

SUSTAINABILITY ASSESSMENT OF PRECAST CONCRETE SEGMENTS FOR TBM TUNNELS

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Abstract.

Nowadays, several tunnels bored with Tunnel Boring Machines (TBM) are already in service and various dozens are being constructed around the world. The internal support of these usually consist of precast concrete segmental rings with a low – moderate amount of concrete since these elements are mainly compressed in service conditions and low tensile stresses only appear during initial transient situations (demoulding, stocking, transportation, manipulation and thrust of the jacks). Structural fibres have proved to be an interesting solution to replace part or the total amount of the rebars. In fact, fibre reinforced concrete (FRC) has already been applied in more than fifty TBM constructed tunnels so far. However, the use of FRC is not consolidated yet in this type of tunnels due to the lack of specific design methods until the publication of the last version of the Model Code 2010 as well as the high inertia to change exhibited by the technical community.

In this scientific contribution, a multi-criteria decision-making model based on the MIVES method is proposed for assessing the sustainability index of precast concrete segments. This model is able to take into account the three main pillars of the sustainability (economic, environmental and social). By using this model, different reinforcement alternatives (rebars, fibres or the hybrid solution) can be assessed for specific boundary conditions (e.g., tunnel and segment geometry, concrete dosages, transport distances, risks during the manufacturing of the segments). Likewise, this model is designed to minimize the subjectivity of the decision and to facilitate the task of deciding which concrete reinforcement strategy is the most suitable in terms of sustainability. Finally, the model is used to assess the sustainability of different precast concrete segments (with different reinforcement solutions), which are potential alternatives to be used in a real tunnel placed in the metropolitan area of Barcelona.

1 INTRODUCTION

For economic and technical reasons, the use of fibre-reinforced concrete (FRC) to partly or entirely replace traditional passive rebar reinforcement in concrete elements has increased in classic applications, particularly as a result of the inclusion of FRC in the fib Model Code 2010 [1]. Precast concrete segments used to line TBM tunnels [2] are one of the structural elements where the use of FRC may be more interesting due to the technical and, more generally, economic advantages associated [3-4]. In terms of design, the tensile stresses generated in both transitional stages and service are usually low or, even, inexistent. Therefore, only minimal reinforcement is required to ensure adequate ductile behaviour in the event of cracking [5-7]. In such cases, the use of rebar may be reduced or entirely eliminated. The use of structural fibres is an attractive solution that can enhance concrete performance in these load states [8-10]. If the amount (C_f) and type of fibre are correctly specified, it is possible to avoid spalling and to control the width of cracks that may be caused by dynamic impacts in the stages before erection and, more frequently, during the ram thrusts stage.

The objective of the present research project is to propose a multi-criteria decision making (MCDM) method based on MIVES, an Integrated Value Model for Sustainable Assessment that allows assessing different solutions for reinforcement of precast concrete segments, minimising the subjectivity in the decision making processes by using value functions [11]. MIVES was already validated in industrial buildings [12-14], underground infrastructures [15], hydraulic structures [16-17], wind towers [18], and construction projects [19-20]. Recently, the model was enhanced to include the uncertainties involved in the process of analysis [21]. The method proposed was used to analyse the sustainability of the concrete segments in the Ferrocarrils de la Generalitat (FGC) rail line extension to Terminal 1 of El Prat Airport in Barcelona. In the study, different types of concrete (conventional and self-compacting) and different reinforcement scenarios are analysed, and complete the process by presenting a sensitivity study. The resulting prioritisation of alternatives helped the technical staff in charge of the construction of the tunnel identifying the best solution.

2 METHOD FOR ASSESSING THE SUSTAINABILITY OF TUNNEL SEGMENTS

The method proposed is based on MIVES, which involves the definition of three elements: (1) the boundaries of the system, in order to establish the scope of the analysis; (2) a tree of requirements (R), criteria (C) and indicators (I) that allows decision makers to identify the important factors that must be involved in assessing the sustainability of the type of concrete and reinforcement used in the segments, and (3) the value functions used to convert the attributes or physical units associated with each indicator to unidimensional values (ranging from 0-1). These three elements were defined on seminar of experts from the public and private sectors specialised in the design and manufacture of precast lining segments. The results of the seminars were then used to define the initial requirement tree, to assign the appropriate weight to each element using the Analytic Hierarchy Process (AHP) method [22], and to provide real data from projects to define the value functions and scoring criteria for each indicator, measured in terms of attributes.

