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A multi-criteria decision-making based approach to assess the sustainability of concrete structures

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Abstract. The use of sustainability assessment tools is gaining importance in the construction sector. There exist several methods with different approaches and scopes; however, there is still no consensus about which method should be used to deal with the sustainability assessment of concrete structures. Among these, the multi-criteria decision-making based approach called MIVES seems to be a suitable and flexible model that allows taking into account all those indicators and parameters (of economic, social and environmental nature) involved in the sustainability assessment of concrete structures. The objective of this research document is two-fold: (1) to expose the basis and concepts related with the MIVES model as a sustainability assessment tool and (2) to present 3 real study cases (wind precast concrete towers; steel fibre reinforced precast concrete tunnel linings and reinforced concrete pile-supported slabs) in which this model has been used to make decisions. The authors of this research consider that similar approaches should be included in future national and international structural concrete guidelines (as the Spanish Structural Concrete Code does) to perform sustainability analysis of new designed concrete structures.

Keywords: AHP; decision-making; fibre reinforced concrete; MIVES; structures; sustainability

1. Introduction

There exist several tools, database and methods available to assess sustainability and environmental aspects within the architectural and civil engineering area. However, no consensus has been yet reached respect to which is the most suitable tool to assess the sustainability in building construction. Table 1 presents 8 of these certification tools for building sector.

The acceptance of these methods has shown to be variable, as only two have been internationally applied for decades, while the others are mainly used in the country of origin. These methods also differ in being credits or percentage based rating tools, the application's complexity and the outcomes resulting from each method, which is in most of the cases, either a certification with a qualification of satisfaction or a graphic sustainability index. All these tools have contributed to advance towards a more sustainable construction sector and to raise awareness of this issue within the



sector. Only a few methods are capable of quantifying all the different social, economic and environmental requirements that permit researchers to derive a global sustainability index. The main drawback arises, however, when trying to assess the sustainability of independent structural elements or products (e.g., piles, beams, slabs, pipes, walls) for which these methods are scarcely representative.

Table 1. Different sustainability assessment tools for buildings.

Name	Institution	Origin	Use	C	E	S	CR	PR	C	R
BEAM	BEAM	Hong Kong 1996	N	L	X	L	X	-	L	CQ
BREEAM	BRE	UK 1990	I	-	X	L	X	-	L	CQ
DGNB	DGNB	Germany 2008	N	X	X	X	-	X	H	CQ
EcoEffect	KTH	Sweden 2000	N	X	X	-	X	-	M	GI
Green Star	GBCA	Australia 2003	N	-	X	X	X	-	M	CQ
HQE	AssoHQE	France 1996	N	X	X	X	-	X	M	CQ
LEED	USGBC	USA 2000	I	L	X	L	X	-	L	CQ
VERDE	GBCE	Spain 2010	N	X	X	X	-	X	M	CQ

I. internationally consolidated, N. nationally consolidated

C. Economic requirements (cost, time...). X means included, L means low consideration.

E. Environmental requirements (energy consumption, CO₂ emissions...). X means included.

S. Social requirements (health, safety, quality...). X means included, L means low consideration.

CR. X means credits based rating tool that gives credits to carry out the assessment.

PR. X means percentage based rating tool that assesses the percentage of satisfaction of each indicator.

C. Tool complexity of application. H means high, M means medium, L means low.

R. Result. CQ means certification with a qualification of satisfaction; I means graphic index.

As a potential solution, the MIVES method (from the Spanish Integrated Value Model for the Sustainability Assessment) is herein proposed to assess the sustainability index of concrete products and systems. MIVES is a Multi-Criteria Decision Making (MCDM) method capable of defining specialized and holistic sustainability assessment models to obtain global sustainability indexes. The MIVES method is a MCDM based on the use of value functions to assess the satisfaction of those stakeholders involved in the decision-making process. The use of these functions allows minimizing the subjectivity in the assessment.

A description of the MIVES method is firstly presented and, posteriorly, the method is applied to measure the sustainability index of different alternatives within the field of tunnelling construction and supports for wind turbines.

