Environmental effects of using different construction codes applied to reinforced concrete beam designs based on Model Code 2010 and Spanish Standard EHE-08

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Abstract

Assuming specific behavior models, the variety of design codes currently used for the design of concrete beams inevitably results in different solutions, ensuring service during the expected lifetime with a maximum functional quality and safety. However, from a sustainable design perspective, such differences may have remarkable environmental impacts. This paper analyses if the approach of the newest design code, i.e., the Model Code, leads to a reduction in resource consumption and greenhouse gas emissions (GHG) over the life cycle of concrete beams. To do so, a comparative analysis of the environmental impact of concrete beams was carried out depending on the reference code used for their design (i.e., EHE-08 or Model Code). The results show that reducing the amount of reinforcing steel is essential to minimize the life cycle environmental impacts of concrete beams. Every country may have its own design codes and, thus, the reinforcing steel use can vary for structures subjected to the same loads and with equivalent structural reliability. Hence, regulations play a key role in the sustainability of construction assets. Conclusions depend on the beam's length (**L**), height (**h**) and characteristic compressive strength ($\mathbf{f_{ck}}$). For short beams (4 m), the greater the **h**, the greater the reinforcement difference between the two codes. With regard to beams with **L** = 8 m, these differences can lead to varying steel and GHG savings, e.g., up to 5.0 % with MC-2010 (**h** = 0.6 m and $\mathbf{f_{ck}} \leq 35$ MPa), almost 40 % with EHE – 08 (**h** = 0.6 m and 35 MPa < $\mathbf{f_{ck}} \leq 50$ MPa) and more than 30 % with MC-2010 (**h** = 1.0 m).. For long beams (**L** = 12.0 m), steel consumption is 0.3 % to 19 % lower when the beam is designed with EHE-08, and this difference decreases as $\mathbf{f_{ck}}$ increases.

Keywords

Structural design - Environmental Impact - Life cycle assessment – Civil engineering – Resource consumption – Greenhouse gas

1. Introduction

The construction industry consumes a large amount of resources and energy, which generates significant impacts on the environment [1]. In this context, Zabalza Bribián et al. [2] and Blankendaal et al. [3] reported that the construction industry contributes to 24 % of the total material extraction worldwide. In Spain, every habitable square meter requires 2.3 tons of more than 100 types of construction and building materials [2,4], with concrete being of particular interest due to its extensive use. According to Lippiatt and Ahmad [5], approximately 1 ton of concrete per person is produced in the world every year. At the building scale, this implies that the energy embodied in buildings constructed in mild climates might represent 25 % of the total life cycle energy of a building [6]. Consequently, evaluating the environmental effects associated with concrete use are of particular interest to increase the sustainability of the construction industry.

So far, the environmental behavior of concrete has been assessed based on varying compositions and applications. A number of studies have applied the life cycle assessment (LCA) methodology to estimate the environmental impacts of building frames [7,8], structures [9,10] and urban elements

[11–15]. LCA was also used to understand the effects of greening concrete manufacturing through recycled aggregates or industrial by-products [16–20]. Here, the design phase is crucial to determine the resulting environmental burdens of a system. To this end, Muigai et al. [21] formulated a design framework towards the selection of more sustainable concrete infrastructure.

However, the role of legislation is fundamental, as it might encourage the design of material-intensive structures to ensure the functionality and safety of the product. In this sense, some construction codes provide preliminary suggestions regarding the design of more sustainable systems using a reliability-based (probabilistic) method. Examples include the *fib* model code 2010 (MC-2010) for concrete structures [22] and the Spanish code (EHE-08) [23]. Since the appearance of reinforced concrete (RC) in the mid-nineteenth century, key design issues for structural concrete codes have gradually progressed from considering limited strength and cost variables to addressing durability and environmental issues [21]. However, there is still a lack of grasp of the design approach for RC structures and its influence on the environmental impacts. MC-2010 is a recommendation for the design of structural concrete, written with the intention of setting the guidelines for future codes [24]. As such, the results of the latest research and development works are used to generate updated recommendations for structural concrete in each country. Inevitably, some differences exist between the structural design approach proposed by MC-2010 and the one proposed by other design standards such as the Spanish code EHE-08 [23].

These differences in the design of concrete structures may result in different solutions, all of which ensure service during the expected lifetime with a maximum functional quality and safety, but with different environmental impacts. Therefore, a key question is whether new design codes minimize the use of natural resources and greenhouse gas emissions over the life cycle of concrete structures. This study focuses on concrete beams to conduct an assessment coupling a parametric analysis and LCA. The objective of this research is to carry out a comparative analysis of the environmental impact of concrete beams depending on the reference code used in their design. To this end, a large number of simply supported beams were evaluated according to EHE-08 and MC-2010 standards and varying basic parameters, such as the length span, beam geometry, ambient exposure class, and design load combination. In addition to a direct crosswise comparison of the environmental repercussions of both design codes, a complete environmental parametric study was also conducted. Thereby, we believe that this paper represents a meaningful contribution for advancing towards the use of environmental approaches in structural design.

2. Materials and Methods

2.1. Case study selection and parametric analysis

The analysis focused on beams made of reinforced concrete with a constant rectangular cross-section, which are usually applied in building and industrial construction (Figure 1). Usually, passive corrugated steel is used to reinforce the concrete in order to withstand the tensile stresses that the cracked beam is subjected to due to the bending and shear forces that occur from the demolding to the service stages, and eventually in potential failure situations. The area of this reinforcement ($\boldsymbol{A_{sl}}$ and $\boldsymbol{A_{st}}$ for the longitudinal and transversal reinforcement, respectively) is determined by guaranteeing the fulfilment of both the ultimate (ULS) and service (SLS) limit states.