The three requirements under consideration are those that are generally associated with

sustainability: economic, environmental, and social impact. The life cycle analysis (LCA) stages considered were: (1) extraction, transportation, receiving, and in-plant processing of the materials used to fabricate tunnel linings, (2) fabrication and storage of the segments, (3) transport and installation of the segments, and (4) maintenance that may be needed to repair defects detected during the transitional stages (manufacture, transportation and installation). Based on the results of the seminars, 1 km of tunnel was considered representative of all factors involved in assessing the sustainability of the segment, without considering the infrastructure and other elements that are not crucial for the analysis (such as vertical shafts).

The requirements tree comprises 3 requirements (R), 6 criteria (C), and 9 indicators (I) (Table 1). The indicators are independent of each other to avoid overlaps in the evaluation process. Similarly, the indicators included are those considered most representative in terms of assessing the sustainability index (I_s) of each alternative type of segment that meets the various geometric and technical specifications, such as ring diameter and thickness, and service life and maximum loads, respectively.

Table 1: Requirements tree for the sustainability assessment of precast concrete segments for TBM tunnels.

Requirement	Criteria	Indicator	Units	Function
R ₁ Economic ($\lambda_{R1} = 40\%$)	C ₁ Direct costs ($\lambda_{C1} = 90\%$)	I ₁ Total costs ($\lambda_{I1} = 100\%$)	M€/km	DS
	C ₂ Cost of repairs ($\lambda_{C2} = 10\%$)	I ₂ Probability of repair ($\lambda_{I2} = 100\%$)	Attributes	
R ₂ Environmental ($\lambda_{R2} = 45\%$)	C ₃ Resources consumption ($\lambda_{C3} = 30\%$)	I ₃ Cement and aggregates ($\lambda_{I3} = 50\%$)	Ton/km	DCx
		I ₄ Water ($\lambda_{I4} = 20\%$)		
		I ₅ Reinforcing steel ($\lambda_{I5} = 30\%$)		
	C ₄ Emissions ($\lambda_{C4} = 40\%$)	I ₆ CO ₂ emissions ($\lambda_{I6} = 100\%$)	TonCO ₂ -eq/km	DS
C ₅ Energy ($\lambda_{C5} = 30\%$)	I ₇ Embodied energy ($\lambda_{I7} = 100\%$)	MWh/km		
R ₃ Social ($\lambda_{R3} = 15\%$)	C ₆ Labour conditions ($\lambda_{C6} = 100\%$)	I ₈ Noise pollution ($\lambda_{I8} = 70\%$)	Db	DCx
		I ₉ Risks during handling ($\lambda_{I9} = 30\%$)	Attributes	

DS: decreasing S-shape; DCx: decreasing convex

Weights (λ) were assigned using the AHP method and the results were rounded to the nearest multiple of 5. These weightings allow establishing the relative importance of each element in the requirements tree (Table 1). The base scenario (E_0) represents the view that economic and environmental factors are the ones that should have a greater weight ($\lambda_{R1} = 40\%$ $\lambda_{R2} = 45\%$, respectively), the latter being assigned with the greatest weighting. This approach reflects two key factors: the need to promote an environmental sensitivity, and an awareness of the impact these structures may have on future generations in terms of availability of resources and quality of life. While social aspects are taken into account, these are weighted to a lesser degree ($\lambda_{R3} = 15\%$) because it is assumed that requirements are already being met that ensure a suitable working environment and appropriate safety standards. Today, this base scenario would represent the viewpoint of an authority with a high

degree of environmental sensitivity in a developed country in the midst of a good or very good economic situation. However, it may not aptly represent certain viewpoints that might prevail in situations that differ from those described above. Therefore, a sensitivity analysis of the weightings that reflects other possible scenarios was also performed in Section 3.4.

