Sustainability-Driven Decision-Making Model: Case Study of Fiber-Reinforced Concrete Foundation Piles

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Abstract: Currently, foundation piles for inhabited areas are often constructed using a continuous flight auger, which is a cost- and time-efficient technology that does not require stabilization of the borehole wall; the steel bar reinforcement is embedded after the concrete has been poured. However, this reinforcement operation can lead to severe construction and structural issues. Thus, several improvements to this technology have been proposed since its first application in the 20th century, such as the use of more fluid concretes. Nevertheless, steel and polymers are emerging as a potential replacement for steel bars in concrete reinforcement for several types of structures and building components, with identified and quantified benefits from a sustainability perspective. Accordingly, this paper proposes and validates a multicriteria decision-making approach designed with multidisciplinary experts within the construction field to assess the sustainability index of concrete pile foundations. The results of a case study enable us to conclude that polymeric fiber-reinforced concrete piles are the most sustainable due to their cost–structural efficiency ratio, high durability, and minimal risks during construction. Steel fiber-reinforced concrete alternatives were also found to be more sustainable than traditional reinforced concrete. Nonetheless, these results are unrepresentative of the current practice as direct costs were found to be the main driver in the decision-making processes, while other costs and both environmental and social indicators are disregarded. This justifies the urgency to provide sustainability-driven decision-making approaches capable of objectively quantifying the satisfaction degree of economic, environmental, and social indicators involved in the analysis. **DOI: 10.1061/(ASCE)CO.1943-7862.0002073.**

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Introduction

Construction activities lead to remarkable impacts on the global economy (Ahmad et al. 2019; Wells 1985), environment (Huang et al. 2018), and society (Zhang et al. 2019). Accordingly, these impacts have often been assessed from the holistic point of view of sustainability since this concept was defined as the coexistence of economic, environmental, and social issues (Kaur and Garg 2019). Sustainability and component performance are expected to be enhanced if the construction processes are optimized and uncertainties diminished (Okema 2000; Salimi et al. 2018). These uncertainties pose a challenge in the case of underground infrastructure, such as tunnels and foundations (Pujadas-Gispert et al. 2018, 2020) and especially, in deep foundations (Buyle-Bodin and Madhkhan 2002).

With respect to the latter, piles are widely utilized in building construction and can be classified depending on the following characteristics: (1) *interaction with other piles*—isolated single piles and groups of piles that are spaced closely or apart; (2) *materials*—onsite reinforced concrete, precast concrete, steel, timber, and composite; (3) *mechanical features*—end bearing piles and friction piles; (4) *cross-section shape*—circular, polygonal, laminated profiles, and rectangular diaphragm walls; (5) *diameter*—micropiles ($\text{Ø} \leq 300$ mm), conventional diameter ($300 < \text{Ø} < 800$ mm), and large diameter (≥800 mm); and (6) *construction process*—driven and bored piles (Tomlinson and Woodward 2008). This last classification category is the most used, and each of its two types have several subtypes. The subtypes of driven piles are precast or poured onsite with a cylindrical shaft and steel bottom plate or gravel plug and poured onsite drilled-in displacement micropiles (Armour et al. 2000). Conversely, the subtypes of bored piles are poured onsite with temporary shaft, permanent shaft, bentonite slurry and no shaft, segmental flight auger and no shaft, and continuous flight auger (CFA), all of which are currently used in practice (Bersan et al. 2018; Hosny et al. 2018).

This study focuses on CFA steel-cage reinforced concrete piles (RCPs), which are a cost- and time-efficient solution that is well established in the building construction sector because it is widely accepted to be the quickest pile type for inhabited areas, with a speed three times that of its first competitors (Brown et al. 2007). The construction process (Fig. 1) comprises the following steps: (1) a CFA that performs the excavation without a shaft or slurry; (2) concrete is poured through the hollow stem and the auger is withdrawn ensuring that the bottom always remains within the poured concrete; and (3) the reinforcement cage is pushed or

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Fig. 1. Construction of CFA-RCPs: (a) continuous flight auger excavation; (b) pouring concrete; and (c) pile finished after embedment of steel cage. (Images by J. Camps.)

vibrated into the freshly poured pile (Brown et al. 2007). Thus, RCPs are a cost-effective system for inhabited areas because no hammering is required and also has the advantage that the excavated soil is visible (Rajapakse 2016). However, CFA piles require the soil to be consolidated and the water table to be below the pile unless the soil is very cohesive and the water does not circulate (Brown et al. 2007). CFA piles present several disadvantages: (1) slower process than displacement piles; (2) uncertainty in relation to the pile bearing capacity owing to driving and inspection difficulties; (3) boring process decompresses the soil and encounters difficulties when the pile has to be embedded in particularly hard ground; and (4) concrete must have high workability to avoid clogging and to facilitate the reinforcement embedding process (Brown et al. 2007). This last point represents a challenge and has resulted in the following limitations: (1) reinforcement depths less than 12 m, frequently not more than 6.0 m; and (2) the requirement to use additional equipment such as a bulldozer arm to push the steel cage down with the risk of causing damage to the rebars and/or large deviations in both geometry and position. These are known drawbacks associated with reinforcement placement. Thus, to mitigate the potential structural implications of these known shortcomings, large safety factors must be considered in the design process to guard against the potential lack of reinforcement either because the concrete covers are not guaranteed, which could result in corrosion of the reinforcement, and/or the reinforcement does not reach the required depth, and as a consequence, part of the pile is assumed to be unreinforced. This ultimately leads to larger cross sections that demand both larger excavated volumes and concrete consumption and therefore higher costs and greater environmental impacts. It is also noteworthy that on the construction site, a yard is temporarily required to stack the steel cages, which creates a challenge in terms of mobility and space management in dense urban areas.

Structural fibers that have emerged as a suitable alternative to the traditional steel cage for concrete reinforcement are known as fiber-reinforced concrete (FRC). Accordingly, the acceptance of FRC as a structural material in the *fib* Model Code 2010 (MC-2010) (*fib* 2013) has accelerated the use of FRC, predominantly with steel fibers in structural applications: (1) ground-supported (Meda et al. 2004) and column-supported slabs (de la Fuente et al. 2019), (2) sewerage and drainage pipelines (de la Fuente et al. 2012b, 2013), (3) earth-retaining systems (de la Fuente et al. 2011), and (4) hydraulic and metro tunnel linings (Chiaia et al. 2009; de la Fuente et al. 2012c; Liao et al. 2015a, b; Nogales and de la Fuente 2020; Plizzari and Tiberti 2006; Rinaldi and Zila 2017). The Model Code is a structural concrete design guideline written by the *fib* (Fédération Internationale du Béton), which is intended to be a guidance document for future codes. This document is issued, tentatively, every 10 years with the purpose of incorporating the latest advances in the design of concrete structures. It must be remarked that the *fib* MC-2010 emphasizes the need of dealing with sustainability through the whole design process and proposes criteria and methods to assess the sustainability performance. Likewise, synthetic fibers are being introduced into the flooring (Alani and Beckett 2013), pipeline (Al Rikabi et al. 2018; Ashley and Ali 2014; de la Fuente et al. 2013; Lee et al. 2019; Park et al. 2014), and tunneling (Conforti et al. 2017, 2019) sectors due to the improvements in the mechanical properties inherent with this type of fiber. Accordingly, synthetic fibers have proven to be inert to the aggressive environments that lead to the corrosion and deterioration of the steel reinforcements (Richardson 2004; Hannant 1998), and thus, higher durability and service life with higher reliability can be guaranteed.

