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Sustainability of column-supported slabs for buildings: A multi-criteria assessment

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Abstract

The global construction industry is experiencing significant growth, driving the demand for building floor area. However, this expansion comes with substantial environmental consequences, including high-energy consumption and greenhouse gas (GHG) emissions, together with economic and social impacts. To address these challenges, this research aims at providing designers and decisions-makers with an approach that will aid the quantification of those impacts relevant for the sustainability performance of flooring systems. A holistic sustainability assessment was performed considering economic, environmental, and social aspects using the Integrated Value Model for Sustainability Evaluations. This study focused on various flooring typologies, including reinforced concrete (RC) and fiber-RC (FRC) slabs with solid and waffle (for RC solution) configurations. The most representative criteria and indicators of sustainability for concrete column-supported slabs were identified, measured, and weighted—aggregated in a decision-making tree—in order to obtain a representative a sustainability index (SI) for each alternative. The results of the analysis evidence that the RC solid slab has a higher overall SI than the other alternatives, the FRC alternatives performing with similar SI of that quantified for the RC solid slab solution and the RC waffle slab being that with the lower sustainability performance among those flooring systems considered in this study. The results of a sensitivity analysis showed that those alternatives using FRC have potential for improving the overall sustainability performance.

KEYWORDS

building, decision-making, fiber-reinforced concrete (FRC), integrated value model for sustainability assessment (MIVES), solid concrete slab, sustainability, waffle concrete slab

Andrea Monserrat-López and Irene Josa contributed equally to this work.

1 | INTRODUCTION

Building construction is growing steadily, as evidenced by the significant increase in the flooring business over the past few years—the global gross floor area increased from 218 to 242 billion square meters between 2015 and 2021—as well as forecasts for the near future, which highlight a sharp rise in the global demand for building floor area. Despite the temporary dip during the pandemic, the construction sector has largely returned to pre-pandemic levels in most major economies.[1,2] Growth in emerging economies and developing countries—Africa's building construction sector, valued at USD 5.4 billion, is expected to grow at a compound annual rate of 6.4% by 2024[2]—and the need to renovate aging housing stocks in developed nations[3] are key drivers of this expansion. However, the sector's significant environmental footprint, with over 34% of global energy demand and 37% of GHG emissions attributed to building construction in 2021,[2] demands urgent action. To mitigate these impacts and promote a more sustainable construction sector, efforts must focus on reducing environmental harm while maintaining cost-effectiveness and ensuring compliance with structural reliability standards.

Two effective strategies for reducing the environmental impact of building construction are optimizing design practices and incorporating low-impact materials.[4] Research indicates that early design decisions can significantly lower a building's environmental footprint—for instance, simplifying complex layouts can reduce GHG emissions by 13% per floor plate.[5,6] Numerical optimization methods for slab design have become increasingly popular for achieving these reductions, with various numerical and experimental approaches explored in recent studies.[7]

However, assessments that focus exclusively on environmental impact—typically measured by gas emissions—fail to account for the broader aspects of a building's overall sustainability.

A more holistic approach, like the sustainability index (SI), which incorporates environmental, economic, and social factors, provides a better evaluation of sustainability performance. Several tools have been developed to assess buildings from this comprehensive perspective.[8–11] However, these tools generally assess the building as a whole and are not tailored to specific structural elements. In contrast, the Integrated Value Model for Sustainability Assessment (MIVES) offers a method for evaluating sustainability at the level of individual structural components, such as foundations, columns, or slabs.[12] MIVES, a multi-criteria decision-making tool, enables the comparison of different alternatives with similar structural performance, guiding the selection of the most sustainable option early in the design process. It has been successfully applied to structural elements like ceilings[13] and concrete columns.[14]

Given that most of the material in building construction—particularly reinforced concrete (RC)—is concentrated in slabs,[14] designing these elements with sustainability in mind is crucial for reducing the environmental impact of construction. Optimizing slab design by selecting the most efficient structural typology and introducing innovative materials, such as fiber-RC (FRC), aligns with this objective.[15,16]

Building slabs serve as key load-bearing and load-distributing elements,[17] and they come in various structural typologies.[18] Slabs can be unidirectional (load transferred along the shorter side) or bidirectional (load transferred in both directions), and may include solid slabs (flat, directly supported by columns), hollow-core slabs (precast with hollow cores), and waffle slabs (lightweight with spaced ribs).[19,20] RC slab systems are globally prevalent due to their affordability, durability, and good fire resistance. Solid slabs (Figure 1a) are especially common due to their plain ceiling, ease of construction, and cost-effective formwork.[21,22] While waffle slabs (Figure 1b) are more complex to build, they are lightweight and support larger spans without compromising structural stability, with lower susceptibility to vibrations.[21,23]

FRC has emerged as a viable alternative to RC, with acceptance in design codes.[24–29] Its use is growing in elements such as ground-supported slabs,[30] sewer pipes,[31] tunnel linings,[32,33] and solid slabs.[34]

This study addresses a significant gap in sustainability assessment by focusing on slab systems, which are central to material use in construction. The research offers two key contributions: (1) a comprehensive sustainability assessment using MIVES, integrating environmental, economic, and social dimensions into a single SI, and (2) an exploration of FRC in slab systems, showing how hybrid R/FRC solutions can improve sustainability without sacrificing structural performance. This comparative analysis provides valuable insights for both industry practices and future research in sustainable construction materials and methods.

2 | CASE STUDY

This section presents the design alternatives analyzed for the case study, as well as the procedure followed for designing them.

2.1 | Definition of alternatives

For this study, five alternatives were considered for the column-supported slabs: (1) RC solid slab (reference alternative), (2) RC waffle slab, and (3–5) FRC solid slabs with different fiber contents (macro steel fibers). The latter three alternatives were obtained by gradual increment

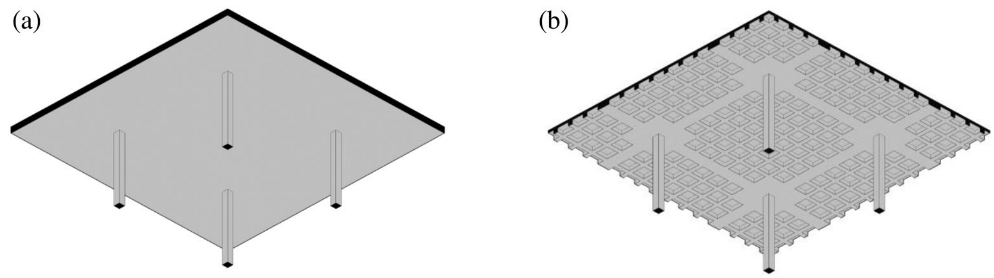

FIGURE 1 Reinforced concrete column-supported slabs: (a) solid slab; (b) waffle slab.

