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Sustainability-Oriented Multi-Criteria Analysis of Different Continuous Flight Auger Piles

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Abstract: With increasing construction activity and concrete consumption globally, the economic, environmental, and social impacts of human activities continue to increase rapidly. Therefore, it is imperative to assess the choice and construction of each structure and structural component from a sustainability-based perspective. In this study, such a multi-criteria decision-making approach using the MIVES method is applied to the choice of grouped continuous flight auger (CFA) piles. Different alternatives of CFA piles are studied: length (10 and 20 m), reinforcement (steel cage reinforcement and structural fibers), and aggregates (natural crushed aggregates and recycled aggregate concrete sourced from stationary and mobile recycling plants), based on experimentally verified mix designs. All alternatives were analyzed considering economic, environmental, and social requirements, using a decision-making tree with eight criteria and eleven indicators, with weights assigned by an expert panel. The results of the analysis showed a clear advantage in terms of all three sustainability requirements for CFA piles with steel fibers and recycled aggregate concrete, with all solutions with steel cage reinforcement having significantly lower values of the sustainability index. Such results demonstrate the need for implementing innovative solutions even in structural members such as CFA piles that are often considered in insufficient detail.

Keywords: MIVES; fiber reinforced concrete; steel fibers; recycled aggregate; recycled aggregate concrete; decision-making; optimal solution

1. Introduction

The construction industry is one of the human activities with the largest impact on the environment, being responsible for the consumption of 40% of the annual raw stone, gravel, and sand production, 16% of annual water consumption, and 40% of annual energy consumption [1]. Additionally, large quantities of construction and demolition waste (CDW) are generated each year, e.g., more than 850 million tons per year in the EU [2].

As such, the construction industry has entered into the focus of international development plans and transitions to circular economy models. For example, two of the UN Sustainable Development Goals [3] are directly related to the built environment: "Industry, Innovation and Infrastructure" and "Sustainable Cities and Communities". The EU has launched several initiatives, such as the waste management directive [4], that set an aim of recycling and recovery of, at least, 70% of CDW by 2020, or the EU Action plan for the Circular Economy [5].

To achieve these ambitious goals, innovations in all aspects of the construction process are mandatory. This includes all the life-cycle stages, from design, across materials, and to construction, use, and end-of-life. In order to facilitate and speed up the market uptake of innovation, practical examples and case studies are of great importance. Additionally,

innovations should focus on all types of applications and structures, not only high-end products in order to demonstrate their feasibility across the entire spectrum of construction industry activities.

In light of this overarching goal, in this study, a practical sustainability-oriented multi-criteria analysis was performed on continuous flight auger (CFA) piles. Piles, in general, are a ubiquitous structural member to which little attention is paid, in part because of their "invisibility" after construction. However, beside the relevant structural task developed (i.e., to guarantee the stability of a building during service), they can be responsible for the consumption of a large amount of materials, and their construction can be time-consuming, as well as dangerous from a health and safety perspective. Therefore, any innovation achieved in pile design and construction can lead to the accumulation of significant benefits.

In particular, CFA piles are a subtype of bored piles [6], considered a cost- and time-efficient solution for urban areas [7]. They are typically constructed as steel-cage reinforced piles (RCPs) by first conducting the excavation using a continuous flight auger drill, followed by pouring of the concrete through the hollow stem of the CFA and its extraction, and finally, by the placement of the reinforcement cage into the poured pile, Figure 1. At the same time, the construction process of CFA piles is accompanied by large uncertainties related to the pile's bearing capacity and owing to inspection difficulties and requirements for adequate concrete workability [7]. Additionally, machinery such as bulldozers may be required to push the reinforcement cage into the poured pile and the storage of the reinforcement cages leads to additional construction site occupancy. As such, the construction process can be dangerous for the workers involved.
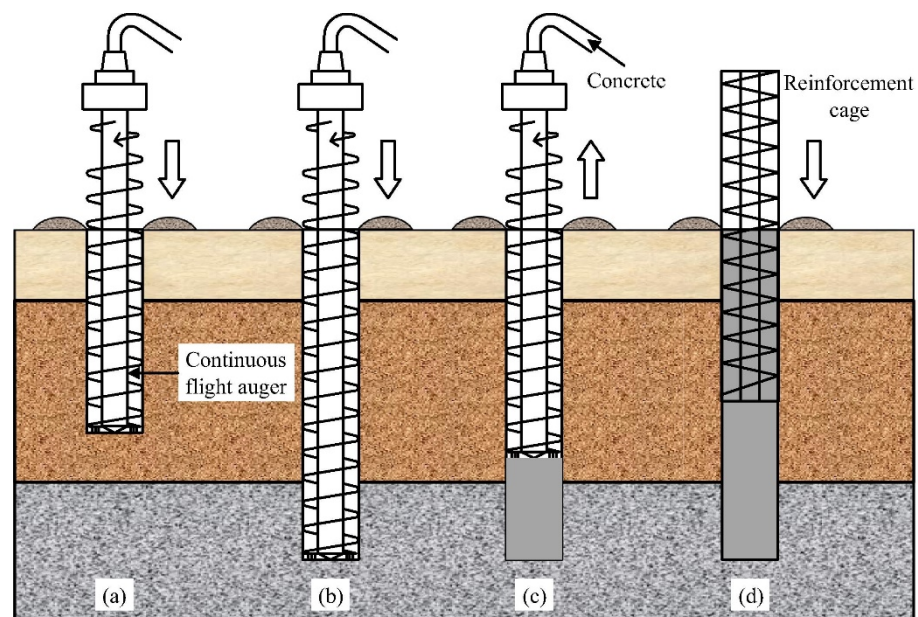

Figure 1. Schematic of CFA pile installation [8], including the drilling into the ground of the CFA pile as in (**a**,**b**), followed by the pumping of concrete (**c**), and insertion of a reinforcement cage (**d**).

The innovation in CFA piles can be achieved on several levels: design, materials, and construction, and within this study, all three levels are considered.

Firstly, the replacement of natural aggregates with recycled concrete aggregates obtained from CDW recycling is considered. Namely, recycled concrete aggregate has been heavily investigated as an alternative to natural aggregate use that can lead to waste reduction and natural resource conservation. The research on recycled concrete aggregate has covered both material and structural aspects to the point that its use in recycled aggregate concrete (RAC) for structural applications is considered for new structural codes, such as the new Eurocode 2 and the *fib* Model Code 2020 [9]. The challenges posed by RAC, such as a lower modulus, higher shrinkage, and creep, are less important for structural

members such as piles and, therefore, their use in such applications can be very beneficial. Additionally, when an existing structure is demolished, a large quantity of CDW is directly available, and if a new structure is built in its place, mobile crushers can be used to produce recycled concrete aggregate on site for immediate use. This would have an additional impact on reduced transportation distances, which are critical for maintaining any environmental benefits of RAC [10].