Fiber-reinforced concrete piles (FRCPs) have already attracted the attention of researchers. Accordingly, several experimental programs have been conducted to consider steel fiber-reinforced concrete (SFRC) as a structural material (Akdag and Özden 2013; Buyle-Bodin and Madhkhan 2002; Ozden and Akdag 2009; Sterin et al. 1984). The purpose of these studies was to prove the postcracking, ductility, and fatigue performances of FRCPs; these properties are required (and mandatory) in deep foundations in soil with low cohesion, in seismically active zones (Ozden and Akdag 2009). The use of synthetic (polymeric) fiber-reinforced concrete (PFRC) in FRCPs has also been explored in marine environments (Sadiqul Islam and Gupta 2016) to enhance durability. Finally, the technical feasibility of piles that comprises of a steel profile embedded into a PFRC was also investigated (Zyka and Mohajerani 2016).

Since different technically viable reinforcement alternatives are available for FRCPs, each of which have different economic, environmental, and social impacts, this study aims to assess the sustainability of CFA-RCPs focusing on the use of traditional steel cages and structural fibers for concrete reinforcement. The construction sector's sustainability awareness is increasing, and its stakeholders are searching for assessment tools to evaluate and improve the impacts their building processes create (Pons and Nikolic 2020). However, to the best of the authors' knowledge, this is the first definition and application of a holistic sustainability assessment model for CFA, preceded by environmental analysis of deep foundations (Giri and Reddy 2014; Pujadas-Gispert et al. 2020) as well as specifically environmental piles (Misra and Basu 2011) and eco-efficient assessments studies (Saravanan 2011) some starting incorporating neighborhood nuisances (Misra and Basu 2012). Hence, a sustainability-driven multicriteria decision-making approach is proposed for the assessment of CFA-RCPs, and a case study is presented. The proposed approach and the outcomes of this research are expected to be useful in the stakeholders' decision-making processes.

Sustainability Assessment of Foundation Piles Based on Integrated Model for Assessing the Sustainability Value of Structures

Integrated Model for Assessing the Sustainability Value of Structures and Delphi Approach

The integrated model for assessing the sustainability value of structures (MIVES) is a multicriteria decision-making (MCDM) model that supports the sustainability analysis of any type of product and construction process. MIVES was designed to minimize the subjectivity associated with the indicators involved, particularly those related to environmental and social requirements, and permit the derivation of an integrated sustainability index (I_s).

The method defines (1) the system boundaries that determine the scope of the analysis, (2) the decision-making tree that gathers the requirements (R), criteria (C), and indicators (I) involved in the decision-making process, (3) the value functions (Alarcon et al. 2011) to convert the attributes or physical units of each indicator into a satisfaction unit that ranges from 0 to 1, and (4) the weights' sets.

The entire procedure involved experts, chosen from a group of representative stakeholders, using the Delphi method (Hallowell and Gambatese 2010), which is explained in detail in Section 2.5. The Delphi method was applied to select the experts as well as to manage the research survey and assign the weights' set following the schema established by del Casanovas-Rubio and Armengou (2018).

The suitability of MIVES for the types of analysis dealt with in this study has been previously confirmed in other areas, such as underground (del Casanovas-Rubio et al. 2019; de la Fuente et al. 2017; Ormazabal et al. 2008), hydraulic (de la Fuente et al. 2016; Pardo-Bosch and Aguado 2015) and electric-power generation (Cartelle Barros et al. 2015; de la Fuente et al. 2017) infrastructure, and building (Josa et al. 2020; Pons and Aguado 2012; Pons and De La Fuente 2013; Reyes et al. 2014; Lombera and Rojo 2010; Lombera and Aprea 2010; Sánchez-Garrido and Yepes 2020) and postdisaster reconstruction (Hosseini et al. 2016a, b). A number of researchers (del Caño et al. 2016, 2012) have also developed methods intended to treat the uncertainties related to the input data.

System Boundaries

This study aims to assess the sustainability index of the technically feasible reinforcement alternatives for CFA piles: traditional steel-cage RCP and steel fiber-reinforced concrete (SFRCP) or polypropylene fiber reinforced concrete (PFRCP). The fibers considered should be structural macrofibers capable of providing a postcracking concrete residual strength according to *fib* MC-2010 (*fib* 2013).

The functional unit is 1.0 CFA pile of length l and diameter Φ considering the life cycle from its instigation to the end of its service life (≥50 years for buildings). The study focuses on the pile but excludes the pile cap because its geometry and reinforcement steel bars are independent of the reinforcement configuration of the pile. However, the reinforcement of the pile top is included with the indicators' quantification. The considered life cycle analysis (LCA) stages were (1) extraction, transport and processing of the constituent materials of the piles including the concrete components (cement, aggregates, water, and admixtures), and reinforcing concrete products (steel bars and fibers); (2) soil boring with a CFA; (3) concrete production; (4) concrete transport and pouring, (5) reinforcement embedding; and (6) pre- and operational stages throughout which repairs during construction and maintenance may be required.

Decision-Making Tree and Elements

During the experts' seminars, the decision-making tree presented in Table 1 was established, relying on these experts' knowledge, expertise, and information from numerous real projects such as the case study and the extend-related technical literature presented in "Introduction" section. This encompasses the economic, environmental, and social requirements (R) according to UN (2005). These Rs are divided into seven criteria (C) and ten indicators (I) which are selected for the decision under consideration, with regard to the type of reinforcement, after a filtering procedure in which the representativeness and independency, with no overlapping, between indicators was guaranteed.

The *economic requirement* (R_1) consists of two criteria: *costs* (C_1) and *construction time* (C_2). The former encompasses three indicators: (1) *direct costs* (I_1) related to materials and construction processes, including labor; (2) *nonacceptance costs* (I_2) caused by disconformities associated with the material properties and/or the piling process; and (3) *durability costs* (I_3) which involve those costs caused by materials' repair due to deterioration—for example,

Table 1. Requirements' tree with weights for sustainability analysis of CPs

Requirements	Criteria	Indicators	Units
R_1. Economic (43.8%)	C_1. Costs (68.8%)	I_1. Direct costs (41.5%)	k€
		I_2. Nonacceptance costs (20.7%)	points
		I_3. Durability costs (37.8%)	points
	C_2. Construction time (31.2%)	I_4. Time (100%)	points
R_2. Environmental (28.7%)	C_3. Resource consumption (52.4%)	I_5. Energy consumption (58.1%)	GJ
		I_6. Water consumption (41.9%)	m^3
	C_4. Emissions (47.6%)	I_7. CO_2 emissions (100%)	$TonCO_2$-equivalent
R_3. Social (27.5%)	C_5. Occupational risks (50.1%)	I_8. ORI index (100%)	weighted person-hours
	C_6. Third-party effects (26.3%)	I_9. Building site space (100%)	points
	C_7. Innovation (23.6%)	I_{10}. New solutions (100%)	points

Note: ORI = operational risk index.

Table 2. Value functions and respective constitutive parameters

Indicator	Equation	Function	X_{max}	X_{min}	C	K	P
I_1. Direct costs	(1, 2)	DS	1.25	0.75	1.00	20	1.93
I_2. Non-acceptance costs	$6 \leq l_p \leq 12$; $0.75 \leq VI_2 \leq 0.50$	MLD (RCP)	—	—	—	—	—
	$12 < l_p \leq 16$; $0.25 \leq VI_2 \leq 0.00$		—	—	—	—	—
	$VI_2 = 0.75$	L (FRCP)	—	—	—	—	—
I_3. Durability costs	RCP: $VI_3 = 0.50$; SFRCP: $VI_3 = 0.75$; PFRCP: $VI_3 = 1.00$	—	—	—	—	—	—
I_4. Time	$6 \leq l_p \leq 12$; $0.75 \leq VI_4 \leq 0.50$	MLD (RCP)	—	—	—	—	—
	$12 < l_p \leq 16$; $0.50 \leq VI_4 \leq 0.00$		—	—	—	—	—
	$VI_4 = 1.00$	L (FRCP)	—	—	—	—	—
I_5. Energy consumption	(1, 2)	—	1.25	0.50	1.3	2.6	1
I_6. Water consumption	(1, 2)	DCx	1.25	0.50	1.3	2.6	1
I_7. CO_2 emissions	(1, 2)	—	1.25	0.50	1.3	2.6	1
I_8. ORI index	$VI_8 = -\frac{0.4}{ORI_{\mathrm{RCP}}} OR + 1$	DL	—	—	—	—	—
I_9. Building site space	RCP: $VI_9 = 0.50$; FRCP: $I_9 = 1.00$	—	—	—	—	—	—
I_{10}. New solutions	RCP: $VI_{10} = 0.50$; SFRCP: $VI_{10} = 0.75$ PFRCP: $VI_{10} = 1.00$	—	—	—	—	—	—

Note: DS = decreasing S-shape; MLD = multilinear decreasing; L = linear; DCx = decreasing convex; DL = decreasing linear; and N/A = not applicable.

corrosion of the steel reinforcement. The latter is represented by the *time* (I_4) required to construct a pile (without disconformities).