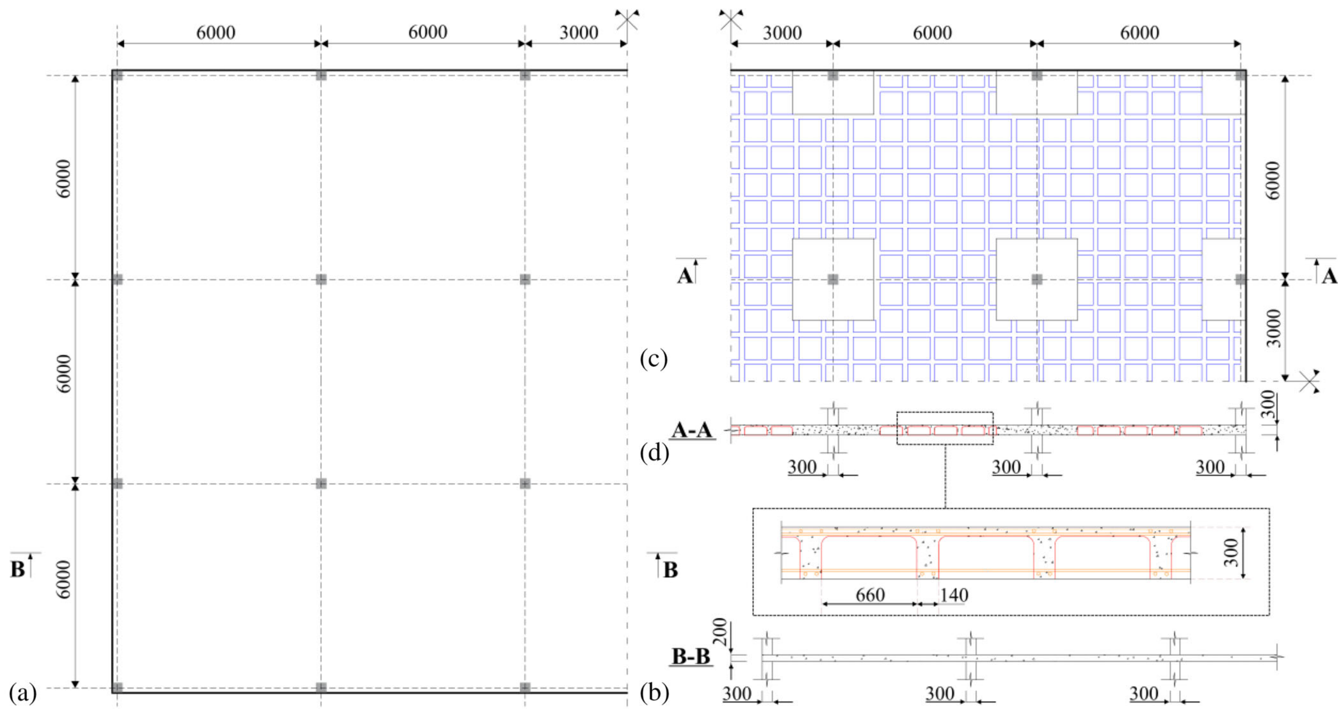

FIGURE 2 Slab geometry in the case study: (a) solid slab (RC and FRC alternatives); (b) schematic section of the solid slab; (c) waffle slab (RC alternative); (d) schematic section of the waffle slab.

of the residual tensile strengths f_{R1k} and f_{R3k} (characteristic values of the residual tensile strengths at the crack mouth opening displacement of 0.5 and 2.5 mm, respectively[35]) up to reaching the magnitude that permitted to omit completely the reinforcement in the form of steel bars. This procedure resulted in the following alternatives according to *fib* Model Code 2010[28] classification: (3) FRC 3c, (4) FRC 6c, and (5) FRC 9c. The first number being the strength class (f_{R1k}) and the letter "c" meaning that the ductility ratio f_{R3k}/f_{R1k} ranges between 0.9 and 1.1.

2.2 | Design of alternatives

The selection of the geometry was oriented to cover office and/or residential buildings. As a result, a $30.3 \times 18.3 \times 0.2\ \text{m}^3$ slab supported by 24 columns with square cross sections of 0.30 m was analyzed for the different alternatives (Figure 2). Taking into consideration the experience related to the construction of this type of slabs in Spain, a thickness of 0.20 m was adopted for the solid slabs (Figure 2a,b) and a thickness of 0.30–0.25 m and 0.05 m were adopted for the lightening expanded polystyrene blocks and the top concrete layer, respectively—was considered for the waffle slabs (Figure 2b,d).

The loads specified in the Spanish Building Code[36] for residential buildings were taken as a reference to generate the load combinations for ultimate limit state (ULS). Apart from the self-weight (q_{sw}) of 4.80 and 3.72 kN/m^2 for respectively solid and waffle configurations, a dead load (q_G) of 2.00 kN/m^2 and a variable load (q_Q) of 3.00 kN/m^2 were considered. Load partial safety factors $\gamma_G = 1.35$ and $\gamma_Q = 1.50$ were adopted to compute the design load at ULS (q_{sd}): $q_{sd} = \gamma_G \cdot$

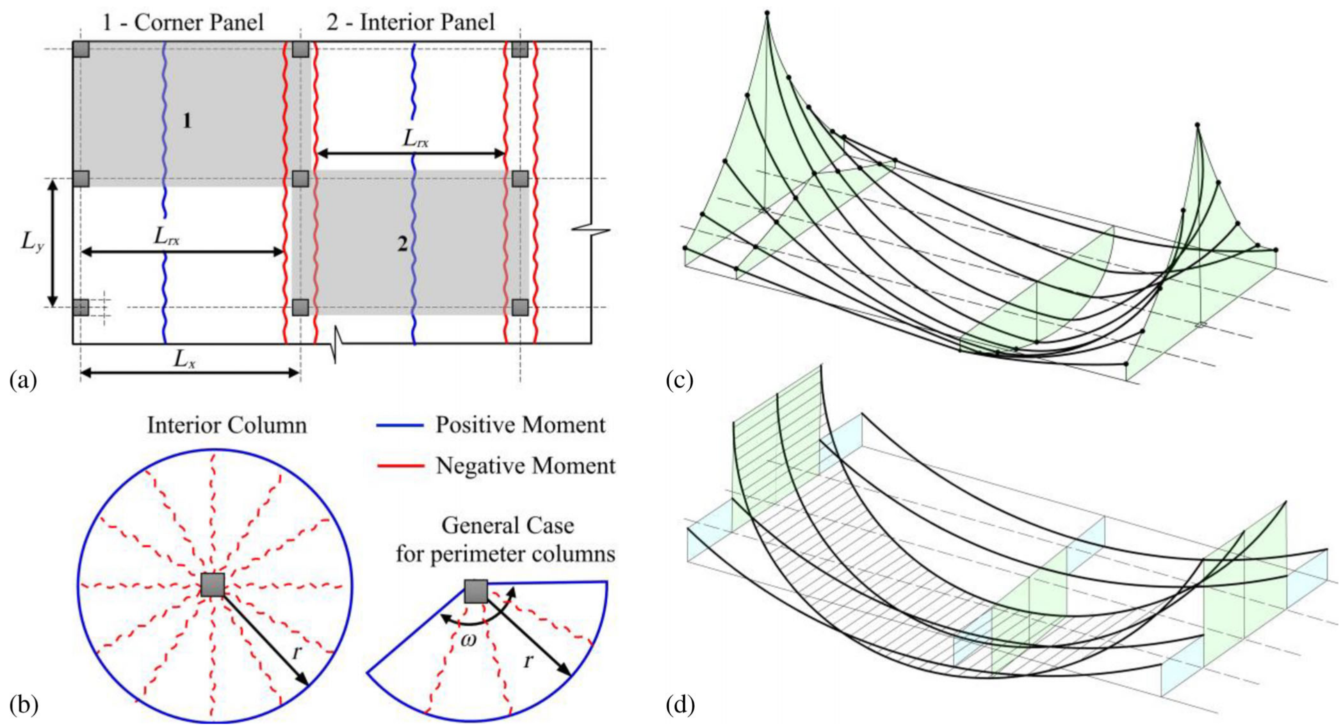

FIGURE 3 Yield line patterns for solid slabs based on[41–43]: (a) global failures; (b) local failures. (c) Typical elastic moment distribution under uniformly distribution load. (d) Simplified moment distribution assumed (adapted from reference 44).

$(q_{sw} + q_G) + \gamma_Q \cdot q_Q = 13.7$ and $12.2\,\text{kN/m}^2$ for solid and waffle solutions, respectively.

In case of alternatives consisting of solid slabs, the design load at ULS was considered for the assessment of the required flexural reinforcement of each alternative by means of Yield Line Method (YLM; Figure 3a,b),[37–39] this being essential aspect for the overall comparative analysis.

The waffle slab solution was analyzed by means of direct design method, that is, dividing the structural element into column and middle strips pursuant to current regulations[35,40] with following simplification of the regular distribution of moments at ULS (Figure 3c,d).