Secondly, structural fibers are used in order to eliminate the need for using steel-cage reinforcement. Namely, the use of fibers in fiber reinforced concrete (FRC) has seen great advances in previous years with successful applications in slabs on grade [11], precast tunnel segments [12], and pipes [13], and even the joint use of RAC and FRC in a pilot test on pile walls [14] among many others. This has been possible due to the benefits enabled by FRC in terms of post-cracking strength, crack control, and fatigue [15]. Finally, structural design models for FRC are available through codes such as the *fib* Model Code 2010 [16].

Consequently, in this study, alternatives to CFA piles considering traditional natural aggregate concrete (NAC) with steel-cage reinforcement, RAC piles with steel-cage reinforcement, and FRC-RAC piles without steel-cage reinforcement are considered. The innovation they bring to CFA piles can be considered on several levels. On the design level, the use of FRC can ensure better continuity of the piles during placing (a common problem with longer CFA piles while placing steel reinforcement), thus potentially enabling the reduction in high safety factors associated with CFA design. On the material level, traditional materials and natural resources can be replaced by recycled and more sustainable materials. Finally, during construction, the elimination of steel reinforcement facilitates and shortens construction time, eliminating the need for heavy machinery for reinforcement placement, freeing up construction site space for reinforcement storage and leading to a safer work environment.

Finally, to provide objectiveness to those statements, all of these potential benefits need to be quantified. For this purpose, a multi-criteria decision-making method is necessary. Among the existing methods, one of the most suitable for this task is MIVES [17–22], a proven sustainability-oriented method that enables easy consideration of all three pillars of sustainability—economic, environmental, and social. The efficiency and robustness of this method, in the context of engineering, has been proven in other studies. For instance, it has been applied in the context of concrete elements [17,19,21], electricity generation systems [18], post-disaster housing technologies [20], or urban development [22].

2. System Boundaries and Choice of CFA Pile Alternatives

Within this study, three CFA pile solutions were considered:

- NAC piles with steel-cage reinforcement
- RAC piles with steel-cage reinforcement
- FRC-RAC piles without steel-cage reinforcement

For CFA pile solutions with RAC, two sourcing strategies for recycled concrete aggregate were considered:

- Mobile recycling plant used on the construction site (recycling of demolition waste of an existing structure at the same location);
- Stationary recycling plant processing municipal CDW, away from a construction site.

The geometry of the piles was selected based on a case study of a school building in Canovellas, Spain, described in detail by Pons et al. [23]. The piles had a diameter of 450 mm. Within the steel-cage reinforcement solutions, longitudinal reinforcement consisting of 6Ø16 mm bars and transverse reinforcement consisting of Ø8 stirrups spaced at 250 mm, was considered [23].

Two CFA pile lengths were assumed: 10 and 20 m. This was done in order to assess the sensitivity of the solution to pile length since lengths greater than 12 m require welding of reinforcement, more construction site occupancy, longer construction time, and higher risks of non-compliance in execution.

Finally, for the concrete mixes, experimental results by Ortiz et al. [14] were used. Concrete mixes NA/SC 12 (NAC), RA/SC 12 (RAC), and FRC-RA/SC 12-35 (FRC-RAC) were considered. The mix design of the concretes is presented in Table 1, whereas the compressive strength and workability are presented in Table 2. It can be seen that all three mixes have comparable compressive strength and workability, enabling their use for the same application. Although the workability of the mixes might not be adequate for direct use in CFA, it could have been achieved with an increase in plasticizer content. Thus, for the purposes of this study, the mixes were considered as adequate and enabling meaningful comparison since the piles produced from these concretes would possess the same mechanical properties. Additionally, only coarse recycled concrete aggregate is used (i.e., aggregate size > 4 mm), in line with previous works that show the use of fine recycled concrete aggregate (<4 mm) poses challenges in terms of workability, due to their extremely high water absorption, shape, and texture [24].

Table 1. Mix proportions of the considered concretes.

| Mix | Cement (kg/m^3) | Water (kg/m^3) | Sand (kg/m^3) | Coarse Aggregate | | Steel Fibers (kg/m^3) | Plasticizer (kg/m^3) |
				NA [1]	RCA [2]		
NA/SC 12	355	170	1230	580	–	–	9.0
RA/SC 12	370	165	1200	–	590	–	9.4
FRC-RA/SC 12–35	370	175	1260	–	520	20	9.9

[1] Natural aggregates; [2] Recycled concrete aggregate.

Table 2. Workability and compressive strength of the concretes.

| Mix | Slump (mm) | f_{cm} [1] (MPa) | |
		7 Days	28 Days
NA/SC 12	55	26.21	35.03
RA/SC 12	55	24.62	33.16
FRC-RA/SC 12–35	55	30.32	37.33

[1] Compressive strength.

Therefore, two groups of CFA piles were considered for comparison: 10 and 20 m piles. They were analyzed and compared separately, as each length was assumed as a separate functional unit. In other words, a 10 m pile cannot be compared with a 20 m pile as the 10 m pile cannot fulfill the same structural function as the 20 m pile. The main characteristics of the alternatives are summarized in Table 3.

Table 3. Main parameters varied for the CFA pile alternatives.