The *environmental requirement* (R_2) involves two criteria: *resources consumption* (C_3), which is represented by both *energy* (I_5) and *water* (I_6) *consumption*, and *emissions* (C_4) of *CO_2* (I_6). The latter three indicators are evaluated considering the LCA phases described in the section "System Boundaries." For the assessment of indicators I_5 and I_7, the local inventory (ITEC 2019) was considered, and international inventories (Circular Ecology 2019; Wuppertal 2014) were used as reference. Nonrenewal resources consumption other than water—for example, aggregates for cement and concrete—were discarded since the concrete component and proportions are essentially the same and independent of the reinforcement alternative, except for slight variations in the admixture quantities that should be redefined to guarantee the workability of the FRCPs. These variations could be taken into consideration in indicator I_1.

Finally, the *social requirement* (R_2) considers three criteria: (1) *occupational risks* (C_5) by means of the occupational risk index (ORI) (I_8) developed by del Casanovas et al. (2014) to identify and quantify the potential risks the workers are subjected to during construction; (2) the *third-party effects* (C_6) are taken into account considering the *building site space* (I_9) required for stacking the concrete reinforcement materials; and (3) *innovation* (C_6) through the indicator *new solutions* (I_{10}) for reinforcing concrete. This last indicator was incorporated to encourage research and development of new reinforcing technologies. Steel cages for RCPs have been satisfactorily utilized worldwide for more than a century (Tomlinson and Woodward 2008), but fibers are a promising technically feasible alternative. Still, the building sector tends to react slowly and with reticence to changes; thus, the introduction of improvements, which could attract initial reservations, should be motivated by using MCDM approaches that also recognize and reward the innovation.

Other indicators attributed to the requirement R_2 could also have been included, such as *recyclability potential*, which was disregarded since it was found to have a minor impact on the sustainability index. Foundation piles can often be subsequently reutilized if they are found to be in sound structural condition.

Value Functions

The aforementioned value functions (Alarcon et al. 2011) were assigned by experts to each indicator (I_{ind}). Following MIVES, these functions were mathematically expressed by Eq. (1) in the case of indicators I_1 and I_5–I_7 (Appendix I) and followed simpler equations for the other indicators because the relation between the value and satisfaction of the indicators followed specific patterns described in detail at the end of this section (Table 2). Thus, there is an allowed computation of the value of each indicator (VI_{ind}) and I_s of the RCP that is subject to evaluation. I_s ranges from 0.0 to 1.0 and is obtained by multiplying VI_{ind} by the corresponding indicator weight and summing the result with those obtained for the same criterion. The same process is repeated upward (from indicators to requirements) to derive the I_s

$$VI_{\mathrm{ind}}(X_{\mathrm{ind}}) = A + B\left[1 - e^{-K(\frac{|X_{\mathrm{ind}} - X_{\mathrm{min}}|}{C})^{P}}\right] \tag{1}$$

where A is the value of VI_{ind} for X_{min}; X_{min} is the minimum abscissa value of the indicator interval assessed; X is the abscissa value for the indicator assessed; P_i is a shape factor that defines whether the curve is concave ($P < 1$), convex ($P > 1$), linear ($P = 1$), or S-shaped ($P > 1$); C approximates the abscissa at the inflexion point; K tends toward $VI_{\mathrm{ind}}(X_{\mathrm{ind}})$ at the inflexion point; B is the factor that prevents the function from exceeding the range (0, 1) according to Eq. (2); and X_{max} is the abscissa value of the indicator that gives a response value of 1 for increasing value functions

$$\boldsymbol{B} = \left[1 - e^{-\boldsymbol{K}_i(\frac{|\boldsymbol{X}_{\mathbf{max}} - \boldsymbol{X}_{\mathbf{min}}|}{\boldsymbol{C}_i})^{\boldsymbol{P}_i}}\right]^{-1} \tag{2}$$

The value function allows physical units of each indicator—for example, €, $kgCO_2$— to transform into dimensionless values also ranging from 0 to 1. These values represent the sustainability or satisfaction of each indicator. Table 2 presents the equations, shapes, and constitutive parameters of the value functions for the 10 indicators of this study presented in the previous section.

Indicators I_1 and I_5–I_7 are referred to as RCPs: $X_{\mathrm{ind}} = X_{\mathrm{alt}}/X_{\mathrm{RCP}}$, X_{alt}, and X_{RCP} being the argument of the indicator (Eq. 1), the magnitude for the alternative (FRCP), and the magnitude of the reference (RCP), respectively. In this experts-based method definition, the following criteria were assumed for defining the value functions' constitutive parameters:

- *Direct costs* (I_1) assess the construction costs including material, labor, machinery and equipment, and auxiliary elements. Relying on the competitiveness of the RCP solution due to its widespread usage and considering previous related research projects (de la Fuente et al. 2019), Eqs. (1) and (2) with the parameters depicted in Table 2 were defined. The X_{min} was the reference satisfaction value of 0.75 that was set for this RCP solution. A $VI_1 = 1.0$ is achieved for a 25% cost reduction in comparison to RCP, whereas $VI_1 = 0.0$ is achieved for an increase of 25%. The transition is simulated with an S-shape function (Appendix I) with a remarkable sensitivity to increasing/decreasing costs to emphasize the market behavior.

