Journal of Cleaner Production 351 (2022) 131463

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Evaluating the sustainability of soil improvement techniques in foundation substructures

Antonio J. Sánchez-Garrido [a,*], Ignacio J. Navarro [a], Víctor Yepes [b]

[a] Dept. of Construction Engineering, Universitat Politècnica de València, 46022, Valencia, Spain
[b] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022, Valencia, Spain

ARTICLE INFO

Handling Editor: Zhen Leng

Keywords:
Sustainability
Construction
Multi-criteria decision analysis
Life cycle assessment
Modern methods of construction
Soil improvement
Foundations
ELECTRE IS
TOPSIS
COPRAS

ABSTRACT

The soil is not always suitable or competent to support a direct shallow foundation in construction. In many cases, to avoid costly deep foundations, it is indicated to replace, improve, or reinforce such soil. This paper focuses on evaluating the contribution to sustainability between different soil improvement techniques and the outcome of their application to the foundation of a single-family house as an alternative to the one built. The life-cycle performance in sustainability is compared between the baseline design (without intervention), backfilling and soil compaction, soil-cement columns, rigid inclusion of micropiles, and nailing of precast joists. To characterize sustainability, a set of 37 indicators is proposed that integrate the economic or environmental aspects of each design alternative and its social impacts. A sustainability ranking is obtained for the different alternatives based on the ELECTRE IS method for multi-criteria decision-making (MCDM). The sensitivity of the obtained results is evaluated against different MCDM methods (TOPSIS, COPRAS) and different criteria weights. The evaluation provides a cross-cutting view, comparing the ability and reliability of each technique to prioritize the ground consolidation solution that best contributes to the sustainability in the design of a building's substructure.

1. Introduction

The structural design of buildings consists in finding the optimal path to allow the transmission of loads to the ground. The different elements conforming to the superstructure (beams, slabs, columns) need to be disposed of and dimensioned so that the service loads are transmitted to the substructure or foundation, which is the element responsible for the adequate transmission of those loads to the ground. Typical building structures usually transmit light to moderate loads to the ground over a large area. However, if the competent soil is at significant depths, the cost of conventional foundations becomes excessive (Yepes, 2020). In these cases, to optimize the designed foundation, a soil replacement, improvement, or reinforcement intervention may be indicated.

The structural design of foundations is different from that of the superstructure elements since soil mechanics and foundations are on the borderline between geotechnical and structural theory. Foundations are one of the construction elements that generate the greatest impacts at any level (Mercader et al., 2010). Without the support of a correct geotechnical study, a wrong choice of the type of foundation may lead to excessive material consumption rates. Concrete is indisputably the versatile material for constructing substructures because of its moldability, impermeability, and ease with which it can be injected into the ground. However, its massive use entails high environmental costs associated (Li and Zheng, 2020), above all, with the amount of energy consumed and CO_2 released in the manufacture of Portland cement. In addition, the extraction of aggregates and other necessary raw materials involves the destruction of particular habitats and the emission of different air- and water pollutants in the area. Despite the significant impacts of concrete use, foundation elements are still one of the less optimized elements in the design of building structures (Pujadas-Gispert et al., 2020). Often the same structural strength can be achieved using 50–60% of the amount of cement typically used. Recycling cement could avoid the emission of 300 million tons of CO_2 per year, while processing recycled aggregates can save 40–70% of CO2 emissions compared to the conventional use of aggregates (Ellen MacArthur Foundation, 2019). Consequently, the optimization of foundation elements arises as an essential step towards the sustainable future claimed by our society.

The above data highlight among construction companies the need to promote environmental sustainability through a reasonable resource consumption model (Pellicer et al., 2014) in line with the United Nations Sustainable Development Goals (SDG). In substructures, materials such as concrete can be saved by reducing excessive regulatory specifications,

---

* Corresponding author.
E-mail addresses: ajsangar@doctor.upv.es, ajsangar@doctor.upv.es (A.J. Sánchez-Garrido), ignamar1@cam.upv.es (I.J. Navarro), vyepesp@cst.upv.es (V. Yepes).

https://doi.org/10.1016/j.jclepro.2022.131463
Received 21 September 2021; Received in revised form 14 March 2022; Accepted 19 March 2022

using high-strength materials, or improving the design. Due to its constructive ease and use of materials, the most economical foundation corresponds to the one that can transmit loads to the ground in the most elementary way, i.e., only by pressure under its base (El-kady and Badrawi, 2017). For this purpose, the soil must be as favorable as possible and with medium or high resistance characteristics. When the bearing capacity of the ground is not sufficient (Nicholson, 2015), one can choose to modify the ground to improve its properties or behavior through soil improvement techniques. Such intervention can be aimed at making the soil compatible with the original project or to resize and change the typology of the foundation, adapting it to the new geotechnical conditions.

There are many possible soil treatment classifications depending on its field of application (Ministry of Public Works, 2002). These techniques have experienced an important development in the last decades, allowing the construction of structures in reasonable time and cost in adverse geotechnical conditions. During the last decade, the most well-known soil improvement procedures for construction have been refined, such as the rigid inclusion of micropiles (Mollaali et al., 2014), pressurized cement grout injections with the Jet-grouting system (Makovetskiy and Zuev, 2016), or the use of soil-cement columns (Do and Pham, 2018). Efforts have also been made to improve the behavior of unsuitable soils by using fly ash as a stabilizer for very soft clay soils (Baqir et al., 2020) or by using glass dust residues for strength enhancement in expansive soils (Blayi et al., 2020). Recently, several studies have researched the integration of more environmentally friendly techniques, such as soil improvement piles with recycled sludge (Mochida et al., 2021) or soil consolidation using drained-timber rods (Chai et al., 2021). However, very few studies focused on optimizing foundations through any of these treatments (Abba et al., 2017) or dedicated to the sustainable application of these soil improvement techniques (Mahmutluoglu and Bagriacik, 2021).

In construction engineering, sustainable design issues require that decisions are made from a cross-cutting approach to seek solutions that balance the necessary economic growth, social welfare, and respect for the environment sought by the 2030 Agenda. The decision is rarely easy to make since the criteria that condition the decision are not always objective and are influenced by different aspects that are often in conflict (economy, deadlines, safety, environment, society, and durability, among others). Appropriate tools are needed to evaluate this decision process rigorously. The existing literature includes different Multi-Criteria Decision Making (MCDM) methods as a tool for selecting sustainable design solutions applied to architecture and civil engineering (Zavadskas et al., 2016a; Zamarrón-Mieza et al., 2017; Navarro et al., 2019; Ogrodnik, 2019). However, there is no universally accepted metric as to their preferred use. The best known classical techniques that have appeared over time are, in chronological order: SAW (MacCrimmon, 1968), ELECTRE (Roy, 1968), TOPSIS (Hwang and Yoon, 1981), PROMETHEE (Brans and Vincke, 1985), COPRAS (Zavadskas et al., 1994), VIKOR (Opricovic, 1998) and more recently MIVES (Aguado et al., 2006).

The assignment of weights associated with each criterion is an important part of the decision-making process. A slight variation in the weights can make the final solution for the same problem favor one alternative. Researchers developed and presented a lot of subjective methods to determine criteria weights. For example, Eckenrode (1965) used and compared six different methods and did not find a significant difference among them. Later, Saaty (1977) presented the AHP method, introducing the ANP method (Saaty, 1996). Most recently, Keršuliene et al. (2010) introduced the SWARA method, and Stanujkic et al. (2017) presented the PIPRECIA method. Turskis et al. (2019) presented the fuzzy model of Eckenrode's classification technique, mentioned above. However, despite the methods described among the many others available among the scientific community, there is a dominant preference for the AHP method to determine the weighting of the criteria (Zavadskas et al., 2016b).

There is no single MCDM model suitable for solving all multifaceted construction problems, including sustainability strategies. Requirements, standards, and objectives depend on a wide variety of characteristics. Selecting the best construction for a building from various alternatives depends on whether the decision-makers are owners, contractors, or other stakeholders (Turskis et al., 2016). Especially in the last five years, there has been an exponential increase in the application of MCDM methods to practically all aspects of the construction sector (Zhu et al., 2021. Some of these MCDM tools above have been used in the sustainable assessment of infrastructure planning (Salas and Yepes, 2020), infrastructures such as bridges (García-Segura et al., 2018; Navarro et al., 2020), building structures (Sánchez-Garrido et al., 2022), constructive elements (Pons et al., 2021) or the management of materials such as pavement composites (Torres-Machí et al., 2015), among others. Other novel methods have been used in fuzzy environments to ensure sustainable prevention of occupational accidents in construction companies (Turskis et al., 2019). Some specific studies have been found on the emissions generated by the foundation versus the structure at the construction stage (Sandanayake et al., 2017) o facilitate the decision on the most appropriate pile and column construction technology (Susinskas et al., 2011; Zavadskas et al., 2012). However, to the authors' knowledge, the soil improvement effect of foundations has not yet been applied jointly to the holistic sustainability assessment of building structures.

Starting from the gaps detected in the literature, this study aims to increase the knowledge on sustainable design practices in concrete building substructures, in which joint research process the following objectives are differentiated: (1) to develop a method with a system of specific economic, environmental and social indicators to evaluate sustainability performance, in order to select the best construction procedure among different combined alternatives for soil improvement and building foundation. The choice is based on an MCDM technique belonging to the outranking methods, namely ELECTRE IS; (2) to evaluate the robustness of the proposed methodology using a double sensitivity study of the developed indicator system, comparing it with the use of different MCDMs (TOPSIS and COPRAS) as well as with different weight variation scenarios.

2. Materials and methods

The main objective of this study is to analyze the life cycle impacts of different foundation alternatives from an economic, environmental, and social perspective individually. Then an MCDM model is applied to evaluate the resulting sustainability performance of each design from a holistic perspective. For this purpose, the life cycle assessment (LCA) methodology developed in ISO 14040 (ISO, 2006a; ISO, 2006b) is followed, according to which a rigorous LCA must consist of four steps 1) the definition of the objective and scope of the study, 2) an analysis of the inventory to be accounted for, 3) a description of the methods and assumptions used for the impact assessment and, 4) the presentation and discussion of the results obtained.

2.1. Definition of goal and scope

2.1.1. Goal of the study

This paper aims to compare the contribution to the sustainability of different foundation designs resulting from the application of various soil improvement alternatives in a single-family house conceived as a reference case study (Fig. 1). According to the geotechnical report, the soil has a low bearing capacity, medium-high expansivity and presents a chemical aggressiveness due to its high sulfate content. In addition, during the execution of the works, it is essential to preserve the current "active zone" level, avoiding excavation works in the months of higher temperatures that would cause the loss of soil moisture when exposed to the elements. Table 1 shows the characterization and parameterization of the different geotechnical layers of the existing ground.

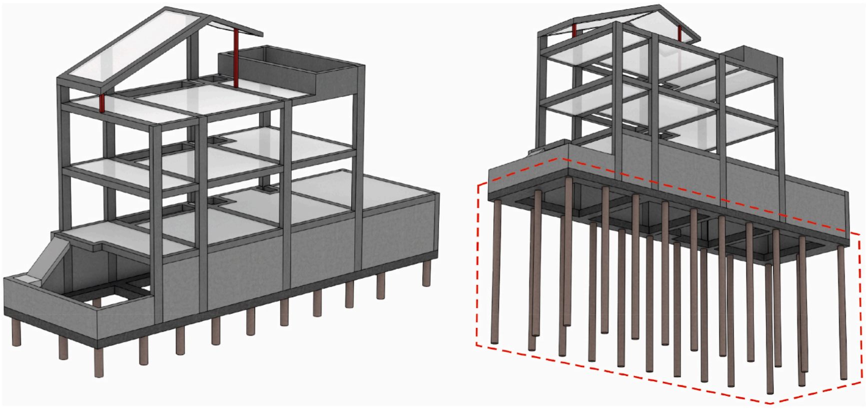


Fig. 1. Three-dimensional model of the structure and baseline foundation design (REF).

Table 1
Characterization and parameterization of natural soil.

	Materials	(m) [a]	GC [b]	N_{20} [c]	N_{30} [d]	USCS Classif.	ρ (kN/m^3) [f]	Cu (kPa) [g]	Ph (kPa) [h]	ϕ (°) [i]	C′ (kPa) [j]	E′ (MPa) [k]	(ν) [l]	(mg/kg) [m]
I	Anthropic infill	0.0 1.6	Collapsibility	7	9	SC [e]	19.0	–	–	18	0.0	3.0	0.30	0.0
II	Brown clays & carbonates	1.6 4.5	Soft soils	4	7	CL [e]	20.0	35.0	130.0	20	5.0	5.0	0.30	450.0
III	Beige loams & gypsum	4.5 10.0	Expansivity	8	15	CH [e]	20.0	50.0	90.0	20	15.0	12.0	0.30	11540.0
IV	Black marls	10.0 17.0	Expansivity Aggressivity	20	27	CH [e]	21.0	75.0	–	23	30.0	30.0	0.30	125.0

[a] Geotechnical model depth.
[b] Geotechnical constraints.
[c] (DPSH).
[d] (SPT).
[e] SC (clayey sands), CL (low plasticity clays), CH (high plasticity clays).
[f] Natural density.
[g] Cohesion without drainage.
[h] Swelling pressure.
[i] Angle of friction.
[j] Effective cohesion.
[k] Soil deformation modulus.
[l] Poisson Coefficient.
[m] Soluble sulfates.

The foundation's mission is to transmit loads of the building to the ground by distributing them so that they do not exceed the ground is bearing pressure or generate inadmissible local effects. Since the soil resistance is usually lower than that of the material composing the structure, the contact surface between the soil and the substructure will be proportionally more significant than the cross-section of the supporting columns or walls. The choice of the type of foundation will depend to a large extent on the type of soil, especially its mechanical characteristics.

The baseline design (REF hereafter) corresponds to the already constructed building and is used as a starting point for this study. It had been projected initially with a deep foundation consisting of 22 units of unsupported bored piles without shaft (Φ35 cm), 4 MPa structural capacity, pile load capacity of 345 KN, and quantities of 7.38 kg/m. Each pile crosses three geotechnical units until it is embedded 1.05 m in the resistant soil layer, representing 8.80 m in length from the pile cap top surface. The strong aggressiveness of the soil requires the use of reinforced concrete with a resistance of 35 MPa and sulfate-resistant cement with special characteristics for strong aggressive environments. The pile caps, the foundation beams, and the garage floor consisting of a 20 cm concrete screed on gravel bedding are also considered. This evaluation does not include the retaining walls as they are common to all designs. However, their eccentric position in the plot perimeter is taken into account as a growth limit for the design of each foundation alternative. No soil improvement actions are contemplated in REF.

