SUSTAINABILITY ANALYSIS OF STEEL FIBRE REINFORCED CONCRETE SLABS

A. BLANCO[1], A. DE LA FUENTE[2] AND A. AGUADO[3]

Department of Civil and Environmental Engineering
Universitat Politècnica de Catalunya
Builgind C1, 202, Campus Nord UPC
Jordi Girona 1-3, 08034 Barcelona, Spain

[1] e-mail: ana.blanco@upc.edu
[2] e-mail: albert.de.la.fuente@upc.edu
[3] e-mail: antonio.aguado@upc.edu

Key words: Concrete, Slabs, Steel Fibre Reinforced Concrete

Abstract. Fibre reinforced concrete has been used in concrete structures without any additional reinforcement when the design is determined by transient load stages (e.g. precast segments for tunnels), in elements with favourable boundary conditions or structures subjected to low load levels (e.g. pavements or pipes). The material has been more recently applied as the primary reinforcement in elements subjected to higher load levels such as slabs. As a result of the experience gained in this type of application the American Concrete Institute (ACI) has published a report on the design and construction of steel fibre reinforced concrete (SFRC) elevated slabs. Despite these advances, in some cases fibres have not been used as primary reinforcement in concrete slabs due to economic reasons. However, in most cases the comparison of this solution with other alternatives such as traditional reinforcement has been made considering only direct material costs disregarding indirect costs, social and environmental factors. Considering the above, the aim of this study is to present a method to evaluate the sustainability of concrete slabs by means of the multi-criteria decision making approach for assessing sustainability MIVES.

1 INTRODUCTION

Fibre reinforcement technology and knowledge has advanced significantly in the past years and, as a result, has expanded to other applications besides the traditional (e.g. pavements or precast elements). In particular, steel fibre reinforced concrete (SFRC) has been successfully employed in flat slabs of several buildings in Europe [1] and in Spain [2] with the fibres as the only or the main reinforcement. Such achievement represents a step forward in the applications of SFRC not only in civil engineering but also in the field of architecture.

The technical advantages of using SFRC in this typology of structures have been extensively studied [3-5], among them are the increased toughness and ductility, the cracking control or the enhanced performance in case of dynamic effects or impacts. Besides these, other advantages related with the construction should be considered when analysing the possibility of using SFRC. Given that fibres are added in the concrete plant when the concrete mix is manufactured, the amount of work on site decreases significantly. The operations of preparing, handling and placing the traditional reinforcement are reduced to localized areas where the traditional reinforcement might be necessary. As a result, the execution time of the structure is also reduced. Furthermore, the use of SFRC makes the vibration of the concrete unnecessary and the occupational safety is improved due to the lack of risks associated to the handling of the traditional reinforcement.

Although the experiences in several buildings mentioned above have confirmed these advantages and proved the technical feasibility of using SFRC in concrete slabs, its use is often not possible due to a partial picture of the benefits reported. In fact, in most cases the decision whether to use steel fibres or traditional reinforcement is made based on the direct material costs of the reinforcement, disregarding the overall costs, social aspects or environmental factors.

Considering the above, the present document aims at proposing a method for the sustainability assessment of concrete slabs using MIVES (a multi-criteria decision making approach for assessing sustainability). The method proposed is used to evaluate two different reinforcement solutions for concrete slabs of an office building in Spain taking into account economic, environmental and social aspects. Furthermore, a sensitivity study is conducted to analyse different scenarios.

2 METHOD FOR ASSESSING TE SUSTAINABILITY OF CONCRETE SLABS

2.1 General features

The method developed in the present study is based on the method MIVES [6-11]. This model requires defining three fundamental aspects: (1) the boundaries of the system that determine the scope of the analysis, (2) the requirements tree, the criteria and the indicators involved in the decision-making process and (3) the value functions that convert the attributes or physical units associated with each indicator into one-dimensional values from 0 to 1. The Analytic Hierarchy Process (AHP) method [12] is used to assign an appropriate weight to each element: requirements, criteria and indicators.