- *Non-acceptance costs* (I_2) evaluate the magnitude of the costs from unsuccessful construction processes. In RCPs, nonconformities may be caused in the case of steel cage misalignment, such as insufficient concrete cover and/or depth. In that scenario, the longer the pile is, the higher the likelihood of geometric deviations. Accordingly, and considering again the RCP as the reference widespread but improbable solution, a decreasing multilinear function shape is assigned to this indicator for RCPs. For pile lengths (l_p) below 6.0 m, $VI_2 = 0.75$ was considered, while VI_2 decreases to 0.0 for $l_p \geq 16.0$ m. For $l_p > 12.0$ m, the longitudinal steel bars should be connected by welding and/or lapping to guarantee continuity of the reinforcement; this connection renders the cage more prone to nonconformities. For FRCPs, a $VI_2 = 0.75$ was assigned since it is assumed that both the concrete admixtures and concrete-pumper pipe diameter are selected to meet workability requirements equivalent to the RCP solution. In the case where a large quantity of fibers is used, the probability of the occurrence of technical issues increases, and this can be accounted for by reducing the satisfaction value.
- *Durability costs* (I_3) assesses the potential durability of the different alternatives. Firstly, the degradation risks of the steel-based reinforcing alternatives due to potential corrosion during the service life were contemplated, and consequently, the risk of reducing the bearing capacity in the elements that are difficult to inspect was considered. The corrosion mechanisms and reduction of the bearing capacity, in the case when this occurs, can be less severe for SFRCPs ($VI_3 = 0.75$) than for RCPs ($VI_3 = 0.50$). Conversely, synthetic fibers do not corrode and are resistant to most chemical attacks expected in underground environments—for example, contamination of the phreatic water and marine soils; consequently, $VI_3 = 1.00$ was considered since no retrofit/repair costs associated with durability issues are expected.
- *Time* (I_4) evaluates the average time devoted to concrete reinforcing tasks. FRCPs ($VI_4 = 1.00$) present the quickest construction process since the fibers are directly introduced in the concrete mixer. RCP requires more time to introduce the steel cage into the excavation filled with concrete and to previously weld the two consecutive parts of the steel cage in the event the cage is longer than 6 meters. VI_4 follows the same pattern as VI_2 for RCPs.
- *Energy consumption* (I_5), *water consumption* (I_6) and *CO_2 emissions* (I_7) are assessed with the same value functions that, to encourage environmentally sustainable solutions, assume a value of 0.60 for the reference RCP, and maximum (1.00) and minimum satisfactions (0.00) are obtained for a decrease of 50% and an increase of 25% of X_{ind}, respectively, through a convex function (Appendix I).
- *ORI index* (I_8), previously introduced in Section 2.3, is defined as the sum of all the risks of the activities performed during the building process (del Casanovas et al. 2014). The risk of an activity is assessed by ranking the probability (P) of the occurrence of an accident multiplied by the level of severity of its most probable consequence (C) and by the exposure (E) of the workers to the risk, expressed in time (h).
- *Building site space* (I_9) evaluates the satisfaction related to the onsite space required for stacking the reinforcement materials. A $VI_9 = 1.00$ was assigned to FRCPs and $VI_9 = 0.50$ for RCPs. With regard to the latter, constructors have already accepted and integrated the space requirements, and consequently, null satisfaction would be unrepresentative. Accordingly, in the case of long steel cages and/or high demands on space for stacking, such as a significant number of piles to be constructed, VI_9 could be reduced accordingly.
- *New solutions* (I_{10}) consider the integration of new technologies into the construction sector, which in this case are reinforcement alternatives for concrete foundation piles and awards the level of innovation. The standard RCP solution was assigned with $VI_{10} = 0.5$, while values of $VI_{10} = 0.75$ and 1.00 were assigned to SFRCPs and PFRCPs, respectively. Synthetic fibers are being used in structural elements as mentioned in Section 1; nevertheless, to the best of the authors' knowledge, no previous studies have reported their use in piles. Thus, the maximum satisfaction is assigned to PFRCPs.

Weight Assignment with Delphi Method

To select the experts, determine the weights of the requirements, criteria and indicators of the requirement tree, the Delphi method, as presented in (Hallowell and Gambatese 2010), was fully adhered to throughout this entire procedure. In this study, 28 qualified experts were identified and invited to participate in the surveys, 23 of whom initially accepted and 17 participated, which is more than the minimum number of panelists recommended for this method. The participants were from various backgrounds including academia, construction industry, public administration, and civil engineering and architecture. This diversity of backgrounds provided a wider vision and enriched the developed method. The weights were assigned by the direct assignment method.

As proposed by the Delphi method (Hallowell and Gambatese 2010), the median absolute deviation, as defined in Eq. (3), is used to determine the consensus of the panelists. According to the procedure, the consensus is reached when the median absolute deviation is $<1/10$ of the range of possible values. As the range of the weights is 0%–100%, the consensus is reached when the median absolute deviation is <10%, as assumed by Casanovas-Rubio & Armengou (del Casanovas-Rubio and Armengou 2018)

$$Median\ absolute\ deviation_i = \frac{\sum_{j=1}^{n} |w_{ij} - median_i|}{n} \quad (3)$$

where i is the requirement, criterion or indicator considered; j is a panelist; n is the total number of panelists (17 in this study); w_{ij} is the weight assigned to the requirement, criterion, or indicator i by the panelist j; and the $median_i$ is the median of the weights assigned by the panelists for the requirement, criterion, or indicator i.

Two rounds of surveys were conducted to reach a consensus on the weights. In the first round, the experts were asked to assign weights to the requirements, criteria, and indicators according to their preferences, with the total sum of the requirements and each independent set of criteria and indicators being 100%. In the second round of surveys, the panelists were provided with the results of the first round (the mean values) and asked to adjust their assigned weights, if possible, to the results of the first round while retaining their preferences at the same time. They were asked to provide reasons for the weights that deviated by more than 10% from the mean of the first round. The results of rounds one and two are presented in Appendixes II and III, respectively.

As established in Delphi, to reduce judgement-based bias, which comprises collective unconscious, contrast, Von Restorff, myside bias, recency, primacy, and dominance effects, the following controls were implemented: (1) randomized question order,

(2) iteration and anonymity, and (3) reporting of means as feedback. Reasons for outlying responses were included as part of the feedback of the third round; nonetheless, a consensus was reached in the second round.

As presented in Table 1, the resulting weights show that the *economic* requirement (43.8%) is the most important when selecting the type of pile, whereas the *environmental* (28.7%) and *social* (27.5%) requirements have similar weights. This weights' set reflects that the decision making is still driven by economics, while the environmental and social requirements are of moderate importance. This could be a symptom of construction stakeholders becoming more sensitive to the potential impacts of both requirements.

Within the economic requirement, the importance of *cost* (68.8%) is approximately double that of the *execution time* (31.2%). The importance of possible *nonacceptance costs* (20.7%) represents half that of the construction process costs when selecting the type of pile (41.5%), and these costs notably lower than the *durability* aspects (37.8%). *Resource* consumption (52.4%) is considered to be slightly more important than *emissions* (47.6%), whereas *energy* consumption (58.1%) is more relevant than *water* consumption (41.9%). *Occupational risks during construction* (50.1%) resulted in being the most important criterion within the social requirement, whereas *third-party effects* (26.3%) and technology *innovation* (23.6%) have similar weights.

Finally, it is worth noting that the value functions and weights proposed in this study might be representative of a competitive market mainly driven by costs and with remarkable sensitivity toward the environmental and social indicators presented in Table 1. Nevertheless, should other stakeholders' preferences be considered, these functions and weights could be properly calibrated as this level of flexibility is permitted by the model.

Case Study: School Building in Canovellas (Spain)

Description of Structure

The case study is on the new public elementary educational center of Canovellas, Barcelona, Spain. This center was designed by the Beta Architecture studio (Camps and Felip 2014) and built in 2018 by the Department of Education (Pegenaute 2018). The database used in this study relies on the construction documents and as-built drawings (Camps and Felip 2016) as well as the onsite experience of the professionals involved. This building had a cost of 3.3 M€, of which the foundations represented 10%. The total surface area of 3,430 m^2 is divided into a basement of 14×17 m, a ground and first floor of 17×100 m, and an attic of 4×100 m. The underground level is the location of an archaeological site from the Neolithic, the ground and first floor accommodate all the school premises (Brković et al. 2015), and the attic services the educational space.

The building has a reinforced concrete (RC) framed structure distributed in a grid of maximum size 5.5×8.2 m, with onsite columns of 25×90 cm and beams of 55 cm in height, as well as precast TT slabs 45 cm in height and a poured onsite topping layer of 5-cm thickness. Deep foundations were required to transmit the heavy service loads from the structure to a solid formation consisting of clay and sandy clay with a resistance of the base (unit end bearing) of $q_b = 2.775$ MPa and a resistance of the shaft (unit side friction) of $f_p = 0.019$ MPa. The foundations are composed of 187 CFA piles with $\text{Ø} = 45$ cm and length $= 15.9$ m, as shown in Fig. 2. These piles work individually or are grouped in caps from two to six elements. As per project, the reinforcement consisted of steel cages of 6-m depth with 6Ø16 and 1eØ8c/24 as depicted in Fig. 3. Fig. 1 presents the construction process with a flight auger.