Once the design bending moments (M_{Ed}) were derived, the required reinforcement was evaluated by performing a cross-sectional analysis. For this purpose, a characteristic value of the compressive strength (f_{ck}) of 30 MPa was assigned for RC and 45 MPa for FRC solutions. This f_{ck} is referred to that obtained by means of cylindric specimens. Additionally, the characteristic yield strength of reinforcing steel in tension (f_{yk}) of 500 MPa was imposed. In case of FRC solutions, FRC strength classes 3c, 6c, and 9c were considered in accordance with the classification adopted in reference 28. It was assumed that $f_{R1k} = f_{R3k}$, which is consistent with the ductility class "c" ($0.9 < f_{R3k}/\text{f}_{R1k} < 1.1$). The correspondent fiber amount for each FRC strength class was computed through the semiempirical statistical correlation proposed by Tiberti et al.[45] In this study, Equation (1) was proposed to estimate the mean value f_{R3m}, being $f_{\text{cm,cube}}$ the mean cube compressive strength of concrete (in MPa), V_{f} the volume fraction of fibers, $L_{\text{f}}/\phi_{\text{f}}$ the fiber aspect ratio and f_{uf} the fiber tensile strength (in GPa).

$$f_{R3m} = \sqrt{f_{\text{cm,cube}}} \cdot 1.430 \cdot \left[V_{\text{f}} \cdot \left({}^{L_{\text{f}}}/_{\phi_{\text{f}}} \right) \cdot f_{\text{uf}} \right]. \tag{1}$$

The mean cube compressive strength ($f_{\text{cm,cube}}$) was computed according to the Clause 5.1.4 of the *fib* Model Code 2010.[28] The mean values f_{R3m} were determined by imposing coefficient of variation (CV) of 25%, 20%, and 15% for FRC 3c, FRC 6c, and FRC 9c alternatives, respectively, and assuming that f_{R3} is normally distributed. The adopted reduction of CV due to the increment of the residual tensile strength and, as a consequence, the fiber content, was evidenced by Cavalaro and Aguado.[46] Finally, the fibers with tensile strength of 1300 MPa and the aspect ratio of 80 were considered—typical value for the macro steel fibers used for the structural purposes. At this point, it is important to mention that the computed amount of traditional reinforcement (in weight) was increased by 20% in order to account for anchorages, splices, auxiliary reinforcement, and other purposes (i.e., adjusting to specific bar diameters).

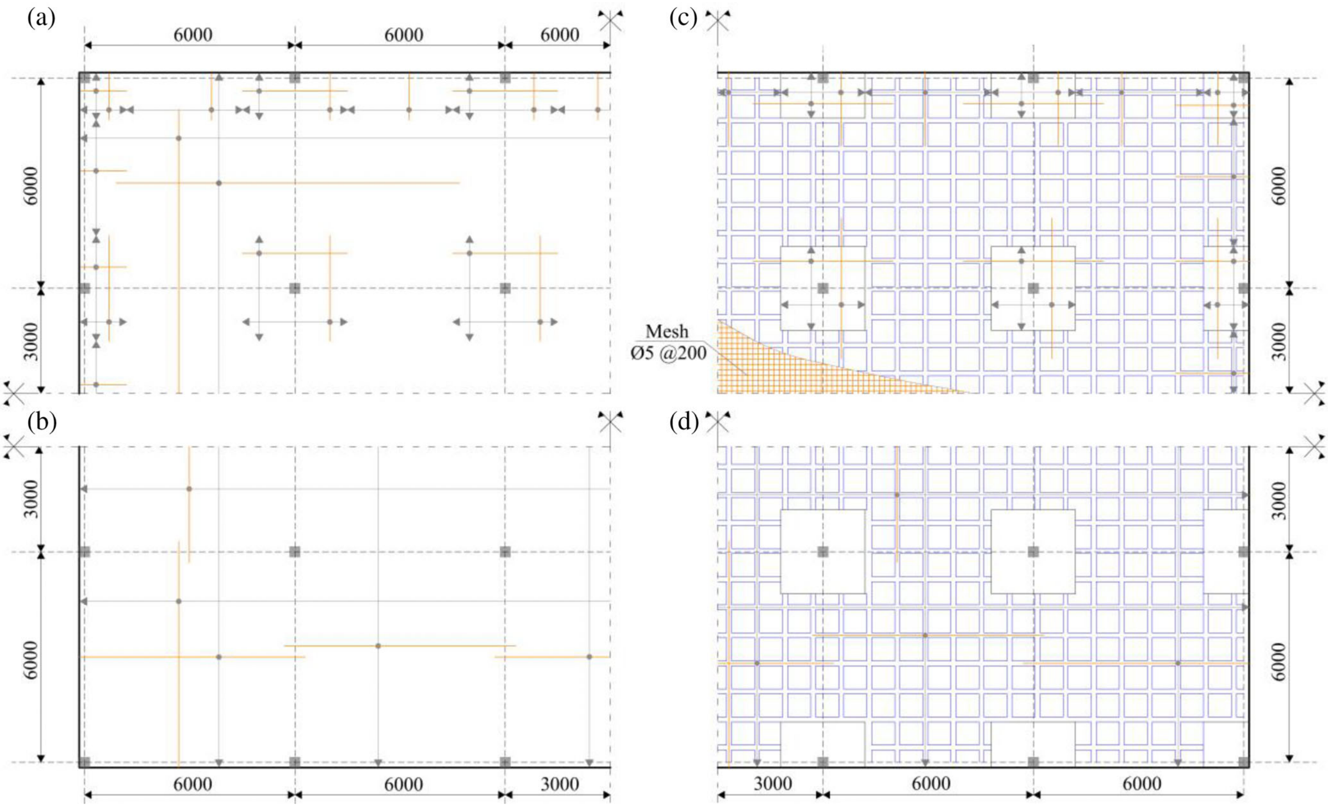

FIGURE 4 Schematic reinforcement layouts in the case study: (a) top reinforcement of the solid slab; (b) bottom reinforcement of the solid slab; (c) top reinforcement of the waffle slab; (d) bottom reinforcement of the waffle slab.

Regarding the traditional reinforcement, Figure 4 presents the adopted layouts for both solid and waffle alternatives. In the case of the solid slabs, specific conditions were imposed to the top reinforcement layout (Figure 4a): a continuous top mat was assumed in order to remove trip hazards before and during the concrete placement,[47] fulfilling the minimum required reinforcement for crack control of the slab. The rest of the top reinforcement guaranteed the adequate flexural behavior, as per YLM was concentrated over the columns in accordance with the following ratios[41]: the areas of $0.50{\cdot}L_x \times 0.50{\cdot}L_y$, $0.50{\cdot}L_{x/y} \times (0.20{\cdot}L_{y/x} + \text{E.D.})$, and $(0.20{\cdot}L_x + \text{E.D.}) \times (0.20{\cdot}L_y + \text{E.D.})$ were respectively placed over the internal, edge, and corner columns—E.D. in the presented expressions is equal to the distance between the centerline of column to edge of the slab, that is, edge distance. The bottom reinforcement layout (Figure 4b) was placed across the bays.

In the waffle slabs, the top reinforcement (Figure 4c) was mainly concentrated in the vicinity of the solid areas over the internal, edge, and corner columns; those being equal to $0.40{\cdot}L_x \times 0.50{\cdot}L_y$, $0.40{\cdot}L_{x/y} \times (0.20{\cdot}L_{y/x} + \text{E.D.})$, and $(0.20\ L_x + \text{E.D.}) \times (0.20{\cdot}L_y + \text{E.D.})$, respectively. Additionally, the mesh of 5 mm wires with a pitch of 150 mm in both directions (see Figure 4c) was considered for purposes of controlling temperature and shrinkage induced-cracking in compliance with the national recommendations.[48,49] The bottom reinforcement (Figure 4d) of the waffle slabs was placed in the ribs across the bays.

The established design approach, along with the given geometry and material properties, allowed calculating the required concrete volume (V_c), content of steel bars (C_s), and fibers (C_f). Table 1 presents the summary of the material properties for each alternative as well as the material quantities required for the posterior sustainability analysis. Taking into account that the waffle slab has variable depth, the square meter of a slab was considered as a representative unit to integrate all factors involved in the assessment of the SI of each alternative.

3 | SUSTAINABILITY ASSESSMENT

This study used the method MIVES to assess the sustainability of the five alternatives presented in the previous section through the SI. This section includes an introduction to the method MIVES, a description of the boundary conditions considered, and the assessment model.

TABLE 1 Material properties and quantities of the materials for the case study.