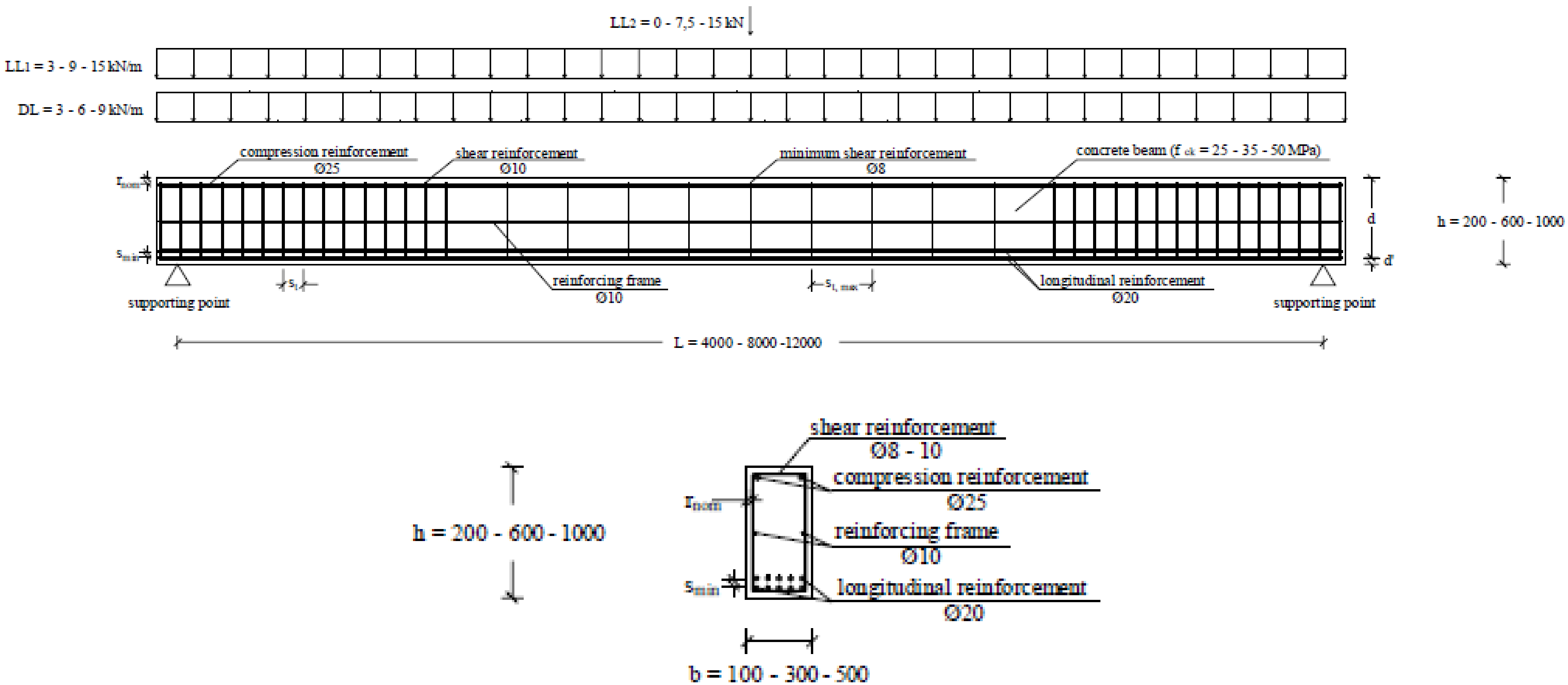


Figure 1. Main geometric and loading parameters involved in the analysis. Dimensions in mm.

These limit states are based on the safety approach established in the design guidelines for reinforced concrete structures. In this regard, the structural safety criteria are common in most of these guidelines (e.g., maximum deformations allowed, minimum ductility requirements, and partial safety factors for loads and material strengths). However, several requirements related to durability (e.g., allowed crack widths w_{max}, cement content c_{cem}, water/cement ratio w/c and concrete cover $c_{concrete}$) and formulations to assess the strength capacity of the cross-sections of the beam might differ because of the model applied, although the theoretical service and safety conditions remain the same. Consequently, reinforcement consumption and distribution can be different for the same beam geometry and design loads; thus, the environmental impact associated with each alternative can also vary.

The production of beams is considered to be developed through a high-quality control procedure. Beams are designed to work under a simply supported configuration from both ends by using elastomeric pads. Regarding the concrete and reinforcing durability aspects, a conventional environment without presence of any type of chlorides, sulfates or chemical products was assumed. These ambient exposure conditions were assumed to be representative of those cases in which the beams are subjected to any range of humidity conditions (protected or not from rain or water below the phreatic level), being the carbonation of concrete and rebar de-passivation the main degradation processes. The main structural parameters involved in this study are gathered in Table 1.

Table 1. Main structural (geometrical and mechanical) parameters considered.

Variables	**Values**
Length, **L** [m]	4.0 – 8.0 – 12.0
Concrete section, b x h [m^2]	0.1 x 0.2 – 0.3 x 0.6 – 0.5 x 1.0
Characteristic concrete compressive strength f_{ck} [MPa]	25 – 35 – 50
Uniformly distributed dead load (**DL**) [kN/m]	3.0 – 6.0 – 9.0
Uniformly distributed live load (LL_1) [kN/m]	3.0 – 9.0 – 15.0
Punctual live load (LL_2) [kN]	0.0 – 7.5 – 15.0

Common geometrical and mechanical parameters were selected. Beam lengths (***L***) comprised from 4.0 to 12.0 m and rectangular cross-sections with width (***b***) varying from 0.1 to 0.5 m and height (***h***) from 0.2 to 1.0 m were considered. The aspect ratio of the cross-section $\boldsymbol{h}/\boldsymbol{b}$ was kept constant with a value of 2.0. This range could represent short beams used for private building construction, for instance, and the maximum length that is usually considered for RC structural applications with high loads and large free spans. Although using passive reinforcement might be technically feasible, lengths larger than 12 m would usually require either the use of prestressed or posttensioned strands or a limit in the service loads to control crack widths and deflections during service life.

The permanent loads considered were (1) the self-weight (**SW**) of the beam, which resulted from multiplying the cross-section area ($\boldsymbol{A_c}$) by the specific weight of RC ($\boldsymbol{\gamma_c}$ = 25 kN/m^3); (2) a uniform distributed load (**DL**) with values ranging from 3.0 to 9.0 kN/m; (3) a uniformly distributed live load ($\mathbf{LL_1}$) that varies from 3.0 to 15.0 kN/m, and (4) a punctual live load ($\mathbf{LL_2}$) ranging from 0.0 to 15.0 kN. Both live loads can act in any part of the beam. These loads are properly combined considering the partial safety and simultaneity factors ($\boldsymbol{\psi}$) established in the guidelines to obtain the design bending and shear envelopes. These envelopes are then used to obtain the minimum amount of reinforcing steel required to withstand these design loads with the structural reliability fixed in both codes, which is equivalent.

Finally, the characteristic value of the compressive concrete strength ($\boldsymbol{f_{ck}}$) was assumed to vary between 25 and 50 N/mm^2. The lower value was fixed by EHE–08 for RC structural applications, whilst the upper value divides the classification of concrete strength into normal and high. In this regard, this kind of beam is designed with normal strength concrete; however, concrete additives and curing procedures currently used in precast concrete production lead to real values of $\boldsymbol{f_{ck}}$ easily higher than 50 N/mm^2.