Generally, the reinforced concrete structures themselves for single-family homes that require piles or other deep foundations are not very sustainable and, in many cases, economically unavailable for the developer. This type of foundation is not considered the most suitable, as a first option, to solve the problem of a low bearing capacity and very aggressive soil. There are several optimization possibilities, such as soil improvement or consolidation interventions together with compensated foundation solutions or lighter weight structural typologies. This study is based on the evaluation data of the so-called reference solution (REF) to compare it with four sustainable alternatives combining other foundation types with different ground improvement options. This paper is limited to the intervention on the substructure, leaving for future research to integrate the sustainable assessment of the superstructure of the building.

The first alternative method for ground modification (called B + C hereafter) consists of "Backfilling and Compaction." This involves replacing the first 1.5 m of soil with a backfill of selected material compacted in successive layers of 30 cm thick until a dry density of not less than 95% of the maximum density obtained in the Modified Proctor test is reached. The foundation is a 25 MPa reinforced concrete raft, 65 cm thick, with a maximum percentage of recycled aggregates of 20%, poured with a pump and UNE-EN 10080 B 500 S steel amount of 70 kg/m^3.

The second alternative for improving and reinforcing soil characteristics (S-CC hereafter) is based on the use of Ø45 cm "Soil-Cement Columns." This technique consists of mixing the natural soil with injected cement grout, with a consumption of 80 kg/m, creating mass columns that resist between 5 and 15 Mpa. The substructure is a reinforced concrete mat foundation of 30 MPa and 50 cm depth, with recycled aggregates as above, sulfate-resistant cement, poured with pump and UNE-EN 10080 B 500 S steel amount of 80 kg/m^3.

The third alternative to be evaluated as a soil treatment (RIM hereafter) consists of "Rigid Micropile Inclusion." It has been calculated with Ø114.3 mm micropiles, steel casing pipe EN ISO 11960 N-80, 562 N/mm^2, 60.3 mm outside diameter and 5.5 mm thickness, and cement grouting using a global injection system. The foundation has been designed as a continuous footing 120 cm wide and 50 cm thick, supported in the zone of influence of the inclusions. The concrete used also contains 20% recycled aggregates, sulfate-resistant cement poured by pump, and UNE-EN 10080 B 500 S steel amount of 15 kg/m^3.

Al last, the fourth soil reinforcement alternative (CNJ hereafter) is based on "Consolidation by Nailing of Joists." Precast prestressed concrete joists, 300 × 10 × 10 cm, were used, with three 8 mm diameter steel bars in the central part, driven into the ground by hydraulic ramming. The type of foundation is the same as the previous shallow one, with a width of 160 cm and an approximate steel amount of 22 kg/m^3.

The geotechnical finite element analysis software PLAXIS v.8.6 has been used for the modeling. The calculation method selected is Plastic. The soil material calculation model is Mohr-Coulomb and Linear Elastic for the rigid elements, including all the ground improvement elements of the different techniques studied. The improvement elements are modeled as plate elements. Being a 2D representation, it is calculated per linear meter, so the stiffness values of the elements must be converted to the precise distribution. The width of the foundation limits the influence of the deformation in-depth: the greater the deformation, the greater the deformable thickness. The settlements considered are drained settlements. No consolidation settlements are foreseen. All analyses are carried out in a service situation without considering the seismic effect. Geotechnical level II soil pressure relief due to the excavation to be carried out in each of the proposed alternatives is considered. Fig. 2 represents the geotechnical model of each soil improvement and foundation alternative described below, along with the graphical results of the deformations. Table A1 with the Mohr-Coulomb geotechnical parameters and Table A2 with the calculation results for the four soil improvement alternatives considered are provided in the appendices.

In summary, five design alternatives for the building substructure, including the reference design, are considered in the performance evaluation. In every foundation alternative except REF, recycled concrete has been used with a maximum percentage of recycled aggregates of 20%. The inventories with the quantities of the different materials required for each of the solutions analyzed, the waste generated, and the characteristics of the machinery and equipment used in construction are given in Section 2.3.

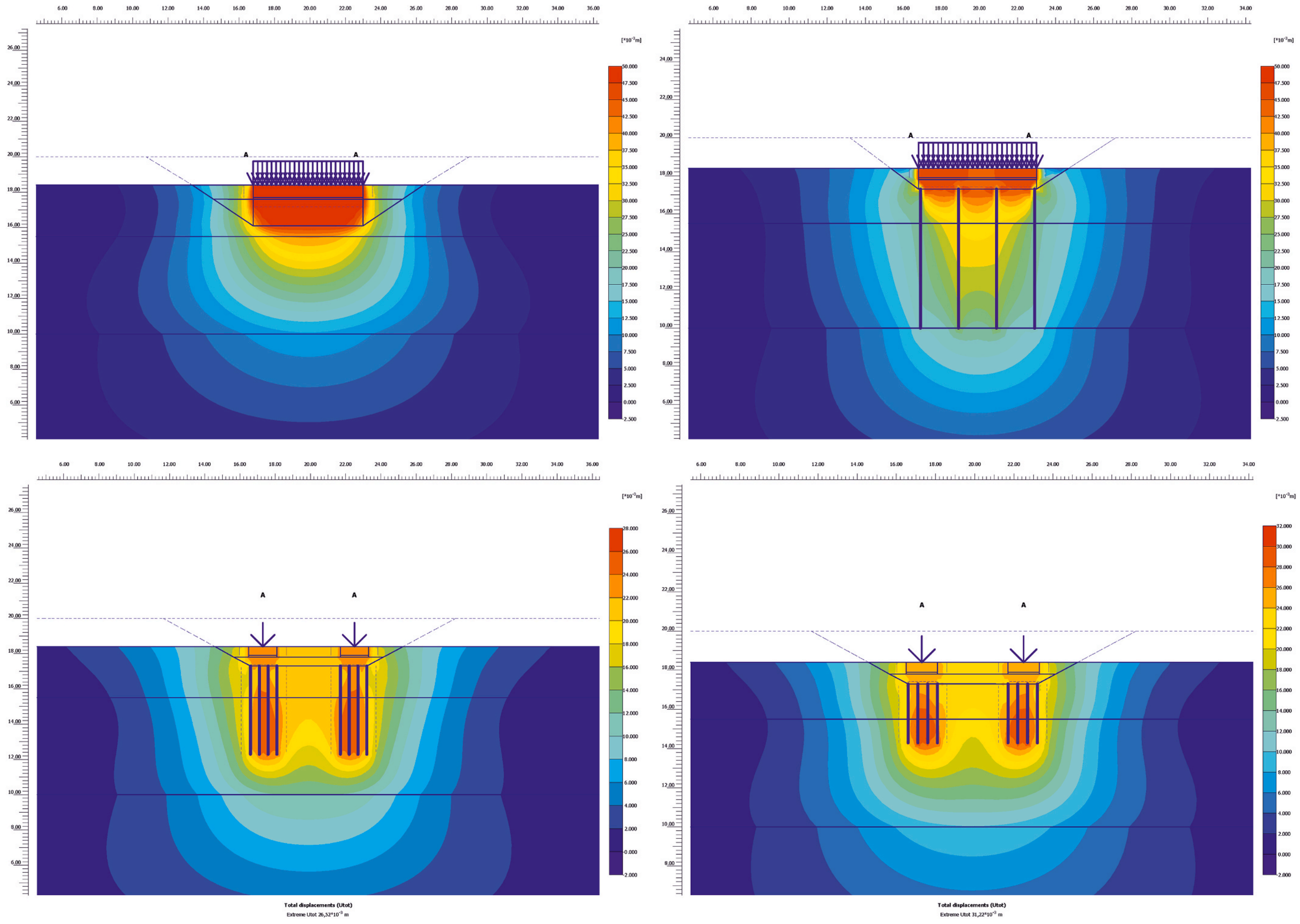


Fig. 2. Deformed mesh and results with total displacements for each alternative.

2.1.2. Functional unit

According to ISO 14040, both the economic (LCC), environmental (LCA), and social (SLCA) life cycle analysis must be based on the same functional unit for the results of the assessments to be comparable. The functional unit considered in this analysis consists of the substructure for a single-family row house located in Jaén (Spain) consisting of a basement, two floors above ground, and a turret, occupying a plot with rectangular dimensions of 20.00 m × 6.20 m and a built-up area of 384.69 m^2. Construction and maintenance activities are included for a nominal service life of 50 years, as required by the Spanish Structural Code.

It is assumed that the existing solution, corresponding to the reference design defined in Section 2.2.1, meets the conditions of structural safety, bearing capacity, serviceability, and durability of the foundation elements concerning the soil. In order to make the evaluations of the alternatives comparable, the functionality of each design shall be the same. Here, an optimization strategy is evaluated from the point of view of sustainability in the foundation design as a function of the applied soil improvement. The proposed substructure's geometry and variables are determined in compliance with the ultimate and serviceability limit states, making the evaluated designs functionally equivalent in terms of safety and structural durability.

2.1.3. System boundaries

The system analyzed covers from the production of the different construction materials to the end of the service life of the building. For the definition of the product system of the present analysis, in the case of foundation/soil improvement, a "cradle to grave" approach has been considered, considering the impacts derived from the production of the materials involved in the construction stage, including transport activities, as well as the proportional part of maintenance during the use stage. Although it is assumed that the structure will be demolished, it is considered that the foundation has already produced the final consolidation of the soil, remaining buried without requiring any action until another building is constructed. The economic cost of maintaining the building in the first ten years after its construction is passed on to the foundation according to the conservation operations contained in the maintenance schedule. The maintenance strategy in terms of durability is implicit in the sizing of the structural element, in terms of reinforcement coating or the type of concrete used depending on the aggressiveness of the soil. The objective of the ten-year maintenance cost assessment is to establish the degree of the economic viability of the building during the first ten years after its construction. In the life cycle cost analysis, maintenance costs have been evaluated from the first decade up to the maximum useful life stipulated in the codes for 50 years. For this purpose, the increase in preventive and corrective

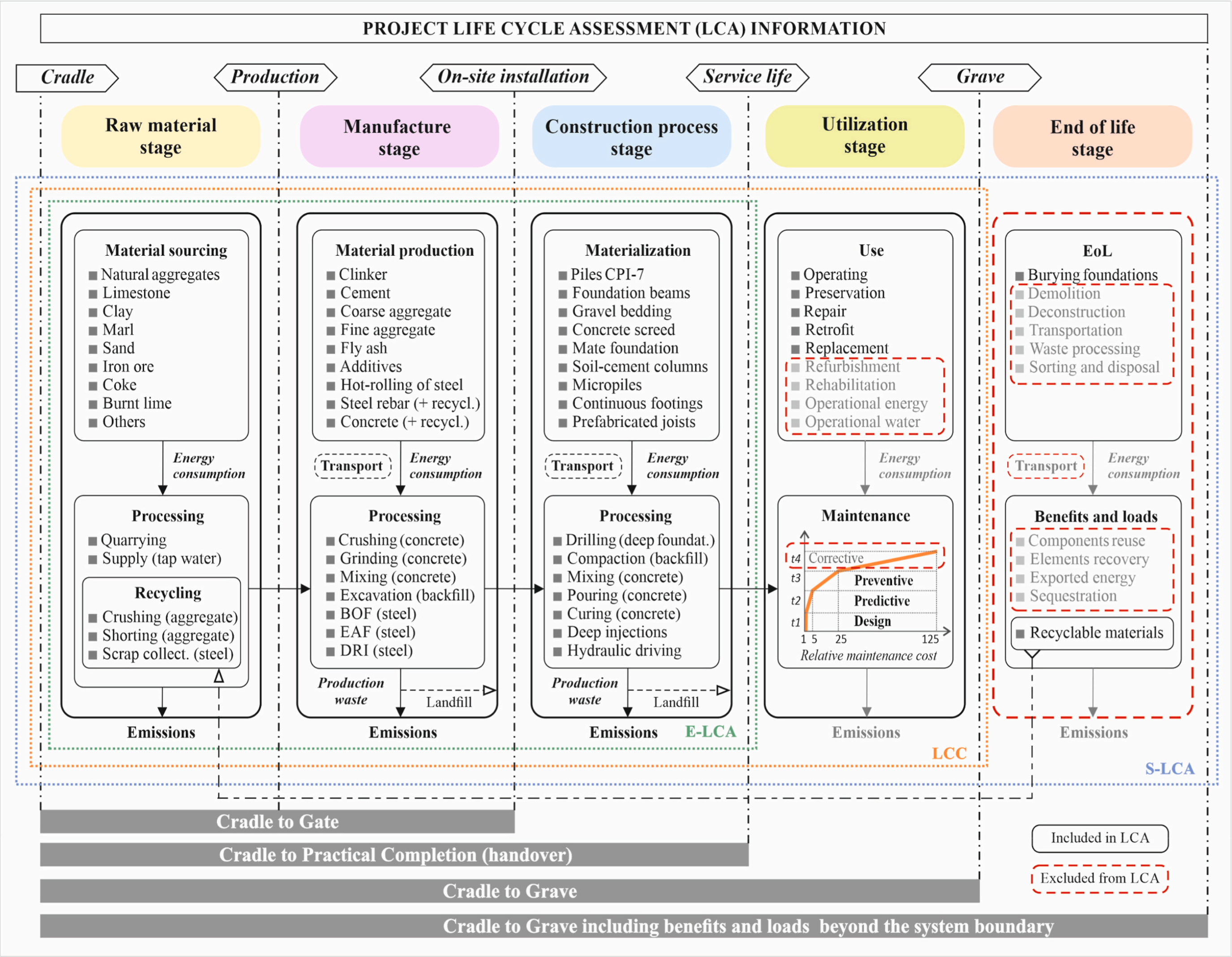


Fig. 3. System boundaries considered in sustainability assessment for foundation and soil improvement.

maintenance costs every 10 years has been taken into account, assuming the progressive depreciation of the building. The replacement value is used by calculating its current cost and taking into account the use and quality of the construction. The correction coefficients are applied under national real estate valuation procedures.

As is logical in the life cycle analysis comparison, processes considered identical or standard among the different design alternatives have been excluded from the product system (Martínez-Blanco et al., 2014; Navarro et al., 2020). Consequently, activities related to the execution and maintenance of the superstructure of Fig. 1 (columns, beams, and slabs) and the basement retaining walls have been excluded. In cases where a foundation mat does not resolve the substructure, a minimum concrete screed on gravel bedding is considered a finish for the basement floor. Fig. 3 summarizes the system limits considered in this LCA.