Alternative	Material properties					Material quantities			
	f_{ck} (MPa)	$f_{cm,cube}$ (MPa)	f_{yk} (MPa)	f_{3Rk} (MPa)	f_{3Rm} (MPa)	V_c (m^3/m^2)	C_s (kg/m^2)	C_f (kg/m^2)	EPS blocks (m^2/m^2)
RC waffle	30	38	500	—	—	0.15	11.6	0.0	1.0
RC solid	30	38	500	—	—	0.20	17.0	0.0	0.0
FRC 3c	45	60	500	3.4	5.8	0.20	10.0	8.0	0.0
FRC 6c	45	60	500	6.0	8.9	0.20	4.1	12.0	0.0
FRC 9c	45	60	500	9.6	12.7	0.20	0.0	17.0	0.0

Abbreviations: EPS, expanded polystyrene; FRC, fiber-reinforced concrete; RC, reinforced concrete.

3.1 | MIVES method

MIVES was chosen for this study due to its ability to provide a comprehensive, transparent, and customizable framework for sustainability assessments. Its advantages, such as the use of value functions, integration of real-world data, and stakeholder involvement, made it particularly suitable for assessing the sustainability of column-supported slabs. Although the method is somewhat complex and time-intensive, its benefits outweigh these challenges, and its adaptability to sustainability assessments provides significant added value over other MCDA approaches.[12]

MIVES structures the problem within a multi-criteria decision-making framework, enabling the sustainability assessment of different alternatives according to pre-established objectives. In this study, a three-level MIVES tree is developed to define this assessment framework. The three levels range from the most general to the most specific: requirements, criteria, and indicators. Among these, indicators are the only elements directly evaluated during the assessment process. Their evaluation can be based on either qualitative or quantitative variables, with varying units and scales depending on the specific indicator.

To integrate all indicators into a final SI, each indicator is assigned a weight—representing its relative importance—and a value function. The value function is a mathematical tool that converts the qualitative and quantitative variables of the indicators, each with their different units and scales, into a normalized score on a scale from 0 to 1. The weights and value functions are defined through a decision-making process guided by expert input.

To ensure the robustness of this framework, seminars were held to define the decision-making tree, including the requirements, criteria, indicators, weights, and value functions. These seminars involved nine experts—civil and industrial engineers, architects, and specialists from both the public and private sectors, as well as academia—who were experts in building design, construction, FRC, MIVES methodology, sustainability, and occupational risks in construction.

In the following section, the MIVES methodology and its key components are presented: (1) the boundary conditions that define the scope of the analysis (Section 3.2); (2) the decision-making tree, which includes the requirements, criteria, and indicators used in the assessment (section 3.3); (3) the weighting process for each requirement, criterion, and indicator (Section 3.4); (4) the value functions that transform the indicators, with their diverse units of measurement, into dimensionless values between 0 and 1 (Section 3.5); and (5) the aggregation of all indicators into a single SI (Section 3.6).

3.2 | Boundary conditions

A functional unit of 1.0 m^2 of the slab of the structure was assumed as representative for the estimation of the SI index based on the evaluation of all aspects introduced in the decision tree. While cubic meters of structure could potentially be considered for the purpose, square meters were chosen as the preferred unit of measurement due to the analysis of structures with variable thickness. For the sustainability assessment, the processes/stages related to the construction that were included in the study are (1) extraction, transportation, and in-plant processes related to the manufacture of materials, including concrete components (cement, aggregates, water and admixtures), and reinforcement (steel bars); (2) manufacture, transport, concreting, and vibration of concrete; (3) transport and installation of the reinforcement; and (4) manufacture and transport of lightening in the case of the waffle slab.

3.3 | Decision-making tree

The decision-making tree included the three sustainability requirements (R): economic, environmental, and

TABLE 2 Decision-making tree for the case study.

Requirement	W_R (%)	Criterion	W_C (%)	Indicator	W_I (%)	W_t (%)
R_1 Economic	45	C_1 Construction costs	60	I_1 Direct costs	100	27.0
		C_2 Construction time	40	I_2 Time for construction	100	18.0
R_2 Environmental	35	C_3 Outputs	64	I_3 CO_2-eq. emissions	75	16.8
				I_4 Waste generated	25	5.6
		C_4 Resources	36	I_5 Energy consumption	60	7.6
				I_6 Circularity index	40	5.0
R_3 Social	20	C_5 Comfort	30	I_7 Acoustic insulation (R_A)	50	3.0
				I_8 Acoustic impact resistance (Ln_A)	50	3.0
		C_6 Labor risks	70	I_9 ORI	100	14.0

Abbreviation: ORI, occupational risk index.

social. Each of these included different criteria (C), which in turn were divided into measurable indicators (I). The indicators in this study were carefully chosen through consultations with stakeholders and subject matter experts to ensure they provide a comprehensive representation of sustainability for column-supported slabs. These indicators were also meticulously selected to meet the essential attribute criteria outlined by Keeney and Raiffa[50] for an effective decision-making system: they are complete, operational, decomposable, nonredundant, minimal, discriminatory, and comprehensive. Furthermore, as emphasized by Lindén,[51] the indicators are statistically independent, ensuring that no adjustments to the weights are necessary. This three-level structure enabled a systematic, transparent, and robust assessment of sustainability. Table 2 presents the decision-making tree defined for this case study, detailing the requirements, criteria, and indicators.

The first requirement (i.e., R_1 *Economic*) was comprised of two criteria: C_1 *Construction costs* and C_2 *Construction time*. Each of these criteria was assessed by a single indicator. On the one hand, construction costs (C_1) are a critical aspect of economic sustainability, as lower costs can lead to more financially viable projects and contribute positively to the overall sustainability of a construction solution. In the context of this study, this criterion was assessed by the indicator I_1 *Direct costs* (in €/m^2) which included the costs associated with material (concrete, lightening blocks, and fibers) and labor (reinforcement fixing and installation and removal of the formwork) and was calculated based on data from BEDEC.[52] Detailed information on these costs can be found in Table A1. On the other hand, construction time (C_2) is another crucial economic consideration, as it impacts project schedules, time-dependent costs (i.e., preliminaries, equipment costs, overheads, and finance costs), and overall project efficiency. In this study, it was measured using indicator I_2 *Time for construction* (in h/slab) which estimated the time required to execute one slab. For this purpose, the following activities were taken into account: (1) placement of lightening blocks (in case of the waffle slab), (2) reinforcement fixing, and (3) concrete placement (incl., pouring, vibrating, and leveling operations). Detailed information on these costs is reported in Table A2.

The second requirement (i.e., R_2 *Environmental*) was classified into two criteria: C_3 *Outputs* and C_4 *Resources*. Each of these criteria was measured by two correspondent indicators. Outputs (C_3) were assessed using indicators I_3 *CO_2-eq. emissions* (in kg/m^2) and I_4 *Waste generated* (in kg/m^2). The former considered the GHG emissions generated. Information on carbon dioxide equivalent (CO_2-eq.) emissions during the manufacture of concrete, lightening blocks, steel bars and fibers, and formworks was identified in the BEDEC database.[52] Further information on the data obtained for this indicator can be found in Table A3. The latter was obtained by measuring the waste generated during the construction process, which included material waste (i.e., losses of the used materials to produce the work unit) and packaging (i.e., packaging of the materials used for the unit of work). This was calculated using the data from CYPE Engineers.[53] Further information on the data obtained for this indicator can be found in Table A4.

Resources (C_4) were measured through two indicators: I_5 *Energy consumption* (in MJ/m^2) and I_6 *Circularity index* (in points). Indicator I_5 took into account energy consumption (renewable and nonrenewable) and was calculated based on BEDEC[52] considering energy consumption during the manufacture of concrete, lightening blocks, steel bars and fibers, and formworks. Data about these consumptions can be found in Table A3. Indicator I_6 measured the potential for recycling and reusing materials; higher values indicate greater circularity. This indicator was designed based on the C-Indicator.[54] Further details can be found in Table A5.

The last requirement (i.e., R_3 *Social*) was evaluated using two criteria. The first criterion, C_5 *Comfort*, was measured using indicator I_7 *Acoustic insulation* (R_A) (in dB), which considers the airborne sound insulation (sound reduction of external noise indoors), and I_8 *Acoustic impact resistance* (L_A) (in dB), which refers to the impact sound insulation indoors. For the first indicator, higher values indicate greater insulation, while for the second, higher values indicate lower insulation. It is important to underline that, regardless of the selected alternative, the solution must comply with the regulatory requirements. However, in order to achieve adequate sound insulation, different alternatives may require additional materials, for example, leveling mortar of a certain thickness, false ceilings, and so forth. The evaluation of these two indicators was performed based on ISO 140-3[55] and ISO 140-6.[56] Further information on the data considered for their calculation can be found in Table A6.