Considering all these variables, 729 beam designs result from the direct combination of these parameters by considering MC-2010 and EHE–08 as guidelines. Nevertheless, some of the beams are not feasible from a technical and/or economic point of view when imposing the fulfilment of the SLS and ULS since the configuration obtained is unreal and alternative types of beams (based on geometrical and mechanical parameters) could be more appropriate.

2.2. Structural design performance

The aim of the structural study was to analyze the influence of the different variables examined in the parametric study (see section 2.1) on the amounts of materials used in beam production. The volumes of concrete and steel reinforcement required for each case were calculated based on two different regulatory frameworks that define the structural safety and security requirements to be met by concrete structures. Among the different codes and standards, the fib model code for concrete structures MC-2010 and the EHE-2008 were chosen, as these are the first to introduce some initial ideas with regard to the design of more sustainable concrete structures.

The design approach used in both the MC-2010 and EHE-08 codes is based on the limit state design method. Limit states are defined as cases wherein parameters are exceeded and thus a given structure does not fulfil the function it was designed for. For the purpose of this study, two limit states were verified. The ultimate limit state (ULS) covers all limit states giving rise to structural failure due to a complete or partial loss of equilibrium, collapse or breakage thereof, whereas the serviceability limit state (SLS) covers all limit states wherein required functionality, comfort or aspect requirements are not fulfilled. Based on the design load combinations, material characteristics and geometric data, structures must not exceed any of the limit states during construction and service life. For a certain limit state, a checking procedure involves determining the effects of actions applied to the structure or in part thereof and the structure's response for the limit situation examined. Based on a sufficient reliability index, the limit state is guaranteed once verified that a given structural response is no less than the effect of the applied actions. To this end, partial safety factors proposed within the MC-2010 and EHE-08 codes are considered to increase action effects while reducing the strength of each constitutive material. It must be emphasized that EHE–08 is one of the first structural concrete guidelines to include an Annex (Annex 13) devoted to the sustainability performance assessment of concrete structures [25]. The method proposed therein is based on a multi-criteria decision-making method called MIVES and already applied to several types of structures [26–29].

Several considerations were defined to optimize the rebar distribution: (1) straight anchorages are used for the longitudinal reinforcement when a group of bars are no longer required for bending purposes; (2) rebars with 20 mm and 10 mm of diameter are used for the longitudinal and transversal reinforcement, respectively, and (3) those cases that require more than 3 layers of tensile longitudinal reinforcement were excluded since the dimensions of the section are incompatible with the acting forces.

2.3. Life cycle assessment approach

To estimate the environmental impacts of each beam design, the LCA methodology based on ISO 14040-44 [30] was used. The structural design performance and environmental impacts refer to a common functional unit that enables design comparisons. Here, the impacts were related to concrete beams with lengths of 4.0, 8.0 and 12.0 meters to represent different applications in the building construction sector. Within each length, variations in the parameters defined in section 2.1 were applied to understand the changes in material requirements and environmental burdens of each design code. The same service life was assumed in all cases.

As shown in Figure 2, the system boundaries include the manufacturing of prefabricated beams through the acquisition ofraw materials and production of concrete and reinforcing steel, the transport to the building site and the final transport to and disposal in an inert material landfill, which are the main stages of the life cycle in this case. Similar to previous studies, the installation, operation and demolition stages are beyond the scope of this analysis because they are constant in the building process [31, 32].

In terms of material composition, reinforcing steel was composed of 59 % of secondary scrap [33]. The average specific weight of concrete considered in both structural and environmental analyses is 2,400 kg/m^3 and the concrete dosage depends on the target compressive strength (e.g., 25, 35 and 50 MPa) and minimum durability requirements. The life cycle inventories of concrete and reinforcing steel were directly available at the ecoinvent v3 database based on these compressive strengths [34].Regarding transport, we assumed a distance of 30 km from the production to the building site, and 10 km to the landfill. Additional specific background inventories for each process were retrieved from ecoinvent (Appendix A1).

The impact assessment was conducted at the midpoint level through the ReCiPe (H) method [35] attached to the Simapro 8 software [36]. All the indicators were calculated up to the characterization stage and we paid special attention to the climate change values in our results section to provide a relevant indicator that is commonly presented in the construction industry and legislation. Results for the remaining indicators are provided in Appendix A2.

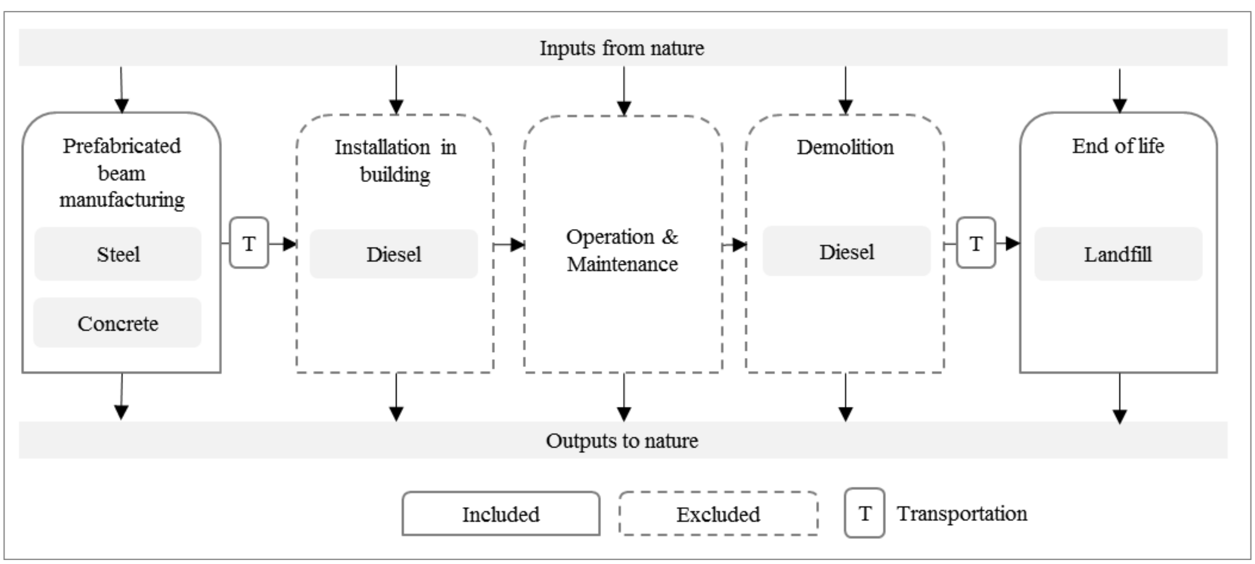


Figure 2. Diagram of the system boundaries for the environmental analysis of beams.

