Environmental Analysis of Buildings Concrete Deep Foundations: The Influence of Prefabrication, Concrete Strength and Design Codes

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Abstract

The building sector has been recognized as the sector with the most potential for delivering significant and cost-effective greenhouse gas emissions reductions. Concrete deep foundations (CDFs) are present in many buildings and constructions. The goal of this study is to assess the construction of CDFs from an environmental (and economic) point of view in order to improve them. To do this, first geotechnical and structural designs of CDFs were carried out, and then a Life Cycle Assessment was conducted. Results have shown that concrete and steel have a significant impact (75-95%) in all environmental categories. Some of the main factors that have shown to enhance their performance are: prefabricating part or the entire CDF; designing CDFs with bored piles with Eurocode (with United Kingdom annexes), while CDFs with driven piles, with current Spanish codes; increasing the concrete compressive strength in bored piles; and performing dynamic load tests on driven piles that verify pile resistance calculations. Study variables have shown a significant effect on the results, it is therefore important to take them into account in future constructions, research and codes. Nevertheless, results may vary based on specific characteristics of each work (e.g. soil, loads, tradition, etc.).

Keywords: LCA, EHE-08, cap, pile, Eurocode, CTE.

1. Introduction

1.1. Background

The building sector has a relevant impact on the consumption of energy and resources and the generation of pollution on the planet (UNEP, 2009a). This sector is considered to have the most potential to reduce greenhouse gas (GHG) emissions (UNEP, 2009a). It is widely reported that the renovation and occupation of buildings contribute by as much as one-third of the global GHG emissions and by more than 40% of the world's energy use (UNEP, 2009b).

It is expected that 80-90% of the building´s energy is consumed during its operational phase (e.g. cooling, ventilation, lighting, heating, appliances, etc.), whilst the remaining 10-20% is consumed during the extraction and processing of raw materials, manufacturing of products, construction and demolition. Nevertheless, according to several studies, the embodied phase can represent as much as 50% of total life cycle impact in very low energy buildings (de Klijn-Chevalerias and Javed, 2017; Dixit et al., 2012; Ghattas et al., 2013). This can be explained by the fact that buildings are beginning to adhere to higher energy efficiency standards, and as a result, the energy consumption during the operational phase is significantly reduced. However, this is also because their building envelopes and technical installations require more materials, some of which are very energy intensive (Sartori and Hestnes, 2007).

Materials are responsible for most of the embodied emissions at the construction stage (Sandanayake et al., 2017). Materials of a building foundation, which is the part of the building responsible for the transfer of loads to the ground, can be responsible for the most negative environmental impacts compared to other building materials (Estokova et al., 2017). Concrete is a common material for foundations because it is convenient to use it in wet conditions, and its raw constituent materials are accessible and cheap (Yin et al., 2015). Therefore, the optimization of the environmental burdens of foundation materials can contribute to overall environmental building performance.

1.2. Concrete deep foundations

The selection of a foundation will basically be determined from the consideration of the bearing capacity of the ground, the building loads and the admissible settlements of the structure. A properly carried out geotechnical study will be essential in order to design and build a suitable foundation as well as to avoid the possible long-term problems that can importantly affect all the structure. Shallow foundations transfer loads into the ground typically near the surface (Fig. 1a). However, when the upper ground layers are weak (or the building's loads are high) and, particularly, in those cases in which the water table is high, a deep foundation (Fig. 1b) can be required in order to transfer the load into a deeper and resistant soil layer (Tomlinson and Woodward, 2014).

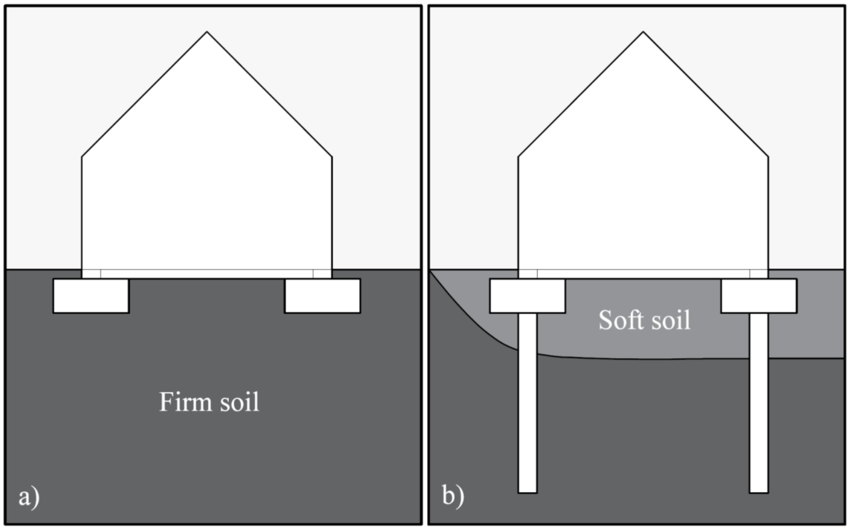

Fig. 1. Simplified layouts of shallow (a) and deep (b) foundations.

Piles are the most common element to transmit loads to the resistant soil when deep foundations are the alternative. They can be driven or bored into the ground. Concrete driven piles are prefabricated (precast) in a factory (typically subjected to high-quality standards) and posteriorly installed on site. Conversely, bored piles are built directly into the ground. This impedes the possibility of visual pile inspections and, in consequence, of identifying problems that might arise during construction and that can end up with economic (Brown, 2005) and environmental costs.

Piles normally work in group by means of a pile cap (Fig. 2), a slab or a beam which distributes the load of the building into them, and in their turn, to the ground. Slender or thick caps can be used for this purpose. Thick caps are the most preferred option because they are cheaper as they contain less steel reinforcement. Pile caps are normally built on site (cast in situ), even if piles are precast. This is explained by the difficulty to fit the prefabricated cap into the piles that, in general, are expected to deviate from its exact position (EN 1992-1-1, 2004). Semi-precast pile caps, which are those built partly in a factory and finished on site, have proved not only to be able to resist more load, but also to be faster to install on site (Chan and Poh, 2000). Productivity therefore increases and possible failures of pit sides are prevented.