	Alternative	Steel-Cage Reinforcement	Recycling Plant	Mix	Pile Length
1	NAC-10	Yes	–	NA/SC 12	10
2	RAC-10-MP	Yes	Mobile	RA/SC 12	10
3	RAC-10-SP	Yes	Stationary	RA/SC 12	10
4	FRC-RAC-10-MP	No	Mobile	FRC-RA/SC 12–35	10
5	FRC-RAC-10-SP	No	Stationary	FRC-RA/SC 12–35	10
6	NAC-20	Yes	–	NA/SC 12	20
7	RAC-20-MP	Yes	Mobile	RA/SC 12	20
8	RAC-20-SP	Yes	Stationary	RA/SC 12	20
9	FRC-RAC-20-MP	No	Mobile	FRC-RA/SC 12–35	20
10	FRC-RAC-20-SP	No	Stationary	FRC-RA/SC 12–35	20

The system boundaries are shown in Figure 2. The methodology for considering each life cycle stage in Figure 2 is explained in the following sections. In particular, the exclusion of the use, demolition, transport of demolition waste, and disposal phases were

not included as they were considered equal for all the alternatives. Keeping in mind the specific loads and conditions to which piles are exposed to, this was deemed acceptable. The functional unit (FU) for each case was a single pile (with a length of 10 or 20 m).
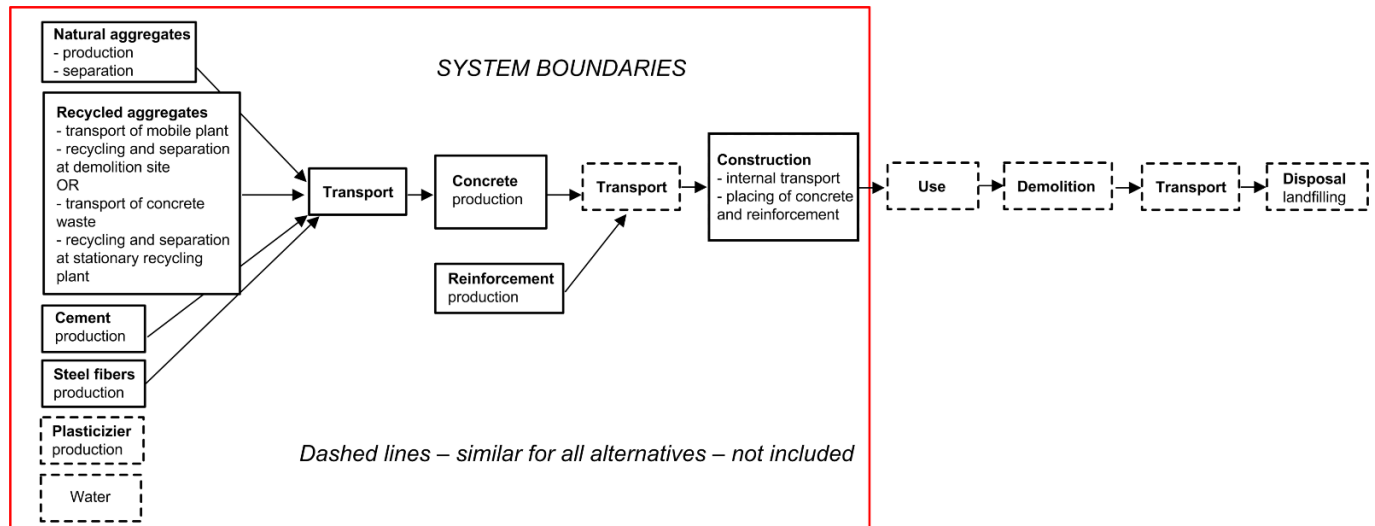

Figure 2. System boundaries.

3. Methodology

3.1. MIVES Method

Until the present, several multi-criteria decision-making methodologies have been developed to objectively consider different factors when making choices between various alternatives. Even though these tools are fundamental in any discipline as a means of making more informed and objective decisions, they are particularly relevant in the context of sustainability because they allow consideration of a multiplicity of factors, including economic, environmental, and social elements.

Among the multi-criteria decision-making methods that have been developed until now, one that has been frequently used in the context of the construction industry is MIVES (from the Spanish *Modelo Integrado de Valor para Evaluaciones de Sostenibilidad*). Its versatility and flexibility have been demonstrated in various fields related to the construction industry, such as urban development [22], buildings [21,25], or energy infrastructure [18].

In MIVES, each of the alternatives of a specific situation is evaluated in order to assess its level of sustainability, which is based on the value of a final index. The defining characteristics of MIVES, that allow obtaining this index, are the use of a decision-making tree to structure the decision and value functions to normalize the indicators. These elements will be described in the following subsections in more detail.

3.2. Decision-Making Tree and Weight Assessment

The foundational part of the MIVES method is the decision-making tree. For this study, a decision-making tree was conceptualized, covering three requirements (economic, environmental, and social, i.e., *R1*, *R2*, and *R3*, respectively), 8 criteria (*C1*–*C8*, described below), and 11 indicators (*I1*–*I11*, described below). The decision-making tree is shown in Table 4, along with the weights assigned across requirements, criteria, and indicators.

Table 4. Decision-making tree considered in the study (bold text represents the assigned weights).

Requirements	Criteria	Indicators	Units
*R*1. Economic **(41%)**	*C*1. Costs **(64%)**	*I*1. Direct costs **(75%)** *I*2. Non-acceptance costs **(25%)**	EUR points
	*C*2. Construction time **(36%)**	*I*3. Construction time **(100%)**	points
*R*2. Environmental **(36%)**	*C*3. Environmental impact **(41%)**	*I*4. Normalized emissions **(100%)**	–
	*C*4. Resource use **(29%)**	*I*5. Non-renewable energy resource use **(38%)** *I*6. Renewable energy resource use **(31%)** *I*7. Water consumption **(31%)**	MJ MJ kg
	*C*5. Waste generation **(30%)**	*I*8. Solid waste generation **(100%)**	kg
*R*3. Social **(23%)**	*C*6. Health and safety **(47%)** *C*7. Third-party effects **(31%)** *C*8. Innovation **(22%)**	*I*9. ORI index **(100%)** *I*10. Building site space **(100%)** *I*11. Innovation potential **(100%)**	weighted person-h points points

The weights across requirements, criteria, and indicators were assigned by a panel of experts. Six experts with a civil engineering background were asked to fill a spreadsheet where they had to assign the weights to the different components of the decision-making tree. Apart from assigning the weight, they were also asked to determine the certainty with which they were doing such assignation. In particular, a point scale ranging from 1 to 3 was used, where 1 meant unsure, and 3 very sure. Subsequently, the weights provided directly by the experts were further weighted using their answers on the 3-point scale. For example, if one expert assigned a weight of 60% to criterion *C*4 with an answer of 1 (unsure) and another expert assigned a weight of 20% with an answer 3, the resulting weighted weight of *C*4 would be $(1 \times 60\% + 3 \times 20\%)/(1 + 3) = 30\%$.

The economic requirement (*R*1) is measured with two criteria: *C*1, costs, and *C*2, construction time. They are defined as follows:

- The first criterion, costs, includes two indicators: direct costs and non-acceptance costs. Indicator *I*1, direct costs, includes the costs of the material for each structural element, as well as the transportation costs. The second indicator, *I*2, refers to the costs that would be incurred in case of non-compliance with execution requirements;
- The second criterion consists of only one indicator, *I*3, time. This indicator is considered as a proxy measure of the economic costs incurred during the construction phase (reinforcement storage, machinery, and personnel requirements during construction.