2.2 Requirements tree

The requirements tree defined in the method proposed (see Table 1) consists of the three requirements (R) generally associated with the sustainability according to the United Nations [13]: economic, environmental and social. These requirements are articulated in 5 criteria (C) and 9 indicators (I). The indicators were selected to be representative (discriminators between solutions) and independent of each other to ensure a proper evaluation.

Table 1: Requirements tree for the sustainability analysis of concrete slabs

Requirement	Criteria	Indicator	Units	Function
R_1 Economic (λ_{R1} = 60%)	C_1 Construction costs (λ_{C1} = 100%)	I_1 Execution cost (λ_{I1} = 85%)	€/m^2	DS
		I_2 Non-conformity cost (λ_{I2} = 15%)	Attributes	
R_2 Environmental (λ_{R2} = 20%)	C_2 Resources consumption (λ_{C2} = 33%)	I_3 Reinforcing steel (λ_{I3} = 40%)	Kg/m^2	DCx
		I_4 Water (λ_{I4} = 30%)	M^3/m^2	DS
		I_5 Energy (λ_{I5} = 30%)	MJ/m^2	DS
	C_3 Emissions (λ_{C3} = 67%)	I_6 CO_2 emissions (λ_{I6} = 100%)	Kg/m^2	DS
R_3 Social (λ_{R3} = 20%)	C_4 Effects on the constructor (λ_{C4} = 80%)	I_7 Risks during construction (λ_{I7} = 80%)	Attributes	
		I_8 Noise pollution (λ_{I8} = 20%)	Db	DS
	C_5 Third-party effects (λ_{C5} = 20%)	I_9 Third-party discomfort (λ_{I9} = 100%)	Attributes	

DS: decreasing S-shape; DCx: decreasing convex

The *economic requirement* (R_1) is defined by a single criterion that is the *construction costs* (C_1). This criterion is evaluated through two indicators: the *execution cost* (I_1), which involves the costs associated with the construction of the concrete slabs, and the *non-conformity cost* (I_2) that correspond to the costs derived from imperfections or errors during the construction. The execution cost is calculated taking into account the formwork (materials and assembly), steel rebars, steel fibres, concrete, labour and auxiliary resources and facilities. The non-conformity costs are evaluated through attributes. For that, an assessment of the risks that increase the probability of a non-conforming product is conducted.

The *environmental requirement* (R_2) is evaluated through two criteria: the *resources consumption* (C_2) and the *emissions* (C_3). The resources consumption is defined by the consumption of *reinforcing steel* (I_3), of *water* (I_4) and *energy* (I_5), whereas for the emissions only CO_2 emissions are considered. The reinforcing steel consumption is evaluated considering the total amount of steel required for the concrete slabs, either longitudinal and transversal reinforcement for the traditional solution or steel fibres for the FRC. In terms of water consumption, only the water used in the manufacturing of the materials and the water used on site are considered. The energy consumption is obtained from the available databases. Finally, the emissions criterion is assessed by quantifying the amount of CO_2 released during the manufacturing of the concrete and the steel required for the construction of the slab.

The *social requirement* (R_3) is determined by means of two criteria: the *effects on the constructor* (C_5) and the *third-party effects* (C_5). Two indicators are considered in the effects on the constructor: the *risks during construction* (I_7) and the *noise pollution* (I_8). The risks during construction in the different stages of the construction process are assessed by means of attributes. For that, the risks during concrete pouring and vibration of the slab are analyzed qualitatively. Notice that the use of steel fibres may cause cuts and lesions to the workers when they protrude on the surface. The third-party effects are evaluated with one indicator, the *third-party discomfort* (I_9). Three variables are used to quantify this indicator, namely the noise pollution, the discomfort for the bystanders and effects on the traffic.