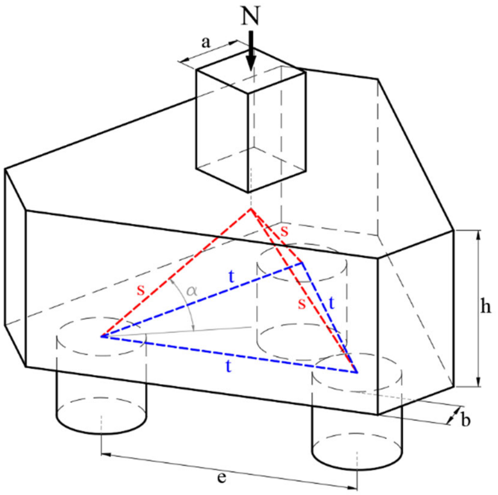

Fig. 2. Geometry and parameter definitions for concrete thick three-pile caps: strut (s), tie (t), distance from the external face of the pile to the edge of the cap (b), axial building load (N), distance between piles (e), pile cap depth (h) and angle at which pile caps spread the axial force from the superstructure through the piles (α) and pillar side (a).

The design of a CDF involves both a geotechnical and a structural designs. There are many codes and standards that regulate both, but it will be of compliance the ones each nation will establish as most appropriate. In Europe, the Eurocode that regulates the geotechnical design is Eurocode 7 (EN 1997-1, 2004), while Eurocode 2 (EN 1992-1-1, 2004) governs the concrete structural design. Moreover, National annexes of Eurocode are also mandatory, which adapt the Eurocode to each country. Nonetheless, in Spain, the Eurocode and annexes are not yet compulsory, and instead, there are the Technical Building Code (CTE-SE-C, 2008) and EHE-08 Structural Concrete Code (EHE-08, 2008).

Regarding the geotechnical design, piles can be designed using diverse methodologies. In Spain and the UK, among other countries, piles are calculated based on ground parameters (EN 1997-1, 2004), and load tests are sometimes used to verify these pile resistances. This is partly explained owing to cultural reasons, ground conditions and economic costs. Dynamic load tests (DLTs) are frequently carried out on driven piles to assume a better pile resistance on calculations (Raison and Egan, 2016), and therefore, to get shorter or thinner piles. Additionally, DLTs do not damage driven piles. However, there is not a code that governs the number of DLTs to perform. In Spain, it is typically around 2% of driven piles, but not less than 5 tests per foundation (Colegio de Ingenieros de Caminos, 2004); while in the UK, it is between 2% and 10% (Raison and Egan, 2016).

1.3. Environmental assessment of concrete deep foundations

Literature has shown that in the construction of CDFs, materials contribute the most to environmental burdens (Zhang and Wang, 2016), followed by equipment and transportation: 77.13%, 13.53% and 9.34% (Sandanayake et al., 2016b), and 66%, 18% and 16% respectively (Sandanayake et al., 2016a).

There are several strategies that have demonstrated to reduce the environmental impacts of foundation materials. These include prefabrication of part or the entire foundation (Wren, 2012), optimization of the amounts of materials (Rose Inman, M., Houlihan Wiberg, 2015) and the use of materials more environmentally friendly (Ondova and Estokova, 2016).

In addition, a prior study analysing the environmental impacts of concrete shallow foundations identified the type of foundation, level of prefabrication, and design building codes, as potential variables to reduce the environmental impacts of this type of foundation (Pujadas-Gispert et al., 2018). It was found that the proper selection of the design variables can lead to a reduction in impacts of around 40-60%.

However, there is scarce literature focused on improving concrete deep foundations from an environmental point of view. This study assesses several variables that have been proved to reduce the environmental impacts in other types of foundations; thereby seeking to obtain data which will help to address this research gap.

1.4. Objectives

The main goal of this research is to analyse CDFs from an environmental (and economic) point of view, considering the variables of level of prefabrication (cast in situ or precast), concrete compressive strength (25, 30, 35 MPa) and building design code used (EHE-08 and CTE, Eurocode with Spanish annexes and Eurocode with the United Kingdom annexes). In addition, a sensitivity analysis evaluates the effect of DLTs on the results of CDFs with driven piles.

The specific objectives are: (1) to conduct a structural analysis of equivalent structural alternatives in order to determine the amounts needed of concrete and reinforcement; (2) to calculate, analyse, and compare the environmental impacts using life cycle assessment and the economic costs of the alternatives; and (3) to assess the influence of study variables and the sensitivity analysis on the environmental burdens (and economic costs) of CDFs; and by doing so, define specific design conclusions and recommendations.

2. Materials and methods

The following section explains the selection of alternatives (2.1), the case study (2.2), the functional unit (2.3), system boundaries (2.4), data sources (environmental and economic) (2.5), and the methods and requirements to conduct the geotechnical design (2.6), structural design (2.7) and life-cycle assessment (2.8).

2.1. Selection of alternatives

Building's loads tend to be more moderate compared to other constructions loads (e.g. bridges, etc.). Therefore, building's pile caps tend to present a few piles. This study considers a three-pile cap because it is the configuration that provides more 3D stability with fewer piles. In addition, two common pile types were selected: driven piles and bored piles. The method contemplated to install bored piles was the continuous flight auger (CFA), which is a common cost-effective method in relatively uniform soil conditions (Brown, 2005). The study variables and their abbreviations are shown in Table 1.

Table 1. Abbreviations used for study concrete deep foundations.

	Variables	**Abbreviations**
1	Pile type	Bored pile (**B**), driven pile (**D**)
2	Pile concrete compressive strength	(**25**), (**30**), (**35**) MPa (Cast in situ); (**40**) MPa (Precast)
3	Pile cap construction system	Cast in situ (**I**) (concrete is poured on site), precast (**P**) (concrete is poured in a specialized facility)
4	Pile cap concrete compressive strength	(**25**), (**30**), (**35**) MPa (Cast in situ); (**40**) MPa (Precast)
5	Building design code	EHE-08 and CTE (**ES**), Eurocode with Spanish annexes (**SP**), Eurocode with United Kingdom annexes (**UK**)
6	Performance of DLTs	yes (*), no ( )

Example: **D40/I25/SP*** – Concrete deep foundation composed of 3 **D**riven piles (with concrete of compressive strength of **40** MPa) and a cast-**In**-situ concrete cap (with concrete of **25** MPa), designed with Eurocode with **SP**anish national annexes and performing DLTs.

2.2. Case study

The case study is a concrete modular housing building located in Barcelona area (Spain). The vertical load to the CDF is 2,300 kN (N in Fig. 2), and the bending moments are 6 kNm and 15 kNm around the axis X and Y, respectively (all these values are unfactored).

The dimensions of the square-shaped pillar that transmits the loads to the CDF are 0.45 x 0.45 m (*a* in Fig. 2).

The soil (Table 2) is composed of an upper stratum of 15 meters of soft clay placed over a stratum of compacted sand. Since this research is aimed at obtaining general results regarding the environmental and economic impacts of CDFs, certain elements which are very dependent on each case study such as the presence of water, seismicity, negative skin friction or chemical action are left out of the scope of the study.