3. Results

Figure 3 shows the total weight of reinforcement required for each beam design based on the parameters provided in Table 1 and following MC-2010 and EHE-08. In addition to the results from the structural analysis, Figure 3 also shows the environmental impacts for climate change generated by the cases under assessment (see secondary axis).

The reinforcement ratio $\boldsymbol{V_s}$ (i.e. the total volume of steel over the total volume of concrete) and design load factor $\boldsymbol{\xi_d}$ = (1.35**DL**·**L** + 1.50(**LL**$_\mathbf{1}$·**L** + **LL**$_\mathbf{2}$))/(1.35**DL**·**L**+1.50(15·**L**+15) were defined herein for each combination of loads and beam geometry. In this regard, the trends obtained were very similar for all the cases analyzed. Therefore, only the $\mathbf{V_s}$ – $\boldsymbol{\xi_d}$ relationships for **L** = 8.0 m, **h** = 0.6 and $\mathbf{f_{ck}}$ = 35 N/mm^2 (Figure 3a) and **L** = 12.0 m, **h** = 1.0 and $\mathbf{f_{ck}}$ = 50 N/mm^2 (Figure 3b) are presented herein as representative of all of them. Moreover, since the results were very dependent on **LL**$_\mathbf{1}$ (besides **h**, **L** and $\mathbf{f_{ck}}$), they were grouped according to this live load. Note that, in **L** = 4.0 m, the total amount of reinforcement responds to the minimum amount required to avoid brittle failure regardless of the load level considered. This amount was a constant value both when the design was defined through EHE–08 and MC-2010. An exception is **h** = 0.6, $\mathbf{f_{ck}}$ ≤ 35 N/mm^2 and **LL**$_\mathbf{1}$ = 15 kN/m, where the amount is controlled by SLS cracking criteria, which are in this case more restrictive, and the required amount of reinforcement is larger.

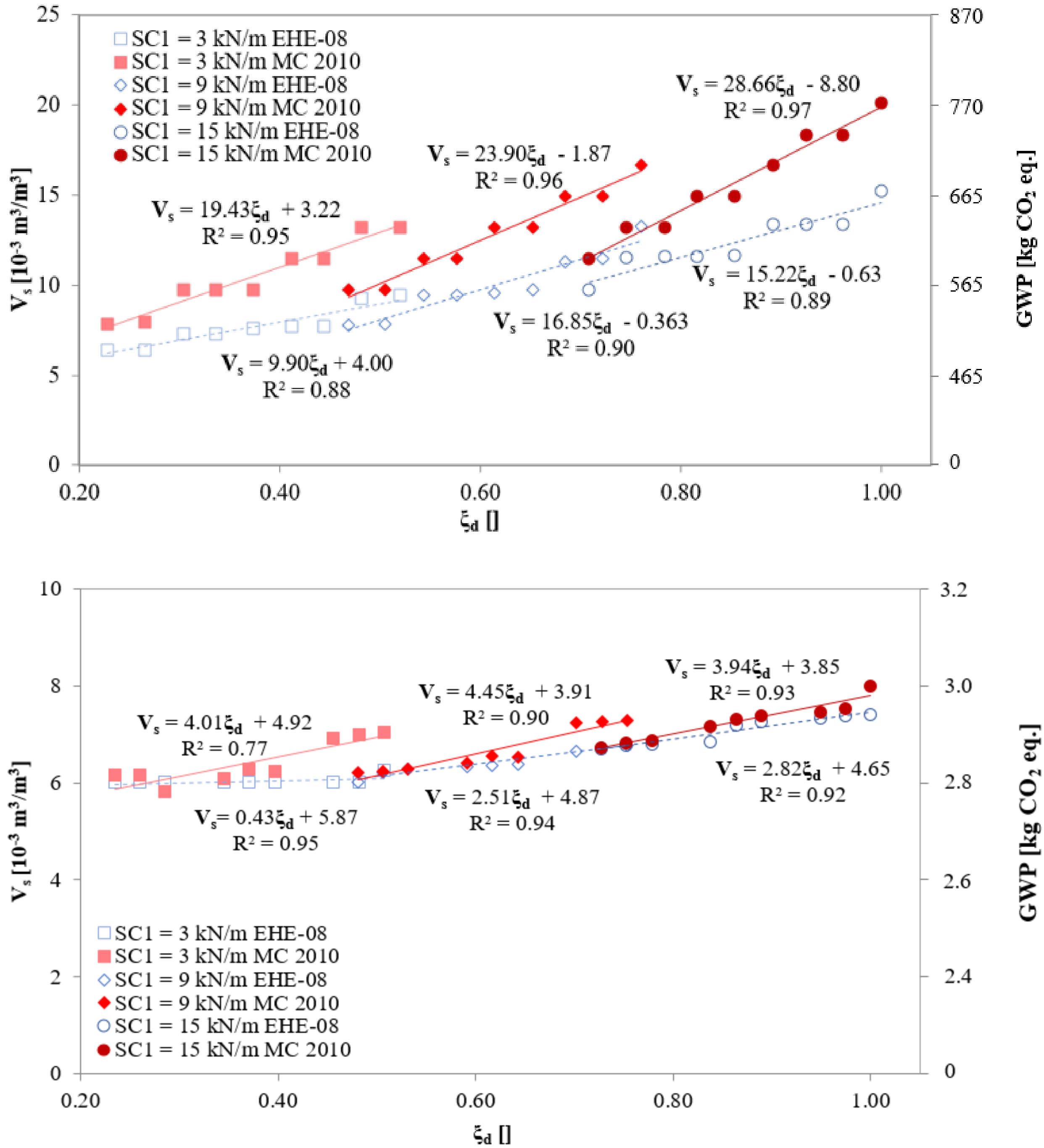


Figure 3. $\mathbf{V_s}$ – $\boldsymbol{\xi_d}$ relationships for: (a, top) **L** = 8.0 m, **h** = 0.6 m and $\mathbf{f_{ck}}$ = 35 N/mm² and (b, bottom) **L** = 12.0 m, **h** = 1.0 m and $\mathbf{f_{ck}}$ = 50 N/mm².

Regarding the cases with **L** = 8.0 m (Figure 3a), if **h** = 0.6 m, the ULS of bending and shear control determine the amount of reinforcement; the total weight of steel decreases with an increase in $\mathbf{f_{ck}}$. If **h** = 1.0 m, reinforcement responds to the minimum values for ULS of bending and shear when the EHE–08 code is considered, whilst the ULS of bending and SLS of cracking/deformation determine the reinforcement configuration when using the MC-2010. Finally, for cases with **L** = 12.0 m, only the beams with **h** = 1.0 m are technically feasible. Regardless of the code used for the design, ULS or SLS are determinant according to the magnitude of $\boldsymbol{\xi_d}$, and all beams require amounts of reinforcement far higher than the minimum.