The second criterion for this requirement, C_6 *Labor risks*, was measured using indicator I_9 *occupational risk index* (ORI) (in ORI/slab). This indicator measures the occupational risks during different stages of construction. The ORI of a construction process is the sum of the ORIs of the different activities with risk on the site. The ORI of each activity was obtained by multiplying the assessment of the probability of occurrence of the accident by the assessment of the most probable consequence of the accident and by the exposure to the risk. Exposure to risk, instead of being quantified as the frequency of occurrence of the risk situation as in other methodologies, was quantified as the total time in person-hours spent on each activity. Person-hours were defined as the uninterrupted working hours required to perform a given activity without taking into account logical work interruptions such as breaks, meals, or other types of stoppages. Further information on this index can be found in Casanovas et al.[57] Additionally, the considered risks for the calculation of the ORI can be found in Table A7.

3.4 | Weight

The analytic hierarchy process (AHP) method was employed to assign weights to the requirements, criteria, and indicators through structured pairwise comparisons. This approach allows stakeholders to express their preferences more accurately and ensures consistency and objectivity in the judgments. The AHP method is widely used in sustainability assessments, including previous MIVES case studies, reinforcing its reliability for this application. The weights were determined through a series of seminars with nine experts in the fields of civil and industrial engineering, architecture, and related disciplines. Among the various methods for aggregating experts' opinions, we selected the mean of their values as the aggregation method. This choice was made to ensure a balanced and representative set of weights reflecting the collective input of the group.[12,58] Considering that all the indicators were chosen to be statistically independent, no adjustments to the weights are necessary.[51]

Table 2 presents the decision-making tree defined for this case study, including the weight established for each requirement (W_R), criterion (W_C), and indicator (W_I), as well as the total global weight (W_t).

3.5 | Value functions

Once the indicators and its relative importance were established, value functions were defined for their normalization. Although recent literature[59,60] suggests that MIVES indicators can be transformed into a dimensionless range between -1 and 1, we opted in this study to limit the normalization to the traditional MIVES range of 0–1[61] for simplicity and consistency with previous works. Various shapes of value functions were considered, including linear, concave up, concave down, and S-shaped. The value of the indicator i being assessed (V_i) was obtained from the corresponding value function according to:

$$V_i(X) = V_i(X_{\min}) + B \cdot \left[1 - e^{-K_i \left(\frac{|X_i - X_{\min}|}{C_i}\right)^{P_i}}\right], \qquad (2)$$

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

For the case study, Table 3 presents the parameters used for the value function of each indicator, which were selected based on the shape and limits discussed and agreed upon during the seminars.

3.6 | SI: Aggregation of indicators

The final result of the SI for each alternative (X_y) is assessed according to Equation (3) as the weighted sum of each indicator, $V_i(X_y)$. As previously mentioned in

TABLE 3 Parameters of the value functions of each indicator for the case study.

		Parameters of the value function				
Indicator	**Units**	X_{min}	X_{max}	**C**	**K**	**P**
I_1 Direct costs	€/m^2	120	30	95.0	5.0	1.9
I_2 Time for construction	h/slab	48	4	11.2	0.3	1.8
I_3 CO_2-eq. emissions	kg/m^2	120	40	84.0	3.5	1.5
I_4 Waste generated	kg/m^2	4	0	1.5	0.8	1.5
I_5 Energy consumption	MJ/m^2	1100	300	500.0	1.5	1.5
I_6 Circularity index	points	3	10	7.0	0.0	1.0
I_7 Acoustic insulation (R_A)	dB	35	90	70.0	20.0	2.5
I_8 Acoustic insulation (L_A)	dB	110	20	50.0	2.0	2.0
I_9 ORI	ORI/slab	280	80	200.0	4.5	1.9

Abbreviation: ORI, occupational risk index.

previous sections, the relative weights of each indicator (w_{I_i}), criteria (w_{C_j}), and requirement (w_{R_k}) were calculated by means of the AHP, and the indicator $V_i(X_y)$ with values function.

$$\mathrm{SI}(X_y) = \sum w_{R_k} \cdot w_{C_j} \cdot w_{I_i} \cdot V_i(X_y) = \sum w_{T_i} \cdot V_i(X_y). \quad (3)$$

A SI value ranging between 0 (low sustainability) and 1 (high sustainability) allows the sustainability assessment of each of the alternatives evaluated.

3.7 | Sensitivity analysis

There are a large number of different technical and scientific sources from which to obtain data for the quantification of the indicators of the decision-making model. These sources, in turn, may consider different assessment approaches and, as a consequence, different final values for the same indicator. For this reason, consistency in the overall assessment of sustainability for a study resides, among other factors, in the consistent use of a single database for the evaluation of all the indicators involved in the study. In the case of this study, data from BEDEC[52] was used for this purpose.

To analyze the effect of such potential variations in the indicators, the Monte Carlo method was applied. The foundation of Monte Carlo is stochastic simulation, which is achieved by repeatedly reproducing an experiment to find a numerical approximation. In this study, the probabilistic analysis primarily focused on the sensitivity of the results to variations in fibers data, as these were identified by the expert panel as having the most significant potential impact on the overall outcomes. However, users of MIVES may choose to apply such analyses on other variables of the model.

TABLE 4 Uncertainty sources considered and corresponding variation.

Indicator	**Uncertainty source**	**Variation (%)**
I_1 Direct costs	Unit cost of fibers	5
I_2 Time for construction	Productivity rates	10
I_3 CO_2-eq. emissions	Embodied carbon coefficient for the fibers	20
	Embodied carbon coefficient for the rebars	20
I_5 Energy consumption	Embodied energy coefficient for the fibers	20

Data related to fibers can have high uncertainties, which is mainly due to the great variety of steel macro fibers available on the market (prices vary considerably, even for the same mechanical properties, between different commercial brands). Additionally, the relative novelty of the material causes uncertainty about its environmental performance, as there are significantly different values for CO_2-eq emissions or energy consumption during the production of the material depending on the reference considered. Hence, for this study, it was considered that the highest sources of uncertainty were direct costs of the fibers (I_1), construction time (I_2), CO_2-eq. emissions—both for the fibers and the rebars—(I_3) and energy consumption—both for the fibers and the rebars—(I_5).

Table 4 presents the uncertainty sources defined in the sensitivity analysis for different indicators and their corresponding variations. Pseudo-random values for the above indicators were generated using a normal distribution, with mean the value taken in the deterministic approach, and standard deviation taken considering the

TABLE 5 Assessment of the indicators included in the decision-making tree for each alternative for the case study.

		Alternative				
Indicator	**Units**	**RC solid**	**RC waffle**	**FRC 3c**	**FRC 6c**	**FRC 9c**
I_1 Direct costs	€/m^2	77.8	74.9	83.3	82.0	85.2
I_2 Time for construction	h/slab	24.0	35.1	15.2	8.5	3.9
I_3 CO_2-eq. emissions	kg/m^2	83.9	73.5	94.5	97.6	104.4
I_4 Waste generated	kg/m^2	1.94	2.76	1.83	1.77	1.70
I_5 Energy consumption	MJ/m^2	726.0	815.2	814.5	820.8	880.5
I_6 Circularity index	points	6	6	5	5	5
I_7 Acoustic insulation (R_A)	dB	64.1	58.4	64.1	64.1	64.1
I_8 Acoustic impact resistance (L_A)	dB	68.5	79.6	68.5	68.5	68.5
I_9 ORI	ORI/slab	189.6	193.6	176.3	165.1	157.3

Abbreviations: FRC, fiber-reinforced concrete; ORI, occupational risk index; RC, reinforced concrete.

variations presented in Table 4. The choice of the probability distribution, as well as the variation considered, were made based on previous literature[13,62,63] and discussions with experts. To obtain the results, 200 iterations were performed.