2.2. *Life cycle impact assessment*

2.2.1. *Selection and definition of indicators*

The sustainability life cycle performance of alternatives for the design of a housing foundation is addressed, considering simultaneously its three dimensions: economic, environmental, and social. It is proposed to adjust the hierarchical tree model deployed in Sánchez-Garrido et al. (2021) that characterizes the global sustainability of the superstructure of a building. For the case at hand, focused on the substructure and

Table 2
Deployment of the criteria tree.

Dimension	Criteria [C] [a]		Sub-criteria (G) [b]		Indicators {I} [b]	
Economic	Construction cost	C1	Production	G1	Design + project management fees (€/m^2)	I1
					Construction management fees (€/m^2)	I2
					License and taxes (€/m^2)	I3
			Materialization	G2	Construction cost - bill of quantities (€/m^2)	I4
			Waste management	G3	Transport of the land by truck (€/m^2)	I5
					Landfill fee to authorized manager (€/m^2)	I6
					Transport of inert waste by truck (€/m^2)	I7
					Fee for delivery of inert waste (€/m^2)	I8
	Service life cost	C2	Use and maintenance	G4	Ten-year maintenance (€/m^2 first 10 years)	I9
Environm.	Endpoint impacts	C3	Ecosystem quality	G5	Agricultural land occupation (points)	I10
					Climate change, ecosystems (points)	I11
					Freshwater ecotoxicity (points)	I12
					Freshwater eutrophication (points)	I13
					Marine ecotoxicity (points)	I14
					Natural land transformation (points)	I15
					Terrestrial acidification (points)	I16
					Terrestrial ecotoxicity (points)	I17
					Urban land occupation (points)	I18
			Human health	G6	Climate change, human health (points)	I19
					Human toxicity (points)	I20
					Ionising radiation (points)	I21
					Ozone depletion (points)	I22
					Particulate matter formation (points)	I23
					Photochemical oxidant formation (points)	I24
			Resources	G7	Fossil depletion (points)	I25
					Metal depletion (points)	I26
Social	Local community	C4	Local employment	G8	Generation of local employment (construction hours)	I27
			Access to material resources	G9	Availability of materials and equipment (scale 1–100)	I28
	Consumers	C5	User safety	G10	Safety factor of the foundation (dimensionless)	I29
					Probability of developing pathological processes (%)	I30
			User's health	G11	Distance to comply with noise pollution levels (m)	I31
					Duration of construction activities (months)	I32
	Workers	C6	Occupational health and safety	G12	Daily exposure of workers to vibrations (dimensionless)	I33
					Max. exposure time to noise equiv. to 87 dBA/day (h)	I34
					Confidence in the construction system (scale 1–100)	I35
			Fair wage	G13	Wage quality vs minimum wage (dimensionless)	I36
	Society	C7	Sustainability Issues	G14	Benefits of each construction method (scale 1–10)	I37

[a] Weighting of the 7 criteria decided by the AHP group according to Section 4.4.

[b] The same weighting is attributed to each subcategory, both subcriteria and indicators (Hagerty and Land, 2007).

ground improvement, the hierarchical structure is particularized, referring to a set of 7 general decision criteria (Table 2) divided into 14 specific sub-criteria until reaching 37 final quantifiable indicators.

In evaluating the economic dimension, the economic resources used in each phase of the life cycle considered are quantified. All impacts are expressed in the same unit of measurement, so there is no need to normalize the inventory data (Swarr et al., 2011). Two different categories of economic impact are identified: the costs associated with conception-materialization, including project fees, fees, licenses, taxes, construction budget, and waste management, and the costs incurred for managing the building's decennial maintenance, as explained in Section 2.2.3.

The environmental dimension is assessed according to the internationally recognized ReCiPe 2008 methodology (Goedkoop et al., 2009). In essence, the method integrates the environmental problem-oriented and damage-oriented approaches by transforming life cycle inventory data into two sets of impact categories: midpoint (18 indicators) and endpoint (3 indicators). In both approaches, emissions and resource extractions are translated into corresponding environmental impact scores using characterization factors (Huijbregts et al., 2017) based on three cultural perspectives, namely individualistic, hierarchical and egalitarian. This analysis adopts the hierarchical perspective as the most common consensus model and the endpoint approach that considers damage to ecosystem diversity (ED), damage to resource availability (RA), and damage to human health (HH).

Finally, to evaluate the resulting social impacts throughout the life cycle of each alternative, the indicator-based methodology proposed by Sánchez-Garrido et al. (2022) for the envelope and structure of a residential building is followed. This methodology considers four impact categories to evaluate the effects of construction and use activities on different stakeholders (UNEP/SETAC, 2009). As in the economic and environmental dimension, the demolition of the foundation is not contemplated, so indicators that contemplate the end-of-life stage of the baseline model are discriminated. A set of indicators is selected based on the stakeholder approach: the local community, consumers, workers, and society. Identifying these stakeholders is based on a hot spot analysis (UNEP/SETAC, 2013) that identifies where the most significant impacts related to the case study may occur in the life cycle.

Two subcategories are considered in the social impact on the Local Community, namely local employment and access to material resources. The E_{ST} (I27) indicator quantifies, in hours, the short-term local employment generated by the construction:

$$E_{ST} = \sum EM_C + \sum LW_C \tag{1}$$

where EM_c represents the machinery or equipment used and LW_c represents local workforce.

The availability of materials and equipment (I28) is evaluated on a qualitative scale with scores between 1 and 100 in response to a questionnaire defined by a seminar of experts with the following parameters: (*Q1*) equipment specialization; (*Q2*) supply of materials; (*Q3*) compliance with site planning; (*Q4*) distance in transporting machinery.

Regarding the social impacts of the Consumers affected by the activities necessary to materialize the functional unit under study, the subcategories of user safety and health are broken down into four indicators. The first of these is the foundation safety factor *FS* (I29), defined as the ratio between the ultimate load and the design load:

$$FS = \frac{Q_F}{Q^{'}} \tag{2}$$

where Q_F is the ultimate bearing capacity of the foundation and Q' is the design load on the foundation. These values are shown in Table A1 and were obtained due to the calculation process described in section 2.1.1.

A second indicator X_{PR} (I30), estimates the risk in the percentage of suffering pathological processes:

$$X_{PR} = \frac{\sum I_E \cdot I_C \cdot [(100 - (C_{CS})]}{3} \tag{3}$$

where I_E is the statistical incidence of the construction elements, I_C is the statistical frequency according to the type of building, and C_{CS} represents the confidence in the construction system (see indicator I33).

The third indicator D_{min} (I31), represents the minimum distance to the noise emitting source to maintain a maximum allowed sound pressure of 75 + 5 dBA according to municipal acoustic regulations and shall be obtained from:

$$SW_D = L_{aeq,T} + 20 \cdot \log(D_0 / D_{min}) \tag{4}$$

where SW_D is the sound attenuation at a certain distance from a punctual directional source, D_0 is the initial distance to the source and D_{min} the final distance to the source; $L_{aeq,T}$ corresponds to the daily equivalent sound pressure level at a workstation, which is calculated for the set of simultaneous activities n_s with the noisiest machinery, being for a working day of 8 h $T = 28800$ s and $L(_{AeqT})_i$ the sound pressure levels during the periods Ti.

$$L_{aeq,T} = 10 \cdot \log \frac{1}{T} \sum_{i=1}^{n_s} T_i \cdot 10^{0.1(Laeq,T)_i} \tag{5}$$

The fourth indicator, T_{CA} (I32), corresponds to the inconvenience derived from the time in months (20 working days/month) during which construction activities last:

$$T_{CA} = \left(\frac{P_{EM} \cdot Q_{EM}{}^{(1-V)} + P_w \cdot Q_A{}^{(1-V)}}{160 \cdot (Q_{EM} + Q_A)} \right) \tag{6}$$

where P_{EM} and P_W are the performance of both equipment & machinery and workers in hours, respectively. Q_{EM} and Q_A quantify major equipment & machinery as well as construction activities. The V factor corrects the previous values to incorporate the simultaneity of activities. $V = 1$ would be considered total simultaneity; $V = 0.3$ is a value close to the real value in a construction site, but the works cannot practically overlap in foundations, so in this evaluation, $V = 0.1$.

As for the social impact on Workers, four indicators belonging to the subcategories of occupational health & safety and fair wages are evaluated. First, the impact on worker safety X_{VT} (I33) in terms of vibrations transmitted to the arm-hand system by the use of the predominant machinery, which shall be quantified as follows:

$$X_{VT} = \left(V_{lim} \middle/ \sqrt{\frac{1}{T_0} \cdot \sum_{i=1}^{n_v} a_{hvi}^2 \cdot T_i} \right) \tag{7}$$

where V_{lim} is the limit value for an unacceptable risk which is set at 5 m/s^2, T_0 is the standard reference period of 8 h; T_i is the duration in hours of exposure to source *i*, n_v is the number of vibration sources to which it is exposed, and a_{hvi} corresponds to the value of the effective weighted acceleration due to source *i*. Table 6 provides, among others, the effective acceleration values of the machines and equipment used in this study, whose data have been extracted from the bibliography and the manufacturers' datasheets.

The second indicator (I34) marks the maximum noise exposure time within the working day for an equivalent daily level of $L_{aeq,T} = 87$ dBA. The maximum hours of exposure per day are obtained by interpolating in Table 3, extracted from the national legislation on the protection of the health and safety of workers against risks related to noise exposure.

The third indicator (I35) determines the confidence in the safety of the construction system and is obtained by scoring (1–100) a questionnaire on the following qualitative parameters: *(Q1)* labor qualification in soil improvement; *(Q2)* technical complexity of the foundation; *(Q3)* quality assurance and control; *(Q4)* habituation to the constructive solution of soil improvement; *(Q5)* Additional risk and accident prevention measures.

Table 3
Limits for equivalent daily noise level ≤87 dBA.

$L_{aeq,T}$ (dBA)	Maximum exposure time
87	8 h
90	4 h
93	2 h
96	1 h
99	1/2 h
102	1/4 h
105	$7^{1/2}$ min
112	$1^{1/2}$ min
117	1/2 min
120	15 s

Fourth, WQ_{ST} (I36) is the indicator that evaluates the short-term wage quality derived from construction can be expressed as:

$$WQ_{ST} = \left(\frac{C_{EM} + C_w}{DW_{min}}\right) \tag{8}$$

where C_{EM} and C_L is the total cost as a function of equipment & machinery hours and labor, with respect to DW_{min} which is the minimum interprofessional reference wage that for 2021 is equivalent to €31.66/day.

Finally, the indicator (I37) used to evaluate the impact on Society through a public commitment to sustainability considers the benefits provided by each constructive alternative on a quantitative/qualitative scale (1–10) in response to the following questions: (*Q1*) performance in construction time, (*Q2*) energy content; (*Q3*) fuel consumption; (*Q4*) risks and inconvenience to neighbors; (*Q5*) suitability of the construction company; (*Q6*) waste recovery; (*Q7*) Accessibility to materials & equipment; (*Q8*) Certifications; (*Q9*) cleanliness of the soil improvement technique.

2.2.2. Normalization

The MIVES technique has been incorporated into the methodology to objectify the social indicators, which are the most difficult to evaluate due to the subjectivity they introduce into the decision. In this way, the variables are normalized using an analysis of values to compare values and heterogeneous weight indicators with different reference units. Table 4 shows the parameterization of all the value functions used in this assessment to transform the physical units of the social indicators into common units (value). More extensive information on the definition of value functions with the MIVES method can be found in Sánchez-Garrido and Yepes (2020).

2.3. Inventory analysis

It involves collecting the data and performing the appropriate calculations to quantify the relevant inputs and outputs of the product system under study. According to ISO 14040, to ensure the quality of these data, they must come from accepted sources. The economic data to evaluate the costs of each of the alternatives throughout the life cycle have been collected from the construction cost database developed by CYPE Ingenieros. The costs of each construction element include the proportional part of the machinery and labor involved in the manufacture of the material and its installation on site. The unit costs of each economic concept are indicated in Euros (€) updated to 2021.

Table 4
MIVES calculator based on value functions for social indicators.

Ind.	Parameters of the value function						
	Best	Graphs	P_i	K_i	C_i	X_{min}	X_{max}
I27	Max.	Linear ↑	1	0.01	788	142	544
I28	Max.	Linear ↑	1	0.01	10.9	1	100
I29	Max.	Concave ↑	0.75	0.9	1.2	1	3
I30	Min.	S-Shaped ↓	2	0.2	25	10	40
I31	Min.	Convex ↓	2	0.05	3.11	1.65	8.95
I32	Min.	Convex ↓	2	0.05	0.94	0.38	2.24
I33	Min.	Linear ↓	1	0.01	0.9	0	1
I34	Max.	S-Shaped ↓	2	0.2	2.5	0	5
I35	Max.	Linear ↑	1	0.01	10.9	1	100
I36	Max.	Concave ↑	0.75	0.9	1.1	1	1.82
I37	Max.	Linear ↑	1	0.01	1.9	1	10

The inventory data to perform the environmental assessment of each alternative according to the ReCiPe methodology have been collected from the Ecoinvent 3.3 environmental database, recognized worldwide as a scientifically reliable and constantly updated database. OpenLCA (GreenDelta, GmbH, Berlin, Germany) was used to develop the model. Table 5 shows the different materials involved in each of the five foundation solutions analyzed for the functional unit under study, as well as the quantities consumed by each of them. The above information is complemented in Table 6 with data on the machinery used's power, performance, and consumption. Table 7 summarizes the inert waste generated and the soils and rocks extracted during the construction phase of the life cycle for each alternative. It is assumed that the transportation of earth by truck of the products from the excavation of any land to a specific landfill site, off-site construction and demolition waste treatment facility, or waste recovery or disposal center is located at a maximum distance of 20 km.

To assess the social impacts, the inventory data used to quantify the indicators related to employment, wages, and accident rates proposed in this study were taken from the Spanish National Institute of Statistics and the official OECD databases. Labor and machinery yields have been collected from national construction cost indicators. Claims statistics related to building pathologies have been consulted in national reports issued by professional liability insurance companies. Data on risk prevention in work exposed to noise and vibration have been extracted from reports made by the companies involved and from surveys published in Spain by the National Institute for Safety and Health at Work (INSST). The qualitative indicators come from interviews and questionnaires carried out by experts or interested parties, such as employees or company management.

3. Multi-criteria decision-making procedure

The last stage of the sustainability assessment consists of aggregating the life cycle performance results, for each sustainability dimension and each alternative, into a single three-dimensional index that allows ranking preferences. The results obtained for the economic, environmental, and social dimensions are aggregated using an MCDM method.

3.1. ELECTRE (The ELimination Et Choix TRadusiant la realitÉ)

This “outranking method” establishes a preference relation between a set of solutions where each shows a degree of dominance over the others concerning a criterion. The different variants of the ELECTRE method are briefly described below.