In environmental terms, the climate change impacts of the cases considered in Figure 3 are directly correlated with the amount of materials used. This is because the main life cycle impacts of beams are related to the raw materials (i.e., quantity of steel and concrete). This trend also applies in the remaining impact indicators (see **Appendix A2**). Previous literature on RC structures also reported on similar patterns (e.g., [32,37,38,39,40,41]). In this sense, in cases with **L** = 8.0 m the maximum impacts of reinforcing steel have a larger contribution to the total environmental impacts of the beam, representing up to 50-90 % of the life cycle impacts.

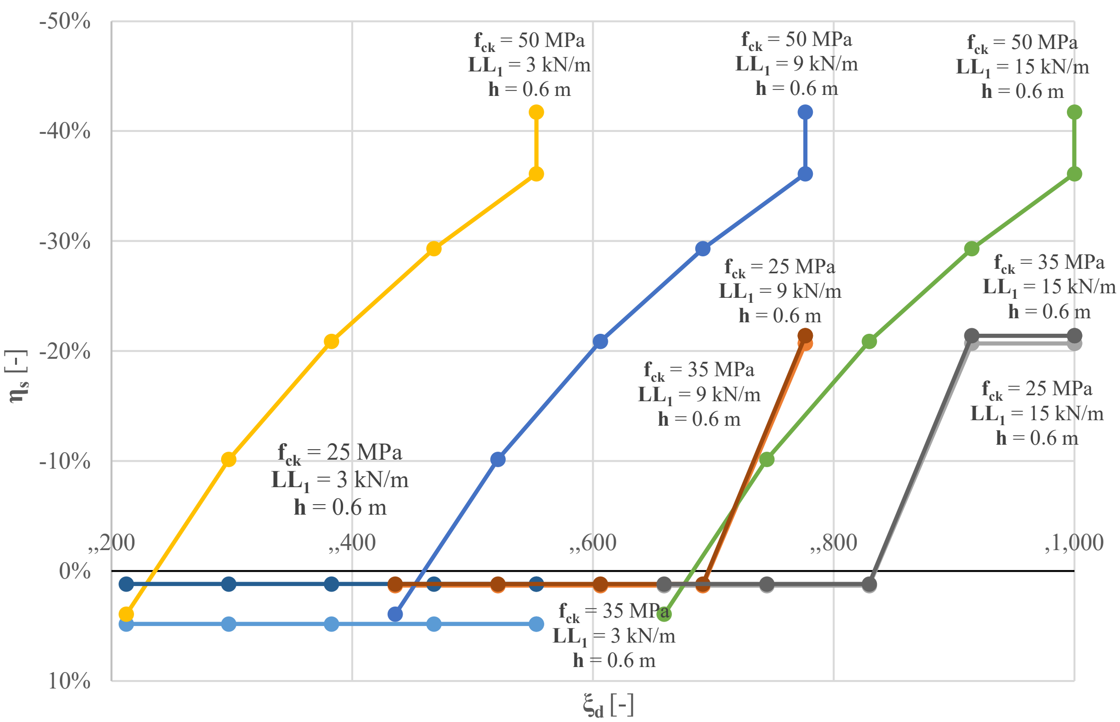
In particular, the results obtained from the study enable the estimation of climate change values for beams using the reinforcement ratio ($\boldsymbol{V_s}$) in each of the cases. To do so, equation (1) was estimated for determining the climate change impacts for cases with **L** = 8.0 m, **h** = 0.6 m and $\mathbf{f_{ck}}$ = 35 N/mm^2, and equation (2), for cases with **L** = 12.0 m, **h** = 1.0 m and $\mathbf{f_{ck}}$ = 50 N/mm^2.

Equation (1) $$y_{(kg\ CO_2\ eq.)} = \left(20.4 \cdot V_{s\ (Vsteel/Vconcrete)} - 77.4\right) + 439.0$$

Equation (2) $$y_{(kg\ CO_2\ eq.)} = \left(84.8 \cdot V_{s\ (Vsteel/Vconcrete)} - 493\right) + 2.8$$

In terms of reinforcing in the configuration of each alternative analyzed, the relative difference in total steel consumption ($\boldsymbol{\eta_s} = \mathbf{V_{s,EHE\text{-}08}/V_{s,MC\text{-}2010}} - 1$) was considered. Figures 4, 5 and 6 depict the $\boldsymbol{\eta_s}$ – $\boldsymbol{\xi_d}$ relationships for beams with **L** = 4.0, 8.0 and 12.0 m, respectively. As shown in Figure 4 (cases with **L** = 4.0 m and **h** = 0.6 m), the steel consumption required using the EHE–08 code is between 2 and 5 % lower with respect to the quantity required using the MC-2010 code when $\mathbf{f_{ck}}$ ranges from 25 to 35 MPa and $\mathbf{LL_1}$ = 3 kN/m. In the remaining cases, the steel consumption tends to be much higher (up to a 42 %) with the use of MC-2010 as the load increases. If **h** = 1.0 m, the steel consumption is 20 % ($\mathbf{f_{ck}}$ = 50 MPa) and 33 % ($\mathbf{f_{ck}}$ = 25 and 35 MPa) higher with the EHE–08.

As observed in Figure 5 (cases with **L** = 8.0 m, if **h** = 0.6 m), the steel consumption obtained with MC-2010 is higher in all cases; in this sense, a reduction from 3 to 32 % is obtained when EHE–08 is considered in the structural design. Likewise, if **h** = 1.0, the steel consumption is up to 15 % lower when using EHE–08 for $\mathbf{f_{ck}}$ = 25 or 35 MPa, $\mathbf{LL_1}$ = 9 or 15 kN/m and $\boldsymbol{\xi_d}$ > 0.6; for the rest of cases, a greater consumption results from the use of EHE–08. Finally, Figure 6 shows the cases with **L** = 12.0 m. Here, cases designed with the EHE–08 code require a lower quantity of steel. The reduction increases with $\boldsymbol{\xi_d}$ and decreases with $\mathbf{f_{ck}}$, given that the latter does not play an important role in the flexure design, as usually occurs for those cross-sections that do not require compressive reinforcement, for the geometry and load levels studied.