The economic requirement (R_1) is represented by two criteria: direct costs (C_1) and repair costs (C_2). Criterion C_1 is defined by the total costs (I_1), which integrates the costs associated with all the different stages of lining segment production represented in the LCA. The costs of the plant and its installation and of the amortisation of the elements associated with manufacture and handling of the segments are not considered given that they rarely are a decisive factor. The same assumption was made for the cost of the TBM. The criterion C_2 is evaluated by means of the repair probability indicator (I_2). This indicator qualitatively assess costs associated with the repair of any defects that might appear during any of the transitional phases taking into account the probability of such defects according to the type of reinforcement used. The assessment of the risks discussed above is conducted by defining attributes based on the experience of the seminar participants.

The three criteria in the environmental requirement (R_2) are the consumption of natural resources (C_3), emissions (C_4) and energy consumption (C_5) associated with the LCA stages. The purpose of C_3 is to evaluate total consumption of materials from natural sources and identify solutions that would minimise such consumption. To this end, three indicators were defined: cement and aggregates (I_3), water (I_4) and steel used to reinforce the concrete (I_5). The weight assigned to I_5 ($\lambda_{R5} = 30\%$) is lower than the one assigned to I_3 ($\lambda_{R3} = 50\%$) because the steels used to reinforce concrete, although more scarce than the aggregates used to produce the concrete, contain as much as 60% recycled steel. Criteria C_4 and C_5 are represented by the indicators CO_2 emissions (I_7) and embodied energy (I_8). The value functions assigned to each indicator are intended to favour reinforcement solutions that minimise both CO_2 emissions and embodied energy and are respectful of the environment and energy sources. The following items were included in the LCA to quantify both indicators: (1) extraction of materials, (2) treatment of materials, (3) segment fabrication, and (4) segment transport. The consumption associated with the installation, operation and maintenance of the TBM is not considered in the analysis since it does not discriminate between the different types of concrete or reinforcement used in the precast segments. Similarly, the consumption associated with the repair of segments damaged in the transitional phases was not taken into account either.

Finally, in social requirement (R_3), the criterion labour conditions (C_6) was evaluated by way of two indicators. The indicator noise pollution (I_8) varies according to the type of concrete used. For instance, solutions relying on the use of self-compacting rather than traditional concrete are associated with significantly lower noise levels in the work environment because the traditional method requires strong vibration energy to ensure compaction of the material. The risks during handling (I_9) of the segments, particularly the risk to workers of cuts and lesions when fibres on the surface of the segment protrude and are liable to cause injury. While surface polishing and inspection are always carried out, the risk increases with the C_f and when metal fibres are used since these are sharper and more rigid

than plastic fibres. In the absence of more precise criteria and statistical data, this indicator was evaluated on the basis of attributes that were ranked in the seminars by the technicians with experience in plants producing precast segmental linings and by others with experience in TBM operation, two situations in which the workers may have to handle or touch the segments and are thus exposed to the risks described above.

To evaluate the sustainability index (I_s) of each alternative solution, value functions assigned using the method previously proposed [11-14, 23] were used. The generic form of a value function is represented by eq. 1, which allows assessing the sustainability (satisfaction) associated with each indicator (I_{ind}) by transforming the physical units to a dimensionless value between 0.0 and 1.0.

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

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

In eq. 1, B is the value of I_{ind} for X_{min} ; X_{min} is the minimum abscissa value in the indicator interval assessed; X is the abscissa value for the indicator assessed; P_i is a shape factor which defines whether the curve is concave ($P_i < 1$), convex ($P_i > 1$), linear ($P_i = 1$) or S-shaped ($P_i > 1$), see fig. 4; C_i approximates the abscissa at the inflexion point; K_i tends towards I_{ind} at the inflexion point; B, the factor that prevents the function from exceeding the range (0, 1), is obtained by eq. 2, X_{max} being the abscissa value of the indicator that gives a response value of 1 for increasing value functions. The form of the value functions assigned to each indicator (see Table 1) is a decreasing S-shape curve (DS) for I_1 and I_6 - I_7 and a decreasing convex curve (DCx) for I_3 - I_5 and I_8 .

3 CASE STUDY: FGC EXTENSION TUNNEL TO TERMINAL 1 AT BARCELONA AIRPORT

3.1 Description of the case study

The project to connect the Prat de Llobregat FGC station with Barcelona Airport [24] includes a 2.84 km long tunnel run bored using a TBM 10.60 m in diameter. The design calls for a tunnel lining (Fig. 1a) comprising a universal ring with a mean length of 1.60 m and an internal diameter of 9.60 m. The ring is 0.32 m thick and is composed of 6 segments and 1 key. The initial project proposes concrete segments reinforced with B500SD steel bars ($f_{yk} = 500 \text{ N/mm}^2$) and concrete with a characteristic compressive strength value f_{ck} of 45 N/mm^2 .