Table 2. Parameters and characteristics of the study case soil.

Ground stratum	Parameter	Abbreviation	Value	Unit
Soft clay	Undrained shear strength	c_u	15	kN/m^2
	Weight density	γ_n	17	kN/m^3
Compacted sand	Angle of shearing resistance	ϕ'	39	º
	Weight density	γ_n	18	kN/m^3

2.3. Functional unit (FU)

The FU considered in this analysis is a CDF consisting of a reinforced concrete (RC) pile cap and three RC piles taking into account different levels of prefabrication, concrete compressive strengths and building design codes and performing DLTs on driven piles. All alternatives were designed for a service life of 50 years.

2.4. System boundaries

In Fig. 3, the LCA phases and the elements considered in each stage are shown. Life cycle phases in this case run from the extraction of materials until completion of on-site construction (cradle to gate approach). Moreover, each phase includes the impact of transportation. Nonetheless, vibration and the pumping of concrete were not considered, as a preliminary analysis showed no significant environmental impacts. The use phase was excluded because well-designed foundations do not require maintenance or repairs. Similarly, the decommissioning was excluded because foundations are usually left installed after their end of life, not implying relevant impacts.

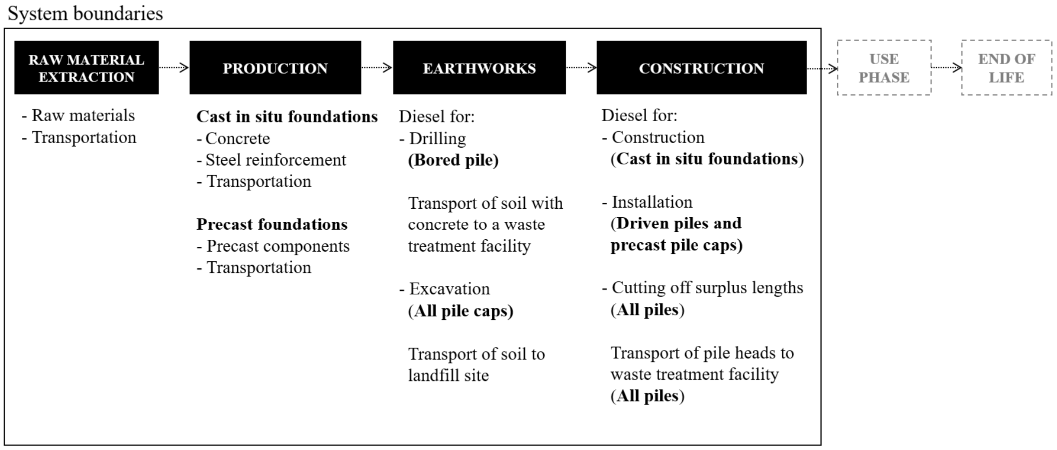

Fig. 3. Life cycle diagram and system boundaries of the construction of a CDF.

2.5. *Data sources*

Several data sources were consulted to calculate the environmental burdens of CDFs. The amounts of resources were retrieved from the *Construction Technology Institute of Catalonia* (ITeC, 2019). Nonetheless, certain items were not found there and were therefore consulted to manufacturers. Keller Cimentaciones ("Keller Cimentaciones," 2017) provided diesel consumption to build piles and perform DLTs, and average distances to transport piling machines. In addition, concrete dosages were provided by the *Spanish National Association of Ready-Mixed Concrete Manufacturers* (ANEFHOP, 2019). LCA processes were retrieved from Ecoinvent v.3.0.3.0 database (Swiss centre for life cycle inventories, 2013). Study distances and their source are summarized in Table 4. For further information of this section please see Supplementary Material 1.

Table 4. Transport distances used to calculate the system.

Item	Transportation		Distances (km)	Retrieved from
	From	To		
Cement	Place of production	Concrete plant Precast concrete plant	75	(Pujadas-Gispert et al., 2018; Sanjuan-Delmás et al., 2015)
Aggregates	Place of production	Concrete plant Precast concrete plant	40	
Steel reinforcement	Place of production	Construction site Precast concrete plant	130	
Concrete	Place of production	Construction site	30	
Soil	Construction site	Landfill sites	30	
Waste	Construction site	Waste management facility	30	
Additives	Place of production	Concrete plant Precast concrete plant	100	(Mendoza et al., 2012)
Piling machine	Previous construction site	Construction site	500	Facilitated by companies
Precast units	Precast concrete plant	Construction site	150	(The Concrete Centre, 2009)

The economic comparison takes only into account the CDFs designed with ES and SP. Both are calculated with the same economic items. Most of them were retrieved from (ITeC, 2018), although some specific prices that were not found there were provided by manufacturers (transport of piling and driving machines, and DLTs). Economic costs of CDFs designed with UK were calculated but not included in this paper. This is because it has seen that it is difficult to establish an economic comparison between CDFs when the costs of items are retrieved from different databases, as each database makes its assumptions.

2.6. Geotechnical design

For the calculation of the geotechnical design of study alternatives, several best UK and Spanish practices were followed. First, the distance between piles (e in Fig. 2) was considered three pile's diameter, which guarantees the optimal transfer of building's loads to the ground, and hence there is no group effect (CTE-DB-SE-C, 2008). Second, all piles were embedded a minimum of six diameters into the firm soil (CTE-DB-SE-C, 2008). In addition, geotechnical values for base and shaft pile resistances were set at 20.000 kN/m^2 and 120 kN/m^2 respectively (CTE-DB-SE-C, 2008). Besides, pile resistances were calculated factoring strengths and actions when they were designed with ES and SP, while a global safety factor was used instead (Gepp et al., 2014) with CTE (BS EN 1997-1:2004+A1:2013, 2004; EN 1997-1, 2004; UNE-EN 1997-1, 2016) guaranteeing structural reliability.

2.7. Structural design

CDFs are made of concrete and steel. Compression strengths selected for cast-in-situ concrete were 25, 30 and 35 MPa; and 40 MPa for precast concrete. These strengths are representative on an international scale, although some of them are more common than others depending on geographical localization. Steel for reinforcement was B-500-S. And partial factors for concrete (1.5) and steel reinforcement (1.15) were selected according to (EHE-08, 2011; EN 1992-1-1, 2004). Moreover, the surrounding environment was classified as XC2 by EC-2 and IIa by EHE-08, which conditions the width of concrete covers and hence the durability of concrete structures.