ELECTRE I consists of reducing the size of the set of efficient solutions. In ELECTRE II, three coincidence thresholds and two discordance thresholds are established. In ELECTRE III and IV, pseudo-criteria are involved so that fuzzy outranking relations are established, reinforced by substituting dichotomous relations (there is outranking or not) by others of a gradual type. ELECTRE IV is similar to ELECTRE III but is simplified by eliminating each criterion's set of weights. In ELECTRE TRI, the outranking relationship is not used to compare the actions of the alternatives with each other but is compared with reference actions. ELECTRE IS (Roy and Skalka, 1984) is a revision of ELECTRE I. However, it incorporates the idea of fuzzy outranking relationships, which allows us to speak of gradations in the relational intensities.

Table 5
Inventory data with material quantities and fuel consumption used in the economic-environmental assessment.

Material description	Properties	Alternatives					Unit
		REF	B + C	S-CC	RIM	CNJ	
Cement (ground)	1500 kg/m^3	–	–	24640.00	10350.00	–	kg
Concrete (fck≤30 Mpa; class II-IV)	2500 kg/m^3	59.34	97.65	78.12	58.25	67.05	m^3
Precast concrete (fck≤30 Mpa)	2500 kg/m^3	–	–	–	–	10.58	m^3
Natural gravel	1450 kg/m^3	35.547.77	–	–	–	–	kg
Recycled gravel (crushed concrete)	2000 kg/m^3	–	–	–	85582.08	85582.08	kg
Recycled aggregates (from C&DW)	2000 kg/m^3	–	–	79236.00	76444.50	76444.50	kg
Compacted granular sub-base	1850 kg/m^3	–	409.200.00	–	–	–	kg
EPS (3 cm)	25 kg/m^3	2.89	–	–	4.18	4.18	kg
Rebar steel	7850 kg/m^3	2831.69	5754.84	5059.20	619.76	1429.46	kg
Wire and tips	7850 kg/m^3	19.58	31.75	27.63	9.38	10.23	kg
Wire mesh	7850 kg/m^3	695.35	–	–	695.35	695.35	kg
Galvanized strip (3 × 0.1 cm rolls)	7850 kg/m^3	–	4.63	3.70	0.86	0.88	kg
Timber (pine)	420 kg/m^3	–	0.01	0.01	–	–	m^3
Formwork board (22 mm)	10 uses	–	–	–	0.02	0.02	m^3
Structural steel (S275JR)	7850 kg/m^3	–	–	–	2543.40	–	kg
Shoring and % of props	150 applic.	–	6.39	5.11	5.94	6.10	kg
Recoverable metal formwork	200 uses	–	5.90	4.72	7.50	6.60	kg
Water (excluding concrete mix)	–	–	–	18480.00	3600.00	–	dm^3
Primers, resins and release agents	0.9 kg/l	–	1.06	0.85	0.99	1.01	kg
Fuel consumption (Diesel)	–	929.55	537.13	1336.63	1193.28	552.73	liters

3.1.1. ELECTRE I

First, the optimal value of each criterion among the alternatives must be obtained, which will be the maximum if the criterion is to be maximized and the minimum if it is to be minimized. Then, each score of the initial decision matrix (r_{ij}) is normalized, depending on whether one wants to maximize (r_{ij+}') or minimize (r_{ij-}'), as follows:

$$r_{ij+}{}' = r_{ij} / max_j r_{ij} \tag{9}$$

$$r_{ij-}{}' = r_{ij} / min_j r_{ij} \tag{10}$$

Two conditions are established to test that one alternative is preferable or over-qualifies the other, using the dominance ratio and the concordance and discordance indices, which are normalized to the values of the ratings and weights. In a pair of alternatives (A_j and A_k), the concordance index (c_{jk}) is the sum of the weights of those criteria whose value in A_j is greater than in A_k, where w_i are the weights of criterion i. The concordance index will be a value between 0 and 1.

$$c_{jk} = \sum_{i=1}^{n} w_i \; con \; j,k = 1,\dots,n \; y \neq k \tag{11}$$

The discordance index (d_{jk}) expresses the most significant, positive difference in the ratings for which alternative A_j is worse than A_k, so only pairs in which A_j does not over-rate alternative A_k are taken into account. If the A_j rating is higher than the A_k rating, the discordance index is 0.

$$d_{jk} = \max_{i=1,\dots,m} \left[r_{ik}^{'} - r_{ij}^{'} \right] \; con \; j,k = 1,\dots,n \; y \neq k \tag{12}$$

The pairwise comparison with this information and the overall position obtained can be performed. The concordance threshold c^* is calculated as the next value greater than or equal to the average, which exists in the concordance matrix numbers. In the same way, the discordance threshold d^* is determined with the next value less than or equal to the average and that exists in the numbers of the discordance matrix. An A_j alternative outperforms A_k if:

$$c_{jk} > c^* \; and \; only \; if \; d_{jk} < d^* \tag{13}$$

This expression is known as the dominance test. Numerically it distinguishes the A_k alternative as better than A_j when its concordance index is above the over-qualification threshold, and the discordance is below the non-over-qualification threshold.

3.1.2. ELECTRE IS

This method is an adaptation of ELECTRE I to fuzzy logic. The main novelty is pseudo-criteria, allowing the decision-maker to choose the decision parameters as intervals instead of fixed (true) values. The discrimination between two alternatives (A_j, A_k) for a criterion i through its pseudo-criterion is performed by a function based on both an indifference threshold q_i and a strict preference threshold p_i ($p_i \geq q_i$). The concordance condition will be:

$$C_{jk}\left(A_j, A_k\right) = \begin{cases} 0 & p_i < r'_i(A_k) - r'_i(A_j), \\ \dfrac{r'(A_j) + p_i - r'(A_k)}{p_i - q_i} & q_i < r'_i(A_k) - r'_i(A_j) \leq p_i \\ 1 & r'_i(A_k) - r'_i(A_j) \leq q_i \end{cases} \tag{14}$$

The concordance index values are aggregated in the concordance matrix using the weights w_i, as in ELECTRE I, obtaining an overall concordance index c^*. To obtain the discordance matrix for each pair of alternatives (A_j, A_k), a discordance indicator per criterion (with value 0 or 1) is calculated. It is established based on the veto threshold, the effect of which is modulated by the value of the overall concordance index c^*. This indicator indicates whether the results of the alternatives on the criterion are opposed to the statement "A_j globally outranks A_k". The no veto condition can be expressed as follows:

$$r'_i(A_j) + v_i\left(r'_i(A_j)\right) \geq r'_i(A_k) + q_i(r'_i(A_k))\eta_i \tag{15}$$

$$\eta_i = \frac{1 - C_{jk} - w_i}{1 - c^* - w_i} \tag{16}$$

where v_i is the veto threshold concerning the i criterion ($v_i \geq p_i \geq q_i$); r'_i is the normalized score for each criterion according to each alternative; η_i the importance coefficient; and c_{jk} represents the concordance index for each pair of alternatives.

3.2. Other MCDM methods used in the sensitivity study

The robustness of the obtained results is validated against different MCDM methods. In this case, three of the most representative classical MCDM techniques in the literature, belonging to different groups within the classification proposed by Hajkowicz and Collins (2007) and De Brito and Evers (2016), are confronted. The main evaluation results obtained by applying the outranking method (ELECTRE IS) are

Table 6
Inventory of data on the types and characteristics of machinery used in construction.

Construction equipment	Power	Performance	Consumption	a_{hv} (m/s^2) [a]	dB(A) [b]
Road train (2-axle rigid truck + 3-axle trailer): MAM 40 t	283 kW	–	40 L/100 Km	–	88
Complete pile boring equipment: (CPI-7)	126 HP [c]	7.69 m/h	31.5 L/h	0.8	101
Pump truck parked on site, for pumping concrete	132 kW	35–90 m^3/h	4 L/h (idling)	0.9	82
Loader on tires: 1.9 m^3 capacity	120 kW	220-130 m^3/h	8.3 L/h	0.5	85
BPR 70/70 vibrating tray with manual guidance: 300 kg/70 cm	9.3 kW	90 m^2/h	1.6 L/h	5.0	83
Tanker truck (3 axles, general cargo): 8 m^3 capacity	239 kW	–	30 L/100 Km	–	88
Skid Steer Loader	37.5 kW	30 m^3/h	1.1 L/h	0.8	85
Vibrating screed (gasoline engine): 3 m wide	1.3 HP [c]	3 m^3/h	0.70 L/h	0.2	76
Pneumatic hammer (pile head demolition)	3.5 kW	2.40 m/h	–	12.0	89
Backhoe Loader	70 kW	60 m^3/h	7.34 L/h	0.8	85
Front unloading dumper: payload 2 t	18.2 kW	–	4.10 L/h	1.2	85
Self-propelled tandem compactor: 9.65 t, width 168 cm	63 kW	160 m^3/h	5.67 L/h	1.0	84
CF-3 piloting equipment powered by diesel engine (Mixpile)	126 HP [c]	150 m/day	31.5 L/h	0.8	101
P13 grout injection equipment (Mixpile)	18 HP [c]	15–80 L/min	4.5 L/h	–	85
Deep grouting equipment/low pressure pump/drilling carriage	88 HP [c]	7.41 m/h	22 L/h	0.8	96

[a] Overall effective acceleration (vibration).
[b] Sound pressure level (noise).
[c] 1.0 HP = 0.7457 kW.

compared with a distance-based method (TOPSIS) and another direct scoring method (COPRAS).

3.2.1. *TOPSIS (Technique for order of preference by similarity to ideal solution)*

This “distance-based method” uses the concept of ideal and anti-ideal to select alternatives. It allows evaluating the performance of alternatives, maximizing the distance of negative ideal solutions (NIS), and minimizing the distance of positive ideal solutions (PIS) so that it is possible to find acceptable solutions by discretizing variables. Firstly, the scores r_{ij} for each alternative *i* and each criterion *j* are normalized as follows:

$$r_{ij}^{'} = r_{ij} \Big/ \sqrt{\sum_{j=1}^{m} r_{ij}^{2}} \tag{17}$$

Each of these values is multiplied by its relative weight (w_i) to obtain the weighted normalized value (v_{ij}). Through the L_2 metric, the Euclidean distance to the PIS (D_j^+) and to the NIS (D_j^-) of each alternative is obtained, where v_i^+ and v_i^- are the best and worst score for the criterion *i* considering every alternative *j*.

$$D_j^+ = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^+\right)^2} \tag{18}$$

$$D_j^- = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^-\right)^2} \tag{19}$$

The relative distance to the ideal of each alternative *j* is calculated, where, C_j^* is the relative proximity coefficient representing a set of solutions, which will be ordered from lowest to highest. The best is the highest score, farthest away from the NIS.

$$C_j^* = D_j^- \Big/ D_j^+ + D_j^- \tag{20}$$

3.2.2. *COPRAS (COmplex PRoportional ASsessment)*

It is included within the “scoring methods” based on evaluating the alternatives using direct arithmetic operations consisting of adding the normalized value of each criterion by its corresponding weight. The evaluation of the criteria to be maximized and minimized is performed separately, determining the relative importance of each alternative as:

$$Z_j = Z_+ + Z_- \tag{21}$$

Previously, each r_{ij} score is normalized as follows:

$$r_{ij}^{'} = r_{ij} / max_j r_{ij} \tag{22}$$

The first term (Z_+) in Eq. (21) is the component of the *m* criteria to maximize. In case there are no criteria to minimize, the COPRAS method is exactly the same as the SAW, obtaining the sum for each alternative (S_{+j}) as the product of each normalized criterion ($r_{ij}^{'}$) and its relative weight (w_i).

$$S_{+j} = \sum_{i=1}^{m} w_{+i} \cdot r_{+ij}^{'} \tag{23}$$

The second term (Z_-) in Eq. (21) is the component of the *n* criteria to be minimized. S_{-j}, is the same expression as S_{+j} but applied to the minimized criterion, S_{-min}, the minimum value of S_{-j} of all the alternatives.

$$S_{-j} = \sum_{i=1}^{n} w_{-i} \cdot r_{-ij}^{'} \tag{24}$$

Table 7
Construction waste generated in each of the design alternatives according to the LCA.

Waste generated	REF	B + C	S-CC	RIM	CNJ	Unit
Soil and stones [a]	39369.13	422096.00	114080.00	87243.92	79856.00	Kg
Gravel and rocks [a]	384.45	3045.56	701.72	947.95	947.95	Kg
Iron and steel [c]	151.70	155.95	136.19	849.87	62.73	Kg
Concrete	2543.97	752.40	1844.28	2212.74	2051.55	Kg
Wood	0.00	6.52	5.22	47.47	6.23	Kg
Paper, cardboard	68.83	29.02	22.32	176.59	35.72	Kg
Plastic	–	–	–	31.05	–	Kg

[a] Transport by truck of materials from excavation to a landfill or off-site C&D waste treatment plant located at a maximum distance of 20 km.

$$Z_{-} = \frac{S_{-min} \cdot \sum_{j=1}^{n} S_{-j}}{S_{-j} \cdot \sum_{j=1}^{n} \frac{S_{-min}}{S_{-j}}} \tag{25}$$

Since $S_{\text{-}min}$ is a constant, the expression simplifies as follows:

$$Z_{-} = \frac{\sum_{j=1}^{n} S_{-j}}{S_{-j} \cdot \sum_{j=1}^{n} \frac{1}{S_{-j}}} \tag{26}$$

Finally, to compile the preference ranking, the performance index P_i is calculated for each alternative, where Z_{max} is the maximum relative importance value.

$$P_i = \frac{Z_j}{Z_{max}} \times 100 \tag{27}$$

4. Results and discussion

Table 8 summarizes the responses to the five alternatives obtained by evaluating each indicator in Table 2 according to the procedures described in Section 2.2, depending on the sustainability dimension to which it belongs. Based on these values, the results of the individual criteria considered in the life cycle assessment for each one-dimensional approach to sustainability are analyzed below.

