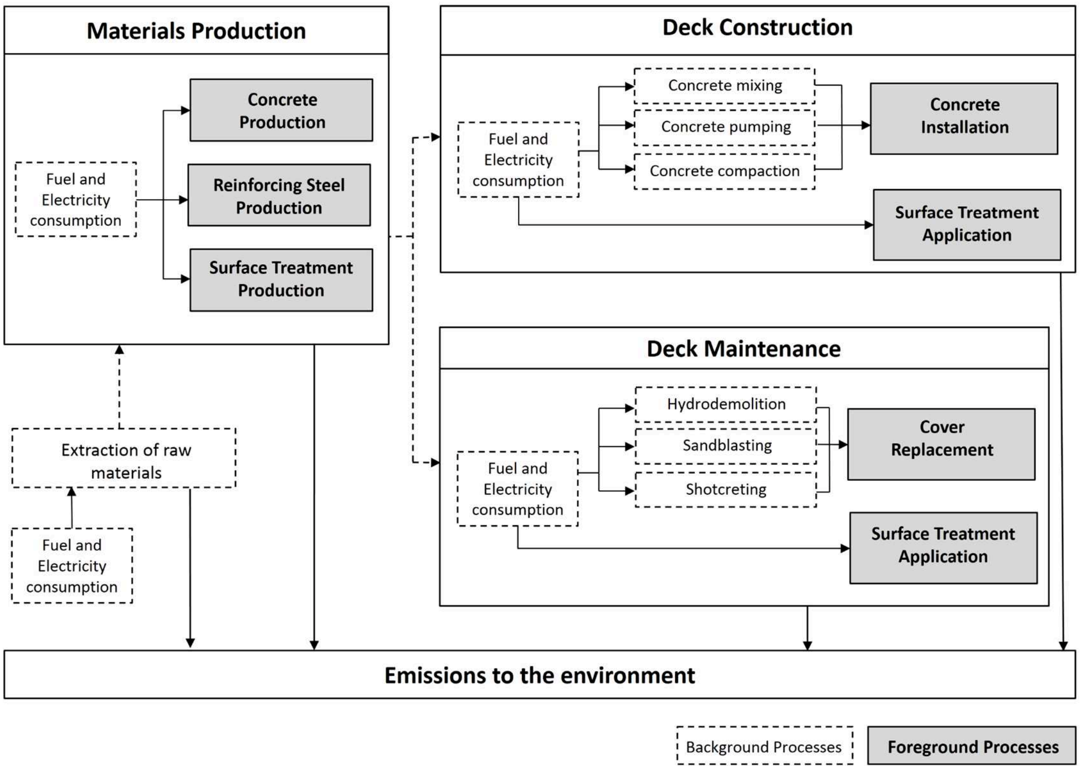

Fig. 2. System boundaries considered in the assessment

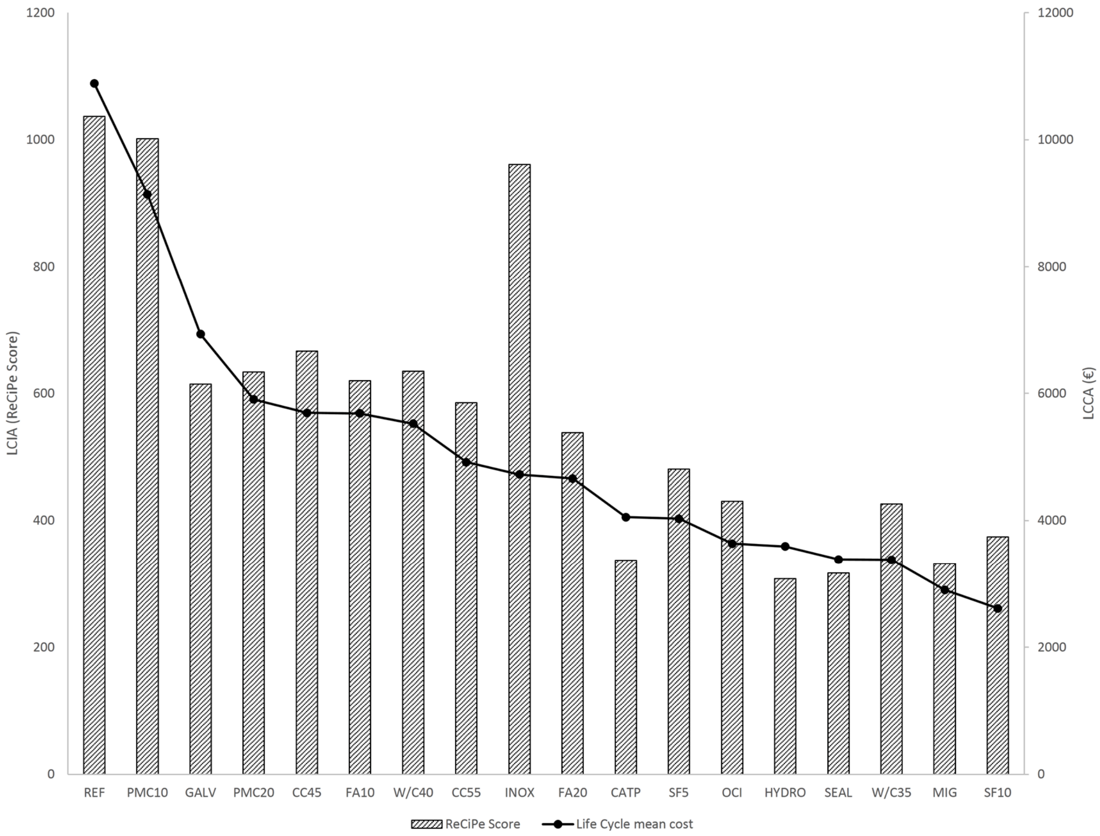

Fig. 3. Assessment results