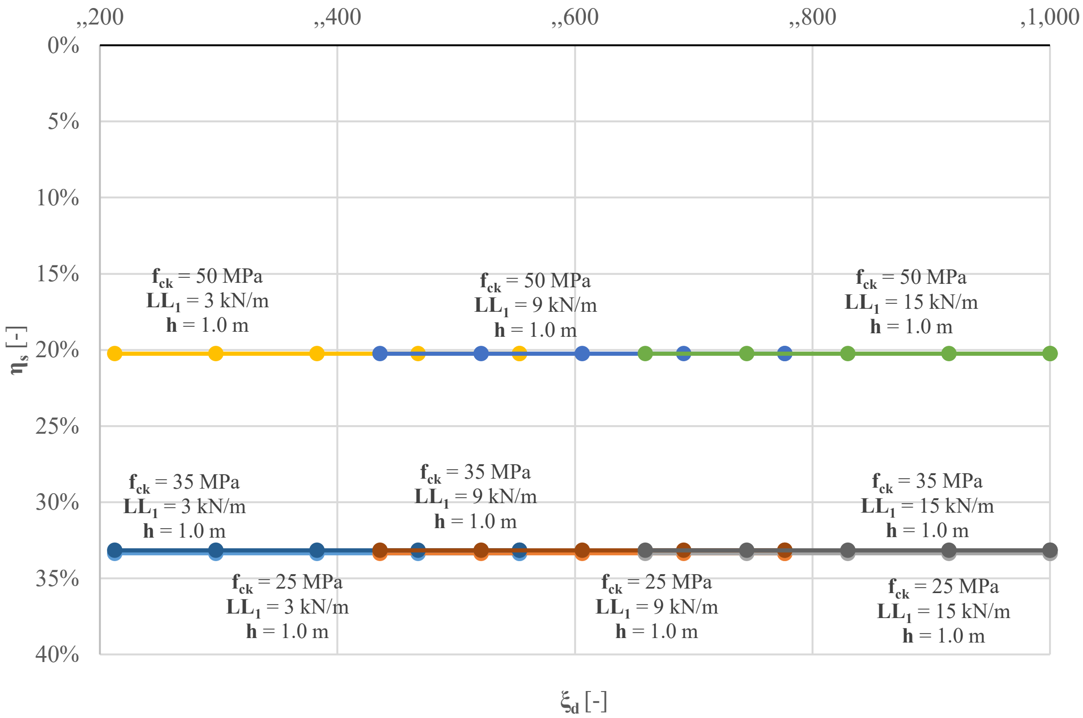
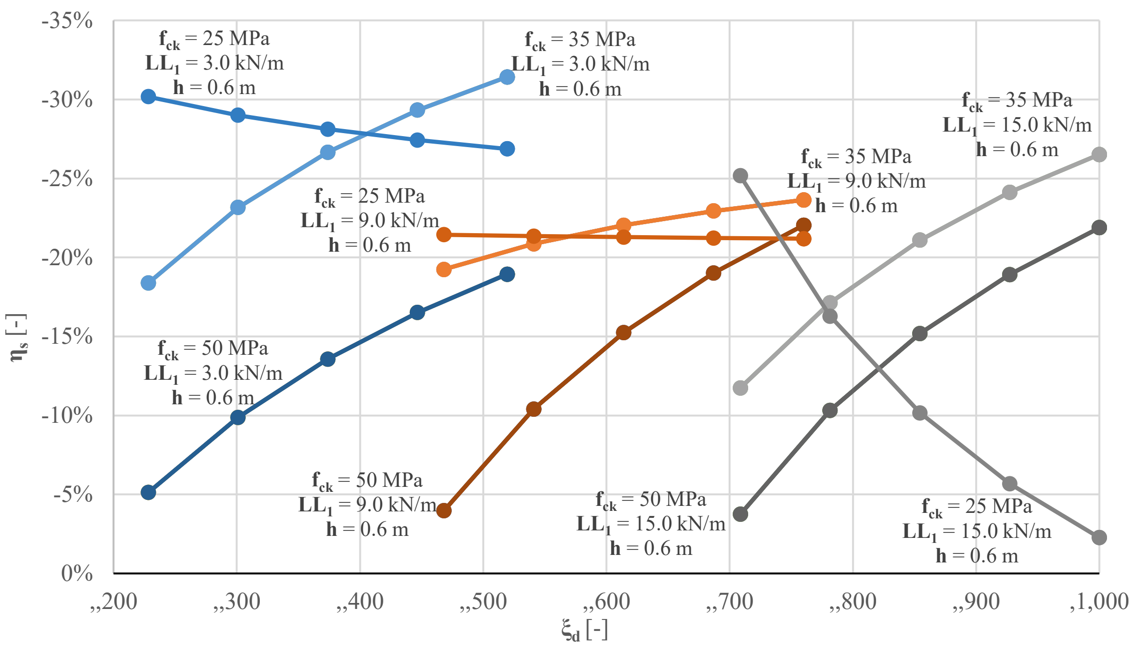


Figure 4. η_s – ξ_d relationships for **L** = 4.0 m: (a, top) **h** = 0.6 m and (b, bottom) **h** = 1.0 m.