2. MIVES Method

MIVES is a multi-criteria decision-making method capable of defining specialized and holistic sustainability assessment models to obtain global sustainability indexes of structures or products. MIVES combines: a) a specific holistic discriminatory tree of requirements (Figure 1); b) the assignation of weights for each requirement (α_i), criteria (β_i) and indicator (γ_i); c) the value function concept [1] to obtain particular and global indexes and d) seminars with experts using Analytic Hierarchy Process (AHP) [2-3] to define the aforementioned parts. The sustainability index (SI) is assessed by means of Equation 1.

$$SI = \sum_{i=1}^{i=N} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot I_{ind}(X_i) \tag{1}$$

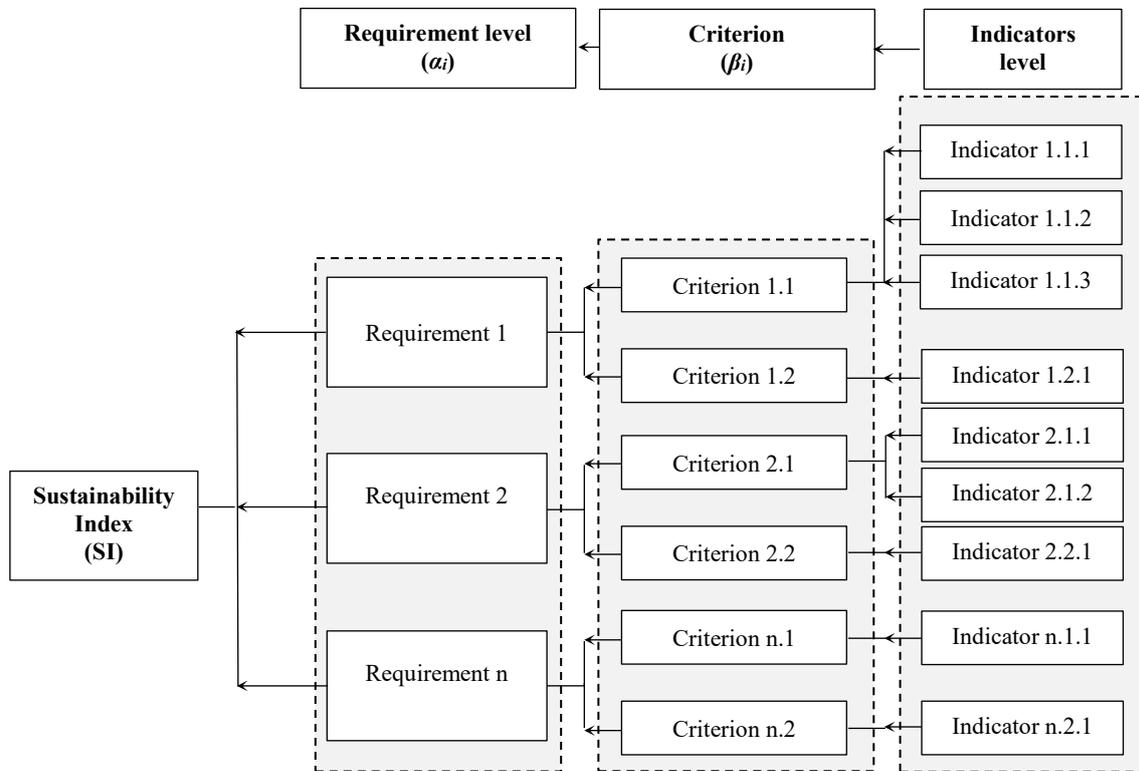


Figure 1. General requirements tree

Value functions (V_{ind}) are assigned to the previously described indicators. These functions transform physical units of each indicator (e.g., €/m³, Ton/m³, dB) into dimensionless values ranging from 0 to 1. These values represent the sustainability or satisfaction of each indicator. Equation 2 shows the general form of a value function.

$$V_{ind}(X) = A + B \left[1 - e^{-K_i \left(\frac{|X_{ind} - X_{min}|}{C_i} \right)^{P_i}} \right] \tag{2}$$

In Equation 2, B is the value of V_{ind} for X_{min} ; X_{min} is the minimum abscissa value of 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 ($P_i > 1$) (Figure 2); C_i approximates the abscissa at the inflexion point; K_i tends towards V_{ind} at the inflexion point; B , the factor that prevents the function from exceeding the range (0, 1), is obtained by Equation 3, X_{max} being the abscissa value of the indicator that gives a response value of 1 for increasing value functions.