Codes used to calculate the amounts of concrete and steel reinforcement in CDFs are shown in Table 3. In addition, the structural approach used to calculate pile caps was the strut-and-tie approach (ACHE, 2003; Goodchild et al., 2014) proposed by (Ritter, 1899) with the tension elements provided by reinforcement (*t* in Fig. 2) and the concrete acting as struts (*s* in Fig. 2). This approach is declared to be usually used (Miguel-Tortola et al., 2018) and suitable (EHE-08, 2011; Miguel et al., 2007; Souza et al., 2009) for designing thick pile caps, while the Eurocode (EC-2, 2004) states that flexural-based methods are also applicable.

Table 3. Building actions, geotechnical and structural design codes.

Design	ES	SP	UK
Actions	(CTE-DB-SE-AE, 2009)	(UNE-EN 1991-1-1:2003/AC:2010, 2010)	(BS EN 1990:2002+A1:2005, 2002) (NA to BS EN 1990:2002+A1:2005, 2004)
Geotechnical	(CTE-DB-SE-C, 2008)	(UNE-EN 1997-1, 2016)	(BS EN 1997-1:2004+A1:2013, 2004) (NA+A1:2014 to BS EN 1997-1:2004+A1:2013, 2007)
Structural	(EHE-08, 2011)	(UNE-EN 1992-1-1:2013/A1, 2015)	(BS EN 1992-1-1:2004+A1:2014, 2004) (NA+A2:2014 BS EN 1992-1-1:2004+A1:2014 UK, 2005)

*Terminology: EHE-08 and CTE (**ES**); Eurocode with Spanish annexes (**SP**); Eurocode with United Kingdom annexes (**UK**).*

Bored piles tend to be reinforced only superior meters when there are no lateral forces or seismicity. This length has been considered herein six meters according to (NTE, 1977; Raison and Egan, 2016). Conversely, driven piles are reinforced the entire length, and have an extra (stirrups) reinforcement in the head and toe, considered 500 mm and 200 mm respectively, according to (BS EN 12794:2005, 2005; UNE-EN 12794:2006+A1:2008, 2008). These are explained because driven piles have to resist extra stresses during handling and driving. Moreover, all piles, bored or driven, were reinforced according to the minimum steel amounts requirements that each code dictates.

2.8. Life-cycle assessment

LCA methodology was used to calculate the environmental impacts. This method is well established in scientific literature and has been standardised through global standards (ISO 14040:2006, 2006; ISO 14044:2006, 2006). The software SimaPro 8.4.0.0 (PRé Consultants, 2017) was used for the implementation of the LCA, along with the calculation method ReCiPe 2016 Midpoint, Hierarchist version (Huijbregts et al., 2016).

The impact categories considered were selected according to the product declaration of construction products (EN 15804:2012+A1:2013, 2013) and authors' expertise: Global warming potential (GWP, kg CO_{2eq}), Ozone depletion potential (ODP, kg CFC-11_{eq}), Terrestrial acidification potential (TAP, kg SO_{2eq}), Freshwater eutrophication potential (FEP, kg P_{eq}), Photochemical oxidant formation potential (POFP, kg NMVOC), Mineral depletion potential (MDP, kg Fe_{eq}), Fossil depletion potential (FDP, kg oil_{eq}) and Cumulative energy demand (CED, MJ).

3. **Results and discussion**

This section comprises: preliminary remarks (3.1); Environmental performance of CDFs according to study variables (3.2): Prefabrication (3.2.1), Codes (3.2.3)**,** Concrete compressive strength (3.2.3); Sensitivity analysis (3.3); Environmental and economic discussion of several significant study CDFs (3.4).

3.1. Preliminary remarks

An important element to consider when addressing the environmental and economic impacts of CDFs is the angle (*α* in Fig. 2) at which the pile cap spread the axial force (*N* in Fig. 2), from the superstructure through the piles, which determines the depth (*h* in Fig. 2) of the pile cap. This angle is typically 45º (Jones, 2013), but might range from 21.8º to 45º with UK, and from 26.6º to 63.4º with ES and SP. A preliminary analysis was carried out considering this angle (α in Fig. 2) 40º, 45º, 50º and the smallest angle that the concrete strut could resist, always taking these angle constrains into account. CDFs with the shallowest angles (i.e. smaller cap depths) resulted better environmentally in most impact categories because they accounted for smaller concrete volumes. Nevertheless, at the same time, these alternatives showed higher impacts in those categories highly dependent on steel (FEP and MDP) because they had more steel; the reduction of the depth of the CDF was compensated with more steel reinforcement.

Similarly, (bored and driven) piles were calculated with the smallest cross-sections as possible in order to save concrete on piles and cap. Driven piles resulted in smaller cross-sections than bored piles as concrete for driven piles was more resistant. Nevertheless, driven piles smaller than 235 mm of side were not considered in order to prevent the pile from breaking in this type of soil.

3.2. Environmental performance of CDFs according to study variables

3.2.1. Prefabrication

The main characteristics of piles and caps considered for the CDFs alternatives are shown in Supplementary Material 2.

Prefabrication can make vary the content of concrete and steel in CDFs. These materials have shown an important role in the environmental burdens of CDFs. They accounted for most of the burdens (75-95%) in all impact categories.

Fig. 4 compares the GWP emissions of the construction of CDFs with bored piles with CDFs with driven piles (which are precast). They have a cast-in-situ cap and were calculated with SP. Concrete and steel accounted for 85-90% of the GWP emissions in CDFs with bored piles, while 78-85% in CDFs with driven piles. In these latter cases, concrete got lower impact percentages (up to 25% less) compared to CDFs with bored piles because they required less concrete (Fig. 4). Conversely, they got higher percentages in steel (up to 25% more) because they are all length reinforced in contrast to bored piles that have only superior meters (according to study load combination). In addition, precast products require transport to site and installation (piling, pile cutting, excavation and precast installation), which accounted for 8% of GWP emissions both.