The indicators previously described are assigned *value functions* in order to evaluate the sustainability index ($\boldsymbol{I_s}$) of the alternatives, which ranges from 0.0 to 1.0 and normally remains below 0.8. This approach was already applied in previous studies [6, 14-17]. This function transforms physical units of each indicator (e.g. €/m^2, kg/m^2, dB) into dimensionless values ranging from 0 to 1. These values represent the sustainability or satisfaction of each indicator. Eq.(1) shows the general form of a value function.

$$\boldsymbol{I_{ind}}(\boldsymbol{X}) = \boldsymbol{A} + \boldsymbol{B}\left[1 - e^{-\boldsymbol{K_i}\left(\frac{|\boldsymbol{X_{ind}} - \boldsymbol{X_{min}}|}{\boldsymbol{C_i}}\right)^{\boldsymbol{F_i}}}\right] \tag{1}$$

In Eq.(1), $\boldsymbol{B}$ is the value of $\boldsymbol{I_{ind}}$ for $\boldsymbol{X_{min}}$; $\boldsymbol{X_{min}}$ is the minimum abscissa value in the indicator interval assessed; $\boldsymbol{X}$ is the abscissa value for the indicator assessed; $\boldsymbol{P_i}$ is a shape factor which defines whether the curve is concave ($\boldsymbol{P_i}$<1), convex ($\boldsymbol{P_i}$>1), linear ($\boldsymbol{P_i}$=1) or S-shaped ($\boldsymbol{P_i}$>1) (see Figure 1); $\boldsymbol{C_i}$ approximates the abscissa at the inflexion point; $\boldsymbol{K_i}$ tends towards $\boldsymbol{I_{ind}}$ at the inflexion point; ***B*,** the factor that prevents the function from exceeding the range (0, 1), is obtained by Eq.(2), $\boldsymbol{X_{max}}$ being the abscissa value of the indicator that gives a response value of 1 for increasing value functions.

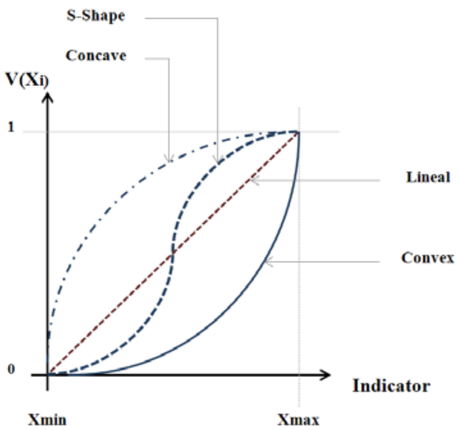

Figure 1: Shapes of the value function

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

The form of the value functions assigned to each indicator (see Table 1) is a decreasing S-shape curve (DS) for I_1, I_4-I_6 and I_8 and a decreasing convex curve (DCx) for I_3.

The *weights* (λ) of each requirement, criterion and indicator are assigned by applying the AHP method and represent the importance of each element in the requirement tree. Notice that the weights assigned to the requirements in Table 1 correspond to a situation where the economic requirement is strongly prioritized in order to simulate a more entrepreneurial view of the analysis or to take into account a situation of financial recession on the part of the authority or agency that has to take the decision and make the investment. Even though this scenario may be realistic, and therefore considered in the study, it is hard to accept from the sustainability point of view. This scenario will be referred to as base scenario ($\mathbf{E_0}$).For the purpose of this study; two additional scenarios prioritizing other requirements will also be considered in order to evaluate the sensitivity of the method (see section 4).

3 CASE STUDY: OFFICE BUILDING IN ARRASATE-MONDRAGÓN

3.1 Description of the structure

The structure selected for the case study is the project of the head office building of LKS in Arrasate-Mondragón (Guipúzcoa), which is a pioneer experience in Spain in the use of steel fibres as the main reinforcement in concrete slabs. All the data corresponding to the geometry, materials, etc. used in the present study was obtained from a Doctoral Thesis [18].

The building has 4 floors and a semi-basement that provides access to the offices. The four façades are oriented with the cardinal points. The construction involves the basement (floor -1), the ground floor and three other floors. The dimensions of the basement below ground level are 43.0 x 20.0 m, whereas at ground level the dimensions are 23.0 x 20.0 m. The total built surface of the building is 3506 m^2; from which 862 m^2 correspond to the basement and 661 m^2 to each of the other four floors above ground.