$$B = \left[1 - e^{-K_i \left(\frac{|X_{max} - X_{min}|}{C_i} \right)^{P_i}} \right]^{-1} \tag{3}$$

There have already been numerous applications of MCDM in engineering [4], most focusing on economic aspects and fewer about environmental issues or social aspects. The MIVES method is a unique MCDM based on the use of value functions [5] to assess the satisfaction of the different stakeholders involved in the decision-making process. The use of these functions allows minimizing the subjectivity in the assessment. So far, MIVES has already been used for industrial buildings [6-8], underground infrastructures [9], hydraulic structures [10-11], wind towers [12], sewage systems [13], post-disaster sites and housing selection [14-15] and construction projects [16-17]. It should be highlighted that in the current Spanish Structural Concrete Code [18], MIVES method is proposed for assessing the sustainability of concrete structures [19]. Finally, it must be added that the MIVES method has even been expanded to include the uncertainties involved in the process of analysis [2].

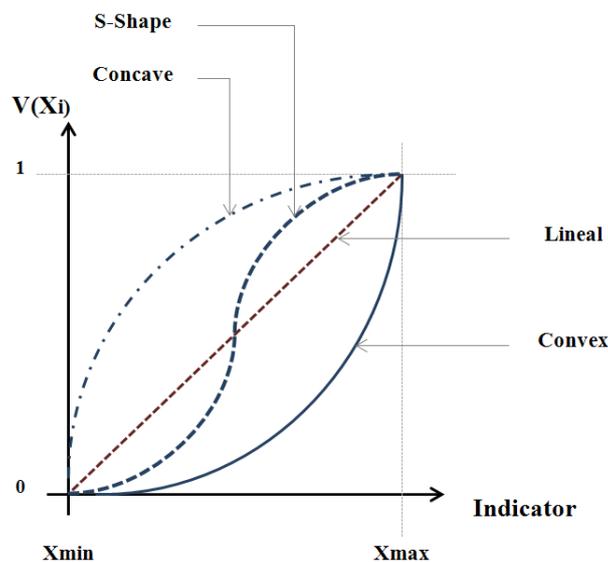


Figure 2. Shapes of the value function

3. Example of application 1. Segmental linings for tunnels

3.1. Introduction

The use of precast concrete linings (Figure 3) to resist the earth actions in TBM-constructed tunnels is a widespread practice. These elements are generally reinforced with steel curved-cages. However, the replacement of this traditional reinforcement for structural fibres is increasing due to diverse reported technical and economic advantages as well as the acceptance of the fibre reinforced concrete (FRC, hereinafter) as structural material in several standards.



Figure 3. Precast concrete segments: (a) Traditional reinforcement (Metro L9 of Barcelona) and (b) FRC full – scale bending test carried out at the UPC of Barcelona

Besides, it should be born in mind that these segments are, usually, subjected to reduced bending moments and the likelihood of cracking is relative low (especially during service). In this regard, the higher bending moment basically occur during transient loading stages (see Figure 4) for which the segments are designed no to crack; thus, minimum reinforcement is required. As a consequence, the competitive amount of structural to be used as a replacement of the rebars makes the FRC an attractive material for this application.

Even though different current code already permits the use of FRC in structural elements and the solution has proven to be both technically and economically attractive in the segmental linings used in over 50 TBM tunnels built to date, some restrictions still persist concerning the use of FRC in this particular application. Among these, the main factors that designers and contractors compare traditional and FRC solutions are based solely on direct material costs without taking into account either indirect costs or social and environmental factors, that is, without considering the sustainability of possible solutions.

The aim of this practical example of application of MIVES consist in proposing a multi-criteria decision-making method based on the MIVES to assess the different viable solutions for reinforcement of precast concrete segments.



Figure 4. Some of the transient load situations in which the segments are subjected to bending moments: (a) demoulding and (b) stacking at the yard

3.2. Sustainability assessment MIVES model for precast concrete segments

The requirements tree defined for the sustainability assessment of precast concrete segments is presented in Table 2. In this case, although a cradle to cradle LCA could be carried out, a cradle to the placement of the segments inside the tunnel has been considered. This can be assumed since the type of reinforcement is not a variable that affects the rest of operations after the placement of the segments. Based on the results of the seminars, 1 km tunnel was considered to be enough representative to integrate all those factors involved in assessing the sustainability of the segment, omitting consideration of infrastructure and other elements not crucial to the analysis, such as vertical shafts and stations.