assuming cost optimized maintenance strategies

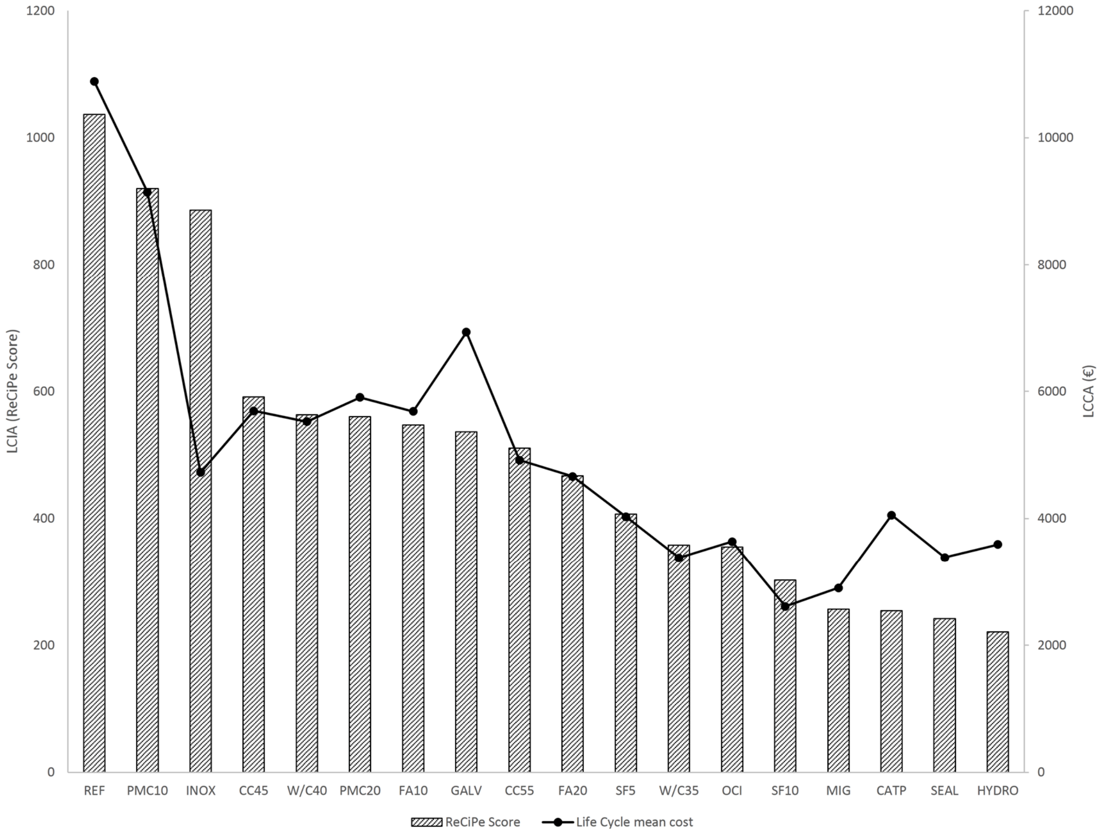

Fig. 4. Assessment results assuming environmentally optimized maintenance strategies