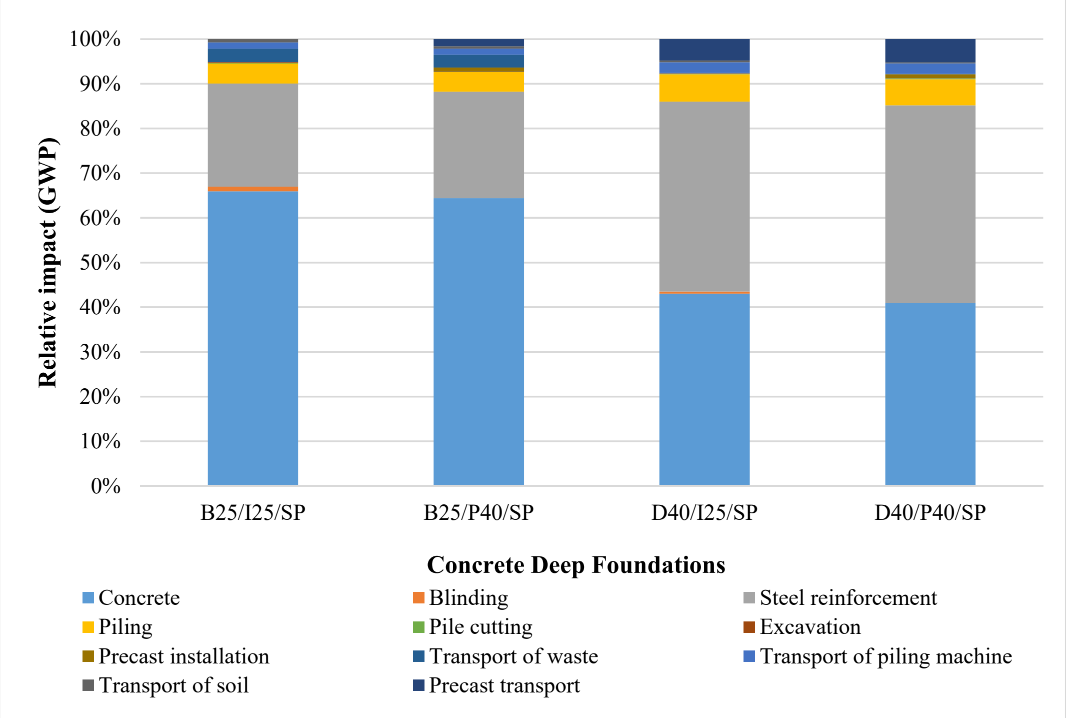

Fig. 4. Relative GWP emissions of the construction of CDFs designed with SP. *Terminology: bored pile (**B**); driven pile (**D**); concrete compressive strengths: (**25**), (**40**) MPa; cast in situ (**I**); precast (**P**); Eurocode with Spanish annexes (**SP**); global warming potential (**GWP**).*

Results show that piles are more important in the environmental performance of a CDF than the pile cap because piles contain more concrete. Driven piles can spare significantly these materials compared to bored piles because they are more resistant for the same section as higher concrete strengths are used. In addition, codes assume that driven piles can withstand more load compared to bored piles since they are produced in a factory under high-quality control protocols and uncertainties are reduced.

The use of smaller cross-section of piles also lead to smaller caps because the size of the piles conditions the width of the cap. It must be emphasized, however, that the smaller the pile cross-section is, the greater the depths of the cap would be; or concrete with a higher compressive strength will be required for struts (s in Fig. 2) to resist compression.

Nevertheless, it should be bear in mind that prefabricated concrete has more environmental burdens for the same volume of concrete. In this study, prefabricated concrete (40 MPa) accounted for 23-29% more GWP emissions compared to cast-in-situ concrete (25 MPa). This is because prefabricated concrete tends to have higher strengths which require larger amounts of cement. Cement is the component with higher environmental impacts in the mixture although it is in a small proportion. Cement accounted for 75-80% GWP emissions of concrete herein. Furthermore, precast products must be transported and assembled on site, which imply extra burdens.

Fig. 5 compares the environmental impacts of CDFs with bored piles with CDFs with driven piles designed with SP. For the sake of simplicity, the environmental categories of ODP (~GWP) and TAP, POFP, FDP (~CED) are not shown. CDFs were designed applying the minimum amounts of concrete and reinforcement that each code dictates. CDFs with driven piles accounted for smaller values in most categories (up to 15%), although they got higher results in FEP and MDP categories (19-33%), because they had more steel. In addition, those CDFs with a precast cap accounted for up to 7% more environmental impacts compared to those with a cast-in-situ cap. This is because the extra strength of prefabricated concrete was not fully used in some cases as codes limit the minimum depth of the cap. Besides, the slight reduction of depth was compensated with more steel bar reinforcement, which is more pollutant than concrete for the same volume.

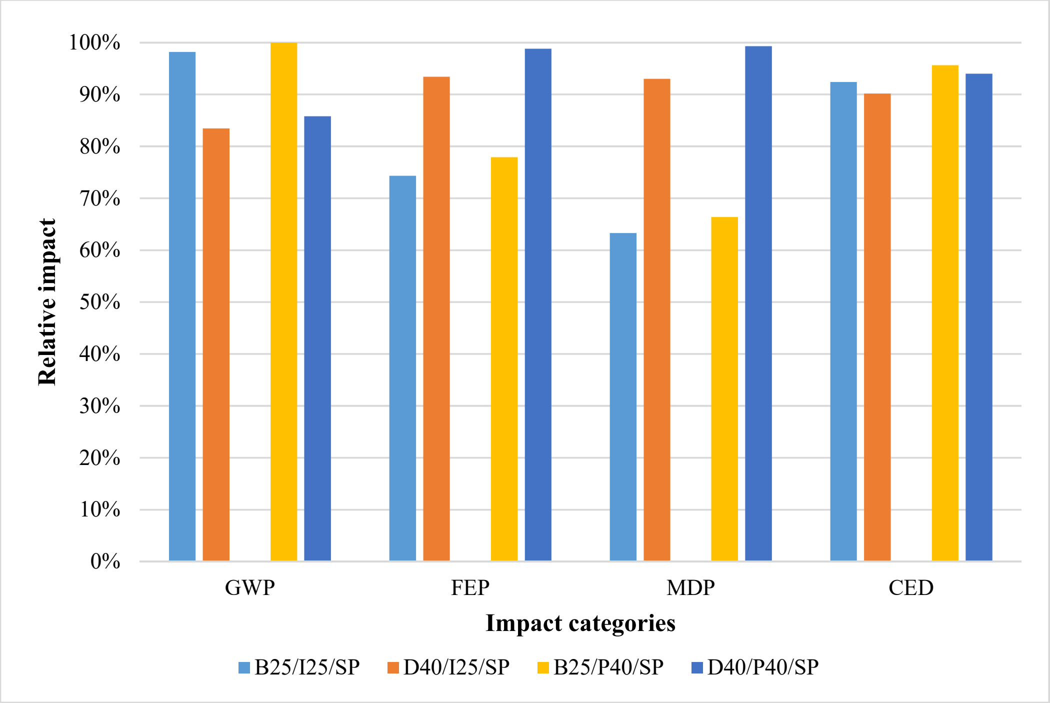

Fig. 5. Relative impact of CDFs with driven and bored piles, and a cast-in-situ cap designed with SP. *Terminology: bored pile (**B**); driven pile (**D**); concrete compressive strength: (**25**),(**40**) MPa; cast in situ (**I**); precast (**P**); Eurocode with Spanish annexes (**SP**); global warming potential (**GWP**); freshwater eutrophication potential (**FEP**); mineral depletion potential (**MDP**); cumulative energy demand (**CED**).*

However, CDFs tend to be oversized in reality. By instance, companies and designers try to standardize products and solutions in order to save money on the design. They normally prefer to invest this money in oversize constructions that enhances safety. Furthermore, constructions on site sometimes might be unpredictable in terms of amounts of resources and waste. For example, concrete leakage is provable when bored piles are built on highly permeable grounds (e.g. silt, very soft fillings, clay, etc.). Therefore, the environmental feasibility of prefabricating a CDF depends to a large extent on the quantities of materials used. It would also be interesting to take all unforeseen events during construction into account, although they are specific of each work and some of them might be difficult to quantify.