The environmental requirement (*R*2) is measured using three criteria: *C*3, environmental impact, *C*4, resource use, and *C*5, waste generation. They are defined as follows:

- Criterion *C*3, environmental impact, is measured using one indicator, *I*4, normalized emissions. The data sources and quantification of the indicator are explained in the following sections. The indicator consists of normalizing, through equal weights, environmental impacts calculated using the LCA methodology described in subsequent sections: global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), and photochemical ozone creation potential (POCP);
- Criterion *C*4, resource use, consists of three indicators: *I*5, non-renewable energy resource use, *I*6, renewable energy resource use, and *I*7, water consumption;
- Criterion *C*5, waste generation, consists of one indicator, *I*8, solid waste generated.

The social requirement (*R*3) is measured using three criteria: *C*6, health and safety, *C*7, third-party effects, and *C*8, Innovation. They are defined as follows:

- Criterion *C*6, health and safety, is measured using the Occupational Risk Index (ORI), which is an index to measure safety during project design and construction processes (Casanovas et al., 2014). It is based on the analysis of the activities carried out in these processes, the probability of certain risks, and the severity of their consequences. The

health and safety risks that are possible in the present work are: (1) collision with or entrapment by a moving load, due to its movement or detachment—Mechanical load handling, (2) blows to upper and lower limbs—Manual load handling, (3) cuts, blunt trauma, and other injuries due to light equipment—Work with light equipment, (4) Burns—Welding, (5) Traffic accident—Transport of equipment and materials to the construction site, (6) Same-level falls—All types of work, (7) Back injuries—Manual load handling. As reflected by Casanovas et al. [26], the last two risks, (6) and (7), are not considered in the calculation of the ORI;

- Criterion *C7*, third-party effects, is measured by examining the extension needed for the construction of the different alternatives. This is done through indicator *I10*, called Building site space;
- Criterion *C8*, Innovation, is measured through indicator *I11*, innovation potential. The relationship between innovation potential and sustainability has recently started to be acknowledged in the literature [27].

At this point, the authors would like to highlight the fact that the criteria and indicators defined in the decision-making tree do not intend to be exhaustive, but representative, of the most relevant impacts that need to be considered. Therefore, there may be other issues related to sustainability that arise from the various stages of the life-cycle of the alternatives considered that have not been incorporated in the study. In fact, one of the objectives of MIVES is to facilitate decisions and this involves, among others, defining a set of criteria that is not excessive in terms of number of indicators.

3.3. Value Functions

Within MIVES, value functions are used to convert the units of each indicator (Table 4) into a dimensionless form between 0 and 1. Subsequently, the values obtained using the value functions and the assigned weights are used to calculate the sustainability index I_s, also ranging from 0 to 1, but typically below 0.8 [28]. The general form of a value function, used to assess the value of satisfaction for indicator i, V_i, is the following [25,28]:

$$V_i = A + B \left[1 - e^{-K_i \left(\frac{|X_{i,\text{ind}} - X_{i,\text{min}}|}{C_i} \right)^{P_i}} \right] \tag{1}$$

where A is the value of V_i for $X_{i,\text{min}}$; $X_{i,\text{min}}$ is the minimum abscissa value of the indicator interval assessed; $X_{i,\text{ind}}$ is the abscissa value for the indicator being assessed; P_i is the shape factor that defines whether the curve is concave ($P_i < 1$), linear ($P_i = 1$), convex or S-shaped ($P_i > 1$); C_i approximates the abscissa at the inflection point; K_i tends toward V_i at the inflexion point; B is a factor that prevents the function from exceeding the range (0, 1):

$$B = \left[1 - e^{-K_i \left(\frac{|X_{i,\text{max}} - X_{i,\text{min}}|}{C_i} \right)^{P_i}} \right]^{-1}, \tag{2}$$

where $X_{i,\text{max}}$ is the indicator abscissa value that leads to a response value of 1 for increasing value functions. An illustration of value function shapes is provided in Figure 3.

Considering the indicators presented in Table 4, the following choices of value functions were adopted:

- Indicators *I1*, *I4*, *I5*, *I7*, and *I9* were modelled using a decreasing S-shaped function (DS). This function is useful when the values of the indicators can be considered to be within a minimum satisfaction range in terms of sustainability up to a certain point, where the function decreases more sharply.
- Indicators *I2*, *I3*, *I6*, *I8*, *I10*, and *I11* were modelled using linear functions. While an indicator with a decreasing function (DL) was used for *I2*, *I3*, *I6*, *I8*, and *I10*, an increasing linear function (IL) was defined for indicator *I11*. Linear functions are commonly used when there are no significant changes in terms of sustainability value between consecutive values of the indicator.
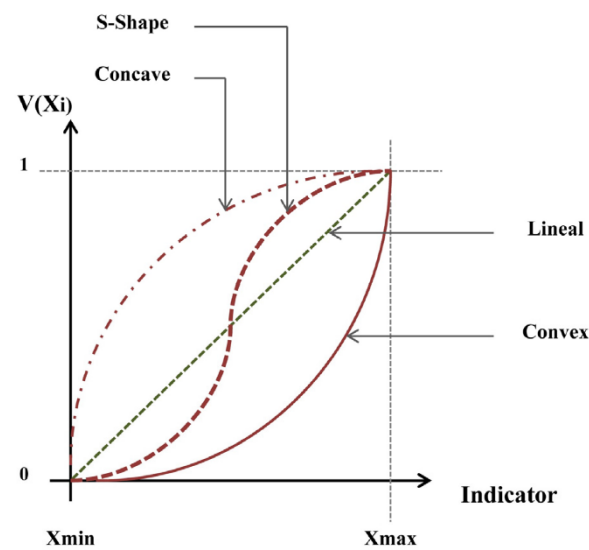
Figure 3. Value function shapes [25].

4. Multi-Criteria Analysis

4.1. Data Sources for Analysis

When quantifying the indicators, a consistent and methodological use of databases for sourcing input data was followed as much as possible.

For economic indicators, the BEDEC database by ITeC [29] was used for costs of cement, steel reinforcement, steel fibers, sand, natural crushed aggregates, and recycled aggregates. As the BEDEC database pertains to Catalonia, Spain, it was considered as adequate for the purposes of the study and the case study considered. The unit prices of the materials are presented in Table 5.