It must be emphasized that the reinforcement alternatives for a certain segment, either traditional reinforcement, FRC or hybrid configurations (rebars + fibres), considered for a certain boundary conditions (lining thickness, internal diameter and loads) should comply with the structural and project requirements. Otherwise, these should not be considered as alternatives to be compared.

3.3. Case study: segmental lining of the L9 Extension to the Barcelona Airport.

As an example of application of this MIVES model, the segmental lining of the L9 Tunnel Extension to the Barcelona Airport has been considered. This consists in a 2.84 km long TBM-constructed tunnel in service since 2016. The lining (Fig. 5) was made up with 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.

Table 2. Requirements' tree proposed to assess the sustainability of precast concrete linings

Requirement	Criteria	Indicator	Units	Function
R ₁ Economic (40%)	C ₁ Direct costs (90%)	I ₁ Total costs (100%)	M€/km	DS
	C ₂ Cost of repairs (10%)	I ₂ Probability of repair (100%)	Attributes	
R ₂ Environmental (45%)	C ₃ Resources consumption (30%)	I ₃ Cement and aggregates (50%)	Ton/km	DCx
		I ₄ Water (20%)		
		I ₅ Reinforcing steel (30%)		
	C ₄ Emissions (40%)	I ₆ CO ₂ emissions (100%)	TonCO ₂ -eq/km	DS
C ₅ Energy (30%)	I ₇ Embodied energy (100%)	MWh/km		
R ₃ Social (15%)	C ₆ Labour conditions (100%)	I ₈ Noise pollution (70%)	Db	DCx
		I ₉ Risks during handling (30%)	Attributes	

For the former project, conventional reinforced concrete (CRC) segments with 110 kg/m³ of steel rebars and concrete with a characteristic compressive strength value f_{ck} of 45 N/mm² were designed. 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 to ensure adequate ductile behaviour in a hypothetical cracking situation. However, 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).

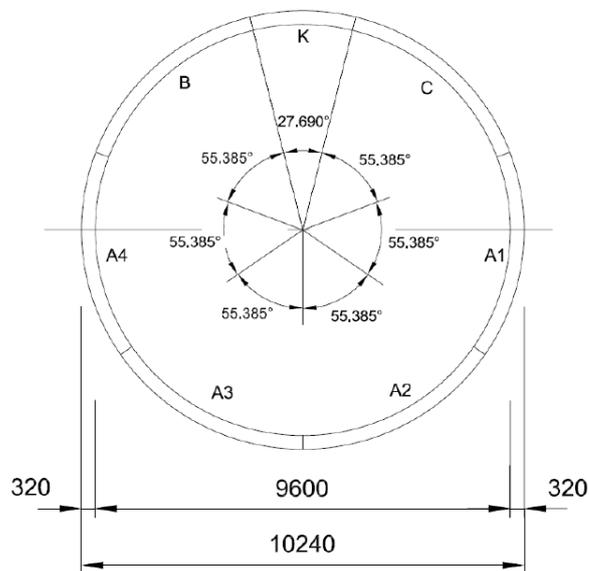


Figure 5. Dimensions (in mm) of the tunnel lining (L9 Extension to the Barcelona Airport)

The different concrete dosages are presented in Table 3.

Table 3. 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	2.80	2.80	4.60
Steel fibres	0	50	45

Hooked – end steel fibres with a yielding strength of 1000 N/mm², length of 50 ± 5 mm and a diameter of 1.0 ± 0.1 mm were used for both FRCs. In this regard, the experimental results on notched prismatic specimens according to the testing procedure EN 14651:2005 have confirmed that 50 kg/m³ (FRC) and 45 kg/m³ were sufficient to reach the required 4d ($f_{R1k} = 4.0$ N/mm² and $1.1 \leq f_{R3k}/f_{R1k} < 1.3$) strength class to replace all the rebars while guaranteeing the ductile behaviour of the segments. It is worth to note that SC-FRC requires 10% less fibre material than FRC 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.