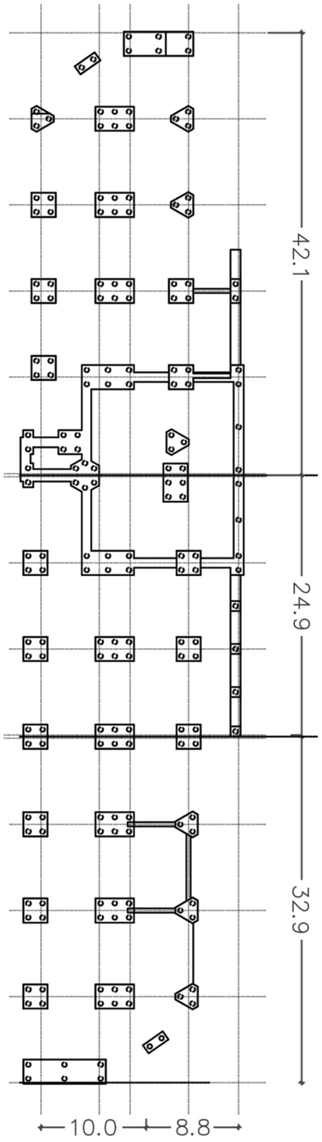

Fig. 2. General foundation plan of Canovellas school.

Alternatives Analyzed and Data

The three main alternatives for reinforcing CFA piles introduced and described in the first section and illustrated with a representative case study in the previous section were considered: (1) the previously described RC constructed solution (RCP) with a 6 m rebar cage and two alternative solutions consisting of (2) SFRCP, and (3) PFRCP. These alternatives were subsequently studied in terms of sustainability for future similar projects.

Both the geometry and mechanical properties of the piles were established based on the loads to be resisted and transmitted to the soil. This information and the mechanical properties of the soil was extracted from the reference project. The mechanical performance (i.e., flexural residual strength) of the fiber-reinforced concretes was established by means of sectional analysis (de la Fuente et al. 2012a) and the design recommendations for FRC structures proposed by the *fib* MC-2010.

A 500 N/mm^2 yield strength steel type B-500S was considered for the cage production. Steel fibers for concrete reinforcement can exhibit different geometries and mechanical performances. For this study, steel macrofibers have an aspect ratio of $60 \leq \lambda_f \leq 80$,

$\lambda_f = l_f/\Phi_f$; l_f *is* the length, and Φ_f is the diameter of the fiber with a tensile strength (f_{fu}) ranging from 1,000 to 1,200 $\mathrm{N/mm^2}$. For the synthetic fibers, macrofibers with $40 \leq \lambda_f \leq 60$, $500 \leq f_{fu} \leq 650$ $\mathrm{N/mm^2}$ and $5 \leq E_f \leq 9$ $\mathrm{MN/mm^2}$ were included in the analysis. Table 3 presents the main features considered regarding the reinforcement alternatives.

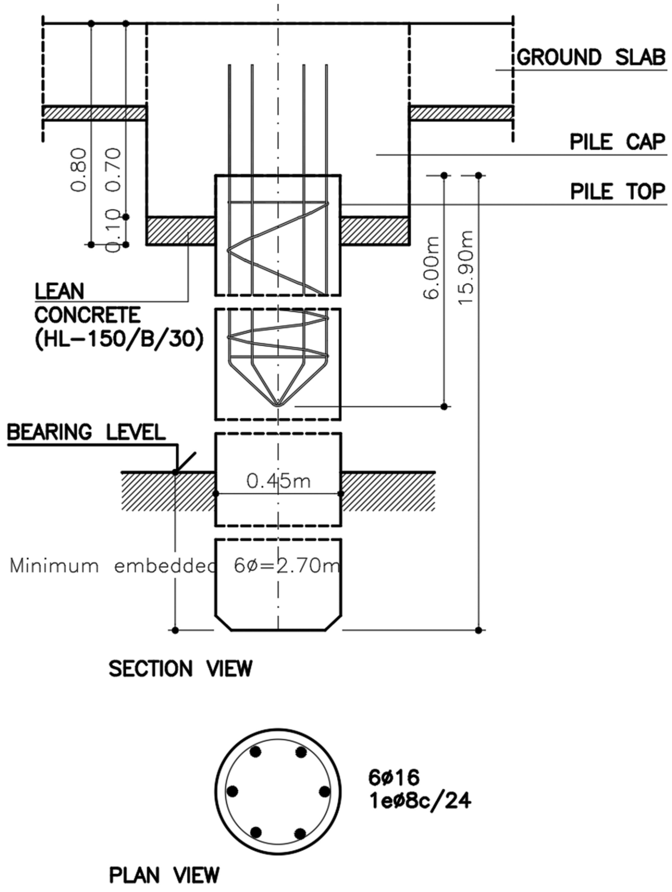

Fig. 3. Detail of geometry and reinforcement of pile.

Table 3. Main features considered for each reinforcement alternative

Type of pile	Reinforcement type	Amount	Cost
RCP	Steel-cage (6.0 m)	6Ø16 + stirrups Ø8@24	1.17 €/kg[a]
SFRCP	Steel macrofibers	30 $\mathrm{kg/m^3}$	1.25 €/kg[b]
PFRCP	Synthetic macrofibers	6 $\mathrm{kg/m^3}$	3.50 €/kg[b]

[a] Including welding and assembly.
[b] Representative cost of the fibers.

Regarding the information presented in Table 3, firstly, the 6.0-m-long steel cage considered for the RCPs guarantees a minimum reinforcement and continuity, whereas the remaining 9.9 m is unreinforced. This type of partially reinforced RCP is permitted in the standards applicable in Spain (MV 2008), among other countries (Brown et al. 2007; Johnson 2013), due to the technical difficulties related to embedding a reinforcement throughout the full pile depth. Conversely, fibers provide a continuous reinforcement, and these can substitute the steel cage in this project provided that the residual strength of the FRC is sufficient for (1) controlling cracks due to thermohygral phenomena such as concrete shrinkage and (2) resisting minor bending moments, which is inferior to the cracking bending moment of the cross section. Based on this and using the *fib* (2013) as a design guideline for FRC alternatives, quantities of 30 and 6 $\mathrm{kg/m^3}$ of steel and synthetic fibers, respectively, were found necessary to fulfill these two requirements. If the loads, soil conditions, and pile cross section had been different, other FRC strength requirements would have dominated, which would have resulted in a requirement for different quantities of fibers.

For concrete, a characteristic compressive strength (f_{ck}) of 25 $\mathrm{N/mm^2}$ after 28 days was considered, with a plasticizer admixture to guarantee the fluid consistency, a maximum aggregate diameter of 20 mm, and cement content higher than 375 $\mathrm{kg/m^3}$. The same concrete composition was also assumed for the SFRC and PFRC; however, this should be slightly modified by increasing the quantity of the admixture (superplasticizer) to compensate for the reduction in consistency owing to the addition of fibers. These modifications, however, can be disregarded in this analysis since they do not have a significant impact on the economic and environmental indicators.

Quantification of Indicators

Quantification of the indicators mainly relied on the construction documentation (Camps and Felip 2016) and the local database (ITEC 2019), especially for the cost (I_1–I_4) and environmental (I_5–I_7) indicators. Environmental indicators are also based on other European databases (Circular Ecology 2019; Wuppertal 2014) and specific studies regarding steel (Alberti et al. 2018) and polypropylene fibers (Yin et al. 2016). Table 4 summarizes the quantification of the environmental indicators (I_5–I_7) for each alternative along with the references used, considering the phases and the boundaries described in Sections 2.2 and 2.3, respectively.