3.2.2. *Codes*

This section compares the environmental impacts of CDFs with bored and CDFs with driven piles using ES, SP and UK. CDFs were designed with minimum amounts of steel and concrete in order to stablish a fair comparison between these codes. In addition, the compressive concrete strength for cast-in-situ piles and caps was set up at 30 MPa. This is because there is no case of CDF with driven piles and a cast-in-situ cap with 25 MPa concrete strength in this study, since concrete struts could not resist compression loads.

CDFs with bored piles designed with UK resulted in 7-32% lesser impacts compared to those calculated with ES because less concrete was used. This is explained because ES and SP include an upper limit for concrete compressive strength of piles. This limit is particularly restrictive for bored piles because of the uncertainties linked to their construction process. In this sense, ES is even more restrictive than SP (CTE-DB-SE, 2009; Gepp et al., 2014; UNE-EN 1997-1, 2016). In addition, a smaller concrete pile cross-section normally implies less steel in the pile, as it is easier to comply with code minimum distances between reinforcing bars. In this regard, UK reinforces piles the most (for cast-in-situ and driven piles) for the same pile section; while ES, the least.

CDF’s with driven piles designed with SP and UK resulted in higher impacts compared to ES: FEP (15% SP; 30% SP), MPD (18% SP; and 38% UK), and other categories (6-18% SP, 10-18% ES). This is because ES reinforces fewer piles for the same cross-section.

When it comes to pile caps, ES allows a higher design value of concrete compressive strength of cap struts (*s* in Fig. 2), which permits to lower the pile depth (*h* in Fig. 2), with a subsequent increase in steel reinforcement. Conversely, ES states a larger distance from the external face of the pile to the edge of the cap (*b* in Fig. 2) compared to SP and UK, which increases the amounts of concrete and steel.

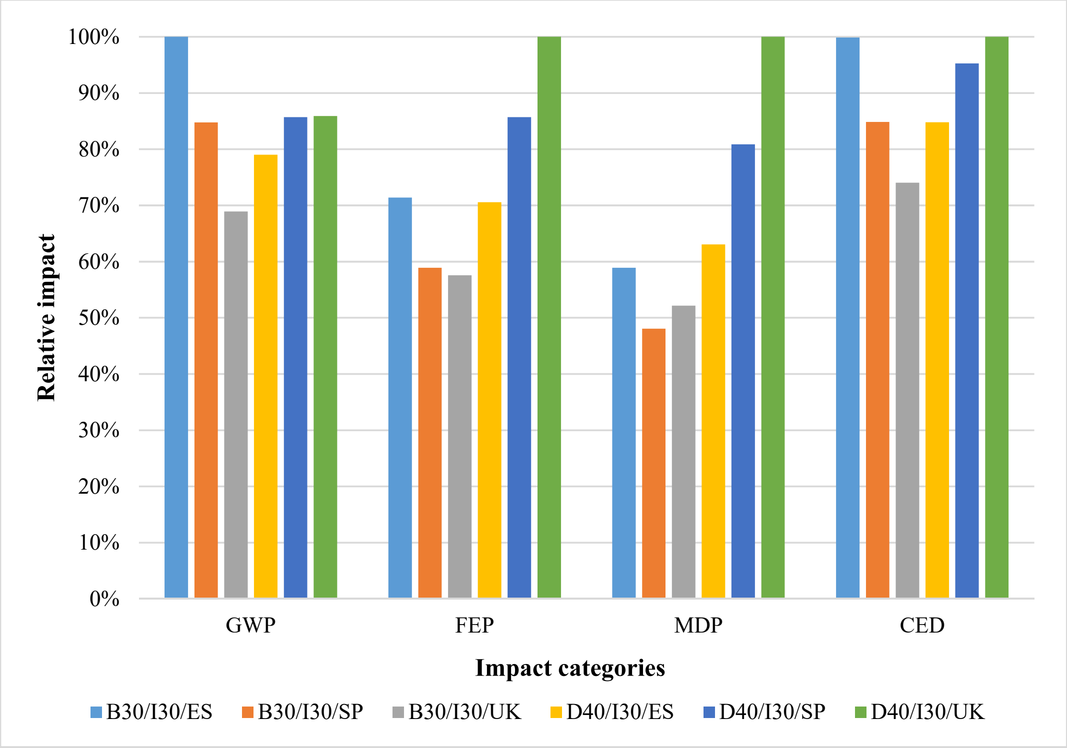

Fig. 6. Relative impact of CDFs designed with ES, SP and UK with concrete of 30 and 40 MPa compressive strength. *Terminology: bored pile (**B**); driven pile (**D**); concrete compressive strength (**30**),(**40**) MPa; cast in situ (**I**); EHE-08 and CTE (**ES**); Eurocode with Spanish annexes (**SP**); Eurocode with United Kingdom annexes (**UK**); global warming potential (**GWP**); freshwater eutrophication potential (**FEP**); mineral depletion potential (**MDP**); cumulative energy demand (**CED**).*

3.2.3. *Concrete compressive strength*

Fig. 7 presents the results obtained when concrete of different compressive strengths (25 MPa, 30 MPa and 35 MPa) were tested for building bored piles and cast-in-situ caps designed with SP. Results of ODP, TAP, POFP and FDP impacts categories are not shown as they have a similar trend to CED. Changing the compressive strength of concrete from 25 to 35 MPa in bored piles reduced the environmental impacts of CDFs from 18 to 25%. The amounts of concrete and steel were decreased considerably, which completely counteracted the higher environmental burdens associated to higher concrete strengths. As can be seen, this difference is more important between bored piles with concrete strengths of 25 MPa and 30 MPa, than 30 MPa and 35 MPa. Conversely, no significant difference in the environmental burdens (less than 7%) was found between CDFs with caps of different concrete strengths. There are several possible explanations for such a result. First, the cap has a low repercussion on the environmental burdens of the CDF as it accounts for a small part of it. In addition, structural design codes fix the minimum depth of the cap impeding in some cases its environmental optimization. Similar results were obtained for CDFs designed with SP and UK.