The structural solution adopted for the design consists of a grid of 8.0 m x 8.0 m with round and rectangular reinforced concrete columns supported directly on slabs of 30 cm of thickness corresponding to the slabs of the ground floor, floors 1, 2 and 3. This type of floor is constructed around a central core that contains the facilities and services of the building, which means that the slabs have openings. A top view of this type of floor is shown in Figure 2. The columns are aligned horizontally in sections A, B, C and D and separated 8.0 m, 4.5 m and 5.4 m, respectively, and vertically in sections 1, 2, 3, 4 and 5, which separated 7.8 m. Notice that the largest areas of the grid (8.0 m x 7.8 m) are located between sections A and B. The slab of the basement (floor -1) has a similar distribution as the one shown in Figure 2, however it includes two more sections horizontally (sections 6 and 7), adding 10.0 m more to the lateral dimension of the building. Each floor of the building has a perimetral terrace for maintenance that extends 1.15 m from the concrete structure. These terraces are made of metallic structure.

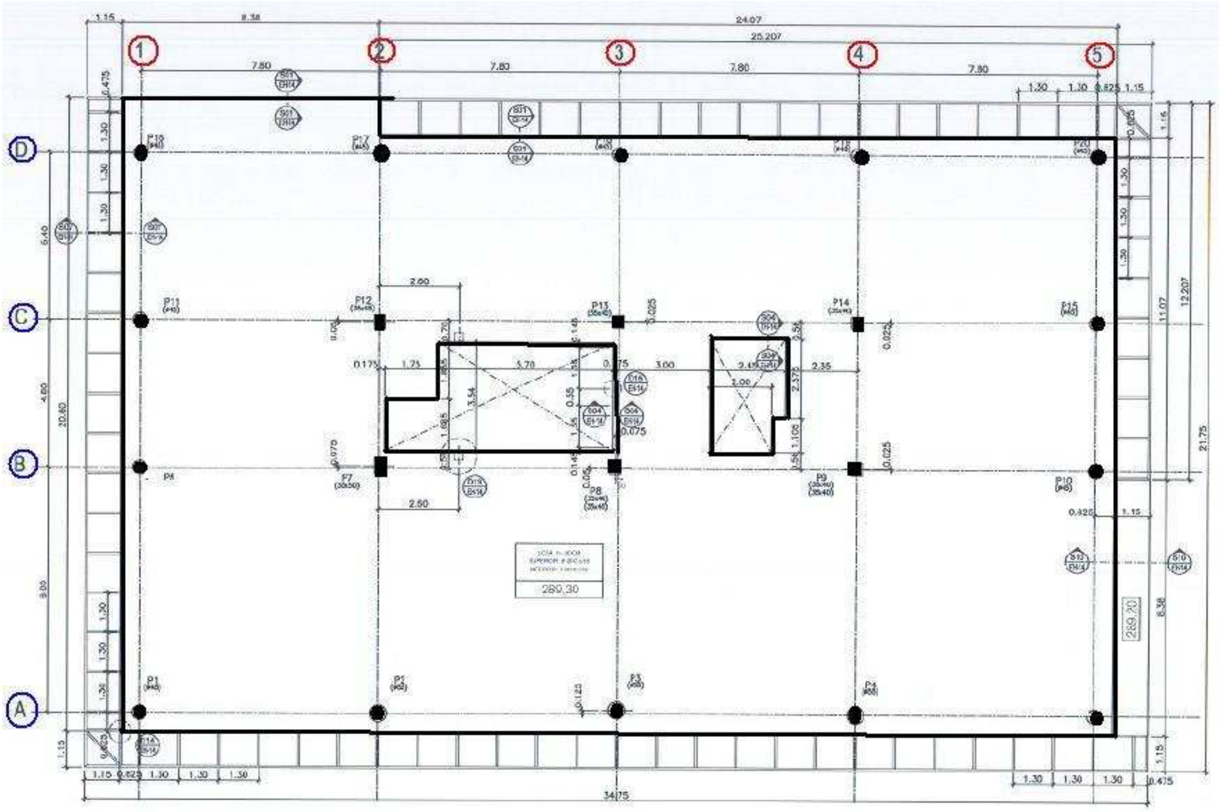

Figure 2: Slab configuration for ground floor and floors 1, 2 and 3 [18, 19]