4.1. LCC assessment results

The life cycle cost assessment was performed to estimate the economic impacts generated on the building by the foundation and ground improvement on the 124 m^2 of the plot area. The costs for each alternative (Fig. 4) are analyzed for the construction phase, including the previous production stage, and the service life. The latter considers the proportional costs of decennial maintenance, taking into account the house's replacement value, which depreciates as it approaches the established 50 years of useful life. It is observed that the RIM and S-CC alternatives incur the most in the increase of total life cycle costs, with +11.2% and +6.3% concerning the REF base option. On the opposite side, the preferred alternatives are CNJ and B + C, which account for −15.7% and −11.3% reduction on total REF costs. However, the pairs of preferred or non-preferred alternatives do not share the same foundation typology (footing vs. mat foundation). The extreme case is observed in CNJ, which obtains the lowest impacts and RIM the highest, including maintenance costs, with the particularity that both designs have similar continuous footings. Therefore, soil improvement type is the

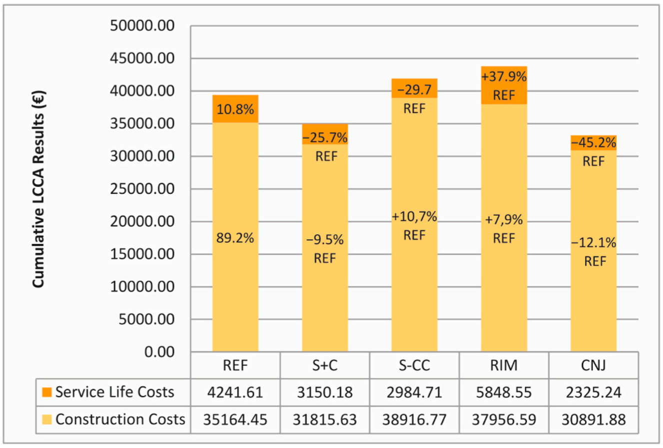


Fig. 4. Economic life cycle assessment results.

Table 8
Responses for alternatives according to the indicators evaluated.

Dimension	Criteria	Sub-criteria	Alt.	REF	B + C	S-CC	RIM	CNJ
			Ind.	x_{ij}	x_{ij}	x_{ij}	x_{ij}	x_{ij}
Economy	C1	G1	I1	36.28	18.94	33.64	29.57	29.44
			I2	15.55	8.12	14.42	12.67	12.62
			I3	9.70	9.05	11.03	10.98	8.60
		G2	I4	220.57	205.63	250.63	249.62	195.50
		G3	I5	0.86	10.01	2.70	2.06	1.90
			I6	0.41	4.75	1.28	0.98	0.90
			I7	0.09	0.03	0.07	0.09	0.07
			I8	0.12	0.04	0.08	0.13	0.09
	C2	G4	I9	5.55	4.12	3.91	7.65	3.04
Environmental	C3	G5	I10–I18	567.68	810.21	740.40	744.86	473.05
		G6	I19–I24	1.377.00	1.811.62	1.839.89	1.987.97	1.072.51
		G7	I25–I26	1.150.90	1.574.15	1.557.82	2.847.83	797.50
Social	C4	G8	I27	373.95	300.90	544.09	499.79	300.27
		G9	I28	18.00	71.00	27.00	41.00	75.00
	C5	G10	I29	3.00	2.00	2.20	2.10	1.60
			I30	25.64	15.92	22.59	25.98	22.31
		G11	I31	8.95	2.05	4.65	6.35	1.65
			I32	1.24	0.81	1.48	1.45	0.80
	C6	G12	I33	0.71	0.22	0.50	0.71	0.53
			I34	0.21	4.32	1.89	1.00	3.89
			I35	42.00	71.00	51.00	41.00	52.00
		G13	I36	1.65	1.35	1.65	1.55	1.26
	C7	G14	I37	5.45	5.76	5.74	4.59	6.74

determining factor in assessing the best life-cycle performance in economic terms. In this case study, soil consolidation by nailing precast joists (CNJ) under the continuous footings is the preferred option, followed closely by soil replacement and compaction (B + C) for raft foundation support. The basic alternative (REF) remains equidistant between the two lower impact designs and the other higher-cost options in terms of economic dimension.

4.2. LCA results

The environmental impacts resulting from the construction of each alternative are shown in Fig. 5. In this case, construction has a balanced impact on ecosystem quality. Overall, the impact on human health is approximately 2.2–2.6 times greater than the impact on the ecosystem for all alternatives, remaining about the same for the B + C, S-CC, and RIM designs, and decreasing for REF and CNJ by 27% and 43%, respectively. However, the most significant differences are in the damage to resource availability, with the worst result in RIM, with a negative impact on resources 80% greater than the subsequent least favorable designs B + C and S-CC. Since RIM and CNJ share the same continuous footing typology with minor size variations, their environmental ranking as the worst and best alternative is directly related to the type of soil improvement employed. These results are explained by comparison according to Table 5. The RIM option needs to use 10.35 Tn of concrete (micropiles and grouting surcharges), produce 2.55 Tn of hot rolled steel, and consume 3600 L of water as well as 1193 L of fuel. In contrast, the CNJ design only requires 10.58 m3 of concrete to prefabricate the joists and diesel consumption of 552 L.

It is worth noting that the REF alternative used as a baseline obtains the second lowest impacts, only behind the CNJ design and with a wide difference of −25% over the third (S-CC). For this case study, it is concluded that, from an environmental point of view, it is only appropriate to consider a soil improvement for the foundation according to the CNJ design. Any of the other options considered generate more negative impacts on the environment than the direct design by deep pile foundation without soil intervention. It should be noted that this study does not consider the reuse of the excavation soil volume as backfill, which would partially reduce the results obtained, especially for B + C in which 1.5 m of soil is replaced. As it is an expansive clayey soil with aggressive sulfates, it has been destined for landfill.

4.3. SLCA results

The results on each design option's social life cycle impacts are presented here. Fig. 6 shows the results with the normalized score (according to Table 4) and weighted responses for each alternative on different attributes on each stakeholder group, namely Local Community, Consumers, Workers, and Society. In this graph, with total ranges between 0 and 1, the higher value indicates a greater preference or positive social impact. It should be clarified that only impacts on local economic development and workers are evaluated logically during the construction phase. On the other hand, impacts on consumers understood as users are only linked to the use and maintenance phase during the useful life of the building. Finally, the public commitment to society in sustainability covers the entire life cycle considered, from "cradle to grave."

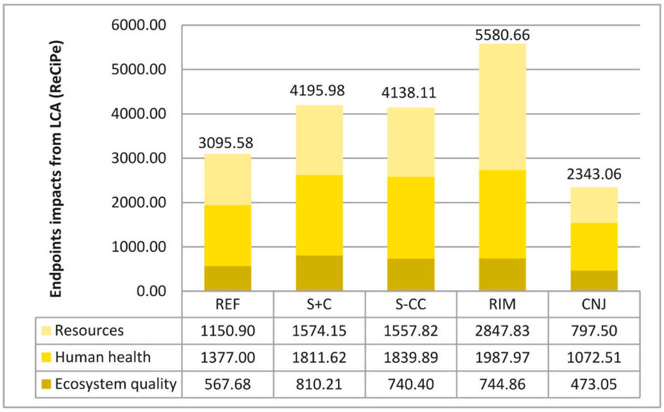


Fig. 5. Environmental life cycle assessment results.

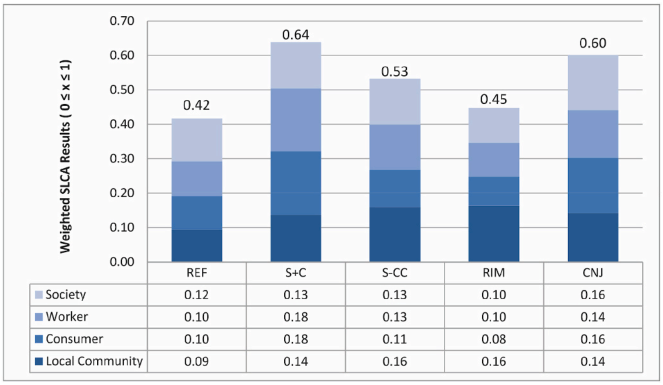


Fig. 6. Social life cycle assessment results.

It is observed that the positive impact on the Local Community is very similar in the four alternatives, around 0.15, except for the REF, which is below 0.10. This difference is due to the imbalance between job creation (I27) and the difficulty of local access to specific equipment and machinery (I28), which causes uncertainty in meeting project deadlines. In the case of Consumers, the index representing the positive impact is strongly penalized in those solutions that generate a higher level of nuisance derived from construction, both in terms of noise level (I31) and duration of the works (I32). This is the case of REF, RIM, and S-CC that use drilling and/or injection machinery for piles, micropiles, and soil-cement columns, respectively. In the group of Workers, the positive impact is significantly higher in alternative B + C. This is because this alternative has fewer health and safety risks from construction machinery noise (I33) and vibration (I34). In addition, the greatest confidence (I35) is obtained in the construction system as it is a basic raft foundation on a backfill executed with conventional machinery and quality control of compaction. Finally, the five alternatives have similar behaviors concerning Society (I37), with CNJ being slightly better. This is justified by being a construction system that requires the shortest construction time, causes minimal dust and noise nuisance without risk of scour or vibration for neighbors, and the cleanliness of the dry execution by hydraulic nailing of the precast concrete elements. Overall, the study results for the social life cycle assessment affirm that B + C with an aggregate rank of 0.62 is the most suitable design among the alternatives, followed by CNJ, S-CC, RIM, and REF with ranks of 0.59, 0.52, 0.44, and 0.43, respectively.

4.4. AHP group weighting results

This section shows the weightings of each criterion resulting from the application of the Analytical Hierarchy Process (Saaty, 1980), with the participation of a group of five experts, all of them active professionals with experience between 7 and 33 years in civil engineering, architecture, and construction. The expert's voting power suggested in the present paper is based on the recent study by Sodenkamp et al. (2018), where the relevance of each expert is derived based on a neutrosophic approach. A simplified version is presented here, where two parameters are considered to determine the voting power of each expert, namely their expertise (self-assessment) and their consistency when fulfilling the evaluation matrix. To date, not much has been written on assessing one's competence before evaluating a decision objectively. To overcome

Table 9
Relevance of AHP group experts.

Definition of the experts' profile	Attribute	DM_1	DM_2	DM_3	DM_4	DM_5
Experience						
Years of professional activity	PA_k	19	7	33	23	21
Years sustainability experience	SE_k	2	5	11	0	0
Availability to research						
Advanced Degree (BDs, MSc, PhD)	AD_k	2	3	3	1	1
Primary author in JCR articles	AA_k	1	2	3	0	0
General knowledge						
Construction Engineering	K_{C1}	4	4	4	4	4
Structural Design	K_{C2}	5	5	4	2	2
Specific knowledge						
Economic Issues	K_{C3}	4	4	4	5	5
Environmental issues	K_{C4}	3	4	4	2	1
Social Issues	K_{C5}	3	3	3	1	2
Other merits	K_{C6}	3	4	5	2	1
Expert's competences	Ψ_{DMk}	0.616	0.713	0.880	0.423	0.397
Expert's inconsistency	ε_{DMk}	0.755	0.945	0.691	0.970	0.693
Credibility or relevance of the expert	$\boldsymbol{\theta}_{\mathbf{DMk}}$	**0.342**	**0.273**	**0.497**	**0.104**	**0.223**

Table 10
Weighting of the criteria decided by the AHP group.

Criteria	Weights resulting from the A_{DMK} pairwise comparison matrices weighted with the credibility of each expert					AHP-G
	DM_1	DM_2	DM_3	DM_4	DM_5	
(C1) Construction cost	0.168	0.076	0.166	0.247	0.188	**0.159**
(C2) Service life cost	0.051	0.153	0.057	0.019	0.054	**0.071**
(C3) Environmental impacts	0.292	0.127	0.270	0.063	0.310	**0.239**
(C4) Local community	0.073	0.144	0.082	0.030	0.081	**0.088**
(C5) Consumer	0.319	0.334	0.328	0.380	0.253	**0.319**
(C6) Worker	0.066	0.075	0.062	0.141	0.078	**0.074**
(C7) Society	0.033	0.090	0.034	0.121	0.037	**0.051**

this problem, the authors have chosen to follow the Delphi method's idea for characterizing expert profiles. In this case, specific knowledge in the particular fields of evaluation (sustainability, construction) is included in the construction of the voting power coefficient for each expert, following the methodology applied by Sierra et al. (2016).

To determine the relevance of each expert in the group's decision, the credibility of each participant was parameterized according to their competencies and the consistency of their judgments. The resulting competence of expert i is translated into a coefficient between 0 and 1 that is a function of experience, research, and knowledge and is defined (Ψ_i) as:

$$\Psi_i = \left(\frac{PE_i}{max\{PE_k\}} + \frac{ES_i}{max\{ES_k\}} + \frac{AD_i}{max\{AD_k\}} + \frac{AA_i}{max\{AA_k\}} + \sum_{m=1}^{n} Kc_{m,i} \Big/ n \right) \Bigg/ 10 \tag{28}$$

where PE_i quantifies the active professional years of expert i; $max\{PE_k\}$ is the maximum number of years of experience among the experts; ES_i counts the years of specialization in sustainable design; $max\{ES_k\}$ is the maximum of this attribute among the group of experts; AD_i characterizes the academic degree of the expert (1 = bachelor, 2 = master, and 3 = doctorate; AA_i represents the scientific production as primary author in the number of JCR articles (0 = none, 1 = 1 to 3, 2 = 4 to 10 and 3 = more than 10). The parameters $Kc_{m,i}$ represent the expert's knowledge in different fields related to the decision problem. In this case, $n = 5$ fields have been chosen, representing their knowledge in construction engineering, structural design, economic analysis, environmental assessment, and social involvement.

Finally, the inconsistency (ε_i) of expert i is defined as the quotient between the consistency rate (CR) of his/her decision matrix and the maximum acceptable consistency rate (CR_{lim}). In principle, higher values of inconsistency may invalidate the expert's evaluation. However, following Saaty (1980) well-known method, some degrees of inconsistency are acceptable, depending on the number of criteria involved in the decision. For the case of considering more than five criteria, an inconsistency limit of 10% is allowed.

$$\boldsymbol{\varepsilon}_i = CR/CR_{lim} \tag{29}$$

Therefore, the credibility (θ_i) of expert i is obtained by simplification of the fuzzy function formulated in Sánchez-Garrido et al. (2021) as the Euclidean distance between each point and the ideal point of maximum credibility ⟨1, 0⟩.

$$\theta_i = 1 - \sqrt{\{(1 - \Psi_i^2) + \varepsilon_i^2\}/2} \tag{30}$$

Table 9 shows the profiles of the five experts according to the characterization parameters derived from Eq. (28)–(30) until obtaining the credibility index that represents the weight or relevance of each expert in the group's decision. As can be seen, all the inconsistency parameters ε are below 1, which means that the limiting inconsistency has not been reached in any case.