Table 5. Unit prices of constituent materials for the concrete mixes.

Component	Price (EUR/kg)
Cement	0.0966
Sand 0/4 mm	0.0162
NA 4/12 mm	0.0162
RA 4/12 mm	0.0110
Steel reinforcement	1.1700
Steel fibers	1.2500

For transportation costs, the costs of diesel were taken according to official data by the Spanish Ministry of Transport, Mobility and Urban Agenda [30] as 1.1 EUR/L.

Data for environmental indicators was mostly obtained from the Ecoinvent V2.0 database [31–33] and from European manufacturers' Environmental Product Declarations (EPDs) [34,35] with the exception of the recycled concrete aggregate data (taken from Marinković et al. [10]). Impact category indicators chosen for their major contribution to green-house gasses and gasses released from burning fossil fuels (GWP, EP, AP, and POCP) were obtained either from EDPs (for cement and steel fibers) or calculated using an Excel-based software developed by the authors. In both cases, life cycle inventory (LCI) modeling and impact assessment (LCIA) was performed using LCA: namely, the attributional approach and cut-off for recycling within LCI and the CML (The Institute of Environmental Sciences of the Faculty of Sciences of Leiden University) baseline problem-oriented (mid-points) methodology for LCIA [36]. Data for resource use and solid waste generation are directly reported in the applied database, EPDs and literature. In the case of the mobile recycling plant, it was assumed that for each campaign of 2500 t, the mobile plant (20 t) was transported 100 km, whereas the obtained recycled concrete aggregate was

transported 25 km from the site to the concrete plant. Waste generated after recycling (fine particles) was transported 30 km to a landfill. In the case of a stationary recycling plant, it was assumed that concrete waste was transported 25 km from the demolition site to the recycling plant and 25 km from the recycling plant to the concrete plant. Waste generated in stationary recycling plants was assumed negligible. Transport distances for natural aggregate, steel fibers, and reinforcement were assumed as 100 km and for cement 50 km. All transport distances were doubled to account for the return trip and a medium-sized truck 16–32 t was used as the transportation type.

Data for the social indicator *I9* was obtained from the database by CYPE Ingenieros [37], which provides information on times needed in the construction processes of different structural elements. As for indicators *I10* and *I11*, they were assigned through expert evaluations as it was described above. Note that, among the experts, there was a civil engineer specialized in social aspects related to construction engineering.

4.2. Quantification of Indicators and Calculation of Value Functions

Indicator values were assessed separately for 10 and 20 m-long piles.

The values of indicators for each alternative for 10 and 20 m-long piles are presented in Tables 6 and 7, respectively. The direct costs (*I1*) were calculated using the data presented in Section 4.1 and the concrete mixes presented in Section 2. Non-acceptance costs (*I2*) were assessed as higher for 20 m-long piles, for piles with steel-reinforcement cages (due to potential placement problems) and with recycled aggregates (due to potential quality control problems). Time (*I3*) was assessed as longer for 20 m-long piles and for piles with steel-cage reinforcement.

Table 6. Indicator values for 10 m-long piles.

	Indicators	Units	NAC-10	RAC-10-MP	RAC-10-SP	FRC-RAC-10-MP	FRC-RAC-10-SP
I1	Direct costs	EUR	247.4	266.2	243.3	167.2	147.1
I2	Non-acceptance costs	points	2	4	3	2	1
I3	Construction time	points	3	3	3	1	1
I4	GWP	$kgCO_2$-eq.	617.6	614.0	625.3	548.6	558.5
	EP	$kgPO_4^{3-}$-eq.	0.246	0.233	0.242	0.19	0.198
	AP	$kgSO_2$-eq.	1.457	1.388	1.441	1.178	1.224
	POCP	kgC_2H_4-eq.	0.217	0.209	0.214	0.127	0.132
I5	Non-renew. en. res. use	MJ	4753.0	4537.7	4686.7	3363.6	3494.9
I6	Renew. en. res. use	MJ	169.6	173.9	173.9	131.2	131.2
I7	Water consumption	kg	5052.7	5281.5	5281.5	4960.0	4960.0
I8	Solid waste generation	kg	28.5	654.1	28.6	586.4	35.0
I9	ORI index	w. p.-h	0.075	0.076	0.076	0.041	0.041
I10	Building site space	points	2	2	2	1	1
I11	Innovation potential	points	1	2	3	2	3

Table 7. Indicator values for 20 m-long piles.

	Indicators	Units	NAC-20	RAC-20-MP	RAC-20-SP	FRC-RAC-20-MP	FRC-RAC-20-SP
I1	Direct costs	EUR	497.5	535.0	489.3	334.5	294.2
I2	Non-acceptance costs	points	3	5	4	2	1
I3	Construction time	points	5	5	5	1	1

Table 7. *Cont.*

	Indicators	Units	NAC-20	RAC-20-MP	RAC-20-SP	FRC-RAC-20-MP	FRC-RAC-20-SP
	GWP	$kgCO_2$-eq.	1237.0	1229.9	1252.4	1097.2	1117.1
I4	EP	$kgPO_4^{3-}$-eq.	0.493	0.467	0.485	0.380	0.396
	AP	$kgSO_2$-eq.	2.919	2.781	2.886	2.355	2.448
	POCP	kgC_2H_4-eq.	0.436	0.420	0.430	0.255	0.264
I5	Non-renew. en. res. use	MJ	9536.81	9106.23	9404.19	6727.11	6989.72
I6	Renew. en. res. use	MJ	340.54	349.13	349.13	262.36	262.36
I7	Water consumption	kg	10,111.957	10,569.594	9919.999	10,569.594	9919.999
I8	Solid waste generation	kg	57.1	1308.3	11,172.8	57.1	70.1
I9	ORI index	w. p.-h	0.15	0.151	0.151	0.083	0.083
I10	Building site space	points	4	4	4	2	2
I11	Innovation potential	points	1	2	3	2	3

Within the environmental requirement and indicator *I4*, for each of the four environmental impacts (GWP, EP, AP, and POCP) a DS value function was first applied and then aggregated using equal weights (0.25) for each one (0.25 × V_{GWP} + 0.25 × V_{EP} + 0.25 × V_{AP} + 0.25 × V_{POCP}) as suggested by previous studies [38]. Indicators *I5–I8* were calculated using the data and approach presented in Section 4.1.