3.2 Initial structural solution

The initial structural solution consisted in a concrete with a characteristic compressive strength of 30 MPa reinforced with traditional steel bars with characteristic yield strength of 500 MPa. The main difference between the initial solution and the proposal of SFRC is the reinforcements in the slabs of the ground floor and floors 1, 2 and 3. The design and the traditional reinforcement for the foundations, the basement (floor -1), the walls of the basement and the concrete columns remain the same in both solutions.

The traditional reinforcement in the slabs supported by the concrete columns may be classified in the following groups of reinforcement:

- *Bottom base reinforcement*: located in the entire surface at the bottom of the slab in order to bear positive bending moments. It consists of a grid rebars of 12 mm of diameter separated 15 cm. This configuration is the same for all floors.
- *Top base reinforcement*: located in the entire surface at the top of the slab in order to bear negative bending moments. This reinforcement presents the same configuration as the previous one and is the same for all floors.
- *Bottom reinforcement*: located at the bottom of the slab only in certain areas where the bottom base reinforcement is not enough to resist positive bending moments.

- *Top reinforcement*: located at the top of the slab only in certain areas such as columns or cantilevers where the top base reinforcement is not enough to bear the negative moments.
- *Punching transversal reinforcement*: located over the concrete columns in the shape of a cross with a variable number of branches in order to bear tangential stresses and to avoid punching failure.
- *Ring-beam or edge-beam reinforcement:* longitudinal and transveral reinforcement located in the external perimeter of the slab and at the edges of the openings of the slab (for the facilities).

Table 2 presents the total amount of traditional reinforcement (in kg) in each floor and the resulting steel content in kg/m^3. The reinforcement is grouped in base reinforcement (BaR), bottom reinforcement (BR), top reinforcement (TR), punching transversal reinforcement (PR) and ring-beam reinforcement (RR).

Table 2: Amount of steel in the initial solution [18]

Reinforcement	Ground floor	Floor 1	Floor 2	Floor 3	Roof floor
BaR	19565 kg	14550 kg	14550 kg	14550 kg	14550 kg
BR	1366 kg	210 kg	210 kg	210 kg	1125 kg
TR	3479 kg	2075 kg	2075 kg	2075 kg	2733 kg
PR	2820 kg	2456 kg	2456 kg	2456 kg	2456 kg
RR	781 kg	781 kg	781 kg	781 kg	781 kg
Amount (kg/m^3)	**111 kg/m^3**	**107 kg/m^3**	**107 kg/m^3**	**107 kg/m^3**	**117 kg/m^3**

The budget for the structure (without taxes) in the initial solution is 1,060,000€, which is divided into different concepts: foundations, walls and slab of the basement (325,000€), concrete columns (75,000€), slabs for ground floor and floors over the ground (510,000€) and metallic structure (150,000€).

3.3 Solution with SFRC

The alternative solution is based on the substitution of the steel rebars by steel fibers, where possible, maintaining the same thickness of the slab and the characteristic compressive strength of the concrete. The main goal is to reduce the cost associated to the structure, which is significantly affected by the labor and the preparation and placement of the traditional reinforcement. The steel fibers used present circular cross-section of 1.3 mm, a length of 50 mm and a wavy geometry along its length. The SFRC is produced in a concrete plant, adding 100 kg/m^3 of fibres to the concrete mix.

The use of traditional reinforcement as a complement for the steel fibres was considered necessary in certain areas of the slabs due to their singular geometry. Some examples are the edges of the grid (the four corners of the slab), openings in the slabs, perimetral cantilevers, cantilevers with façade loads or in the embedment of the slab of the ground floor with the wall of the basement. In all cases, the steel rebars exhibit a yield strength of 500 MPa. Furthermore, additional anti-progressive collapse rebars (APC) where included to avoid that local failure may lead to collapse of the entire structure such as reported in some buildings with a structure of slabs supported on concrete columns [20].