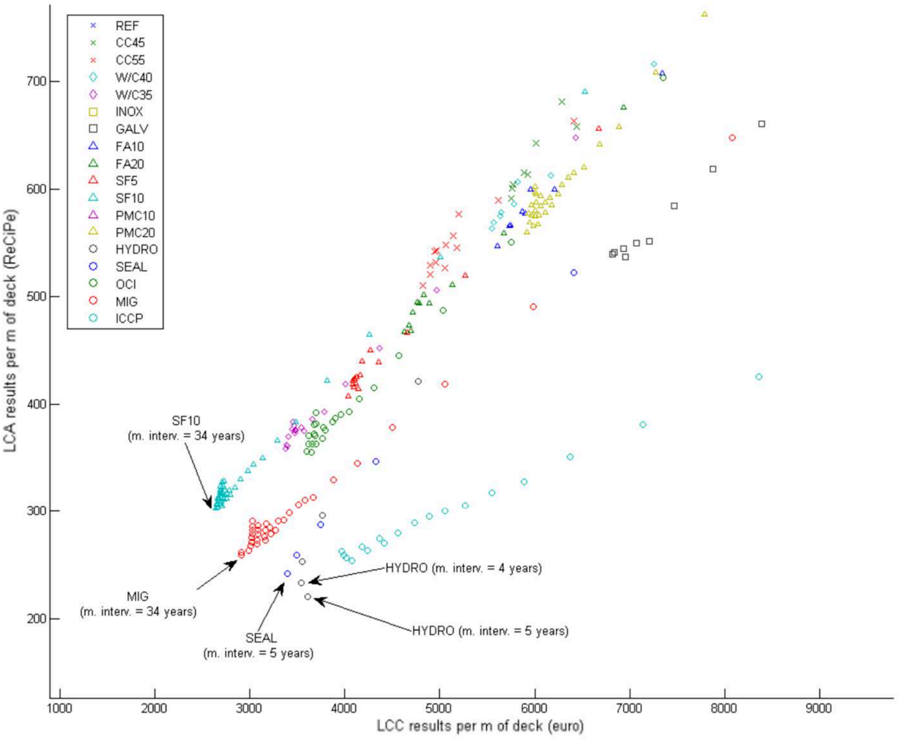

Fig. 5. Representative solutions of the Pareto optimal set

Table 1

Alternative concrete mixes assumed in the preventive designs

Concrete mix components	REF[a]	W/C40	W/C35	SF5	SF10	FA10	FA20	PMC10	PMC20	OCI
Cement (kg/m^3)	400	400	400	342.2	302.2	370.2	358.2	400	400	400
Water (l/m^3)	172	160	140	172	172	172	172	172	172	172
Gravel (kg/m^3)	926.7	993.9	1016.9	980.1	980.1	980.1	980.1	926.7	926.7	926.7
Sand (kg/m^3)	827.9	993.2	1024.2	1007.5	1024.9	965.7	941.3	827.9	827.9	827.9
Fly Ash (kg/m^3)	-	-	-	-	-	40	80	-	-	-
Silica Fume (kg/m^3)	-	-	-	20	40	-	-	-	-	-
Styrene Butadiene Latex (kg/m^3)	-	-	-	-	-	-	-	40	80	-
Organic Inhibitor (kg/m^3)	-	-	-	-	-	-	-	-	-	12
Plasticiser (kg/m^3)	-	6	8	-	-	-	-	-	-	-
f_{ck} (MPa)	32	39	47	32	32	32	32	42	42	32
E_c (GPa)	29	31	32	29	29	29	29	31	31	29

Notes:

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

Table 2

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

Inventory data concept	Ecoinvent dataset
Cement	Cement production, Portland [kg]
Gravel	Gravel production, crushed [kg]
Sand	Silica sand production [kg]
Plasticiser	Plasticiser production, for concrete, based on sulfonated melamine formaldehyde [kg]
Inhibitor	EDTA production [kg][a]
Styrene Butadiene Latex	Latex production [kg]
Hydrophobic treatment[b]	Ethoxylated alcohol (AE3) production, petrochemical [kg]; Silicone product production [kg]
Sealant treatment[c]	Cement production, Portland [kg]; Silica sand production [kg]; Butyl acrylate production [kg]
Reinforcing steel	Reinforcing steel production [kg]
Stainless reinforcement	Steel production, chromium steel 18/8, hot rolled [kg]
Galvanized reinforcement	Reinforcing steel production [kg]; Zinc coating, coils [m^2]

Notes:

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

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

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

Table 3

Life cycle inventory data on process performances and energy consumptions

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

Notes:

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

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

Table 4

Assumed transport distances and transport modes

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

Notes:

[a] Distance from production facility to concrete plant

[b] Distance from concrete plant to installation site

[c] Distance from production facility to installation site

Table 5
Assumed carbonation rate coefficient *k* depending on the concrete type considered, according to Fib Bulletin 34 (Fib, 2006)

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

Table 6
Unit costs (€) considered in the LCCA

m^3 of concrete HA30	83.62
m^3 of concrete HA30 (w/c=0,4)	97.99
m^3 of concrete HA30 (w/c=0,35)	104.26
m^3 of concrete HA30+10%FA	101.63
m^3 of concrete HA30+20%FA	101.23
m^3 of concrete HA30+5%SF	131.40
m^3 of concrete HA30+10%SF	137.58
m^3 of concrete HA30+Organic corrosion inhibitor	164.30
l of styrene butadiene rubber latex	4.70
kg of steel (B 500 S)	1.24
kg of stainless steel	5.24
kg of galvanized steel	3.62
m^2 of hydrophobic treatment	17.78
m^2 of sealant treatment	29.04
m^2 of inhibitor surface treatment	19.76
m^2 of cathodic protection	63.54
m^2 of hydrodemolished cover[a]	27.68
m^2 of sandblasting	4.29
m^2 of reinforcement priming	11.73

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

Table 7

Durability parameters assumed for the alternative designs

Design alternative	D_0	($x10^{-12}$ m^2/s)	$C_{crít}$	(%)	r_x	(mm)	Mean service life (years)	Sources
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.		
REF	9.56	1.02	0.6	0.1	35	1.75	4	Spanish Ministry of Public Works, 2008
CC45	9.56	1.02	0.6	0.1	45	2.25	10	
CC55	9.56	1.02	0.6	0.1	55	2.75	15	
W/C40	5.90	0.48	0.6	0.1	30	1.75	9	Vedalakshmi et al., 2009; Cheewaket et al., 2014
W/C35	3.84	0.29	0.6	0.1	30	1.75	20	
INOX	9.56	1.02	5	0.94	30	1.75	-	Bertolini et al., 1996
GALV	9.56	1.02	1.2	0.21	30	1.75	12	Darwin et al., 2009
OCI	3.81	0.29	0.71	0.1	35	1.75	26	Bolzoni et al., 2014
MIG	2.72	0.22	0.6	0.1	35	1.75	36	
SF5	3.16	0.25	0.38	0.06	35	1.75	16	Frederiksen, 2000; Manera et al., 2008
SF10	1.32	0.17	0.22	0.03	35	1.75	42	
FA10	5.89	0.48	0.6	0.1	35	1.75	10	Otsuki et al., 2014
FA20	5.00	0.39	0.6	0.1	35	1.75	12	
PMC10	7.00	0.61	0.6	0.1	35	1.75	7	Ohama, 1995; Yang et al., 2009
PMC20	2.91	0.23	0.6	0.1	35	1.75	32	
ICCP	9.56	1.02	2.49	0.1	35	1.75	53[a]	Bertolini et al., 2009
HYDRO	7.39	0.67	0.6	0.1	35	1.75	5[b]	Zhang and Buenfeld, 2000
SEAL	4.66	0.35	0.6	0.1	35	1.75	11[b]	Medeiros et al., 2012

Notes:

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

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

Table 8

Assessment results considering LCC optimized maintenance intervals

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

Table 9

Assessment results considering LCA optimized maintenance intervals

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

Table 10

Uncertainty derived from the chosen discount rate

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

Notes:

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

Table 11

Uncertainty derived from the chosen impact assessment methodology

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

Notes:

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