This value of strength ensures sufficient strength to bear the flexural compression that occurs in the service phase and subjected to the soil pressure. The designers also verified that the design forces do not exceed the crack resistance of the segment in any of the loading stages and fixed a minimum reinforcement of $13\Phi 12 \text{ mm}$ on each side (Fig. 1b) to ensure adequate ductile behaviour in a hypothetical rupture situation. The concrete cover (c) must be

greater than 4 cm to protect the reinforcement from possible chemical attack. Notice that the layout of the tunnel passes under industrial areas where aggressive groundwater may be present.

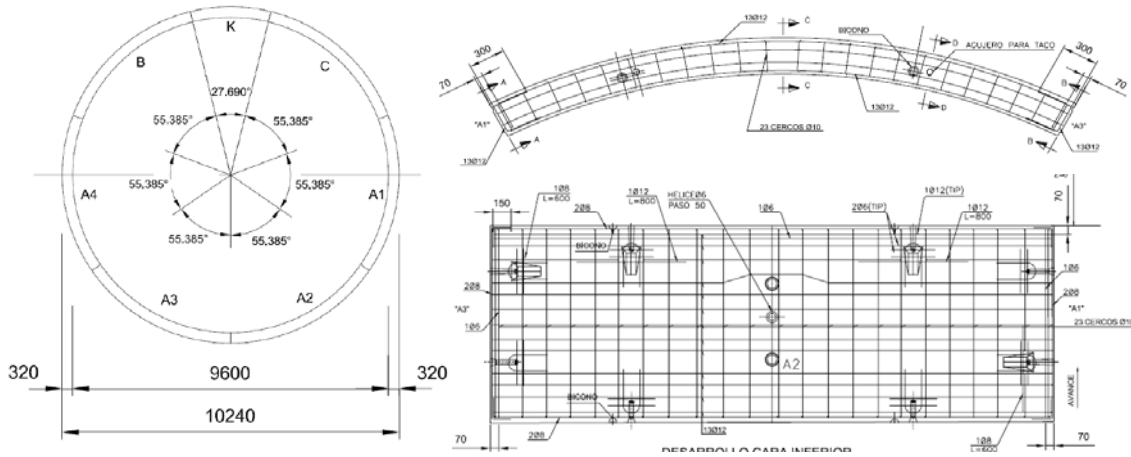


Figure 1: (a) Ring configuration and (b) frontal section view and (c) top view of reinforcement cage.

Therefore, the original proposal specified the use of conventional reinforced concrete (CRC), however due to the economic recession affecting Spain in the past years and the publication of the new Spanish Structural Code EHE-08 [25], two new solutions for the segments using only FRC have been proposed: (1) using conventionally vibrated FRC concrete and (2) using self-compacting fibre-reinforced concrete (SC-FRC).

Table 2 shows the dosages used in the fabrication of the different types of concretes considered for the production of the segments. Two aspects of this process are of particular interest: (1) the same granular skeleton was used for the CRC and the FRC (the loss of workability is compensated with the vibration time); (2) the fine fraction (cement, sand 0/5, and fine aggregate 5/12) used in the SC-FRC is 36% greater than that of the CRC and FRC in order to guarantee the self-compactability of the SC-FRC. For the same reason, the content of superplasticiser in the SC-FRC was 50% higher than in the CRC and FRC.

Table 2: Dosages (in kg/m³) considered for the different concrete mixes.