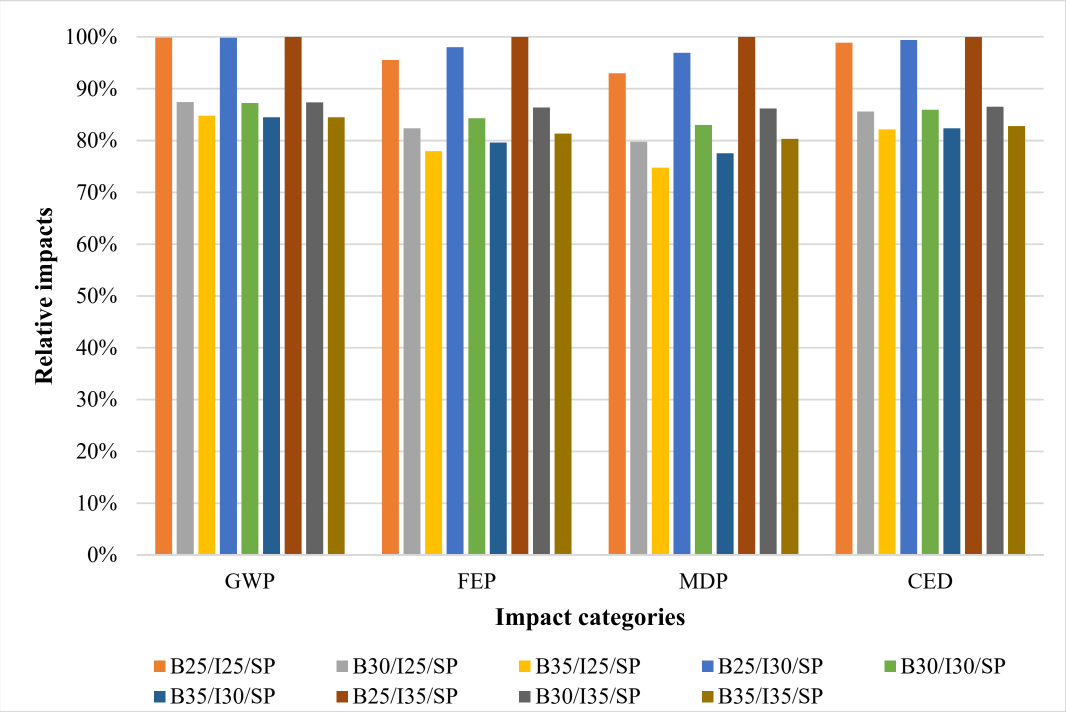

Fig. 7. Relative impact of CDFs with bored piles and different concrete compressive strengths designed with SP. *Terminology: bored pile (**B**); concrete compressive strength: (**25**), (**30**), and (**35**) MPa; cast in situ (**I**); Eurocode with Spanish annexes (**SP**); global warming potential (**GWP**); freshwater eutrophication potential (**FEP**); mineral depletion potential (**MDP**); cumulative energy demand (**CED**).*

3.3. Sensitivity analysis

It is relatively common to perform DLTs when the economic benefit of their performance is greater than its cost. In this study, it has been considered that DLTs validated the geotechnical calculations. Fig. 8 compares the environmental impacts of CDFs with driven piles and a cast-in-situ cap in relation to whether DLTs are performed. CDFs with precast caps are not shown because they got similar results. For the sake of simplicity, impact categories of ODP, TAP, POFP and FDP are not depicted because they had a similar trend to CED.

The performance of DLTs on driven piles reduced the environmental impacts of CDFs: 8-14% ES, 10-13% SP, and 4-5% UK. The optimization on the quantities of concrete and steel completely counteracted the environmental impact of performing DLTs. Eurocode with United Kingdom annexes (UK) is more conservative in this sense compared to ES and SP.

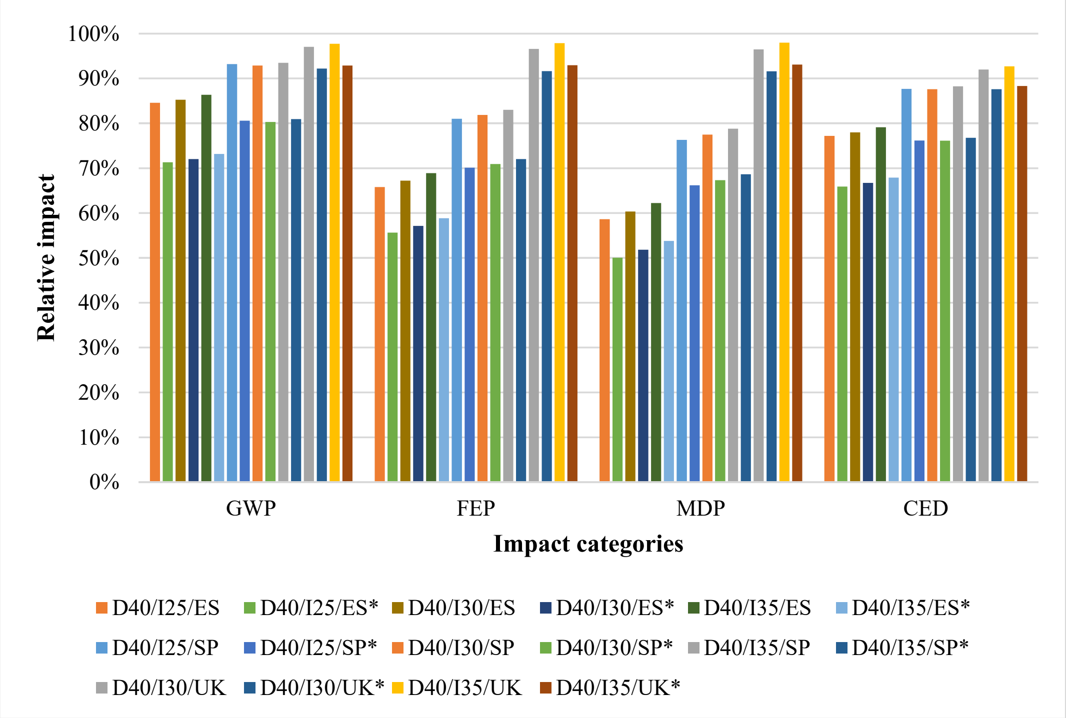

Fig. 8. Relative impact of CDFs with driven piles and a cast-in-situ cap with and without DLTs. *Terminology: driven pile (**D**); concrete compressive strength: **(25)**,**(30)**, **(35)**,**(40)***

*MPa; cast in situ (**I**); EHE-08 and CTE (**ES**); Eurocode with Spanish annexes (**SP**); Eurocode with United Kingdom annexes (**UK**); dynamic load tests (*****); global warming potential (**GWP**); freshwater eutrophication potential (**FEP**); mineral depletion potential (**MDP**); cumulative energy demand (**CED**).*

3.4. Environmental and economic discussion of relevant significant study CDFs

Table 5 shows the environmental and economic costs of several representative CDFs of the study designed with the current Spanish codes (ES) and the Eurocode with Spanish Annexes (SP).