Table 3 presents the total amount of reinforcement (kg) in each floor and the resulting steel content in kg/m^3. The reinforcement is grouped in reinforcement for positive moments in edges of the grid (ER), the complementary reinforcement in certain areas (CR), the APC reinforcement (ApcR) and the steel fibres (SF).

Table 3: Amount of steel in alternative solution with SFRC [18]

Reinforcement	Ground floor	Floor 1	Floor 2	Floor 3	Roof floor
ER	512 kg	1025 kg	1025 kg	1025 kg	2131 kg
CR	2233 kg	1930 kg	2058 kg	1832 kg	2674 kg
ApcR	3103 kg	2627 kg	2627 kg	2627 kg	4378 kg
Amount (kg/m^3)	**23 kg/m^3**	**29 kg/m^3**	**29 kg/m^3**	**29 kg/m^3**	**49 kg/m^3**
SF	100 kg/m^3	100 kg/m^3	100 kg/m^3	100 kg/m^3	100 kg/m^3
Total amount (kg/m^3)	**123 kg/m^3**	**129 kg/m^3**	**129 kg/m^3**	**129 kg/m^3**	**149 kg/m^3**

Notice that the APC reinforcement represents additional rebars that could have also been included in the initial solution. If this reinforcement is excluded from the calculations, the amount of traditional reinforcement of this solution reduces significantly, ranging between 11 and 26 kg/m^3.

3.5 Concrete mixes

The concrete mixes considered for the initial solution with RC and the alternative solution with SFRC are presented in Table 4. The differences observed in the mix respond to the need to compensate the loss of workability of the fresh concrete due to the addition of fibres. Therefore, changes in the content of cement, water and aggregates are detected. Furthermore, fly ash was also added to the mix with steel fibres.

Table 4: Concrete mixes of the initial solution (RC) and the alternative proposed (SFRC)

Components	Characteristics	RC	SFRC
Cement (kg/m^3)	CEM I	300	400
Aggregates (kg/m^3)	-	1905	1850
Water (kg/m^3)	-	165	185
w/c (-)	-	0.55	0.41
Admixture (kg/m^3)	Fly ash	-	120
Fibres (kg/m^3)	Steel	-	100

3.5 Evaluation of the indicators

The indicators where evaluated according to Eq.(1) and the resulting values are presented in Table 5. Notice that, for the evaluation of the risks during construction (I_7), a high workability of the concrete mix was assumed for the initial solution with reinforced concrete (RC). Moreover, a normal execution control was considered for the assessment of the non-conformity costs (I_2).

Table 5: Values of the indicator (X_i) for each alternative

Indicators	RC	SFRC
I_1 Execution cost (€/m^2)	0.251	0.433
I_2 Non-conformity cost (-)	0.674	0.740
I_3 Reinforcing steel (kg/m^2)	0.523	0.281
I_4 Water (m^3/m^2))	0.687	0.516
I_5 Energy (MJ/ m^2)	0.821	0.686
I_6 CO_2 emissions (kg/m^2)	0.595	0.275
I_7 Risks during construction (-)	0.248	0.437
I_8 Noise pollution (Db)	0.504	1.000
I_9 Third-party discomfort (-)	0.461	1.000

3.6 Sustainability indices (I_s) for each alternative

The parameters that define the value function of each indicator are presented in Table 6. These values were agreed in seminars with experts and complemented by the criteria reported in the literature. The sustainability indices are presented in Table 7 based on the requirements tree defined (see Table 1), the values of X_i obtained for each solution (Table 6) and the parameters of the value functions presented in Table 4. Notice that the values of Table 7 correspond to the base scenario (**E_0**).

Table 6: Values of I_s and I_R obtained for each alternative

	RC	SFRC
I_s	**0.378**	**0.485**
I_{R1}	0.314	0.479
I_{R2}	0.616	0.349
I_{R3}	0.332	0.640

The results presented in Table 6 show that the solutions that use steel fibres as an alternative to steel bars result in a higher I_s value, particularly 28.3% higher. The better performance of the SFRC solution is the result of two factors: the reduction of the overall costs and the noise pollution or discomfort to the labour and third-party.