MATERIALS	CRC	FRC	SC-FRC
CEM I 52.5	315	315	381
Sand 0/5	817	817	1.200
Fine aggregate 5/12	404	404	500
Coarse aggregate 12/20	810	810	200
Water	150	156	165
Superplasticiser (% c)	2.80 (0.9)	2.80 (0.9)	4.60 (1.2)
Steel fibres	0	45	50

The reinforcement was different in each case, for the CRC segments (CRCS), the total amount of steel bar used was 110 kg/m³ (Fig. 1b), whereas the analysis conducted for the

FRC and SC-FRC showed that only 50 kg/m³ was required for FRC and 45 kg/m³ for SC-FRC to achieve strength class 4.0d. SC-FRC requires 10% less fibre material than CRC because of the better orientation of the fibres in the pouring process of the self-compacting concrete due the flow forces and boundary conditions imposed by the walls of the mould. This analysis was performed using the numerical model Analysis of Evolutionary Sections (AES) [26], considering the same design values for axial forces (N_d) and bending moments (M_d) of the original project and considering the constitutive equation of the Model Code 2010. The fibre used was MasterFiber 502 with hooked-end anchors and a length of 50 ± 5 mm, a diameter of 1.0 ± 0.1 mm, and an elastic limit of 1000 N/mm².

In terms of workability, slump values of less than 5 cm for CRC and FRC with the Abrams cone test were obtained, being this fact an indication of very dry concrete; however, the vibration energy generated in the segment moulds is sufficient to adequately compact these concrete mixes. Likewise, values of 65 – 68 cm obtained in the slump flow testing for the SC-FRC confirmed the sufficient flowability to facilitate the self-compacting process. Finally, the mean compressive strength (f_{cm}) values obtained at 1, 7 and 28 days with cylinder specimens $300 \times \Phi 150$ mm² were very similar for the different concrete mixes, reaching values of $f_{cm,1} = 20.2$ N/mm², $f_{cm,7} = 53.0$ N/mm² and of $f_{cm,28} = 64.5$ N/mm². These results reflect that the specified f_{ck} of 45 N/mm² is reached.

3.2 Evaluation of indicators

The construction of the tunnel lining involves 28,322 m³ of concrete. The manufacturing of the 12,425 segments will take place in an existing plant at 110 km from the TBM access shaft and will require 9 months with two 8-hour work shifts a day. The plant is expected to be in operation for a period of 16 months between the start of preparations and final shutdown. Subsequently, the information required and the criteria assumed to evaluate the indicators is presented. The results of the evaluation are presented in Table 3.

Table 3: Indicator values (X_i) obtained for each alternative.

Indicator	CRCS	FRCS	SC-FRCS
I ₁ Direct costs (M€/km)	2.89	2.60	2.61
I ₂ Probability of repair	Moderate	Low	Low
I ₃ Cement and aggregates (Ton/km)	66,444	66,444	64,603
I ₄ Water (Ton/km)	15,590	10,863	11,668
I ₅ Reinforcing steel (Ton/km)	1,097	499	449
I ₆ CO ₂ emissions (TonCO ₂ -eq/km)	5,305	4,601	5,083
I ₇ Embodied energy (MWh/km)	12,411	9,375	9,904
I ₈ Noise pollution (Db)	90	90	60
I ₉ Risk during handling	Reduced	High	High

In the indicator I₁, which corresponds to the direct costs, the following aspects are assessed: (1) investment in the plant, (2) materials for the manufacture of the segmental linings, (3) personnel involved, (4) auxiliary equipment, (5) consumables, and (6) transport. The aspects that represented a difference in cost depending on the solution used to fabricate the segments are the following: (1) the cost of materials for the manufacture of concrete

(Table 2), (2) the reinforcement solution used (bars or fibres), and (3) the personnel required for the preparation of the reinforcement (2 per shift for CRCS and none for FRCS and SC-FRCS). The evaluation of indicators I_3 and I_5 is based on the consumption of materials shown in Table 2, taking into account that the CRCS use 110 kg/m^3 of steel bars. The estimate for indicator I_4 is calculated by applying the values in Table 2 for the concrete manufacture and using the values for water consumption associated with the production of steel bars and fibres from [27].

The emissions of $\text{CO}_2\text{-eq}$ (I_6) and energy (I_7) involved in the LCA processes of the materials used in the concrete were calculated using the mean values listed in the Inventory of Carbon Energy version 2.0 [28]. The estimation of indicator I_6 for bars and steel fibres is based on [28-29] Finally, indicators I_2 , I_8 - I_9 were evaluated in the seminars, taking into account the following: (1) the information contained in [29] to establish the probability of a segment needing repairs depending on the type of reinforcement (I_2); (2) the information on workplace noise pollution in precast plants and the health risks described in [20] to evaluate I_8 ; and (3) the arguments set out in [30] to define indicator I_9 and specify how it should be assessed.