With the weights (w_{ik}) for each criterion i decided by each expert k and their relevance δ_k within the AHP group, the final weights for each of the seven criteria are obtained as follows:

$$W_i = \frac{\sum_k w_{ik} \cdot \delta_k}{\sum_k \delta_{ik}} \tag{31}$$

According to the results shown in Table 10, the criteria have the following order of priority: C5 Consumer (32.4%), C3 Environmental impacts (22.3%), C1 Construction cost (16.0%), C4 Local community (8.70%), C8 Worker (7.80%), C2 Service life cost (7.10%) and, finally, C7 Society (5.70%). Almost all the experts consider that the most relevant criterion is the social criterion C5, except for DM5, which gives it to the environmental criterion C3, despite having the lowest knowledge index in this area. The group has no clear consensus regarding the least important criterion, where 3 of the 5 DMs attribute it to social criterion C5. In the rest, the criteria are scored unequally depending on each expert's experience, knowledge, and particular preferences. DM2 presents the values of the weights less dispersed concerning its mean with a standard deviation of 0.09 compared to 0.11–0.13 for the rest. The relevance ranking of the final weights entirely coincides with experts DM_1 and DM_3.

Table 11
Decision matrix and sustainability assessment results according to ELECTRE IS.

$v_i \geq p_i \geq q_i$ (values after normalizing)		Preference threshold	Indifference threshold	Veto threshold	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5
Criteria	Weights	p_i	q_i	v_i	REF	B + C	S-CC	RIM	CNJ
C1−	0.159	0.95	0.60	1.19	283.58	256.58	313.84	306.10	249.13
C2−	0.071	0.48	0.30	0.60	5.55	4.12	3.91	7.65	3.04
C3−	0.239	0.50	0.31	0.63	3095.58	4195.98	4138.11	5580.66	2343.06
C4+	0.088	0.00	0.00	0.86	0.37	0.55	0.64	0.65	0.57
C5+	0.319	0.55	0.35	0.69	0.39	0.74	0.43	0.34	0.64
C6+	0.074	0.92	0.57	1.15	0.56	0.70	0.64	0.53	0.54
C7+	0.051	0.00	0.00	0.95	0.25	0.27	0.27	0.20	0.32

ELECTRE IS	**0.55**	**Concordance threshold (c*)**						
		Alternatives	Σ rows	Aggregated dominance matrix				
		REF	**1**	–	0	0	1	0
		B + C	**3**	1	–	1	1	0
		S-CC	**2**	1	0	–	1	0
		RIM	**0**	0	0	0	–	0
		CNJ	**3**	1	1	1	0	–
			Σ columns	**3**	**1**	**2**	**3**	**0**
			Ranking	**Level IV** (D)	**Level II** (B)	**Level III** (C)	**Level V** (E)	**Level I** (A)

Table 12
Sensitivity of ELECTRE IS results compared to other MCDMs.

MCDM	Alternatives	REF	B + C	S-CC	RIM	CNJ
ELECTRE IS	**Ranking** [a]	**Level IV** (D)	**Level II** (B)	**Level III** (C)	**Level V** (E)	**Level I** (A)
TOPSIS	Dj*	0.099	0.050	0.096	0.141	0.027
	Dj-	0.069	0.117	0.055	0.019	0.124
	Final Score [b]	**0.413** (C)	**0.698** (B)	**0.366** (D)	**0.121** (E)	**0.822** (A)
COPRAS	S + j	0.319	0.509	0.384	0.323	0.464
	S-j	0.327	0.348	0.372	0.465	0.254
	1/S-j	3.055	2.876	2.687	2.152	3.930
	Z+	0.319	0.509	0.384	0.323	0.464
	Z-	0.367	0.346	0.323	0.259	0.472
	Final Score [b]	**0.687** (D)	**0.855** (B)	**0.707** (C)	**0.582** (E)	**0.936** (A)

[a] Order in levels according to the ELECTRE network.
[b] The highest score the best.

4.5. *Tridimensional sustainability assessment*

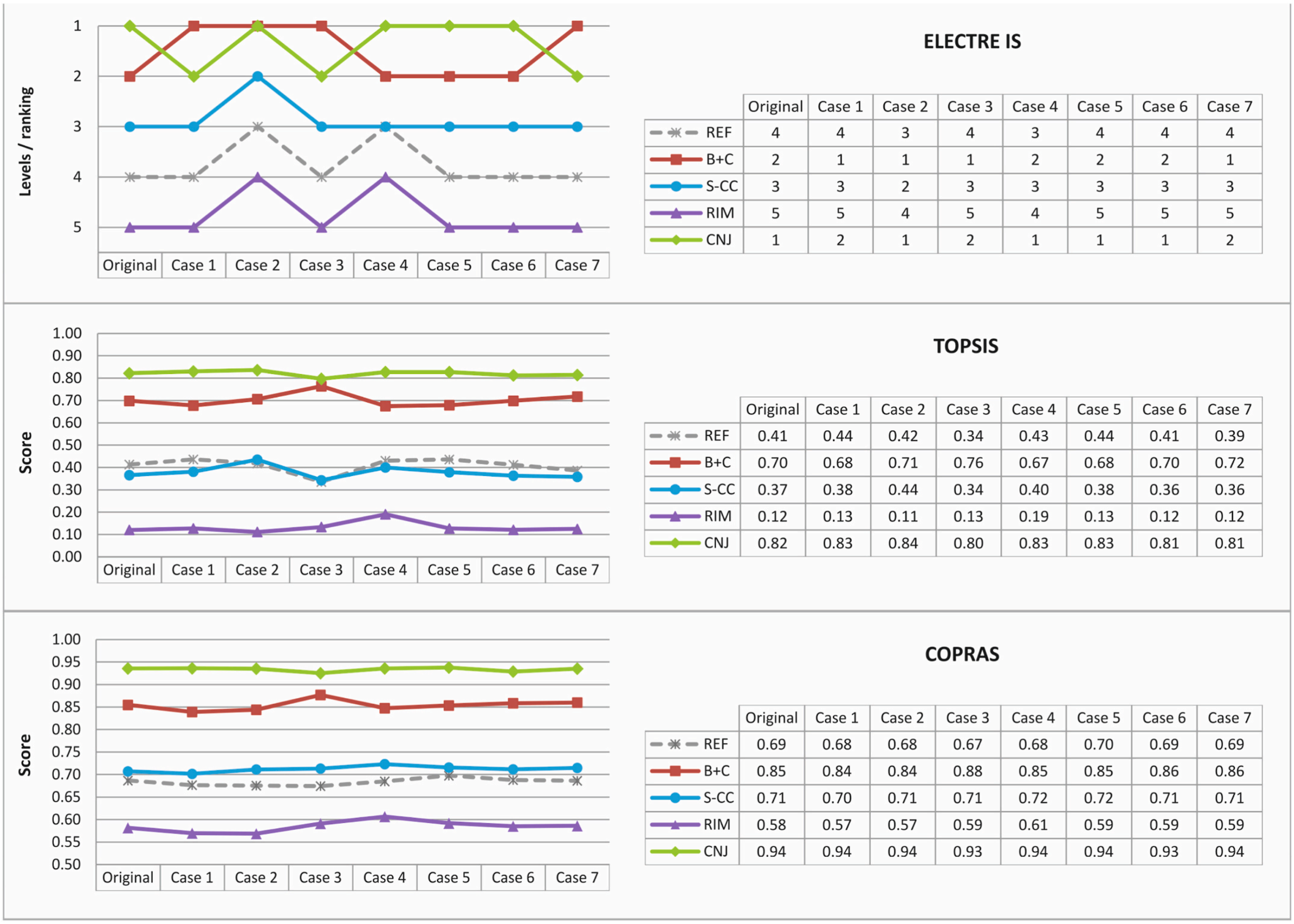
Starting from each alternative's one-dimensional economic, environmental or social performance, a three-dimensional sustainability approach is adopted that considers all criteria to prioritize alternatives from a holistic point of view. Table 11 shows the decision matrix with the interaction between the five alternative solutions and the scores for each of the seven criteria evaluated. These responses vary depending on whether the criteria are quantitative or qualitative and the units that define them. In order to compare numerical or objective values with semantic or subjective values on equal terms, the procedures described in Section 3 are followed. The decision matrix is evaluated when it has all its scores normalized and weighted according to Table 10. The intermediate step in which the sub-criteria are added to the criteria scores is listed in Table A3 in the appendix. For the aggregation of the results, one of the most reputable discrete MCDM methods among those belonging to the so-called "European school of multi-criteria methods" has been chosen. This is the ELECTRE family of methods, based on the definition of outranking relationships between each pair of alternatives. Specifically, this paper uses one of the versions called ELECTRE IS, which incorporates the idea of fuzzy outranking relationships through pseudo-criteria. Table 11 summarizes the relevance of each criterion, the thresholds and coefficients used, and the results with the rankings obtained for each alternative according to the MCDM method. If we look at the comparisons between CNJ and B + C, both dominate in 3 alternatives but are dominated 0 and 1 times, respectively. It follows, therefore, that the CNJ option strictly outranks the other. The design alternative that has resulted in performing the best from a sustainability perspective is CNJ, followed by options B + C, S-CC, REF, and RIM.

4.6. *Sensitivity analysis*

The results' robustness is validated against other MCDM methods (TOPSIS, COPRAS) and different criteria weights using a sensitivity analysis. Despite the difference between the methods (Table 12), the CNJ alternative is the best rated, and B + C is the second-best option in all cases. They also coincide in the last position in the ranking with the RIM alternative. The third preference oscillates between the S-CC alternative in the COPRAS and ELECTRE cases and the REF reference option for the TOPSIS assessment. However, the relative variation in sustainability indices is negligible, with virtually overlapping scores. As for the operation of the methods, COPRAS is very simple as it is based on direct scoring using basic arithmetic operations. This technique concentrates the resulting scores into smaller intervals, as in our case [0.58–0.94]. This leads to a double reading for alternatives with very similar sustainability performances, such as S-CC and REF with 0.71 and 0.69, respectively. On the one hand, it conveys valuable information, namely that the overall performance of the alternatives is not that different. Nevertheless, on the flip side, it may make it difficult for non-expert MCDM decision-makers to discriminate between solutions. In this sense, TOPSIS is easier for any decision-maker to interpret. The positive ideal solution increases the criteria to be maximized. It minimizes the criteria, while the negative ideal solution increases the minimum criteria and reduces the maximum criteria. With the calculations of the distances to the PIS and NIS, a normalization of quadratic values is made, increasing the score for the best alternative and distancing the worst alternative further. In our case, the range of values between the optimal and the worst alternative is [0.82-0.12]. This does not mean that COPRAS is worse, but that the sensitivity of the input data is different from that generated in TOPSIS, whose procedure extends its measurement scale. Although we measure with different techniques, the important thing is that the relative scales are maintained to compare sustainability ratings rather than value indices between methods. Finally, ELECTRE methods are more suitable for ranking alternatives according to pairwise dominance. It has greater utility for discrete problems by offering a global ranking among alternatives and the possibility of comparing them with each other, although without scores. Therefore, it is not possible to aggregate the scores together with the other methods into a single sustainability index. But on the other hand, ELECTRE IS has more versatility than the rest by simultaneously considering the heterogeneity of the scales of criteria and handling inaccurate data closer to real-world decision situations.

An additional sensitivity study is performed to show how the oscillation in the criteria weights may affect the evaluation results. The variation in weights is based on the consideration that the subjectivity implicit in the judgments is likely to condition decision making. Sánchez-Garrido et al. (2021) and Navarro et al. (2020) suggested an explicit way to detect the most subjective criteria using neutrosophic logic, comparing the variation of the resulting weights after defuzzification with those that would result from applying a conventional AHP. Consequently, 7 additional cases have been considered here, one for each criterion, with the possibility of containing the most relevant subjectivity load. The strategy consisted of varying by ±12% half of the criteria, except for one chosen as the most subjective. The latter will see its weight increased or reduced in compensation according to its original lower or higher relevance and provided that the sum of the weights of all the criteria remains at 1. Previous studies have shown that the evaluation results do not vary significantly, with less than 10% changes in the initially assumed weighting factors (Sánchez-Garrido et al., 2021). The results of the overall sensitivity analysis are presented in Fig. 7, and in Table 13 the scores of the weights obtained in the 8 different scenarios for the 7 criteria.

Regardless of the MCDM used, the RIM alternative is the least desirable for all scenarios, and REF and S-CC generally maintain the penultimate and antepenultimate positions, respectively. Only the S-CC alternative reaches the second position with the ELECTRE IS technique



ELECTRE IS

	Original	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
REF	4	4	3	4	3	4	4	4
B+C	2	1	1	1	2	2	2	1
S-CC	3	3	2	3	3	3	3	3
RIM	5	5	4	5	4	5	5	5
CNJ	1	2	1	2	1	1	1	2

TOPSIS

	Original	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
REF	0.41	0.44	0.42	0.34	0.43	0.44	0.41	0.39
B+C	0.70	0.68	0.71	0.76	0.67	0.68	0.70	0.72
S-CC	0.37	0.38	0.44	0.34	0.40	0.38	0.36	0.36
RIM	0.12	0.13	0.11	0.13	0.19	0.13	0.12	0.12
CNJ	0.82	0.83	0.84	0.80	0.83	0.83	0.81	0.81

COPRAS

	Original	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
REF	0.69	0.68	0.68	0.67	0.68	0.70	0.69	0.69
B+C	0.85	0.84	0.84	0.88	0.85	0.85	0.86	0.86
S-CC	0.71	0.70	0.71	0.71	0.72	0.72	0.71	0.71
RIM	0.58	0.57	0.57	0.59	0.61	0.59	0.59	0.59
CNJ	0.94	0.94	0.94	0.93	0.94	0.94	0.93	0.94

Fig. 7. Sensitivity of ELECTRE IS, TOPSIS and COPRAS results under different weighting cases.

Table 13
Different weighting scenarios integrating subjectivity in the MCDM process.

Criteria	AHP-G	Criteria with a 12% weight increase (+) and a decrease of 12% of weight (−) Criteria with a relevant degree of subjectivity (*)						
	Original	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
(C1) Construction cost	0.159	**0.111***	0.159	0.159	0.159	0.178+	0.140−	0.140−
(C2) Service life cost	0.071	0.079+	**0.148***	0.071	0.071	0.071	0.062−	0.062−
(C3) Environmental impacts	0.239	0.268+	0.211−	**0.182***	0.239	0.239	0.239	0.211−
(C4) Local community	0.088	0.098+	0.077−	0.098+	**0.141***	0.088	0.088	0.088
(C5) Consumer	0.319	0.319	0.281−	0.357+	0.281−	**0.285***	0.319	0.319
(C6) Worker	0.074	0.074	0.074	0.083+	0.065−	0.083+	**0.107***	0.074
(C7) Society	0.051	0.051	0.051	0.051	0.045−	0.057+	0.045−	**0.107***
Δw_i in the most subjective C_{ij}	(*)	−30%	+110%	−24%	+61%	−11%	+46%	+ 110%

for scenario 2, where criterion C2 (service life cost) is considered the most subjective. With COPRAS and TOPSIS, the second preference goes to B + C, although only in scenario 3 is close to the first position and almost coincides with TOPSIS. Using TOPSIS and COPRAS, the CNJ alternative is postulated as the preferred alternative, with B + C as the runner-up. This is true in all cases, although in scenario 3 the scores are so close that with TOPSIS, they almost overlap. This case is sensitive to considering environmental criterion C3 with a higher subjectivity level translated into a variation of −24% concerning the original weight. However, the ELECTRE IS method shows a sequence of alternations between the first and second positions of the CNJ and B + C designs in all eight scenarios. This means that, with ELECTRE IS, the alternative is less sensitive to variations in the weights of most of the social criteria (except for case 7). In contrast, the B + C design becomes more desirable and therefore less sensitive when the economic or environmental criteria are more subjective. Only in the case of scenario 2 no dominance relationship would allow discriminating the preference between one of the two alternatives.