Risks during the building process were analyzed using the ORI (I_8) in which the activities performed during the construction of the

Table 4. Quantification of the environmental indicators

Quantification	Units	Type of pile			References
		RCP	SFRCP	PFRCP	
CFA drilling and pouring concrete	(m)	2973	2973	2973	Camps and Felip (2016)
Pile cap preparation	(m)	178	178	178	
CFA machinery	(unit)	1	1	1	
Piles rebars	(kg)	14119	—	—	
Piles steel macrofibers	(kg)	—	14187	—	*fib* (2013)
Piles synthetic macrofibers	(kg)	—	—	2837	
Piles caps rebars	(kg)	1176	3530	3530	Camps and Felip (2016) and *fib* (2013)
I_5. Energy consumption	(MJ)	3320023	3410662	3151588	Circular Ecology (2019) and ITEC (2019)
I_6. Water consumption	(l)	4114965	4257314	3524724	Wuppertal (2014) and Yin et al. (2016)
I_7. CO_2 emissions	($\mathrm{kgCO_2}$-equivalent)	399963	376963	370177	Alberti et al. (2018), ITEC (2019), and Yin et al. (2016)

Table 5. Resulting ORI and components for each pile alternative

Risk—activity	W	Exposure time, E (h)			WxE (weighted h)		
		RC	SFRC	PFRC	RC	SFRC	PFRC
Traffic accident–transport of concrete to construction site	0.040	24.9	24.9	24.9	0.996	0.996	0.996
Traffic accident–transport of steel rebars to construction site	0.030	1.2	1.2	1.2	0.035	0.035	0.035
Blows to upper and lower limbs–manual load handling: installation of reinforcing bars	0.021	12.5	0.0	0.0	0.262	0.000	0.000
Burns–welding	0.007	15.6	0.0	0.0	0.109	0.000	0.000
Collision with or running over by heavy equipment or heavy-goods vehicles–work with CFA pile rig	0.068	4.7	4.7	4.7	0.318	0.318	0.318
Collision with or running over by heavy equipment or heavy-goods vehicles–work with concrete mixer truck	0.068	1.6	1.6	1.6	0.106	0.106	0.106
Collision with or running over by heavy equipment or heavy-goods vehicles–work with concrete pump truck	0.068	0.2	0.2	0.2	0.011	0.011	0.011
Collision with or running over by heavy equipment or heavy-goods vehicles–work with excavator	0.068	31.2	31.2	31.2	2.119	2.119	2.119
Collision with or entrapment by moving load due to its movement or detachment–mechanical load handling with crane	0.065	31.2	6.2	6.2	2.026	0.405	0.405
ORI					5.982	3.991	3.991

foundation piles were identified for the three alternatives and are presented in Table 5. The values of W (PxC/1000) were taken from (del Casanovas et al. 2014), as the technology and safety management practices of the case study match with those for which the guidance values of that research were obtained. The following hypothesis was created:

- The journey by a 6 m^3 mixer truck from the concrete plant to the site (8.8 km, real distance in the Barcelona, Spain, case study context) takes 9 min. A total of 497 m^3 of concrete are needed for the 187 piles.
- The journey by a truck hauling 18,000 kg of rebars from the plant to the site (38.9 km, real distance in the case study) takes 35 min. The total amount of steel needed for the rebars of the 187 piles is 15,295 kg and 3,530 kg for the RC and FRC (only for pile caps) alternatives, respectively.
- The installation of reinforcing bars takes 2 min by two operators per pile only for the RC.
- The welding of the rebars for the RC takes 5 min per pile by one welder.
- The drilling of a pile takes 10 min, and the concreting takes 5 min. The pile rig moves around the construction site 5% of the time required for drilling and concreting (15 min), and two workers could be involved.
- The concrete mixer truck moves around the construction site 5% of the time dedicated to concreting while two workers are performing tasks in the vicinities.
- The concrete pump truck moves around the construction site for a total of 5 min for the construction of 187 piles while two workers can be required.
- The excavator is working during the concreting time (5 min per pile), and two workers could be involved.
- The crane handles the steel reinforcement for 5 min for the RC pile and 1 min for the FRC alternatives while two workers are performing tasks in the vicinities.

The magnitudes quantified for each measurable indicator (designed as measurable) are presented in Table 6. Based on the results presented in Table 6, the following can be noted:

- *Direct costs* increase by 1.9% and decrease by 2.4% for the SFRC and PFRC alternatives, respectively, in comparison to the RC traditional solution according to the material costs presented in Table 3. The FRC piles are reinforced throughout their entire length. In Section 5, other associated costs for the reinforcement are analyzed to allow quantification of the effect of this variable.
- Regarding the environmental indicators, *energy consumption* increases by 2.8% for the SFRC alternative, whereas it decreases by 5.1% when PFRC is considered as the reinforcement. This is related to the manufacturing processes of each type of fiber. A similar tendency was found for the *water consumption*, for which a 3.6% (SFRC) increase and a 14.5% (FRC) decrease of water consumption was estimated. For contextualizing purposes, the reduction in water consumption in the case where polymeric fibers were used would be as much as 600 m^3 (600,000 L) of the water consumption savings. Finally, it was found that the CO_2-equivalent (CO_2-eq) emissions could be reduced by 5.1% (SFRC) and 7.5% (PFRC) with respect to the RC solution.
- A 34.4% reduction to the risk exposition (ORI-based quantification) was observed for the FRC alternatives. Besides the social implication, this reduction could be directly considered as an economical benefit (or saving) when establishing the cost of insurance.

Table 6. Quantification of measurable indicators (per pile) according to reinforcement alternative

Indicators	RC	SFRC	PFRC
I_1. Direct costs (k€)	0.86	0.88	0.84
I_2. Nonacceptance costs (points)	—	—	—
I_3. Durability costs (points)	—	—	—
I_4. Time (points)	—	—	—
I_5. Energy consumption (GJ)	17.75	18.24	16.84
I_6. Water consumption (m^3)	22.0	22.8	18.8
I_7. CO_2 emissions (TonCO_2-equivalent)	2.14	2.03	1.98
I_8. ORI (weighted person-hours/pile)	0.032	0.021	0.021
I_9. Building site space (points)	—	—	—
I_{10}. New solutions (points)	—	—	—

Results and Discussion

The satisfaction of each of the 10 indicators established in Table 1 is computed by means of the value functions defined in Section 2.4 and the indicators' magnitudes presented in Table 6. The requirements' satisfaction is assessed by considering the weights' set listed in Table 1. The results are presented in

Table 7. Global I_S and satisfaction indexes of indicators and requirements for three alternatives

	Value (satisfaction) of each component													
Alternative	VI_1	VI_2	VI_3	VI_4	VI_5	VI_6	VI_7	VI_8	VI_9	VI_{10}	VR_1	VR_2	VR_3	I_s
RCP	0.75	0.75	0.50	0.75	0.51	0.51	0.51	0.60	0.50	0.50	0.69	0.51	0.55	0.60
SFRCP	0.68	0.75	0.75	1.00	0.46	0.45	0.59	0.73	1.00	0.75	0.81	0.52	0.81	0.73
PFRCP	0.81	0.75	1.00	1.00	0.58	0.70	0.61	0.73	1.00	1.00	0.91	0.62	0.87	0.82

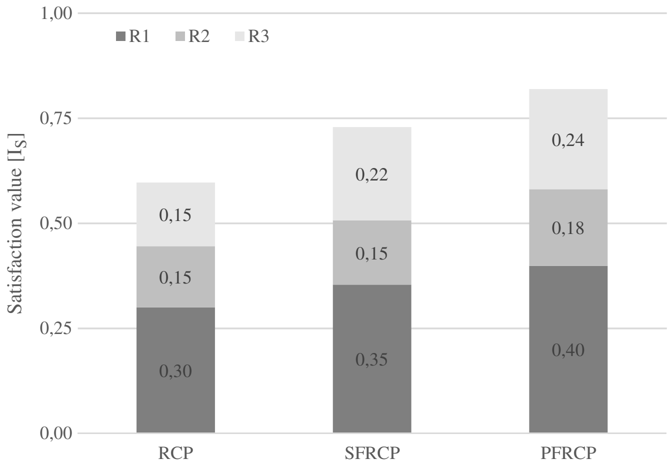

Fig. 4. Weighted requirements' satisfaction ($\alpha \cdot VR$) and sustainability indexes (I_s) for each alternative.

Table 7 along with the sustainability index (I_s) of each alternative analyzed.