Within the social requirement, the ORI index, corresponding to the health and safety risks (*I9*), was calculated following the steps described above. The building site space was calculated considering that traditional reinforcement requires wider spaces for its production than the fiber reinforcement.

The values of the parameters for all value functions are given in Tables 8 and 9 for 10 and 20 m-long piles, respectively. The values of X_{min} and X_{max} were adopted as 10% below and above the lowest and highest indicator values for each value function, respectively (e.g., if indicator values ranged from 10 to 100, X_{min} and X_{max} would be adopted as 9 and 110, respectively).

Table 8. Values of parameters for indicator value functions for 10 m-long piles.

	Units	Type	X_{min}	X_{max}	*C*	*K*	*P*
I1	EUR	DS	292.8	132.4	212.6	3.5	4
I2	points	DL	5	1	1	0.001	1
I3	points	DL	5	1	1	0.001	1
	$kgCO_2$-eq.	DS	687.8	493.7	590.8	3.5	4
I4	$kgPO_4^{3-}$-eq.	DS	0.271	0.171	0.2208	3.5	4
	$kgSO_2$-eq.	DS	1.603	1.060	1.33145	3.5	4
	kgC_2H_4-eq.	DS	0.239	0.114	0.1765	3.5	4
I5	MJ	DS	5228.3	3027.2	4127.7	3.5	4
I6	MJ	DL	191.3	118.1	1	0.001	1
I7	kg	DS	5809.7	4464.0	5136.8	3.5	4
I8	kg	DL	719.5	25.7	1	0.001	1
I9	w. p.-h	DS	0.084	0.037	0.060	0.001	1
I10	points	DL	5	1	1	0.001	1
I11	points	IL	1	3	1	0.001	1

Table 9. Values of parameters for indicator value functions for 20 m-long piles.

	Units	Type	X_{min}	X_{max}	C	K	P
I1	EUR	DS	588.5	264.7	426.6	3.5	4
I2	points	DL	5	1	1	0.001	1
I3	points	DL	5	1	1	0.001	1
I4	$kgCO_2$-eq.	DS	1377.6	987.5	1182.5	3.5	4
	$kgPO_4^{3-}$-eq.	DS	0.5423	0.342	0.442	3.5	4
	$kgSO_2$-eq.	DS	3.2109	2.1195	2.6652	3.5	4
	kgC_2H_4-eq.	DS	0.4796	0.2295	0.3546	3.5	4
I5	MJ	DS	10,490.5	6054.4	8272.4	3.5	4
I6	MJ	DL	384.0	236.1	1	0.001	1
I7	kg	DS	11,626.6	8928.0	10,277.3	3.5	4
I8	kg	DL	12,290.1	51.4	1	0.001	1
I9	w. p.-h	DS	0.166	0.075	0.120	0.001	1
I10	points	DL	5	1	1	0.001	1
I11	points	IL	1	3	1	0.001	1

5. Results and Discussion

The results obtained for the criteria of the 10 and 20 m alternatives are shown in Figures 4 and 5, respectively. The different alternatives are shown through the *x*-axis, whereas the *y*-axis corresponds to the values of the sustainability indexes.

First of all, regarding the 10 m alternatives, it can be seen that the most sustainable alternative is the FRC-RAC-10-SP for the three criteria, followed by the FRC-RAC-10-MP. Secondly, as for the 20 m alternatives, a significant difference can be observed between the FRC-RAC alternatives and the other three cases. Whereas the FRC-RAC alternatives show high values of the sustainability index, the piles made with NAC and RAC all have sustainability indexes lower than 0.4.

When comparing results between the 10 and 20 m alternatives, it can be observed that the results obtained for the social criteria are similar for the 10 and 20 m alternatives. However, for the economic criteria, significant differences were obtained for the NAC and RAC alternatives. Regarding the environmental criteria, such differences are noticeable only in the case of RAC alternatives.
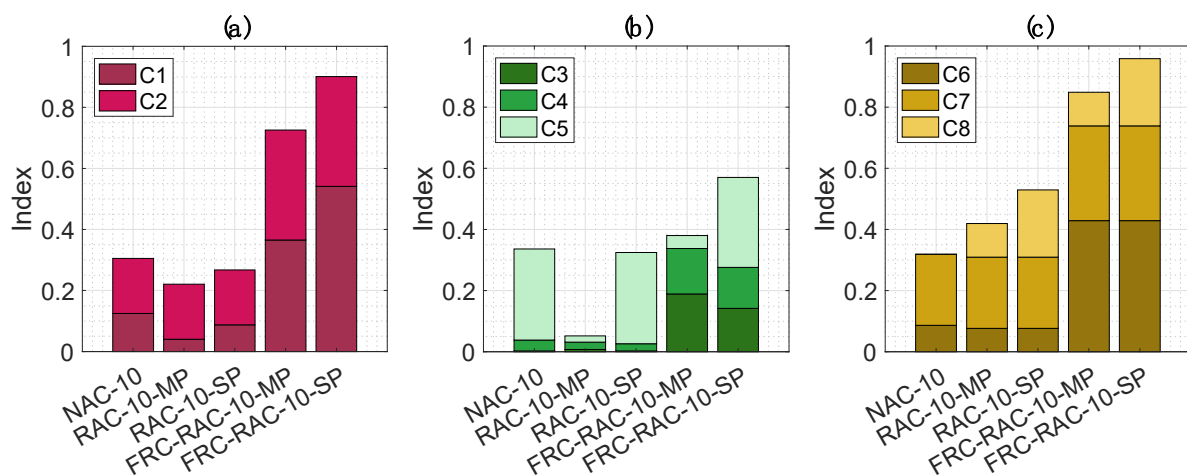
Figure 4. Results of the (**a**) economic, (**b**) environmental, and (**c**) social criteria for the 10 m alternatives.
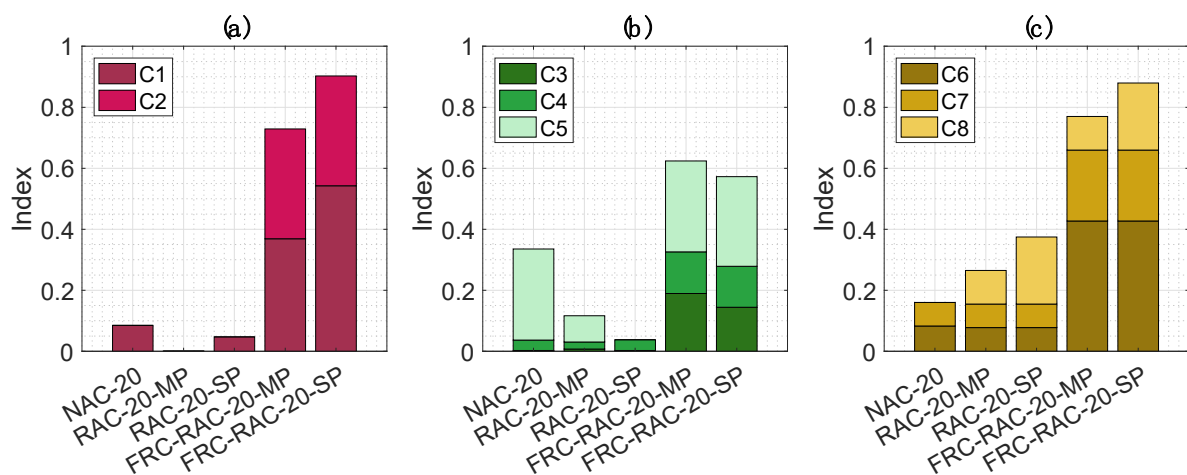
Figure 5. Results of the (**a**) economic, (**b**) environmental, and (**c**) social criteria for the 20 m alternatives.