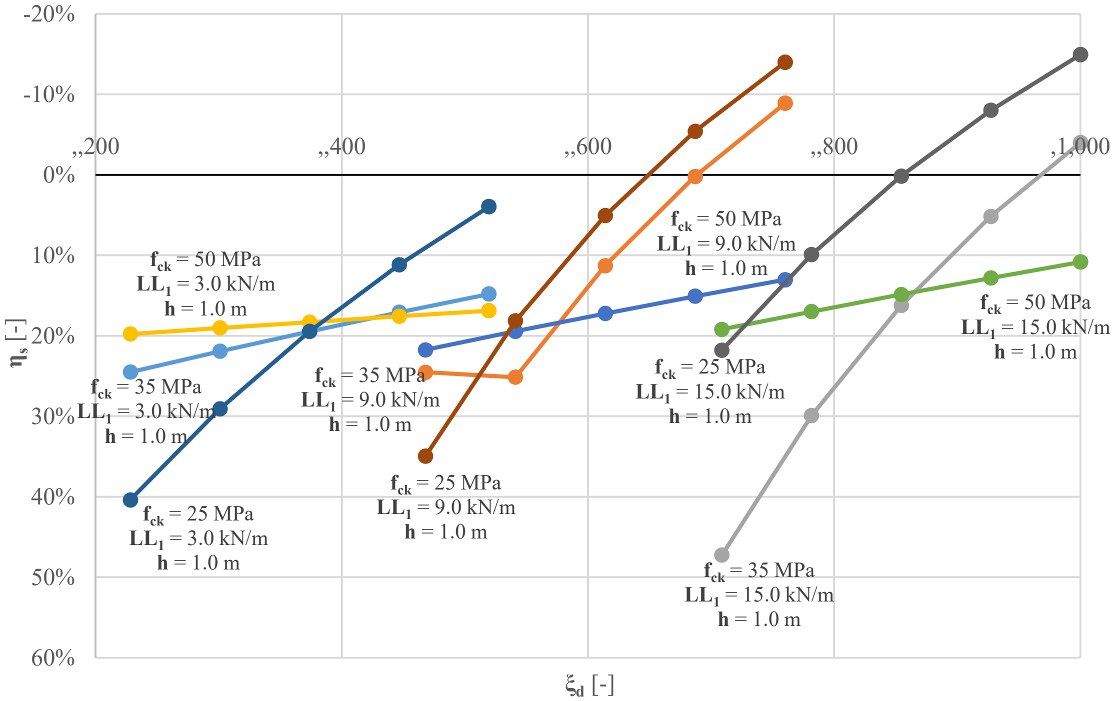


Figure 5. $\boldsymbol{\eta_s}$ – $\boldsymbol{\xi_d}$ relationships for **L** = 8.0 m: (a, top) **h** = 0.6 m and (b, bottom) **h** = 1.0 m.

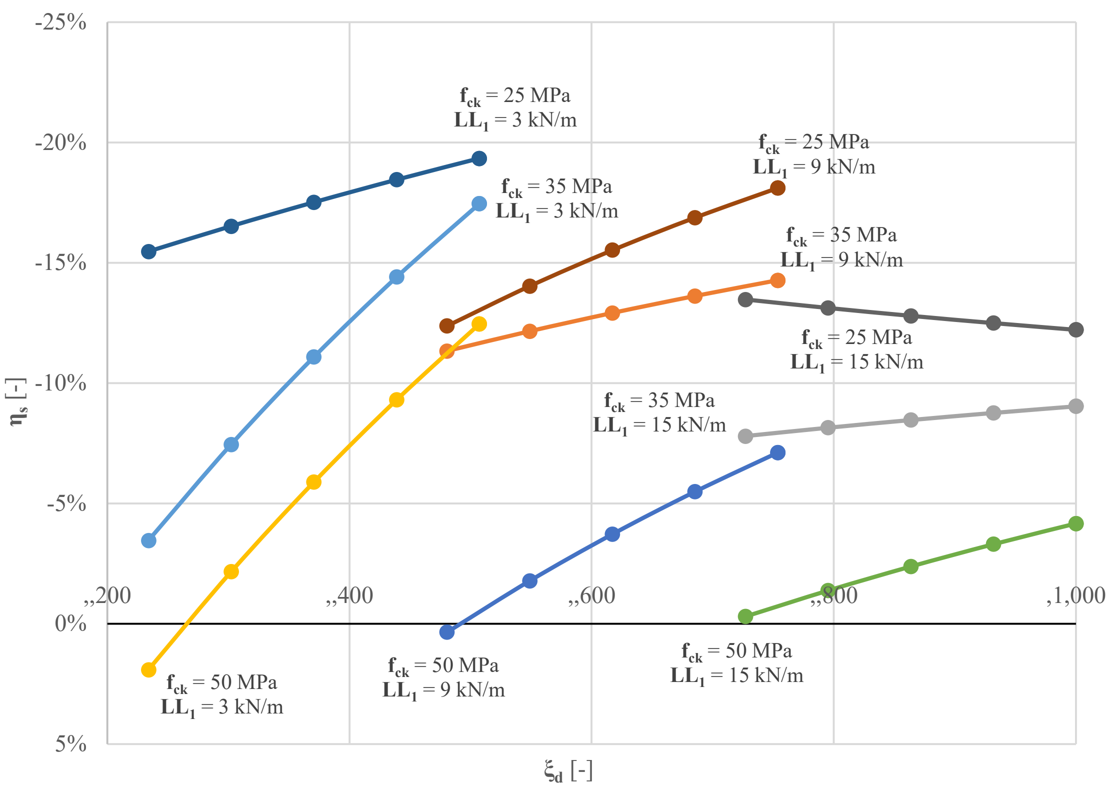


Figure 6. $\boldsymbol{\eta_s}$ – $\boldsymbol{\xi_d}$ relationships for **L** = 12.0 m and **h** = 1.0 m.

4. Discussion

Our results highlight the effects that construction codes can have on the environmental performance of construction assets. Therefore, these potential impacts should be considered during the creation and revision of existing construction codes and legislation, which would in turn support the transition towards a more sustainable industry. Currently, the EU strategy for the sustainable competitiveness of the construction sector [42] includes resource efficiency among its main focus areas. This implies increased environmental standards in the provision of construction services through circular economy strategies and life cycle thinking. However, improving the management of construction and demolition waste or the content of recycled materials in building projects does not entirely solve sustainability problems. Construction codes should also point to the best construction designs in order to fulfil the same function at the lowest environmental and economic costs. We exemplified this problem with the case of RC beams through an integrated approach that ensures the safety of each design while accounting for the environmental impacts of each solution.

So far, some studies have coupled LCA and structural analysis to study RC structures based on the EHE-08 standard [43,44]. Pujadas-Gispert et al. [40] did compare the LCA results of shallow foundations depending on design parameters defined in EHE-08 and EUROCODE [45]. Similar to our results, the authors found that each design code performs environmentally better than its counterpart depending on the structural application. For this reason, comparing our findings with existing literature is not straightforward.

Our results show that the environmental impacts are closely related to the amount of material used for the manufacture of the beam. In this sense, the case studies analyzed revealed that the steel consumption becomes more similar in the two instructions when the concrete compressive strength is higher. This is because the framework needed to meet ULS bending and SLS is lower, as concrete can resist higher stresses by itself.

Those cases in which the beam height is enough to withstand the design loads with the minimum amount of longitudinal reinforcement (to guarantee a ductile behavior in case of cracking in ULS), the Model Code has a lower steel requirement and, thus, leads to the most environmental-friendly design. Contrarily, for those cases in which the beam is slimmer and high loads are applied, it seems that the EHE-08 is more appropriate. Hence, structural engineers seeking to address environmental concerns are encouraged to consider the varying environmental impacts resulting from design codes based on the expected applications of RC beams.