The construction of the tunnel lining involves 12,425 segments (1,775 rings), requiring 28,322 m³ of concrete. The segments will be fabricated in an existing plant specifically designed for the purpose. The distance from the plant to the TBM access shaft is 110 km. The plant is expected to be in operation for a period of 16 months between the start of preparations and final shutdown. It is estimated that the fabrication of all segments will take nine months with two 8-hour work shifts a day.

The data gathered in Table 4 must be considered to assess each of the 9 indicators fixed in the requirements' tree (Table 2). Likewise, the constitutive parameters required to define the specific value functions are presented in Table 5.

Table 4. Values of the main features of the alternative reinforcement configurations

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

By applying the additive formula shown in Equation (1), the requirements' satisfaction degrees and the SI of each reinforcement alternative can be estimated (Table 6).

Table 5. Value function parameters for each indicator

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 6. Sustainability index of each reinforcement alternative

	CRCS	FRCS	SC-FRCS
SI	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 6 highlight that using FRC, vibrated and self-compacting concrete, leads to more sustainable solutions that using conventional reinforced concrete. Specifically, SC-FRCS (SI = 0.856) represents an increase of 48% in SI over CRCS (SI = 0.578) and an increase of 14% over FRCS (SI = 0.754).

4. Example of application 2. Precast concrete wind towers

4.1. Introduction

Precast concrete wind towers have been progressively introduced in the market, these gaining importance over other existing alternatives for heights above 100 m due to diverse technical and economic advantages. However, still there is not an objective tool that allows quantifying the sustainability of wind towers considering the three pillars (economic, environmental and social). The aim of this practical example of application of MIVES consist in presenting the whole procedure carried out to establish the components (tree of requirements, value functions, weights and analysis of the results) that permits to assess the sustainability index of wind towers. As a particular case of sustainability assessment, a precast concrete tower has been chosen.

4.2. Sustainability assessment MIVES model for wind towers

In Table 7 the requirement tree defined is presented. The LCA embraces from cradle to the deconstruction of the wind field. The unit of analysis consist of the structural elements (foundation and tower). Likewise, the maximum transport distance of the precast concrete elements from plant to site is not superior to 350 km. It must be emphasized that this model can be applied to any composition of structural materials that the tower might be made of.

The *economic requirement* (R_1) takes into account the impact of the different costs, both direct and indirect, identified during the seminars. The *environmental requirement* (R_2) is used to consider the impact of the construction process and materials involved in the tower's installation. The *social requirement* (R_3) is used to assess key factors for the social acceptance of wind farms.

Table 7. Requirements' tree proposed to assess the sustainability of wind towers

Requirement	Criteria	Indicator	Unit
R ₁ Economic (50%)	C ₁ Construction cost (40%)	I ₁ Direct cost (50%)	€/tower
		I ₂ Cost deviations (50%)	Points
	C ₂ Maintenance cost (40%)	I ₃ Planned works (100%)	€/tower
	C ₃ Deconstruction (20%)	I ₄ Deconstruction (100%)	€/tower
R ₂ Environmental (35%)	C ₄ Resources consumption (33.3%)	I ₅ Material (100%)	Tn/MW
	C ₅ Energy (33.3%)	I ₆ Energy (100%)	GWh/MW
	C ₆ Emissions (33.3%)	I ₇ CO ₂ (100%)	TnCO ₂ -e/MW
R ₃ Social (15%)	C ₇ Occupational hazards (30%)	I ₈ Risk of accident (100%)	Points
		I ₉ Proportions (50%)	
	C ₈ Perception (60%)	I ₁₀ Flexibility (50%)	
		C ₉ Technology integration (10%)	

The assigned weights ($\lambda_{R1} = 50\%$; $\lambda_{R2} = 30\%$ and $\lambda_{R3} = 15\%$) have been derived from experts' seminars. It can be seen that a higher weight to the economic requirement has been established respect to the environmental aspects. In this regard, it should be mentioned that wind farms have a lower environmental impact in terms of energy than electricity-generation technologies based on fossil fuels. Furthermore, the difference between the energy produced and consumed is positive over the tower's entire life. Thus, in this specific case, a lower weight can be assigned to the environmental requirements. This tree can be used to assess the sustainability index score for towers in other scenarios (different system constraints and/or social perceptions) and from the viewpoint of other stakeholders by adjusting the weightings and boundary conditions accordingly.