Having seen the results separated by criteria, Figure 6a,b shows the results of the global sustainability indexes for the 10 and 20 m alternatives, respectively. Again, alternatives are shown across the *x*-axis, while the sustainability index is represented through the *y*-axis. The bars of the plots have been represented in three different colors, depicting the economic, environmental, and social requirements.
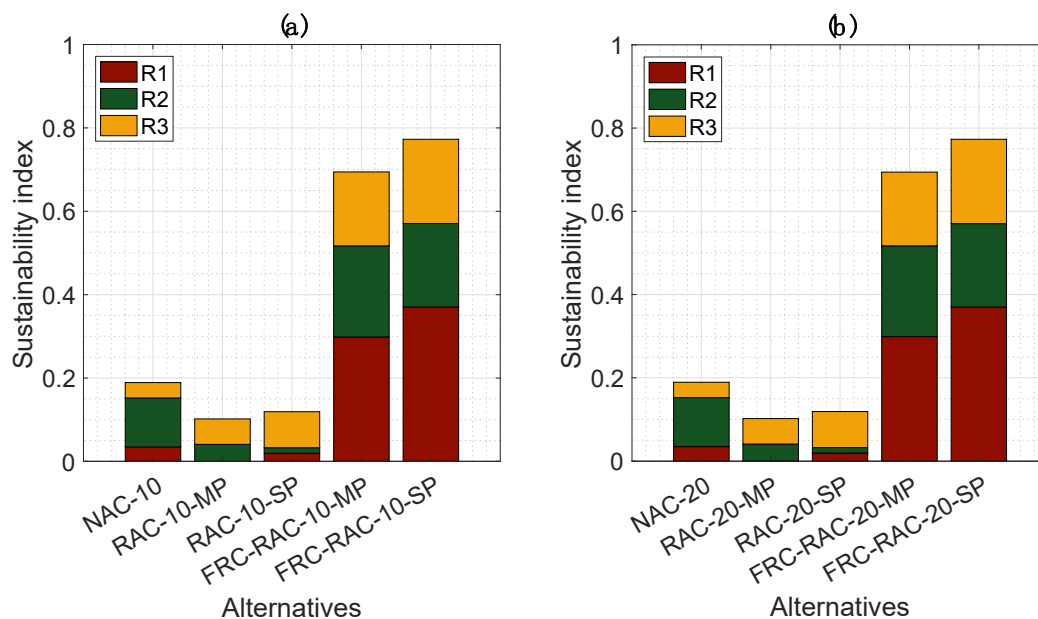
Figure 6. Results of the requirements for: (**a**) the 10 m-alternatives and (**b**) the 20 m-alternatives.

First of all, it can be observed that the results for the alternatives of 10 and 20 m do not present significant differences in terms of the ordering of the alternatives. In both cases, the most sustainable alternatives are FRC-RAC SP and FRC-RAC MP; RAC MP being the last. Those remaining, NAC and RAC SP (of both 10 and 20 m length), take the third and fourth positions.

In both scenarios, the social requirements do not excessively alter the results, and it is the economic and environmental aspects that cause the main contrasts between alternatives. This is coherent with the fact that piles are usually unnoticed by local communities, nor do they affect them unless there are structural problems. The principal impacts potential on society are in terms of innovation and workers' safety. As for the latter, it needs to be noted that the deployment of these structural elements does not carry serious risks.

6. Sensitivity Analysis

With the purpose of examining the robustness of the results, a probabilistic approach was taken for the measurement of the sustainability indexes. Some authors have recommended using statistical techniques, such as Monte Carlo, when the results of some of the alternatives are close [18,39]. As it was observed in the previous section, this is the case of the present study. Therefore, a probabilistic scenario was defined in which uncertainties were admitted in the weighting system.

To carry out the sensitivity analysis, first, a distribution function for the variable with uncertainties needs to be defined. In the present case, it was decided that a PERT distribution would be suitable. The PERT distribution belongs to a family of continuous probability distributions that consists of the following parameters: the minimum, the maximum, and the most likely values that a variable may take. This distribution is commonly used in uncertainty analysis, and it provides a smooth version of the probability density function of a triangular distribution. For the present study, the minimum and maximum values for the distribution's parameters were taken from the surveys answered by experts, and the most likely value was taken as the weighted mean of the experts' responses, as shown in Table 10.

Table 10. Parameters of the PERT distribution.

Parameters	*R1*	*R2*	*R3*
Most likely value	41	36	23
Minimum	25	20	15
Maximum	50	60	30

After the function has been defined, pseudo-random values are generated. When uncertainties are introduced in the weighting system, it is important to pay attention that the sum of the pseudo-random weights add up to 100%. Hence, in each iteration, the values of the weights need to be normalised. After these pseudo-random weights are obtained, and the model is evaluated using these values. In the end, it is possible to obtain a distribution of the sustainability indexes.