4 SENSITIVITY STUDY

The sensitivity of the method proposed is analysed in this section by considering two additional scenarios. The weights assigned for each scenario are detailed subsequently:

- **E_0** (λ_{R1} = 60%, λ_{R2} = 20% λ_{R3} = 20%) simulated a situation in which the economic requirement is prioritized over the others.
- **E_1** (λ_{R1} = 45%, λ_{R2} = 35% λ_{R3} = 20%) assigns more weight to the environmental requirement (R_2) at the expense of the economic requirement.
- **E_2** (λ_{R1} = 45%, λ_{R2} = 20% λ_{R3} = 35%) assumes a greater importance of the social requirements by assigning more weight than in the base scenario at the expense of the economic requirement.

Notice that the new scenarios maintain the same weight values for the criteria (λ_C) and indicators (λ_I) as those used in scenario $\mathbf{E_0}$ (see Table 1). The results of the sensitivity analysis are shown in Table 7.

Table 7: Values of I_s for each scenario of the sensitivity analysis

	RC	SFRC
$\mathbf{E_0}$	0.378	0.485
$\mathbf{E_1}$	0.423	0.466
$\mathbf{E_2}$	0.381	0.509

The results in Table 7 reveal that the solution with SFRC presents higher values of I_s in all the scenarios, thus revealing it is more sustainable than the solution with RC. This difference represents 28.3% in scenario E_0, 10.2% in scenario E_1 and 33.6% in scenario E_2. Nevertheless, the values obtained are considerably low, which indicates that improvements still can be made in order to reach the desired levels of satisfaction (or sustainability). The highest I_s for the original solution with RC corresponds to scenario E_1, in which the environmental requirements present higher weight than the social requirements but lower than the economic.

5 CONCLUSIONS

The present study proposes a method for the analysis of the sustainability of concrete slabs taking into account economic, environmental and social factors based on MIVES. The model allows comparing and prioritising alternative solutions while minimising the subjectivity in the decision-making process. The method is applied to a the real case of an office building in Spain originally designed with reinforced concrete but finally constructed with a SFRC solution. The conclusions drawn from the sustainability indices I_s are presented subsequently:

- The substitution of the traditional reinforcement with steel fibres yields higher values of I_s in all the scenarios considered in the present study, thus revealing that the solution of SFRC is more sustainable.
- The analysis of each of the requirements reveals that the degree of satisfaction for the solution with SFRC is highest for the social requirement, followed by the economic requirement and, finally, by the environmental requirement.
- The higher value of I_{R1} and I_{R3} in the case of the SFRC is explained by the reduction of labour and execution time and the reduction of the noise pollution and discomfort both for the labour and third-party, respectively.

ACKNOWLEDGEMENTS

The authors acknowledge Dr. Aitor Maturana, Associate Professor at the University of the Basque Country, his consent to use data from his scientific work in order to conduct the present study.

REFERENCES

[1] Destrée, X. and Mandl, J. Steel fibre only reinforced concrete in free suspended elevated slabs: Case studies, design assisted by testing route, comparison to the latest SFRC standard documents. In: *Proc. of the fib Symposium "Taylor Made Concrete Structures",* Walraven and Stoelhost Eds. Taylor & Francis Group, Amsterdam, (2008).

[2] Maturana, A., Sanchez, R., Canales, J., Orbe, A., Ansola, R. and Veguería, E. Technical economic analysis of steel fibre reinforced concrete flat slabs. In: *Proc. of XXXVII IAHSWorld Congress on Housing*, (2010).