5. Conclusions

Reducing the amount of reinforcing steel is of paramount importance for minimizing the life cycle environmental impacts of RC structures. In this regard, every country has its own design guidelines for RC structures and, thus, the reinforcing steel consumption could be different for the same structure (subjected to the same load combinations and resulting equivalent structural reliability). Most of the European national guidelines are based on the *fib* Model Code 2010 (MC-2010), which is an international reference guideline. However, every country includes particular requirements based on local models or environmental conditions that could lead to varying degrees of material consumption to guarantee the same reliability level during construction and service phases. In turn, design codes might result in increased environmental impacts. In light of this issue, a coupled structural – LCA analysis has been performed for RC beams with a variety of length, height/length and loading ranges considering the Spanish EHE-08 and the *fib* MC-2010 as structural concrete design guidelines.

According to the beam length (**L**) and height (**h**) and characteristic compressive strength ($\mathbf{f_{ck}}$), the following conclusions can be drawn:

- For **L** = 4.0 m, the greater the **h**, the greater the difference in reinforcement between the two guidelines. For **h** = 0.6 m and $\mathbf{f_{ck}} \leq 35$ MPa, steel amount savings up to 5.0 % can be reached with the MC-2010, GHG emissions also in the same proportion thereof. Nevertheless, if 35 MPa < $\mathbf{f_{ck}}$ ≤ 50 MPa the steel consumption increases from 10.2 % – 41.7 % with respect to EHE – 08. Finally, for **h** = 1.0 m steel consumption is 20.2 % - 33.4 % higher if EHE – 08 is considered in the design.

- For **L** = 8.0 m, the differences in reinforcing steel consumption for both guidelines strongly depend on the parameters considered, resulting in unclear tendencies. For **h** = 0.6 m, reinforcing steel reductions ranging from 2.3 % to 31.4 % can be derived from the use of the EHE – 08; nonetheless, if $\mathbf{f_{ck}}$ = 25 MPa, the differences are barely noticeable. For **h** = 1.0 m and $\mathbf{f_{ck}}$ ≤ 35 MPa, the reinforcement consumption can be 47.3 % higher or 14.9 % lower for the EHE-08 with respect to the MC-2010 depending on the load ratio; in contrast, for 35 MPa < $\mathbf{f_{ck}}$ ≤ 50 MPa, from 10.0 % to 21.0 % steel reductions can be obtained applying MC-2010.
- Finally, for **L** = 12.0 m, the steel consumption is between 0.3 % and 19 % lower when the beam is designed according to EHE-08. This difference decreases as $\mathbf{f_{ck}}$ increases.

Regardless of the magnitude of each range, these tendencies could also be extrapolated to other cross-section geometries (e.g., T and double T) and to other environmental exposures (e.g., marine environments). Similar studies, however, should be made for prestressed or posttensioned reinforced concrete beams since the mechanical behavior and structural requirements are different from those considered herein.

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Appendix A1 ecoinvent processes adapted and used in the LCA of RC beams

Process	**Units**
Concrete, 25MPa {RoW}| concrete production 25MPa, RNA only	m^3
Concrete, 35MPa {RoW}| concrete production 35MPa, RNA only	m^3
Concrete, 50MPa {RoW}| concrete production 50MPa, RNA only	m^3
Reinforcing steel {RER}| production (adapted with 59% of secondary scrap content)	kg steel
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6	tkm
Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO6	tkm
Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill	kg waste

Appendix A2 Maximum contribution of each life cycle stage to the environmental impacts of beam designs with lengths (L) of 4.0, 8.0 and 12.0 m.

		L = 4.0 m				**L = 8.0 m**				**L = 12.0 m**			
		Concrete	Steel	Transport	End-of-life transport and treatment	Concrete	Steel	Transport	End-of-life transport and treatment	Concrete	Steel	Transport	End-of-life transport and treatment
Climate change	kg CO_2 eq	79 %	30 %	4 %	6 %	78 %	57 %	4 %	6 %	92 %	32 %	5 %	7 %
Ozone depletion	kg CFC-11 eq	57 %	26 %	10 %	25 %	57 %	52 %	10 %	24 %	68 %	27 %	12 %	29 %
Terrestrial acidification	kg SO_2 eq	67 %	40 %	3 %	12 %	65 %	67 %	3 %	11 %	86 %	41 %	4 %	15 %
Freshwater eutrophication	kg P eq	51 %	68 %	2 %	3 %	49 %	87 %	1 %	3 %	94 %	69 %	3 %	6 %
Marine eutrophication	kg N eq	73 %	38 %	3 %	7 %	72 %	66 %	2 %	7 %	92 %	40 %	3 %	9 %
Human toxicity	kg 1,4-DB eq	39 %	73 %	5 %	3 %	37 %	90 %	5 %	3 %	86 %	75 %	12 %	7 %
Photochemical oxidant formation	kg NMVOC	65 %	37 %	3 %	15 %	64 %	64 %	3 %	15 %	83 %	38 %	4 %	19 %
Particulate matter formation	kg PM10 eq	55 %	53 %	4 %	10 %	54 %	78 %	4 %	10 %	84 %	55 %	6 %	16 %
Terrestrial ecotoxicity	kg 1,4-DB eq	58 %	44 %	28 %	8 %	58 %	71 %	27 %	7 %	74 %	46 %	38 %	11 %
Freshwater ecotoxicity	kg 1,4-DB eq	37 %	75 %	3 %	4 %	36 %	90 %	3 %	4 %	87 %	76 %	8 %	9 %
Marine ecotoxicity	kg 1,4-DB eq	37 %	74 %	5 %	4 %	35 %	90 %	5 %	4 %	83 %	75 %	13 %	9 %
Ionizing radiation	kBq U^{235} eq	68 %	36 %	5 %	12 %	67 %	63 %	5 %	11 %	85 %	37 %	6 %	15 %
Agricultural land occupation	m^2a	58 %	37 %	3 %	27 %	58 %	65 %	3 %	26 %	74 %	39 %	3 %	35 %
Urban land occupation	m^2a	42 %	19 %	10 %	40 %	42 %	41 %	10 %	40 %	48 %	19 %	11 %	44 %
Natural land transformation	m^2	-69 %	-13 %	-9 %	352 %	-70 %	-15 %	-9 %	1017 %	-62 %	0 %	-8 %	382 %
Water depletion	m^3	71 %	35 %	0 %	13 %	70 %	58 %	0 %	12 %	87 %	36 %	0 %	17 %
Metal depletion	kg Fe eq	12 %	93 %	1 %	2 %	11 %	98 %	1 %	1 %	84 %	93 %	7 %	12 %
Fossil depletion	kg oil eq	60 %	35 %	8 %	19 %	59 %	63 %	7 %	18 %	76 %	37 %	10 %	24 %
Cumulative energy demand	MJ	61 %	37 %	7 %	17 %	60 %	64 %	7 %	17 %	77 %	38 %	9 %	22 %