In light of the results presented in Table 7 and depicted in Fig. 4, the following observations can be noted:

- The PFRCP emerged as the most sustainable solution ($I_s = 0.82$) as it performed more efficiently in the three pillars of sustainability with respect to the other alternatives ($I_s = 0.60$ for RCP and $I_s = 0.73$ for SFRCP). From both the economic (R_1) and social (R_3) perspectives, the PFRCP alternative presents satisfaction values higher than 0.85, and consequently, efforts to improve these requirements can be costly and/or difficult to implement. Conversely, the environmental pillar presents scope for enhancement, particularly with those indicators related to energy consumption (I_5) and CO_2-eq emissions (I_7), both of which are associated with industrial and manufacturing processes of the materials and specifically, the fibers.
- Considering the steel-based concrete reinforcement alternatives from an economic perspective (R_1), SFRCP ($VR_1 = 0.81$) resulted in higher satisfaction with respect to RCPs ($VR_1 = 0.69$). Accordingly, although the RCPs presented greater satisfaction in terms of *direct costs* ($VI_1 = 0.75$)—steel fibers are more expensive (in volume) than steel rebars—the remaining of the economic indicators (I_2–I_4) showed enhanced performance in the case of SFRCPs. The latter is because the *construction time* criterion (C_2) was assigned by the experts with a relatively high weight (31.2%), thus reducing the impact of the *cost* criterion (68.8%). Accordingly, construction *time* (I_4) benefits from drastic reductions when fibers are used, which leads to a satisfaction of $VI_4 = 0.75$ for RCPs and $VI_4 = 1.00$ for FRCPs. Moreover, the performance of the SFRCPs in the *durability costs* (I_3) also contribute to this enhanced satisfaction of SFRCPs. Note that even nowadays, the decision is based on the *direct costs'* satisfaction, and thus, the RCPs solution is chosen preferentially over SFRCPs when from an integrated economic life-cycle point of view, the decision could be the opposite, which emphasizes the requirement for MCDM approaches as presented in this study.
- The environmental requirement (R_2) appeared to be the pillar with the lowest embedded satisfaction ($V_{R2} = 0.51$, 0.52, and 0.62 for the RCPs, SFRCPs, and PFRCPs, respectively). Beyond improving the manufacturing processes of the reinforcements, the use of recycled concrete aggregates for the production of concrete (Ortiz et al. 2017) is proposed as an additional measure to improve the outcome of this requirement. To the best of the authors' knowledge, recycled concrete aggregates were used satisfactorily in pile foundations in previous experimental programs (Kim et al. 2012; Medeiros-Junior et al. 2016; Tam et al. 2018).
- For the social requirement (R_3), both FRPCP alternatives presented similar levels of performance with a VR_3 of 0.81 and 0.87 for steel and polymeric fibers, respectively, and considerably higher for RCPs ($VR_3 = 0.55$) as a consequence of evaluation of the risks (I_8) and required space for the building process (I_9) as well as the innovations (I_{10}). These results were initially expected; however, no previous objective evaluation and quantification has been conducted and reported in the scientific literature.

Finally, as the decisions made by the construction sector are primarily motivated by the economic aspects, a sensitivity analysis considering a range of costs of the reinforcing materials (1.00–1.25 €/kg for the steel bars, 1.00–1.75 €/kg for steel, and 3.30–4.25 €/kg polymeric fibers) was conducted to quantify the robustness of the sustainability index achieved by each alternative (Appendix IV).

Accordingly, the results of this sensitivity analysis confirmed that the I_s presented in Table 7 for costs, which were established as representative for the reinforcing materials (Table 3), are rather insensitive to this variable. I_s values within the range 0.59–0.61 for RCPs, 0.71–0.73 for SFRCPs, and 0.81–0.82 for PFRCPs were derived from this study.

Thus, the order of these alternatives was confirmed based on the decision being reached regarding the sustainability parameters.

Conclusions

Pile foundations are widely used in building construction, with CFA RCPs being among those most frequently considered due to cost and technical aspects. Accordingly, due to the low to moderate structural demands of these types of foundations, structural steel and polymeric fibers emerge as a potential replacement for traditional steel bars used for concrete reinforcement with benefits from the sustainability perspective. Previous studies have focused on the direct costs of piles disregarding other economic indicators along with environmental and social issues. Consequently, solutions from the last century continue to be used for the construction of piles, and the requirement for innovative alternatives that would improve the environmental and social negative impacts of the current solutions are not being considered.

Hence, this study focused on the design of a MCDM model for the assessment of the sustainability of different reinforcement

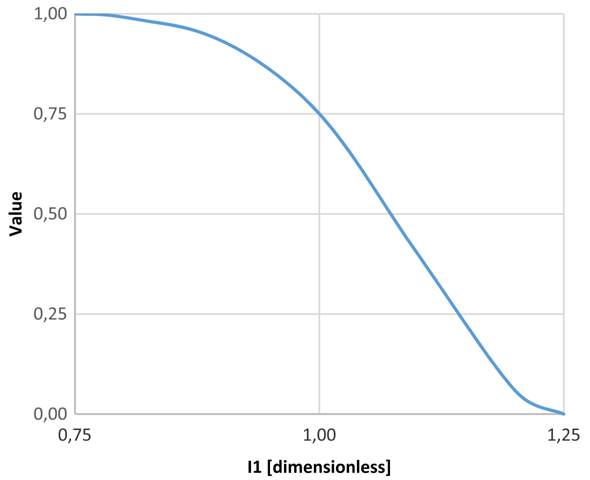

Fig. 5. Value function of I_1.

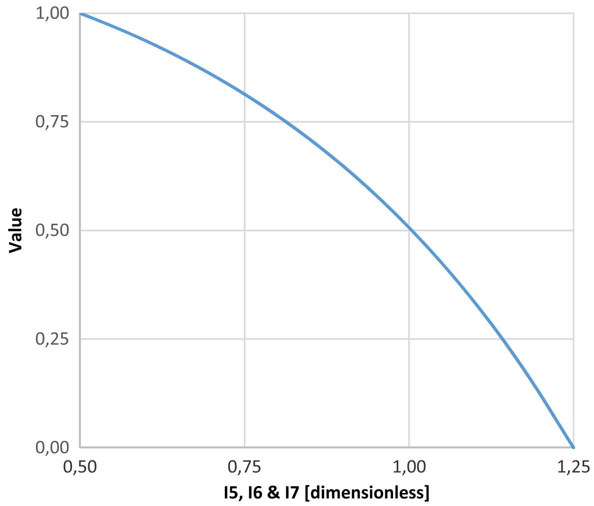

Fig. 6. Value function of I_5, I_6, and I_7.

alternatives for foundation concrete piles—for example, steel bars and steel and polymeric structural macrofibers. The MIVES method was considered for this purpose and experts' seminars were conducted to identify and establish the most representative economic, environmental, and social indicators, as well as the respective weights' sets to perform this sustainability analysis. The resulting model is consistent and could be applied to other case studies. Nevertheless, these new applications would imply verifying the proposed requirements' tree and if necessary, adequate indicators and weights to any specific particularities from the new context.

The suitability of this MCDM model for this purpose was confirmed by means of a case study in which the sustainability of the traditional steel bar and SFRCP/PFRPC concrete foundation piles was assessed. Based on the obtained results, the following conclusions can be drawn:

- PFRCP was found to be the most sustainable ($I_s = 0.82$), with both the economic and social requirement performing with high satisfaction indexes due to the attractive cost-structural efficiency ratio, high durability, and minimal risks during construction.
- SFRPCs showed higher sustainability ($I_s = 0.73$) in comparison to those reinforced with steel bars ($I_s = 0.60$). The former performed better economically, including direct, nonconformity and durability costs, and time; however, the latter presented greater satisfaction in terms of direct costs. This fact could prove that the construction market is driven by direct costs, whereas other costs and both environmental and social requirements are disregarded or not suitably measured.
- The environmental indicators highlight opportunities for improvement in this field for the three reinforcement alternatives. Particularly, production and manufacturing processes of bars and fibers should be enhanced and optimized for this purpose.