4.3. Case study: precast concrete tripod

A prototype precast concrete tripod (Spanish patent No. 7,123,455, see Figure 6) is used as an example of sustainability assessment of wind towers. This support is capable of bearing and resisting the forces

transmitted by large turbines ($P \geq 3.0$ MW) installed at height ranging in 100 – 120 m. This structural system consist of a three-legged tower of 20 m – length precast prestressed concrete segments joined in by means of post-tensioned tendons. These three legs are reinforced transversely with double-T structural steel profiles (Figure 6). In Figure 7 the geometric details of the foundation designed for this precast concrete tower are presented.

The data gathered in Table 8 must be considered to assess each of the 11 indicators fixed in the requirements’ tree (Table 7). Likewise, the constitutive parameters required to define the specific value functions are presented in Table 9.

Table 8. Values of the main features of the proposed tripod tower

Feature	Value	Unit
Height	100	M
Power output of supported turbine	3.5	MW
Foundation weight	698	t/tower
Tower weight	1,263	t/tower
Construction cost	1,022,000	€/tower
Maintenance cost	6,545	€/tower·year
Deconstruction cost	120,200	€/tower
Energy consumption (LCA)	0.68	MW/tower
CO ₂ emissions (LCA)	299	TnCO ₂ -e/tower

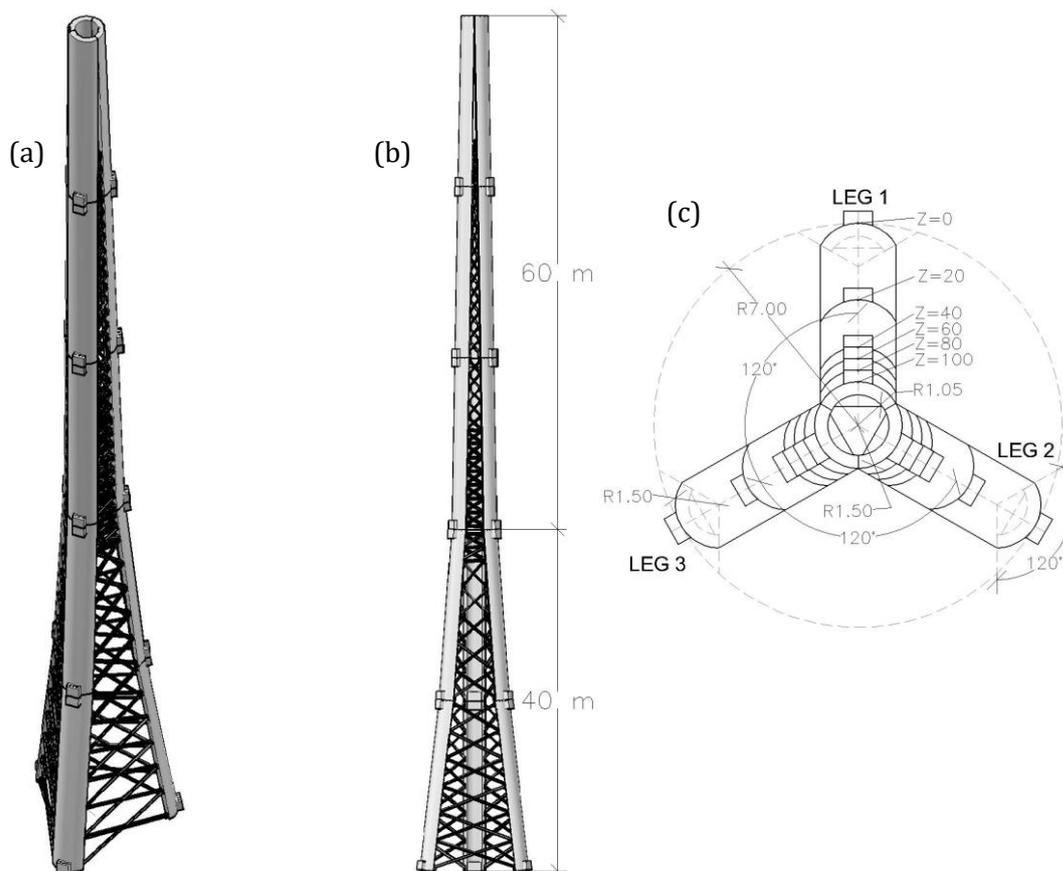


Figure 6. (a) 3D, (b) frontal, and (c) upper views of the precast concrete tripod for wind tower