A conventional solution in Spain is a CDF with bored piles and a cast-in-situ pile cap built with concrete of compressive strength of 25 MPa. Results show that this conventional solution could be optimized changing the strength of concrete from 25 MPa to 35 MPa in piles and cap. In this way, the environmental results could be diminished 7-13% with SP and 10-15% ES; and economic costs up to 8% SP and 9% ES.

In addition, the use of driven piles (performing DLTs) instead of bored piles in this conventional solution reduced GWP emissions up to 20% SP, and 39% ES; although impacts were lowered in FEP (-14% SP and 21% ES) and MDP (-6% SP and 13% ES) categories because driven piles had more steel. Even the fully prefabrication of the CDF (performing DLTs) resulted environmentally better in most categories than the conventional CDF with bored piles, up to 18% SP and 36% ES less. Nevertheless, prefabricating part of the CDF (with driven piles and a cast-in-situ cap) or the entire CDF (driven piles and a precast cap with DLTs) resulted more expensive than built it entirely cast in situ: up to 24% SP, 10% ES; and 27% SP, 19% ES respectively. Additionally, the performance of DLTs on driven piles reduced costs on 13% SP, and 6% ES of CDFs.

Economic costs were mostly retrieved from a referent Spanish construction database. Nevertheless, economic costs are highly influenced by the factors of each work (units, construction company, etc.). It is worth to mention that a foundation is normally selected by its initial cost and security (Pujadas, E., de Llorens, J.I., Moonen, 2013). In addition, driven piles are a frequent solution when there are big loads, toxic or weak soils, etc. In this respect, there are several circumstances that can make them a cost-effective solution that is beyond the scope of this study. For example, the use of wider piles can reduce the costs of the CDF because the number of piles is reduced (e.g. from four to three) and, as a result, the cap become smaller. Furthermore, it is more expensive to increase the length of the pile than choose a wider pile.

Table 5. Relative impact of several relevant CDFs of the study.

Categories	**B25/I25/SP**	**B25/I35/SP**	**D40/I25/SP***	**D40/P40/SP***	**B25/P40/SP**	**B25/I25/ES**	**B35/I35/ES**	**D40/I25/ES***	**D40/P40/ES***	**B25/P40/ES**
GWP	80%	81%	59%	61%	82%	94%	80%	52%	56%	100%
ODP	80%	80%	62%	65%	83%	92%	77%	56%	61%	100%
TAP	79%	80%	69%	73%	83%	92%	78%	60%	66%	100%
FEP	78%	81%	84%	90%	81%	93%	78%	67%	75%	100%
POFP	81%	82%	69%	74%	84%	93%	79%	60%	68%	100%
MDP	73%	78%	93%	100%	76%	88%	74%	70%	80%	94%
FDP	80%	81%	67%	70%	83%	93%	78%	58%	63%	100%
CED	80%	81%	68%	71%	83%	93%	78%	58%	64%	100%
COST	73%	73%	97%	100%	77%	79%	70%	89%	98%	85%

*Terminology: bored pile (**B**); driven pile (**D**); concrete compressive strength: (**25**),(**35**),(**40**) MPa; cast in situ (**I**); precast (**P**); EHE-08 and CTE (**ES**); Eurocode with Spanish annexes (**SP**); dynamic load tests (*****); global warming potential (**GWP**); ozone depletion potential (**ODP**); terrestrial acidification potential (**TAP**); freshwater eutrophication potential (**FEP**); photochemical oxidant formation potential (**POFP**); mineral depletion potential (**MDP**); fossil depletion potential (**FDP**); cumulative energy demand (**CED**); economic cost (**COST**).*

4. Conclusions

This study assessed the environmental (and economic costs) of the construction of concrete deep foundations (CDFs) according to a number of variables. These include the level of prefabrication, the compressive strength of concrete and the building design code used. In addition, a sensitivity analysis was carried out to evaluate the influence of dynamic load tests (DLTs) on the results of CDFs with driven piles. Some of the main findings of the study are summarized below:

- The most obvious finding to emerge is that it is crucial to reduce the amounts of concrete and steel to improve the environmental sustainability of CDFs. These materials accounted for 75-95% of the environmental burdens in all impact categories.

- This study has shown that the use of driven piles instead of bored piles tends to reduce the amounts of concrete in CDFs considerably, although steel reinforcement amounts then increase. Consequently, environmental impacts tend to be reduced in most categories, except in FEP and MDP categories that are highly dependent on the steel amounts.

- Study CDFs were designed with the minimum amounts of concrete and steel reinforcement that codes dictate in order to ensure a fair comparison between these codes. The findings suggest that the Eurocode with United Kingdom annexes reduces the most the environmental impacts of CDFs with bored piles compared to Eurocode with Spanish annexes, and current Spanish codes (EHE-08 and CTE); while these latter do it for CDFs with driven piles. This is explained by the differences between codes, in particular those affecting steel amounts and concrete pile resistances.

- It was also shown that performing DLTs that verify driven pile resistance calculations and increasing the compressive strength of concrete in bored piles, improve the environmental burdens and economic costs of CDFs. Nevertheless, no significant difference was found increasing the strength of concrete in cast-in-situ caps.

- The partial and fully prefabrication of CDFs has shown to reduce the environmental impacts in most categories compared to those CDFs built completely on site; although prefabricating the CDFs resulted more expensive.

The study variables have shown a significant effect on environmental results. It is therefore recommended to take them into account in future constructions and codes. Nonetheless, the findings in this study might be subject to other factors that depend on each case; some of which might be difficult to quantify. In addition, bored and driven piles might be designed following constructive recommendations. Nevertheless, in all cases, they must comply with the mandatory codes analysed herein. Moreover, further research might investigate CDFs and other RC structures considering study variables, and using recycled aggregates, other types of reinforcement, bio-materials and less pollutant cements in order to improve their environmental burdens.

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