[3] Michels, J., Waldmann, D., Maas, S., and Zürbes, A. Steel fibers as only reinforcement for flat slab construction – Experimental investigation and design. *Constr. Build. Mater.*, (2012) **26**:145-155. DOI: 10.1016/j.conbuildmat.2011.06.004

[4] Blanco, A., Cavalaro, S., de la Fuente, A., Grünewald, S., Blom, C.B.M. and Walraven, J.C. Application of FRC constitutive models to the modelling of slabs. *Mater Struct* (2015) **48**(9):2943-2959. DOI: 10.1617/s11527-014-0369-5

[5] Blanco, A., Pujadas, P., de la Fuente, A., Cavalaro, S., and Aguado, A. Assessment of the fibre orientation factor in SFRC slabs. *Compos. Part B-Eng* (2015), **68**:343-354. DOI: 10.1016/j.compositesb.2014.09.001

[6] San José, J. T. and Garrucho, I. A system approach to the environmental analysis of industrial buildings. *Build. Environ* (2010), **45**(3):673-683. DOI: 10.1016/j.buildenv. 2009.08.012

[7] Aguado, A., Josa, A. and Pardo-Bosch, F. How to measure the sustainability of concrete structures? In: *Proc. SB11 World Sustainable Building Conference*. Helsinki, (2011).

[8] Aguado, A., del Caño, A., de la Cruz, M.P., Gómez, D. and Josa, A. Sustainability assessment of concrete structures within the Spanish structural concrete code. *J. Constr. Eng. Manage.* (2012), **138** (2):268-276. DOI: 10.1061/(ASCE)CO.1943-7862.0000419, 268-276

[9] Pons, O. and Aguado, A. Integrated model for sustainable value assessment applied to technologies used to build schools in Catalonia, Spain. *Build. Environ.* (2012), **53**:49-58. DOI: 10.1016 / j.buildenv.2012.01.007

[10] Pons O, the De la Fuente A. Integrated sustainability assessment method applied to structural concrete columns. Constr. Build. Mater. (2013), **49**:882–893. DOI: 10.1016 / j.conbuildmat.2013.09.009

[11] Pardo-Bosch, F. and Aguado, A. Investment priorities for the management of hydraulic structures. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance* (2015), 11(10):1338-1351. DOI: 10.1080/15732479. 2014.964267

[12] Saaty, T.L. *The Analytic Hierarchy Process*. McGraw-Hill. New York, USA, ISBN: 0-07-054371-2 (1980).

[13] United Nations. Resolution ADOPTED by the General Assembly. 60/1. World Summit Outcome (2005).

[14] Alarcon, B., Aguado, A., Manga, R. and Josa, A. A Value Function for Assessing Sustainability: Application to Industrial Buildings. *Sustainability* (2010), **3**(1):35-50. DOI: 10.3390 /su3010035

[15] San-Jose Lombera, J.T. and Cuadrado Rojo, J. Industrial building design stage based on a system approach to their environmental sustainability. *Constr. Build. Mater.* (2010), **24**(4):438–447. DOI: 10.1016 / j.conbuildmat.2009.10.019

[16] Reyes, J.P., San-Jose, J.T., Cuadrado, J. and Sancibrian, R. Health & Safety Criteria for Determining the value of sustainable construction projects. *Safety Sci*. (2014), **62**:221-232. DOI: 10.1016 / j.ssci.2013.08.023

[17] Hosseini, S.M.A., de la Fuente, A. and Pons, O. Multi-Criteria Decision-Making Method for Assessing the Sustainability of Post-Disaster Temporary Housing Units Technologies: A Case Study in Bam, 2003. *Sustainable Cities and Society* (2015), **20**:38-51. ISSN: 2210-6707.

[18] Maturana, A. Estudio teórico-experimental de la aplicabilidad del hormigón reforzado con fibras de acero a losas de forjado multidireccionales, Doctoral Thesis, Universidad del País Vasco, (2013).

[19] Maturana, A., Canales, J., Orbe, A. and Cuadrado, J. Análisis plástico y ensayos de losas multidireccionales de HRFA. *Inf. Constr.* (2014), 66(535). DOI: 10.3989/ic.13.021

[20] Mitchell, D. and Cook, W. Preventing Progressive Collapse of Slab Structures. *J. Struct. Eng.* (1984), 110(7):1513-1532. DOI: 10.1061/(ASCE)0733-9445(1984)110:7(1513)