Table 3 reveals that the use of FRCS (2.60 M€/km) represents a cost saving of 10.0% over CRCS (2.89 M€/km) and 0.4% over SC-FRCS (2.61 M€/km). These differences arise from differences in: (1) materials costs (concrete and steel) of 159.4, 135.9 and 136.5 €/m^3 for the concrete used in CRCS, FRCS and SC-FRCS, respectively; and (2) the manufacturing costs associated with the fabrication of the segments, estimated at 67.2 €/m^3 for CRCS and 62.1 €/m^3 for FRCS and SC-FRCS (a 7.6% reduction compared to CRCS because of labour associated with the use of steel bar reinforcement). The use of SC-FRCS (64,603 Ton/km) also results in a saving of 2.8% in the consumption of cement and aggregates in the concrete as compared to the CRCS and FRCS solutions, with 66,444 Ton/km for both.

The water consumption required in the manufacture of FRCS (10,863 Ton/km) (associated with the manufacture of the steel and the concrete) is some 30.3% lower than in the CRCS segments (15,590 Ton/km), and 6.9% lower than in the SC-FRCS solution. Finally, the manufacture of SC-FRCS (449 Ton/km) represents steel savings of 59.1% over the CRCS solution (1,097 Ton/m³) and of 10.0% compared with FRCS. FRCS (4,601 TnCO₂eq) produces 13.3% and 9.5% lower emissions compared to CRCS and SC-FRCS, respectively, due to the lower consumption of cement and steel in the reinforcement. Furthermore, FRCS (9,375 MWh/km) is the solution that requires the least energy throughout the entire LCA, some 24.5% lower than CRCS and 5.3% lower than SC-FRCS.

3.4 Sustainability indices I_s for each alternative

The constitutive parameters for each value function (see Table 4) were agreed during the seminars, drawing on the experience of the experts complemented by criteria presented in the literature on MIVES and the values of X_i obtained for the three alternatives studied (Table 3). Subsequently, the sustainability indices I_s for each segment solution were calculated (Table 5) for the base scenario E_0 ($\lambda_{R1} = 40\%$, $\lambda_{R2} = 45\%$ $\lambda_{R3} = 15\%$).

Table 4: Constitutive parameters for defining the value functions.

Indicator	X_{max}	X_{min}	C	K	P
I ₁ Direct costs (M€/km)	4,00	2,24	1,00	1,00	2,50
I ₂ Probability of repair	Steel: 0.00 – 0.25 (very high); low fibre content: 0.25 – 0.50 (high); steel + low fibre content: 0.50 - 0.75 (moderate); High fibre content: 0.75 - 1.00 (low)				
I ₃ Cement and aggregates (Ton/km)	70,000	65,000	67,000	0.10	2.50
I ₄ Water (Ton/km)	29,000	7,500	15,000	0.10	2.50
I ₅ Reinforcing steel (Ton/km)	1,350	450	800	1.00	2.50
I ₆ CO ₂ emissions (TonCO ₂ -eq/km)	7,800	3,800	5,000	2.50	200
I ₇ Embodied energy (MWh/km)	18,500	7,500	10,000	2.50	2.00
I ₈ Noise pollution (Db)	150	0	80	3.00	10.00
I ₉ Risks during handling	Very high: 0.00 – 0.25; High: 0.,25 – 0.50; Acceptable: 0.50 – 0.75; Reduced: 0.75 – 1.00				

Table 5: Values of I_s and I_R obtained for each alternative.

	CRCS	FRCS	SC-FRCS
I_s	0.578	0.754	0.856
I_{R1}	0.703	0.899	0.909
I_{R2}	0.513	0.786	0.836
I_{R3}	0.438	0.326	0.775

The results presented in Table 5 show that the solutions that use structural fibres as an alternative to steel bars result in a higher I_s value. Specifically, SC-FRCS (0.856) represents an increase of 48% in I_s over CRCS (0.578) and an increase of 14% over FRCS. The better performance in terms of sustainability of the SC-FRCS solution is a result of two factors: the use of fibres rather than steel bars, a choice that reduces both overall costs and environmental impact; and the use of self-compacting concrete, which leads to a better distribution of the fibres and better mechanical performance than can be achieved with traditional FRC. To analyse the sensitivity of the results obtained (Table 5), three additional scenarios were considered as follows:

- E1 ($\lambda_{R1} = 33\%$, $\lambda_{R2} = 33\%$ $\lambda_{R3} = 33\%$) simulates a reasonable view of all the requirements involved in the analysis and represents sustainability in the strict sense.
- E2 ($\lambda_{R1} = 75\%$, $\lambda_{R2} = 10\%$ $\lambda_{R3} = 15\%$) assigns greater weight to the economic requirement I_{R1} in order to consider a more entrepreneurial view or take into account a possible financial recession on the part of the authority making the investment. This scenario must be considered although it is not desirable in terms of sustainability.
- E3 ($\lambda_{R1} = 25\%$, $\lambda_{R2} = 60\%$ $\lambda_{R3} = 15\%$) gives particular weight to the environmental requirement I_{R2} in order to prioritise solutions respectful of the environment based on use of available resources and respectful of society today and in the future. This scenario represents the vision of a public authority with a high environmental sensitivity and, in general terms, a situation of economic growth.

To facilitate the analysis and interpretation of the results, in these three scenarios the same weight values for the criteria (λ_C) and indicators (λ_I) as those used in scenario E₀ (Table 1) were maintained. The constitutive parameters of the value functions are also maintained

(Table 4). The resulting values of I_R considered in the sensitivity analysis are shown in Table 5. It should be noted that in a more rigorous analysis of sensitivity or cases in which the ranges of values for I_s and I_R of the alternatives are more tight, the use of statistical techniques are recommended to ensure robust results. Table 6 shows the values of I_s for each of the scenarios. The results shown in Table 6 reveal the following:

Table 6: Values of I_s derived from the sensitivity analysis.

	CRCS	FRCS	SC-FRCS
E_0	0.578	0.762	0.856
E_1	0.546	0.663	0.832
E_2	0.645	0.801	0.882
E_3	0.550	0.745	0.845

All the alternatives present the highest value for I_s in the scenario that gives greatest weight to the economic requirement (E_2), showing that all the solutions studied should generate a high level of satisfaction in economic terms. Nevertheless, all the solutions present values of I_s under 0.900, demonstrating that there is still room for improvement in the fabrication of FRC segments. SC-FRCS is the solution that presents high values for I_s in all the scenarios. The ranking of alternatives is the same as that obtained for scenario E_0 . Comparison of FRCS and CRCS shows that the total replacement of rebar with structural fibres in vibrated concrete yields values of I_s between 21% (E_1) and 36% (E_3). The comparison of SC-FRCS and FRCS reveals that the use of self-compacting concrete gives rise to an increase in values of I_s of between 10% (E_2) and 25% (E_1).

4 CONCLUSIONS

This paper proposes a method for assessing the sustainability of precast concrete lining segments for tunnels excavated using a TBM, taking into account economic, environmental and social factors based on MIVES. The model allows comparing and prioritising alternative solutions, minimising subjectivity in the decision process. The method has been used to assess the sustainability of three types of segments (the traditional reinforced concrete solution proposed in the preliminary plan and two alternative solutions involving total replacement of the rebar with fibres) to line a 2.84 km tunnel in Barcelona. The conclusions drawn from the sustainability indices I_s obtained with the model are as follows:

The substitution of the rebar with structural fibres yields higher values of I_s in all the scenarios under study. This conclusion can be extended to cases in which the risk of cracking is low in both the transitional stages (reduced tensile flexural stresses) and the service phase (ring compressed by soil pressure) and the amounts of reinforcement used are the minimum values required to ensure the ductile behaviour of the segment in case of cracking. The use of SC-FRC yields increases in the I_s over FRC for the following reason: although the cost of the SC-FRC concrete mix is some 15% higher than that of FRC, the greater spatial efficiency of the fibre distribution in the case of SC-FRC reduces by 10% the quantity of fibres required to achieve mechanical characteristics equivalent to those of FRC. Likewise, the use of SC-FRC increases the useful life of the moulds and reduces noise pollution in the precast plant, aspects that can be quantified and integrated into the proposed model. The results presented were

accepted by the manufacturer of the segments and will serve as a tool for decision making on similar projects in the future.

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