Figure 7 shows the distribution of the requirements' weights utilized for the sensitivity analysis.
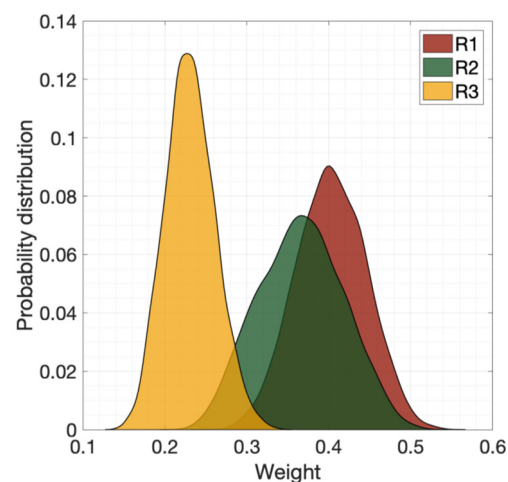

Figure 7. Distribution of weights for the sensitivity analysis.

Results of the sensitivity analyses of the 10 and 12 m-alternatives are shown in Figures 8 and 9. Both the probability distribution and the cumulative distribution have been included. As it can be seen, the relative ordering between sustainability indexes of the different alternatives is maintained in both scenarios.
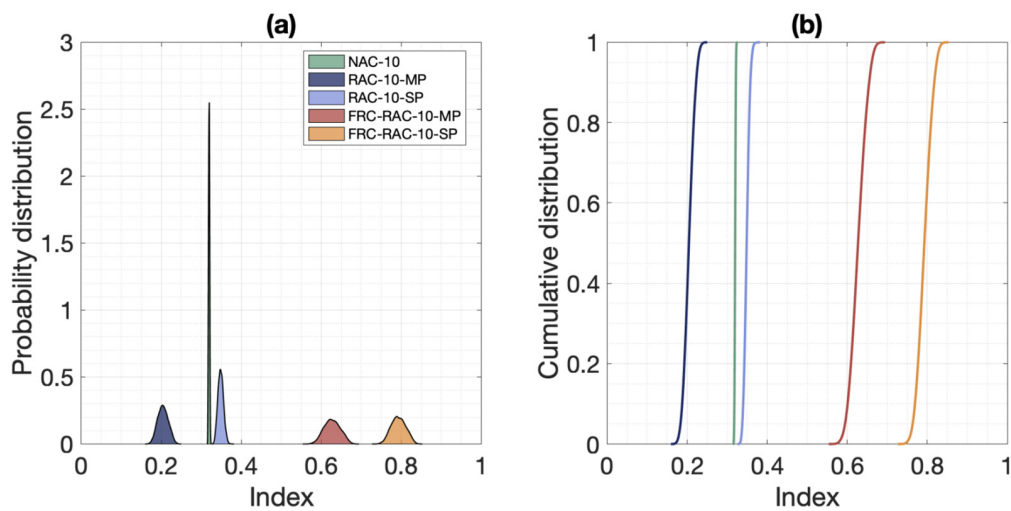
Figure 8. Probability distributions (**a**) and cumulative distributions (**b**) for the sustainability indexes of the 10 m-alternatives with uncertainties in the weights.
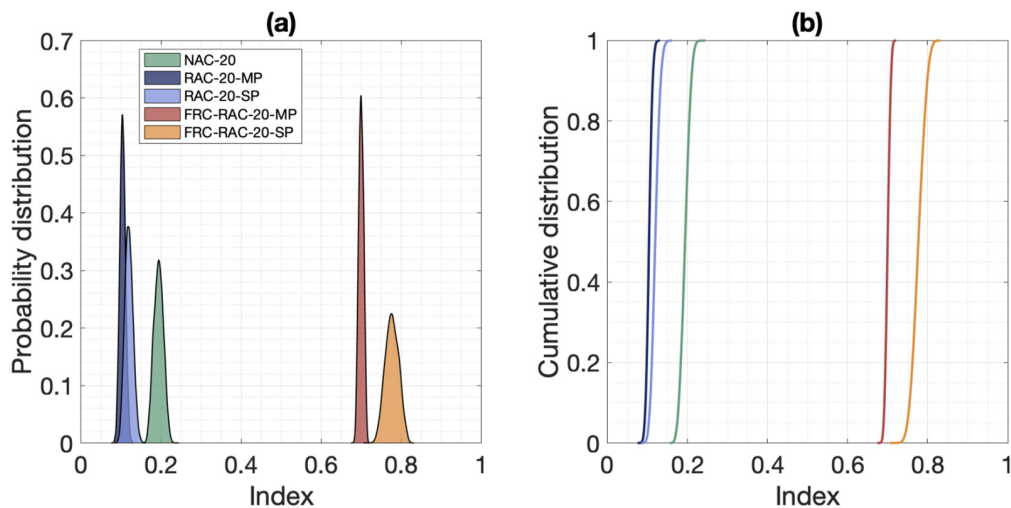

Figure 9. Probability distributions (**a**) and cumulative distributions (**b**) for the sustainability indexes of the 20 m-alternatives with uncertainties in the weights.

7. Conclusions

In this article, a multi-criteria decision-making method, MIVES, was applied to determine the most sustainable choice of 10 and 20-m long CFA piles. For this purpose, CFA piles with and without steel cage reinforcement were considered, with and without steel fibers, and with and without recycled aggregates concrete. Using the MIVES method enabled consistently considering all three pillars of sustainability: economic, environmental, and social. Based on the results obtained in the study, the following conclusions can be drawn:

- CFA piles with steel fibers that completely replace steel cage reinforcement, and with recycled concrete aggregate, were shown to be the most sustainable across all three requirements (economic, environmental, social) and for both pile lengths (10 and 20 m).
- Within alternatives with RAC, it is more sustainable to source recycled concrete aggregate from a stationary recycling plant than from a mobile recycling plant. Contrarily, RAC piles with recycled concrete aggregate sourced from a mobile recycling plant are the least sustainable.
- All alternatives with steel cage reinforcement have a significantly lower sustainability index compared to alternatives with steel fibers. Within the alternatives with steel

cage reinforcement, the length of the pile influences on the results: for 10-m long piles, the alternative RAC-10-SP is more sustainable than the NAC-10 pile, whereas for the 20-m long piles, the alternative NAC-20 is more sustainable than the RAC-20-SP solution.

The results of this study are, of course, contingent on the adopted assumption and data sources used for analysis, and further studies with a wider variety of parameters and value ranges should be investigated in order to draw general conclusions. Nonetheless, the obtained results clearly indicate that using innovative solutions, such as steel cage reinforcement replacement by structural fibers and sourcing recycled concrete aggregate from stationary recycling plants, brings sustainability benefits across economic, environmental, and social requirements. As such, this study can serve as a reference result for decision makers when deciding on alternatives for CFA pile construction.

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