4 | RESULTS AND DISCUSSION

4.1 | Quantification of indicators

Table 5 presents the results for the nine indicators considered in the decision-making tree (see Table 2) by using the value functions proposed (see Table 3). As it can be seen, the reference unit in the case study was one square meter of slab, with solid slab alternatives being 0.20 m thick and the waffle slab alternative being 0.30 m thick. For Indicators I_2 and I_9, their quantification was based on the complete construction of a 30.3×18.3 m^2 slab.

For the evaluation of indicator I_1 (see Table A1), the costs associated with materials used in 1 m^2 of slab were obtained based on reference dosages that fitted with the requirements of each concrete mix (e.g., residual tensile strength in the case of FRC), also including the costs of lightening blocks and fibers as appropriate. To these costs, labor costs identified for the different activities involved in placing the different types of concrete (e.g., conventional concrete or self-compacting concrete) were added. In the case of the evaluation of indicator I_2 (see Table A2), it must be pointed out that the installation and further striking of shoring system were omitted assuming that those activities are identical for all the alternatives and, thus, had no effect on the comparative analysis.

The waste generated during the processes was considered for the evaluation of indicator I_4 (see Table A4), including the following categories: wood, iron, and steel, construction and demolition waste, concrete, paper and cardboard packaging, and plastic. For the evaluation of indicator I_6 (see Table A5), a scale of points was considered to evaluate the potential of circularity for the RC (solid and waffle slabs) and FRC (solid slabs). In the input category, the potential for using recycle materials was evaluated as low (2 points) for FRC and as medium (3 points) for RC. In the output category, only two aspects were considered: (1) the number of different materials—1 or 2 for RC (1 point) and between three and 10 for FRC (2 points)—and (2) the technical recyclability of materials combination—low for FRC (1 point) and medium for RC (2 points).

In the case of the evaluation of the indicators I_7 and I_8 (see Table A6), parquet was considered as the coating for all the alternatives in the case study, since it represents intermediate values of the indicators with respect to the different coating included in the codes.

4.2 | Sustainability index

The results obtained for the economic requirement are shown in Figure 5a. Regarding C_1 (direct costs), the results show that the RC waffle slab exhibits the highest satisfaction ($C_1 = 0.43$), which emphasizes its economic efficiency compared with the other alternatives. This result is well in line with the common perception that waffle slabs, although potentially more complex to construct, offer advantages in terms of cost savings due to the presence of lightening blocks, which reduces the weight of the element (as there is less concrete in 1 m^2)

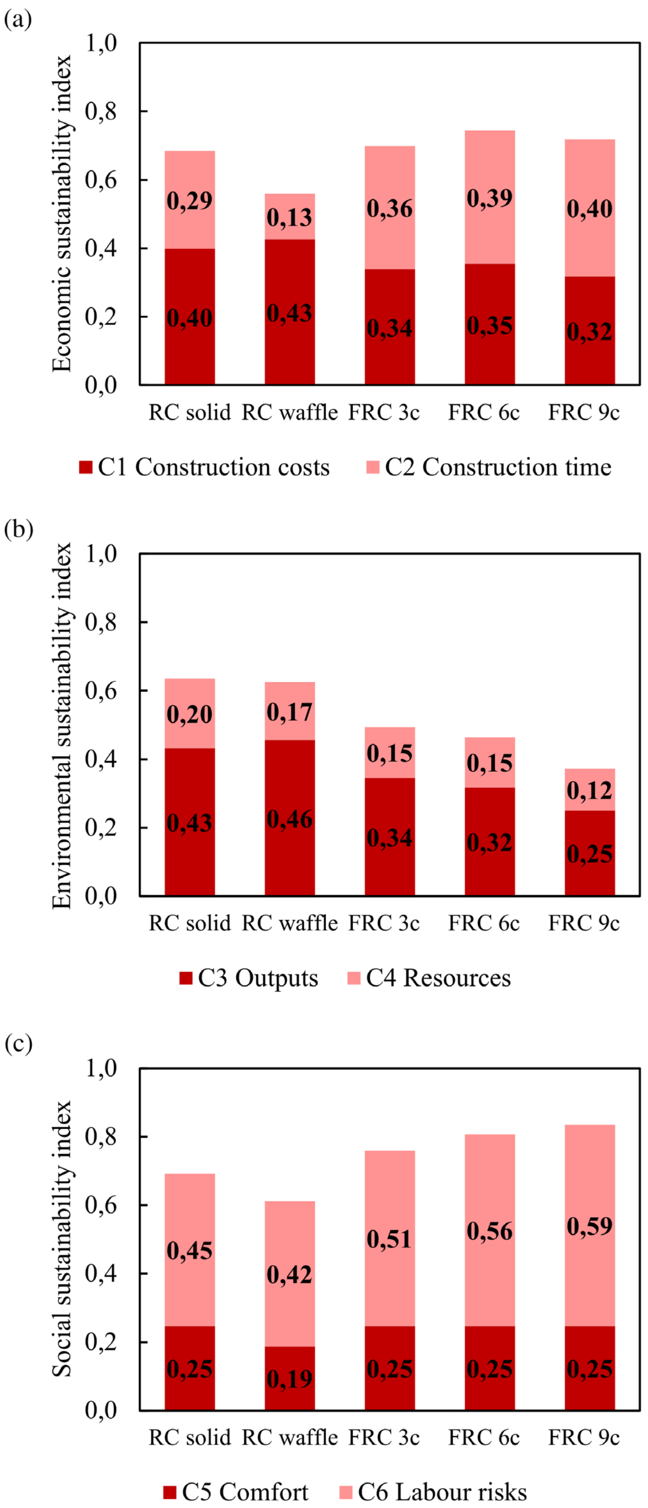

FIGURE 5 Results for the case study: (a) economic requirement R_1; (b) environmental requirement R_2; (c) social requirement R_3. FRC, fiber-reinforced concrete; RC, reinforced concrete.

and, consequently, the costs associated with the required concrete and steel. Conversely, the RC solid slab presents a lower value for this criterion ($C_1 = 0.40$), which suggests that this alternative, while is simpler in terms of the construction procedure (i.e., less activities involved), often incurs higher direct costs, due to the larger amount of concrete and reinforcement required.

FRC alternatives, in turn, indicate less favorable cost-wise sustainability (values of C_1 of 0.34, 0.35, and 0.36 for the FRC 3c, 6c, and 9c, respectively). This is attributed to the higher price of fibers in comparison with the traditional reinforcement (i.e., reinforcing steel bars). However, it is important to emphasize that only the direct costs are considered for this indicator, that is, the time-dependent cost, as the inactivity costs due to inappropriate weather conditions for placing the steel bars, are not considered.

Regarding C_2 (construction time), the results of the assessment reveal that RC waffle slab requires the most time ($C_2 = 0.13$, minimum value) in comparison with other alternatives. This is attributed to the need for the complementary activity involved in the process, that is, the placement of lightening blocks. Moreover, the presence of these blocks reduces the productivity related to the reinforcement placement and/or fixing. The absence of those drawbacks in case of RC solid slab leads to a higher value for the criterion ($C_2 = 0.29$) due to this alternative requiring less time. Finally, the use of FRC permits to partially (or even totally, i.e., FRC 9c) substitute the traditional reinforcement. As a result, FRC alternatives show higher satisfaction for this criterion (values of C_2 of 0.36, 0.39, and 0.40 for the FRC 3c, 6c, and 9c, respectively) with correspondent increment of the latter with the increased content of fibers considered.

The results obtained for the environmental requirement are shown in Figure 5b. In terms of C_3 (CO_2-eq. emissions and waste generated), the RC waffle slab has the highest satisfaction among the different alternatives ($C_3 = 0.46$). The alternatives with fibers present the lowest satisfaction in terms of emissions and waste (values of C_3 of 0.34, 0.32 and 0.25 for the FRC 3c, 6c, and 9c, respectively), while the RC solid slab has an intermediate value for this criterion ($C_3 = 0.43$). At this point, it should be noted that the evaluation of the indicator I_3 (CO_2-eq. emissions) significantly over penalizes the FRC alternatives with respect to the RC alternative. With the aim of ensuring the consistency of the analysis, the emission values have been obtained based on data from BEDEC.[52] Nevertheless, this database only approximately assesses the emissions related to the production of fibers given that this material is relatively new in the construction industry. Therefore, in order to analyze how this consideration affects the final assessment of the SI, a sensitivity analysis considering the uncertainty sources related to fibers is performed and presented in the following section.