While TOPSIS and COPRAS always maintain the CNJ alternative as the winner, with ELECTRE IS, the CNJ option is the most sustainable in 4 scenarios, while B + C is preferred in 3 cases. As a stand-alone tool, ELECTRE has the drawback that it can only discriminate by ranking position without comparing relative scores between alternatives. However, in combination to the other MCDMs, much more reliable results can be obtained. On the one hand, the ranking is verified to be similar to the other techniques. And on the other hand, ELECTRE IS is much more sensitive to a variation in the input data, both in the weights and in the thresholds of the pseudo-criteria. This allows us to support more consensual decision-making between the two preferred alternatives.

5. Conclusions

This paper proposes a methodology to assess the sustainability performance of foundations in buildings from a previously performed ground improvement intervention. The model analyzes the performance of the three dimensions of sustainability based on the life cycle assessment methodology introduced in ISO 14040. The assessment is applied to five different design alternatives for the foundation of a single-family house built on a conflicting terrain. The analysis considers the economic, environmental, and social impacts associated with the construction stage, integrating maintenance as part of the prevention considered in the design and sizing of the concrete elements, assuming a service life of 50 years.

Thirty-seven specific indicators have been selected for foundations, adapting a comprehensive model to characterize sustainability in building structures, developed and validated in previous studies. Three different MCDM techniques, namely ELECTRE IS, TOPSIS and COPRAS, have been applied to assess the resulting sustainability performance of each alternative and validate the robustness of the results. The one-dimensional economic, environmental and social life cycle impacts have been analyzed and then compared with the three-dimensional sustainability performance based on the results of each MCDM method. The CNJ alternative designed with footings and foundation beams on a floor reinforced with precast nailed joists has proven the preferred option from a sustainability standpoint. A sensitivity analysis has been carried out using different scenarios that link the greater or lesser burden of subjectivity in a criterion with the relevance of the rest. The results show that the weights obtained from the experts' opinions can be sensitive to subjectivities that are not quantifiable with conventional analytical procedures, thus influencing decision-making.

This paper fills a gap in research by including effective social impacts, and economic-environmental issues, in the sustainability life cycle assessment of foundations. This holistic approach beyond technical feasibility results in designs with performances more in line with the SDGs than those obtained from conventional one-dimensional assessments. The results and the case study presented can serve as a reference for both private and public sector stakeholders. In addition, the versatility of the decision-making model allows it to be calibrated by adapting it to preferences and situations different from those considered by the group of experts who participated in the seminars.

Soil improvement techniques have undergone significant development in the last decade, and there is now a wide variety of methods. This study has focused on the most commonly used soil improvement interventions with conventional foundations for buildings with light to moderate loads on expansive clay soil with sulfate aggressiveness. Situations with submerged concreting, and other types of foundations in soils of a different nature to the one analyzed, were excluded from this paper. This study has focused on evaluating different soil improvement interventions to optimize the foundation that supports the structure itself. Future lines of research should focus on two aspects, one on evaluation and the other on methodology. First, to maximize the contribution to sustainability, it would be necessary to evaluate the foundation alternatives resulting from this article combined with different structure designs based on modern methods of construction focused on that objective. And second, include the bias of the valuations as an additional parameter for obtaining the expert's voting power, similar to what has been done in this study with the consistency of his valuation.

CRediT authorship contribution statement

Antonio J. Sánchez-Garrido: The present paper represents a result of teamwork, Methodology, Software, Investigation, Writing – original draft. **Ignacio J. Navarro:** The present paper represents a result of teamwork, Writing – review & editing. **Víctor Yepes:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Grant PID2020-117056RB-I00 funded by MCIN/AEI/10.13039/501100011033 and by “ERDF A way of making Europe”.

The authors would also like to thank José Fernando Moreno Serrano (co-director of the company “Alto Almanzora Geological Consulting”) for providing some of the data and geotechnical information needed for this study.

Appendix

Table A.1
Geotechnical parameters of the computational model: Mohr-Coulomb.

Materials	Poisson’s ratio	Modulus of deformation E’ (Mpa)	Angle of friction ϕ (°)	Effective cohesion C′(kPa)	Natural density ρ (kN/m^3)
I. Anthropic infill	0.30	3.0	18.0	0	19.0
II. Brown clays with carbonates	0.30	5.0	20.0	5.0	20.0
III. Beige loams with gypsum	0.30	12.0	20.0	15.0	20.0
IV. Black marls	0.30	30.0	23.0	30.0	21.0
(1) Selected structural fill S2	0.35	100.0	34.0	5.0	20.0
(2) Soil-cement column	0.25	1.000.0	50.0	1.000.0	18.0
(3) Micropiles	0.15	2.000.0	50.0	2.000.0	22.0
(4) Precast concrete joists	0.15	2.500.0	50.0	2.500.0	24.0
II. Brown clays with carbonates IMPROVED (2)	0.3	44.8	21.2	44.8	19.9
II. Brown clays with carbonates IMPROVED (3)[a]	0.3	44.9	20.6	44.9	20.0
II. Brown clays with carbonates IMPROVED (4)	0.3	104.8	21.2	104.8	20.2
III. Beige loams with gypsum IMPROVED (2)	0.3	51.5	21.2	54.4	19.9
III. Beige loams with gypsum IMPROVED (3)	0.3	51.8	20.6	54.7	20.0

[a] Equivalent soil values for an improvement coefficient of 0.02 attributed to the columnar distribution of the alternative.

Table A.2
Results obtained for the comparative study of foundation alternatives according to soil improvement techniques.

Description	Alternatives to compare with REF				Unit
	B+C	S-CC	RIM	CNJ	
Foundation typology	Mat foundation	Mat foundation	Strip footing	Strip footing	–
Soil improvement technique	Replacement & compaction	Soil-cement column	Rigid inclusion of micropiles	Consolidation nailing joists	–
Dimensioning ground improvement, $S_x \times S_y$	–	2.0 × 2.0	0.5 × 3.0	0.5 × 0.5	m
Diameter of enhancement elements	–	0.45	0.114	0.10	m
Area of the element, A	–	0.159	0.01	0.01	m^2
Area of influence, A_f	–	4.0	1.0	0.025	m^2
Coefficient of improvement, ρ	–	0.04	0.007	0.04	–
Length of improvement element, L	–	7.0	5.0	3.0	m
No. of rows elements of improvement	–	4	4	4	–
No. of columns elements of improvement	–	11	18	98	–
Total number of improvement items	–	44	72	392	–
Linear meter improvement element	**-**	**308**	**360**	**1.176**	**m**
Thickness of foundation, D	0,7	0,5	0,5	0,5	m
Width of foundation, B	6,2	6,2	1,6	1,6	m
Thickness of structural backfill type S2, M	1.5 [a]	–	–	–	m
Thickness of the S2 type distribution layer, N	–	0.5	0.5	0.5	m
Thickness of blinding concrete, H	0.1	0.1	0.1	0.1	m
Transmitted load, q	**65**	**65**	**150**	**150**	**kPa/kN/m**
Minimum settlement, S_{min}	1.6	1.1	0.5	1.3	cm
Maximum settlement, S_{max} [b]	**2.4**	**1.4**	**0.7**	**1.5**	**cm**
Limitation of settlements, S	5.0	5.0	2.5	2.5	cm
Ultimate bearing capacity, q_h [c]	210	335	289 [e]	266 [f]	kPa
Allowable ground pressure, q_s [d]	110	145	310	235	kPa
Bearing pressure, q_{ad}	**110**	**145**	**289**	**235**	**kPa**
Vertical soil stiffness k_B	2.2	2.9	–	–	MN/m^3
Vertical soil stiffness k_{BxL}	**2.5**	**3.3**	**-**	**-**	**MN/m^3**
Checking the maximum load capacity	Compliance	Compliance	Compliance	Compliance [g]	–
Structural testing of element stresses	Compliance	Compliance	Compliance	Compliance	
Bearing capacity safety factor FS_h	**3.2**	**5.2**	**2.4**	**2.2**	**-**
Settlement safety factor FS_a	**2.0**	**2.2**	**2.1**	**1.6**	**-**

[a] It has been evaluated from the deformational point of view but considering the expansivity of the soil.

[b] The maximum settlement is referred to the foundation level. In continuous footing models with inclusions, due to the concentration of elements in the design section, the maximum settlement is transferred to the layer of influence of the improvement elements.

[c] Obtained according to CTE (Ministry of Public Works, 2019) using the parameters equivalent soil improvement; effective stresses (FS = 3).

[d] Obtained by iteration with the finite element software Plaxis 8.6 until the maximum allowable settlement value is reached; no safety factor is applied (FS = 1).

[e] Obtained for the equivalent parameters corresponding to an enhancement coefficient of 0.02, due to the concentration of the solution under the columns.

[f] Obtained with weighted parameters due to the influence of the unimproved geotechnical level III.

[g] Value at the limit of the requirement, with an extreme axial force value of 60 kN.

Table A.3
Aggregation of sub-criteria into criteria scores.

	REF			B+C			S-CC			RIM			CNJ		
Ind.	V_I [b]	V_G [b]	V_C [a]	V_I [b]	V_G [b]	V_C [a]	V_I [b]	V_G [b]	V_C [a]	V_I [b]	V_G [b]	V_C [a]	V_I [b]	V_G [b]	V_C [a]
I1	36.28	61.54	**283.58**	18.94	36.11	**256.58**	33.64	59.08	**313.84**	29.57	53.22	**306.10**	29.44	50.65	**249.13**
I2	15.55			8.12			14.42			12.67			12.62		
I3	9.70			9.05			11.03			10.98			8.60		
I4	220.57	220.57		205.63	205.63		250.63	250.63		249.62	249.62		195.50	195.50	
I5	0.86	1.48		10.01	14.84		2.70	4.13		2.06	3.26		1.90	2.97	
I6	0.41			4.75			1.28			0.98			0.90		
I7	0.09			0.03			0.07			0.09			0.07		
I8	0.12			0.04			0.08			0.13			0.09		
I9	5.55	5.55	**5.55**	4.12	4.12	**4.12**	3.91	3.91	**3.91**	7.65	7.65	**7.65**	3.04	3.04	**3.04**
I10	15.2	568	**3096**	27.0	810	**4196**	21.8	740	**4138**	39.4	745	**5581**	13.3	473	**2343**
I11	504.4			700.1			665.7			661.6			434.9		
I12	0.3			0.6			0.5			1.7			0.2		
I13	0.6			1.1			0.9			0.8			0.4		
I14	0.1			0.1			0.1			0.4			0.1		
I15	27.5			41.9			29.3			19.0			10.6		
I16	2.0			2.1			2.6			2.8			1.3		
I17	0.7			1.4			0.9			1.1			0.6		
I18	16.9			36.0			18.7			18.1			11.6		
I19	798.0	1377		1107.7	1812		1053.2	1840		1046.7	1988		688.1	1073	
I20	112.8			188.1			153.6			140.1			80.2		
I21	0.5			0.7			0.7			0.7			0.4		
I22	0.1			0.2			0.2			0.2			0.1		
I23	459.4			506.5			624.2			781.9			299.6		
I24	6.2			8.5			8.0			18.4			4.2		
I25	807.1	1151		1006.5	1574		1065.7	1558		1086.9	2848		582.1	798	
I26	343.8			567.6			492.1			1761.0			215.4		
I27	0.57 [c]	0.57	**0.37**	0.38 [c]	0.38	**0.55**	1 [c]	1	**0.64**	0.89 [c]	0.89	**0.65**	0.38 [c]	0.38	**0.57**
I28	0.18 [c]	0.18		0.72 [c]	0.72		0.27 [c]	0.27		0.42 [c]	0.42		0.76 [c]	0.76	
I29	0.50 [c]	0.63	**0.39**	0.37 [c]	0.71	**0.74**	0.40 [c]	0.59	**0.43**	0.39 [c]	0.51	**0.34**	0.28 [c]	0.47	**0.64**
I30	0.13 [c]			0.34 [c]			0.18 [c]			0.12 [c]			0.19 [c]		
I31	0 [c]	0.16		0.45 [c]	0.76		0.19 [c]	0.28		0.07 [c]	0.17		0.50 [c]	0.81	
I32	0.16 [c]			0.31 [c]			0.09 [c]			0.10 [c]			0.31 [c]		
I33	0.10 [c]	0.24	**0.56**	0.26 [c]	0.77	**0.70**	0.17 [c]	0.40	**0.64**	0.10 [c]	0.26	**0.53**	0.16 [c]	0.57	**0.54**
I34	0 [c]			0.27 [c]			0.07 [c]			0.02 [c]			0.23 [c]		
I35	0.14 [c]			0,24 [c]			0.17 [c]			0.14 [c]			0.18 [c]		
I36	0.89 [c]	0.89		0.62 [c]	0.62		0.89 [c]	0.89		0.81 [c]	0.81		0.51 [c]	0.51	
I37	0.50 [c]	0.50	**0.25**	0.53 [c]	0.53	**0.27**	0.53 [c]	0.53	**0.27**	0.41 [c]	0.41	**0.20**	0.64 [c]	0.64	**0.32**

[a] Weighting of the 7 criteria decided by the AHP group according to Section 4.4.
[b] The same weighting is attributed to each subcategory, both subcriteria and indicators (Hagerty and Land, 2007).
[c] Social indicators transformed into common units according to Table 4 (MIVES).

References

Abba, H.A., Sani, L., Hijab, A.M., Daud, Z., 2017. Novel admixture for improvement of foundations on tropical expansive soils. Int. J. Integr. Eng. 9 (1), 44–49.

Aguado, A., Manga, R., Ormazabal, G., 2006. Los aspectos conceptuales del proyecto MIVES. In: La medida de la Sostenibilidad en Edificacion Industrial (Chapter 6) (pp. 113–134. . Bilbao, Spain.