This type of sustainability-driven multicriteria analysis has been incorporated in several technical documents—for example, *fib* bulletins 83 (*fib* 2017) and 88 (*fib* 2018)—that focus on precast concrete elements and structural concrete design guidelines such as the Spanish Standard EHE-08 (MP 2008) to facilitate the decision-making processes for stakeholders. Public managers of the Spanish infrastructure, such as hydroelectric, sewerage, and water supply, are currently using this methodology to prioritize investments.

Appendix I. Value Functions for I1 and I5–I7

The value functions for I1 and I5–I7 are presented in Figs. 5 and 6, respectively.

Appendix II. Local Weights Assigned by Experts in First Round

Requirements, criteria, and indicators	Weights assigned by panelist (%)																	Mean	Median	Median absolute deviation (%)	Consensus
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17				
Economic	60	60	90	65	40	50	40	35	20	50	25	45	55	28	40	40	40	**46.1**	42.5	12.3	No
Environmental	20	20	5	12	20	30	30	40	45	30	40	25	25	39	40	20	30	**27.7**	27.5	8.8	Yes
Social	20	20	5	23	40	20	30	25	35	20	35	30	20	33	20	40	30	**26.2**	24	7.4	Yes
Costs	50	65	50	50	60	60	70	70	90	70	70	60	80	75	80	80	70	**67.6**	70	8.8	Yes
Execution time	50	35	50	50	40	40	30	30	10	30	30	40	20	25	20	20	30	**32.4**	30	8.8	Yes
Construction process costs	35	40	30	35	40	50	35	50	25	30	40	60	30	50	70	50	50	**42.4**	40	9.4	Yes
Nonacceptance costs	30	30	40	45	10	20	20	20	5	30	10	20	20	15	20	25	20	**22.3**	20	7.1	Yes
Durability	35	30	30	20	50	30	45	30	70	40	50	20	50	35	10	25	30	**35.3**	32.5	10.7	No
Resource consumption	50	40	90	80	50	50	50	65	25	50	40	70	70	55	30	60	50	**54.4**	50	12.1	No
Emissions	50	60	10	20	50	50	50	35	75	50	60	30	30	45	70	40	50	**45.6**	50	12.1	No
Energy consumption	100	65	10	70	50	40	50	70	60	70	55	70	80	50	70	70	70	**61.8**	67.5	13.1	No
Water consumption	0	35	90	30	50	60	50	30	40	30	45	30	20	50	30	30	30	**38.2**	32.5	13.1	No
Occupational risks during construction	20	50	50	60	50	50	35	45	80	30	65	50	45	60	60	40	70	**50.6**	50	10.6	No
Third-party effects	5	30	40	25	25	25	40	30	5	40	15	30	35	30	10	40	10	**25.6**	30	9.7	Yes
Technology innovation	75	20	10	15	25	25	25	25	15	30	20	20	20	10	30	20	20	**23.8**	20	7.4	Yes

Appendix III. Local Weights Assigned by Experts in Second Round

Requirements, criteria, and indicators	Weights assigned by panelist (%)																	Mean	Median	Median absolute deviation (%)	Consensus
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17				
Economic	50	50	60	55	45	45	44	40	25	45	25	45	50	33.3	40	46.5	45	**43.8**	45	6.1	Yes
Environmental	25	25	20	22	20	30	28	35	40	30	40	25	25	33.3	35	25	30	**28.7**	26.5	5.2	Yes
Social	25	25	20	23	35	25	28	25	35	25	35	30	25	33.3	25	28.5	25	**27.5**	25	3.3	Yes
Costs	65	66	65	65	60	65	70	70	85	70	70	65	70	70	70	73	70	**68.8**	70	3.4	Yes
Execution time	35	34	35	35	40	35	30	30	15	30	30	35	30	30	30	27	30	**31.2**	30	3.4	Yes
Construction process costs	40	40	40	45	40	45	45	45	25	40	35	50	35	45	45	46	45	**41.5**	42.5	4.3	Yes
Nonacceptance costs	25	24	25	25	20	20	20	20	5	25	20	20	20	20	20	23	20	**20.7**	20	2.5	Yes
Durability	35	36	35	30	40	35	35	35	70	35	45	30	45	35	35	31	35	**37.8**	35	4.4	Yes
Resource consumption	50	45	60	60	50	55	50	60	30	50	45	60	60	55	50	55	55	**52.4**	52.5	5.7	Yes
Emissions	50	55	40	40	50	45	50	40	70	50	55	40	40	45	50	45	45	**47.6**	47.5	5.7	Yes
Energy consumption	60	63	10	65	60	50	50	65	60	60	60	65	70	60	65	65	60	**58.1**	60	6.4	Yes
Water consumption	40	37	90	35	40	50	50	35	40	40	40	35	30	40	35	35	40	**41.9**	40	6.4	Yes
Occupational risks during construction	50	50	50	56	50	50	40	45	75	40	50	50	45	55	50	45	50	**50.1**	50	4.2	Yes
Third-party effects	25	27	30	25	25	25	35	30	5	35	25	25	30	25	25	30	25	**26.3**	25	3.6	Yes
Technology innovation	25	23	20	19	25	25	25	25	20	25	25	25	25	20	25	25	25	**23.6**	25	1.4	Yes

Appendix IV. Global I_S and Satisfaction Indexes Resulting from the Sensitivity Analysis

Alternative	Value (satisfaction) of each component													
	VI_1	VI_2	VI_3	VI_4	VI_5	VI_6	VI_7	VI_8	VI_9	VI_{10}	VR_1	VR_2	VR_3	I_s
RCP	0.75	0.75	0.50	0.75	0.51	0.51	0.51	0.60	0.50	0.50	0.69	0.51	0.55	0.60
SFRCP	0.68	0.75	0.75	1.00	0.46	0.45	0.59	0.73	1.00	0.75	0.81	0.52	0.81	0.73
PFRCP	0.81	0.75	1.00	1.00	0.58	0.70	0.61	0.73	1.00	1.00	0.91	0.62	0.87	0.82
RCP (2)	0.79	0.75	0.50	0.75	0.51	0.51	0.51	0.60	0.50	0.50	0.70	0.51	0.55	0.60
RCP (3)	0.73	0.75	0.50	0.75	0.51	0.51	0.51	0.60	0.50	0.50	0.68	0.51	0.55	0.59
SFRCP (2)	0.75	0.75	0.75	1.00	0.46	0.45	0.59	0.73	1.00	0.75	0.83	0.52	0.81	0.73
SFRCP (3)	0.52	0.75	0.75	1.00	0.46	0.45	0.59	0.73	1.00	0.75	0.76	0.52	0.81	0.71
PFRCP (2)	0.83	0.75	1.00	1.00	0.58	0.70	0.61	0.73	1.00	1.00	0.91	0.62	0.87	0.82
PFRCP (3)	0.77	0.75	1.00	1.00	0.58	0.70	0.61	0.73	1.00	1.00	0.90	0.62	0.87	0.81

Note: RCP = reinforced concrete piles with cage steel cost of 1.17 €/kg; SFRCP = steel fiber reinforced concrete piles with fiber steel cost of 1.25 €/kg; PFRCP = polypropylene fiber reinforced concrete with fiber polypropylene cost of 3.5 €/kg; RCP (2) = reinforced concrete piles with a cage steel cost of 1 €/kg; RCP (3) = reinforced concrete piles with cage steel cost of 1.25 €/kg; SFRCP (2) = steel fiber reinforced concrete piles with fiber steel cost of 1 €/kg; SFRCP (3) = steel fiber reinforced concrete piles with a fiber steel cost of 1.75 €/kg; PFRCP (2) = polypropylene fiber reinforced concrete with fiber polypropylene cost of 3.3 €/kg; and PFRCP (3) = polypropylene fiber reinforced concrete with fiber polypropylene cost of 4.25 €/kg.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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