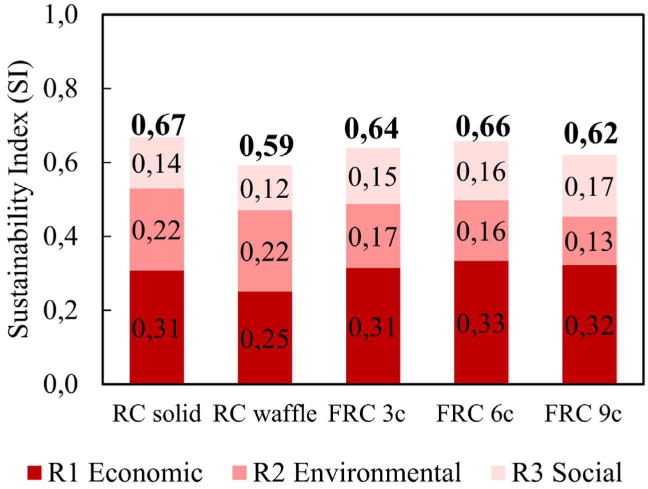

FIGURE 6 Global assessment of sustainability by means of the SI in the case study. FRC, fiber-reinforced concrete; RC, reinforced concrete.

As for C_4 (resources), the RC solid slab demonstrates the highest sustainability ($C_4 = 0.20$) because of having the lowest energy consumption and the highest circularity index, along with the RC waffle slab. FRC alternatives, in turn, show worse results in terms of energy use and recirculation, due to the presence of the fibers in the mass of concrete (values of C_4 of 0.15 for the FRC 3c and 6c, and 0.12 for the FRC 9c).

Finally, the results obtained for the social requirement are shown in Figure 5c. The assessment of C_5 (comfort) differs between the waffle slab ($C_5 = 0.19$) and solid slab alternatives ($C_5 = 0.25$). RC waffle slab exhibits the lowest acoustic insulation score, suggesting a relatively lower performance in sound insulation compared with solid slabs in accordance with the study presented in reference 64. This may be attributed to the composition of the waffle slab, which may not provide as effective acoustic insulation as solid alternatives.

Regarding the C_6 (labor risks, ORI), the results reveal variations in occupational safety among the slab alternatives. The RC waffle slab leads to the lowest ORI score ($C_6 = 0.42$), indicating a higher level of occupational risk during its construction processes. Similarly, the RC solid slab alternative shows slightly lower results ($C_6 = 0.45$) compared with the FRC alternatives, which have C_6 of 0.51, 0.56, and 0.59 for the FRC 3c, 6c, and 9c, respectively. This is due to the higher time needed for the former alternatives, which increases the potential of injuries occurring.

The integrated SI values obtained for each alternative are presented in Figure 6. As it can be seen, after aggregating the economic, environmental, and social requirements according to the decision-making tree presented in Table 3, the RC solid slab achieves the highest overall sustainability score with a SI = 0.67. Nevertheless, considering that the sustainability assessment for the FRC alternatives provides very similar results (values of SI of 0.64, 0.66, and 0.62 for the FRC 3c, 6c, and 9c, respectively), both among them and with respect to the RC solid slab alternative, it cannot be stated that the sustainability of the RC alternative is significantly higher than that of the FRC alternatives and, therefore, that its use represents a comparative advantage in terms of sustainability with respect to the FRC alternatives. On the other hand, the RC waffle slab alternative ranks last in terms of global sustainability (SI = 0.59) and, although the evaluation of the global sustainability of this alternative does not give a clear result either, it does show a perceptible difference with respect to the other alternatives, which share the same structural typology (solid slab).

In terms of the economic aspects, RC alternatives imply less direct costs than FRC alternatives because of the higher material cost for concrete with fibers. Among the two types of RC slabs, the waffle alternative has more economy efficiency thanks to the use of lightening blocks, which means a reduction of the weight and, as a consequence, of the costs associated to concrete and steel. On the other hand, FRC alternatives supposes less time construction because of the partial or even total substitution of the traditional steel bars, which considerably reduces the work required to arrange the reinforcement. In general, RC waffle slab is the least effective (economically wise) alternative because, although being the cheaper alternative considering direct costs, it is more complex to construct and requires more time. However, RC solid slab and FRC slabs are similar in economic terms, although the optimum is reached for the FRC 6c alternative. For this option, the higher costs of FRC alternatives are offset by the shorter construction times they represent, resulting in FRC 6c slab being the most advantageous option.

From an environmental point of view, RC alternatives are better in terms of both outputs and resources, since CO_2-eq. emissions and the circularity of this material are better. Consequently, RC waffle and solid slabs achieve the same environmental satisfaction. On the other hand, FRC alternatives present a lower satisfaction due to the larger amount of emissions and to the lower circularity of the material as the fibers are introduced to the concrete mix.

In terms of social satisfaction, the RC waffle slab is the least recommended option. Although it meets regulatory standards, its insulation performance is lower compared with other alternatives and its longer construction time increases the risk of injury. Solid slabs offer better insulation performance and the use of FRC reduces

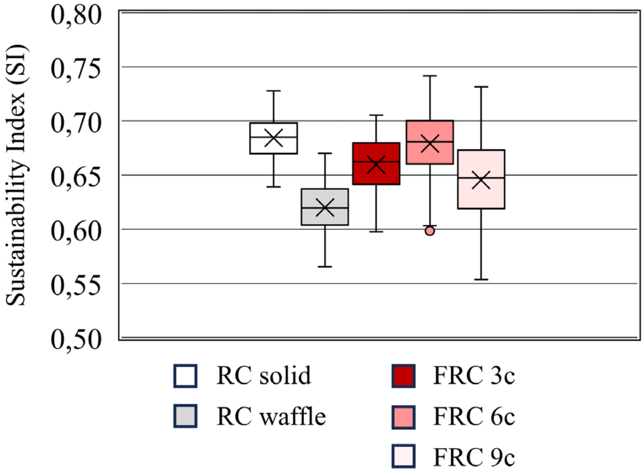

FIGURE 7 Results of the study for the uncertainty analysis. FRC, fiber-reinforced concrete; RC, reinforced concrete.

occupational risks due to shorter construction times. Therefore, the alternative with the highest fiber content (FRC 9c) achieves the highest satisfaction regarding social requirements. Similar observations can be found in reference 65.

4.3 | Sensitivity analysis

Results of the sensitivity analysis are shown in Figure 7. The highest variation in the SI is obtained by FRC 9c (standard deviation, SD = 0.037), which is due to a greater amount of fibers required to reach this FRC strength class and, therefore, a higher uncertainty in the cost and the environmental impact of this alternative. The lowest variation is obtained by the RC solid slab (SD = 0.019), in which uncertainties introduced were low due to the lower uncertainty in traditional construction materials and processes. Overall, the sensitivity analysis shows that the SI of all alternatives varies within a narrow range (between 0.56 and 0.75).

The sensitivity analysis confirms that the high uncertainty related to fibers directly affects the global sustainability performance of alternatives with FRC. Variations on the direct costs of the material and on the emissions and energy consumption during the production have not negligible consequences on the sustainability considered by means of economic, environmental, and social terms.

Nevertheless, to perform a complete study focused on analyzing how the use of fibers affects the overall sustainability of a construction alternative, indirect effects of the use of FRC should be considered. For instance, the use of fibers leads to a reduction in construction time (as confirmed in the evaluation of I_2 *Time for construction*). This time optimization affects other indicators that have not been assessed in this study. For example, the reduction in construction time implies lower indirect costs; that is, it improves the economic requirement assessment (i.e., less time spent on formwork and machinery rental, lower electricity costs on site). In turn, this means a reduction in indirect emissions from machinery needed for construction (environmental requirement), as well as indirect nuisances produced during construction (social requirement).