Baqir, H.H., AL-Soudany, K.Y.H., Al-Gharbawi, A.S.A., 2020. Clay columns stabilized with fly ash in soft soils. In: 4th International Conference on Buildings, Construction and Environmental Engineering (BCEE): IOP Conference Series-Materials Science and Engineering; Vol. 737, 012095. Istanbul Tech Univ, Ayazaga Campus, Istanbul, Turkey, Oct 07-09, 2019. https://doi.org/10.1088/1757-899X/737/1/012095.

Blayi, R.A., Sherwani, A.F.H., Ibrahim, H.H., Faraj, R.H., Daraei, A., 2020. Strength improvement of expansive soil by utilizing waste glass powder. Case Stud. Constr. Mater. 13, e00427 https://doi.org/10.1016/j.cscm.2020.e00427.

Brans, J.P., Vincke, Ph, 1985. A preference ranking organization method (The PROMETHEE method for multiple criteria decision-making). Manag. Sci. 31 (6), 647–656. https://doi.org/10.1287/mnsc.31.6.647.

Chai, X.J., Deng, K., He, C.F., Xiong, Y.F., 2021. Laboratory model tests on consolidation performance of soil column with drained-timber rod. Adv. Civ. Eng., 6698894 https://doi.org/10.1155/2021/6698894, 2021.

Do, D.H., Pham, T.A., 2018. Investigation of performance of soil-cement pile in support of foundation systems for high-rise buildings. Civ. Eng. J 4 (2), 266–277. https://doi.org/10.28991/cej-030990.

De Brito, M.M., Evers, M., 2016. Multi-criteria decision-making for flood risk management: a survey of the current state of the art. Nat. Hazards Earth Syst. Sci. 16, 1019–1033. https://doi.org/10.5194/nhess-16-1019-2016.

Eckenrode, R.T., 1965. Weighting multiple criteria. Manag. Sci. 12 (3), 180–192.

El-kady, M.S., Badrawi, E.F., 2017. Performance of isolated and folded footings. J. Comput. Des. Eng. 4 (2), 150–157. https://doi.org/10.1016/j.jcde.2016.09.001.

Ellen MacArthur Foundation, 2019. Completing the Picture: How the Circular Economy Tackles Climate Change. https://www.ellenmacarthurfoundation.org/publications/completing-the-picture-climate-change. (Accessed 1 April 2020).

García-Segura, T., Penadés-Plà, V., Yepes, V., 2018. Sustainable bridge design by metamodel-assisted multi-objective optimization and decision-making under uncertainty. J. Clean. Prod. 202, 904–915. https://doi.org/10.1016/j.jclepro.2018.08.177.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2009. ReCiPe 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, first ed. (Report I: Characterisation).

Hagerty, M.R., Land, K.C., 2007. Constructing summary indices of quality of life: a model for the effect of heterogeneous importance weights. Socio. Methods Res. 35, 455–496. https://doi.org/10.1177/0049124106292354.

Hajkowicz, S., Collins, K., 2007. A review of multiple criteria analysis for water resource planning and management. Water Resour. Manag. 21, 1553–1566. https://doi.org/10.1007/s11269-006-9112-5.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., Van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Hwang, C.L., Yoon, K., 1981. Multiple Attribute Decision Making-Methods and Applications: A State of the Art Survey. Springer Verlag, Berlin, Heidelberg, New York, ISBN 978-3-642-48318-9.

ISO, 2006a. Environmental Management:—Life Cycle Assessment— Principles and Framework. International Standards Organization, Geneva ISO 14040, 2006.

ISO, 2006b. Environmental Management—Life Cycle Assessment— Requirements and Guidelines. International Organisation for Standardisation. ISO 14044, Geneva, 2006.

Keršuliene, V., Zavadskas, E.K., Turskis, Z., 2010. Selection of rational dispute resolution method by applying new step-wise weight assessment ratio analysis (SWARA). J. Bus. Econ. Manag. 11 (2), 243–258. https://doi.org/10.3846/jbem.2010.12.

Li, X.J., Zheng, Y.D., 2020. Using LCA to research carbon footprint for precast concrete piles during the building construction stage: a China study. J. Clean. Prod. 245, 118754 https://doi.org/10.1016/j.jclepro.2019.118754, 2020.

MacCrimmon, K.R., 1968. Decision Making Among Multiple-Attribute Alternatives: A Survey and Consolidated Approach (No. RM-4823-ARPA). Rand Corporation, Santa Monica, CA.

Makovetskiy, O., Zuev, S., 2016. Practice device artificial improvement basis of soil technologies jet grouting. Procedia Eng. 165, 504–509. https://doi.org/10.1016/j.proeng.2016.11.726.

Mahmutluoglu, B., Bagriacik, B., 2021. Sustainable implementation of glass manufacturing waste and geogrids in the improvement of fine-grained soils. KSCE J. Civ. Eng. 25 (4), 1295–1307. https://doi.org/10.1007/s12205-021-1344-7.

Martínez-Blanco, J., Lehmann, A., Muñoz, P., Anton, A., Traverso, M., Rieradevall, J., Finkbeiner, M., 2014. Application challenges for the social life cycle assessment of fertilizers within life cycle sustainability assessment. J. Clean. Prod. 69, 34–48. https://doi.org/10.1016/j.jclepro.2014.01.044.

Mercader, M.P., Marrero, M., Solís, J.A., Montes, M.V., Ramírez, A., 2010. Quantification of material resources consumed during concrete slab construction. Inf. Constr. 62 (517), 125–132. https://doi.org/10.3989/ic.09.000.

Ministry of Public Works, 2002. Guía de cimentaciones en obras de carreteras, Spain. https://www.mitma.es/recursos_mfom/0710401.pdf.

Ministry of Public Works, 2019. Documento Básico SE-C: Seguridad Estructural Cimientos, Spain. https://www.codigotecnico.org/pdf/Documentos/SE/DcmSE-C.pdf.

Mochida, Y., Olabamiji, O.J., Kasahara, K., 2021. Study on development of soil improvement pile method using recycled soil. Int. J. Geomate 20 (82), 28–33. https://doi.org/10.21660/2021.82.Gx249.

Mollaali, M., Alitalesh, M., Yazdani, M., Shafie, M.B., 2014. Soil improvement using micropiles. In: 8th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE): Numerical Methods in Geotechnical Engineering; Vol. 1, Pp. 535-540. Delft University of Technology, Delft, Netherlands, Jun 18-20, 2014.

Navarro, I.J., Yepes, V., Martí, J.V., 2019. A review of multicriteria assessment techniques applied to sustainable infrastructure design. Adv. Civ. Eng. 2019, 6134803 https://doi.org/10.1155/2019/6134803.

Navarro, I.J., Yepes, V., Martí, J.V., 2020. Sustainability assessment of concrete bridge deck designs in coastal environments using neutrosophic criteria weights. Struct. Infrastruct. Eng. 16 (7), 949–967. https://doi.org/10.1080/15732479.2019.1676791.

Nicholson, P.G., 2015. Soil Improvement and Ground Modification Methods. Elsevier, Butterworth-Heinemann, p. 472.

Ogrodnik, K., 2019. Multi-criteria analysis of design solutions in architecture and engineering: review of applications and a case study. Buildings 9 (12), 244. https://doi.org/10.3390/buildings9120244.

Opricovic, S., 1998. Multicriteria Optimization Of Civil Engineering Systems. PhD Thesis. Faculty of Civil Engineering, Belgrade, p. 302.

Pellicer, E., Yepes, V., Correa, C.L., Alarcón, L.F., 2014. Model for systematic innovation in construction companies. J. Construct. Eng. Manag. 140 (4), B4014001 https://doi.org/10.1061/(ASCE)CO.1943-7862.0000700.

Pons, O., Casanovas-Rubio, M.M., Armengou, J., De la Fuente, A., 2021. Sustainability-driven decision-making model: case study of fiber-reinforced concrete foundation piles. J. Construct. Eng. Manag. 147 (10), 04021116 https://doi.org/10.1061/(ASCE)CO.1943-7862.0002073.

Pujadas-Gispert, E., Sanjuan-Delmas, D., De la Fuente, A., Moonen, S.P.G., Josa, A., 2020. Environmental analysis of concrete deep foundations: influence of prefabrication, concrete strength, and design codes. J. Clean. Prod. 244, 118751 https://doi.org/10.1016/j.jclepro.2019.118751.

Roy, B., 1968. Classement et choix en présence de points de vue multiples. Revue française d'automatique, d'informatique et de recherche opérationnelle. Recherche opérationnelle 2 (1), 57–75.

Roy, B., Skalka, J.M., 1984. ELECTRE IS: Aspects méthodologiques et guide d'utilisation. Document du Lamsade, vol. 30. Universidad Paris- Dauphine, París.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J. Math. Psychol. 15 (3), 234–281. https://doi.org/10.1016/0022-2496(77)90033-5.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York, ISBN 0-07-054371-2.

Saaty, T.L., 1996. The Analytic Network Process. RWS Publications, Pittsburgh.

Sandanayake, M., Zhang, G.M., Setunge, S., Luo, W.K., Li, C.Q., 2017. Estimation and comparison of environmental emissions and impacts at foundation and structure construction stages of a building - a case study. J. Clean. Prod. 151, 319–329. https://doi.org/10.1016/j.jclepro.2017.03.041.

Salas, J., Yepes, V., 2020. Enhancing sustainability and resilience through multi-level infrastructure planning. Int. J. Environ. Res. Publ. Health 17 (3), 962. https://doi.org/10.3390/ijerph17030962.

Sánchez-Garrido, A.J., Yepes, V., 2020. Multi-criteria assessment of alternative sustainable structures for a self-promoted, single-family home. J. Clean. Prod. 258, 120556 https://doi.org/10.1016/j.jclepro.2020.120556.

Sánchez-Garrido, A.J., Navarro, I.J., Yepes, V., 2021. Neutrosophic multi-criteria evaluation of sustainable alternatives for the structure of single-family homes. Environ. Impact Assess. Rev. 89, 106572 https://doi.org/10.1016/j.eiar.2021.106572.

Sánchez-Garrido, A.J., Navarro, I.J., Yepes, V., 2022. Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction. J. Clean. Prod. 330, 129724 https://doi.org/10.1016/j.jclepro.2021.129724.

Sierra, L., Pellicer, E., Yepes, V., 2016. Social sustainability in the lifecycle of Chilean public infrastructure. J. Construct. Eng. Manag. 142 (5), 05015020 https://doi.org/10.1061/(ASCE)CO.1943-7862.0001099.

Stanujkic, D., Zavadskas, E.K., Karabasevic, D., Smarandache, F., Turskis, Z., 2017. The use of the PIvot Pairwise RElative Criteria Importance Assessment method for determining the weights of criteria. Rom. J. Econ. Forecast 20 (4), 116–133.

Sodenkamp, M.A., Tavana, M., Di Caprio, D., 2018. An aggregation method for solving group multi-criteria decision-making problems with single-valued neutrosophic sets. Appl. Soft Comput. 71, 715–727. https://doi.org/10.1016/j.asoc.2018.07.020.

Susinskas, S., Zavadskas, E.K., Turskis, Z., 2011. Multiple criteria assessment of pile-columns alternatives. Baltic J. Road Bridge Eng. 6 (3), 77–83. https://doi.org/10.3846/bjrbe.2011.19.

Swarr, T., Hunkeler, D., Klopffer, W., Pesonen, H., Ciroth, A., Brent, A., Pagan, R., 2011. Environmental life-cycle costing: a code of practice. Int. J. Life Cycle Assess. 16 (5), 389–391. https://doi.org/10.1007/s11367-011-0287-5.

Torres-Machí, C., Chamorro, A., Pellicer, E., Yepes, V., Videla, C., 2015. Sustainable pavement management integrating economic, technical, and environmental aspects in decision making. Transport. Res. Rec. 2523 (1), 56–63. https://doi.org/10.3141/2523-07.

Turskis, Z., Daniūnas, A., Zavadskas, E.K., Medzvieckas, J., 2016. Multicriteria evaluation of building foundation alternatives. Comput. Aided Civ. Infrastruct. Eng. 31 (9), 717–729. https://doi.org/10.1111/mice.12202.

Turskis, Z., Dzitac, S., Stankiuviene, A., Šukys, R., 2019. A fuzzy group decision-making model for determining the most influential persons in the sustainable prevention of accidents in the construction SMEs. Int. J. Comput. Commun. Control 14 (1), 90–106. https://doi.org/10.15837/ijccc.2019.1.3364.

UNEP/SETAC, 2009. Guidelines for social life cycle assessment of products, united Nations environment program. In: Paris SETAC Life Cycle Initiative United Nations Environment Programme. https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2009%20-%20Guidelines%20for%20sLCA%20-%20EN.pdf. (Accessed 20 December 2020).

UNEP/SETAC, 2013. Methodological Sheets for the Subcategories of Social Life Cycle Assessment (S-LCA). https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf. (Accessed 20 December 2020).

Yepes, V., 2020. In: second ed (Ed.), Procedimientos de construcción de cimentaciones y estructuras de contención. Colección Manual de Referencia. Universitat Politècnica de València, p. 480. Ref. 328. ISBN: 978-84-9048-903-1.

Zamarrón-Mieza, I., Yepes, V., Moreno-Jiménez, J.M., 2017. A systematic review of application of multi-criteria decision analysis for aging-dam management. J. Clean. Prod. 147, 217–230. https://doi.org/10.1016/j.jclepro.2017.01.092.

Zavadskas, E.K., Kaklauskas, A., Sarka, V., 1994. The new method of multicriteria complex proportional assessment of projects. Technol. Econ. Dev. Econ. 1 (3), 131–139.

Zavadskas, E.K., Sušinskas, S., Daniūnas, A., Turskis, Z., Sivilevičius, H., 2012. Multiple criteria selection of pile-column construction technology. J. Civ. Eng. Manag. 18 (6), 834–842. https://doi.org/10.3846/13923730.2012.744537.

Zavadskas, E.K., Antuchevičienė, J., Kaplinski, O., 2016a. Multi-criteria decision making in civil engineering. Part II– Applications. Eng. Struct. Technol. 7 (4), 151–167. https://doi.org/10.3846/2029882X.2016.1139664.

Zavadskas, E.K., Mardani, A., Turskis, Z., Jusoh, A., Nor, K.M., 2016b. Development of TOPSIS method to solve complicated decision-making problems—an overview on developments from 2000 to 2015. Int. J. Inf. Technol. Decis. Making 15 (3), 645–682. https://doi.org/10.1142/S0219622016300019.

Zhu, X., Meng, X., Zhang, M., 2021. Application of multiple criteria decision making methods in construction: a systematic literature review. J. Civ. Eng. Manag. 27 (6), 372–403. https://doi.org/10.3846/jcem.2021.15260.