5 | CONCLUSIONS

This study focuses on the assessment of sustainability of concrete column-supported slabs for buildings based on the MIVES approach. This method allows alternatives to be ranked based on sustainability considering economic, environmental, and social requirements. For each requirement, several criteria and indicators were defined in the decision-making tree in order to obtain the SI of each alternative. The case study considers five different alternatives for concrete slabs, namely (1) RC solid slab, (2) RC waffle slab, and (3–5) 3c, 6c, and 9c strength class FRC (according to *fib* Model Code 2020 classification[28]) solid slabs. The following conclusions can be drawn:

- Economically, the FRC 6c solid slab is the most advantageous option considering both direct costs and time construction. In terms of direct costs, RC alternatives are more favorable because of the higher cost associated to FRC; however, FRC alternatives imply less time construction because of the partial or even total substitution of the traditional steel bars.
- Environmentally, RC alternatives (both solid and waffle configurations) show better results in comparison with FRC solutions given that those are less advantageous in terms of emissions and circularity compared with RC alternatives. However, the amount of CO_2-eq emissions and energy consumption during production associated with fibers are significantly variable according to the databases consulted.
- Socially, the FRC solid slab alternatives achieve the highest satisfaction due to the good insulation of this structural typology and the low occupational risks due to the reduced construction time.
- In terms of SI, similar results can be observed for solid alternatives (both RC and FRC solutions), whereas the waffle configuration evidences the lower SI.
- The sensitivity analyses carried out prove that costs, emissions, and energy consumption associated with fibers govern the sustainability assessment of FRC alternatives. Likewise, the results from the sensitivity analysis led to state that FRC solutions could achieve

higher SI values by mainly reducing the environmental impacts associated with the use of fibers.

- Further studies could be focused on the development of a decision-making tree that considers in more detail the time-dependent factors, such as (1) time-dependent costs, (2) the effect of the construction period on the environmental indicators (e.g., the potential reduction of the water consumption, waste generation, and emissions produced), and (3) the influence of the construction period on the social indicators (e.g., noise pollution or other inconveniences that causing discomfort to pedestrians and/or affecting the traffic).

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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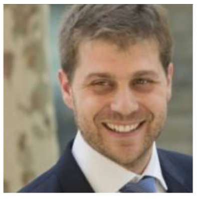

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APPENDIX A

TABLE A1 Data from BEDEC[52] used to calculate the indicator I_1 *Direct costs* of each alternative for the case study.

Product/process	Direct costs (material costs + labor costs)
Concrete for RC (solid slab)	114.17 €/m^3
Concrete for RC (waffle slab)	120.94 €/m^3
Concrete for FRC 3c	125.68 €/m^3
Concrete for FRC 6c	128.46 €/m^3
Concrete for FRC 9c	132.24 €/m^3
Lightening blocks	9.14 €/m^2
Fibers[a]	1.70 €/kg
Rebar fixing[a]	1.48 €/kg
Formwork installation + removal	29.81 €/m^2

Abbreviations: FRC, fiber-reinforced concrete; RC, reinforced concrete.
[a]Information provided by a construction company.

TABLE A2 Data from BEDEC[52] used to calculate the indicator I_2 *Time for construction* of each alternative for the case study.

Product/process	Productivity rate	Crew size
Lightening blocks placement	0.045 h/m^2	2
Rebar fixing (solid slab)	0.012 h/kg	4
Rebar fixing (waffle slab)	0.013 h/kg	4
Placement of conventional concrete	0.170 h/m^3	4
Placement of self-compacting concrete	0.140 h/m^3	4

TABLE A3 Data from BEDEC[52] used to calculate the indicator I_3 *CO_2-eq. emissions* and I_5 *Energy consumption* of each alternative for the case study.

	Global warming potential		Nonrenewable energy consumption		Renewable energy consumption	
Product/process	Product	Construction	Product	Construction	Product	Construction
Placement of RC (solid slab)	259.72 kg/m^3	7.26 kg/m^3	1187.94 MJ/m^3	113.79 MJ/m^3	31.66 MJ/m^3	0.22 MJ/m^3
Placement of RC (waffle slab)	259.72 kg/m^3	9.67 kg/m^3	1187.94 MJ/m^3	151.71 MJ/m^3	31.66 MJ/m^3	0.29 MJ/m^3
Placement of FRC 3c	328.63 kg/m^3	7.26 kg/m^3	1474.96 MJ/m^3	113.79 MJ/m^3	39.36 MJ/m^3	0.22 MJ/m^3
Placement of FRC 6c	360.79 kg/m^3	7.26 kg/m^3	1608.91 MJ/m^3	113.79 MJ/m^3	42.95 MJ/m^3	0.22 MJ/m^3
Placement of FRC 9c	374.58 kg/m^3	7.26 kg/m^3	1666.31 MJ/m^3	113.79 MJ/m^3	44.49 MJ/m^3	0.22 MJ/m^3
Lightening blocks placement	9.82 kg/m^2	0.00 kg/m^2	246.74 MJ/m^2	0.00 MJ/m^2	1.18 MJ/m^2	0.00 MJ/m^2
Rebar fixing	0.94 kg/kg	0.00 kg/kg	15.18 MJ/kg	0.00 MJ/kg	0.64 MJ/kg	0.00 MJ/kg
Fibers	48.44 kg/m^3	0.00 kg/m^3	516.94 kg/m^3	0.00 kg/m^3	43.66 kg/m^3	0.00 kg/m^3
Formwork installation + removal	0.71 kg/m^2	0.00 kg/m^2	11.99 MJ/m^2	0.00 MJ/m^2	119.23 MJ/m^2	0.00 MJ/m^2

Abbreviations: FRC, fiber-reinforced concrete; RC, reinforced concrete.

TABLE A4 Data from CYPE Engineers[53] used to calculate the indicator I_4 Waste generated of each alternative for the case study.

Alternative		Wood	Iron and steel	Construction and demolition waste	Concrete	Paper and cardboard packaging	Plastic
	LER code	17 02 01	17 04 05	17 09 04	17 01 01	15 01 01	17 02 03
RC (solid slab)	kg	0.702	0.395	0.002	0.626	0.216	0
	L	0.638	0.188	0.001	0.417	0.288	0
RC (waffle slab)	kg	0.753	0.389	0.002	1.516	0.086	0.015
	L	0.684	0.185	0.001	1.011	0.115	0.025
FRC 3c	kg	0.702	0.342	0.002	0.572	0.216	0
	L	0.638	0.163	0.001	0.381	0.288	0
FRC 6c	kg	0.702	0.32	0.002	0.533	0.216	0
	L	0.638	0.152	0.001	0.355	0.288	0
FRC 9c	kg	0.702	0.305	0.002	0.475	0.216	0
	L	0.638	0.145	0.001	0.317	0.288	0

Abbreviations: FRC, fiber-reinforced concrete; RC, reinforced concrete.

TABLE A5 Data from BEDEC[52] used to calculate the indicator I_6 *Circularity index* of each alternative for the case study.

	Scale
Inputs	
Potential for using recycled materials	None (1), low (2), medium (3), and high (4)
Outputs	
Number of different materials	1 or 2 (1), 3–10 (2), and more than 10 (3)
Technical recyclability of materials combination	Low (1), medium (2), and high (3)
Material contamination (coating, paints, and material mixing)	None (1), low (2), medium (3), and high (4)

TABLE A6 Data from ISO 140-3[56] and ISO 140-6[56] used to calculate the indicators I_7 *Acoustic insulation* (R_A) *and* I_8 Acoustic impact resistance (Ln_A) of each alternative for the case study.

	Acoustic insulation (R_A)/ Acoustic impact resistance (Ln_A) [dB]	
Coating	Solid slab	Waffle slab
Parquet	64.1/68.5	58.4/79.6
Terrazzo	63.6/69.6	60.9/86.7
Floating floorboard	61.7/57.7	—/60.2
Flooring on strips	59.3/64.9	56.0/68.9
Flooring on strips and false ceiling	72.2/48.9	64.6/55.6

TABLE A7 Considered risks for the calculation of the indicator I_9 *ORI* of each alternative for the case study.[57]

	P	C	W
Fall of people from different levels—Work at height or depth with a difference in level >2 m			
Placing tiles, rebar, and concreting the board	3	20	0.060
Interior openings (mainly in buildings)	3	25	0.075
Exterior openings in facades	3	20	0.060
Blows in the upper or lower extremities—Manual handling of loads			
Reinforcement installation	3	7	0.021

Abbreviation: ORI, occupational risk index.