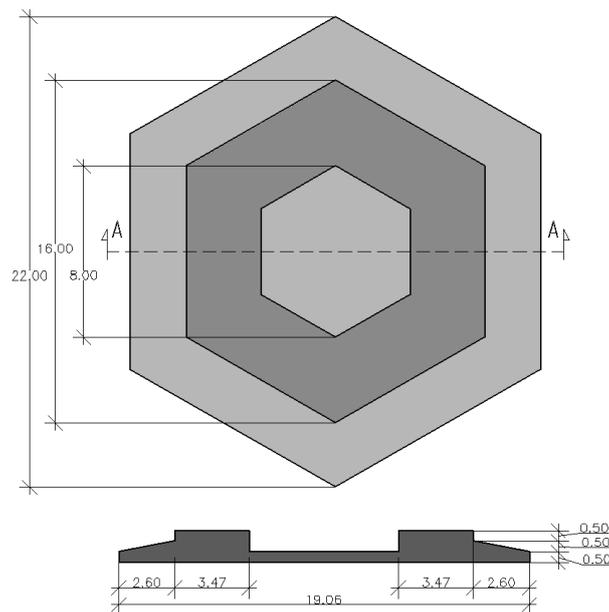


Figure 7. Upper and frontal views of the foundation for the precast concrete tripod for wind tower

Table 10 shows the values for each indicator and requirement for the precast concrete tripod. In this regard, considering the weights established for the three requirements (Table 7), the sustainability index derived from applying the Equation (1) is **SI = 0.68**.

Table 9. Value function parameters for each indicator

Indicator	Unit	x_{max}	x_{min}	C	K	P	Shape
I ₁ . Direct cost	€/tower	2,000,000	900,000	1,100,000	1.00	2.5	DCv
I ₂ . Cost deviations	points	90	40	50	1.00	2.5	DCv
I ₃ . Maintenance work	€/tower·year	10,000	4,000	5,000	0.05	2.5	DCv
I ₄ . Deconstruction	€/tower	250,000	20,000	60,000	0.05	2.5	DCv
I ₅ . Material	Tn/MW	2,000	200	500	0.01	1.0	DL
I ₆ . Energy	GWh/MW	1.5	0	0.75	1.00	1.0	DCx
I ₇ . Emissions	ton CO ₂ -e/MW	1,500	0	750	1.00	1.0	DCx
I ₈ . Occupational hazards	points	2.5	1.5	2.5	0.01	3.0	DCv
I ₉ . Proportions	points	100	0	100	0.01	1.0	DL
I ₁₀ . Flexibility	points	100	0	100	0.01	1.0	DL
I ₁₁ . New patents	points	1	0	1	0.01	1.0	DCx

Table 10. Satisfaction values for each indicator and requirement

Indicator	R ₁	I ₁	I ₂	I ₃	I ₄	R ₂	I ₅	I ₆	I ₇	R ₃	I ₈	I ₉	I ₁₀	I ₁₁	Total
Index V_i	0.57	0.83	1.00	0.33	0.38	0.86	0.80	0.86	0.98	0.64	0.31	0.90	0.60	1.00	0.68

Had other stakeholders' preferences wanted to be taken into account, the requirement weights could be calibrated according the situation. For instance, on the one hand, in case of a private owner (or investor) or in a general economic recession panorama, the economic requirement would have higher relative importance. A possible weights' distribution would be $\lambda_{R1} = 75\%$, $\lambda_{R2} = 15\%$, $\lambda_{R3} = 15\%$, being the final SI = 0.65. On the other hand, in case of economic goodness and/or a country with strong environmental and social sensitivity, a potential weights' distribution would be $\lambda_{R1} = 35\%$, $\lambda_{R2} = 45\%$, $\lambda_{R3} = 20\%$. In this case, the total SI = 0.71.

In view of the results, it is evident that the model allows the decision-maker contemplate different scenarios taking into account different preferences. This model can be applied independently of the structural material of the tower, height, turbine power and transport distance. So, it can be stated that this MIVES model is general for assessing the sustainability of wind towers.

5. Conclusions

The MIVES model has been presented in this paper as a potential tool to assess the sustainability of concrete products and systems. The model allows taking into account the three pillars of the sustainability objectively by means of the satisfaction function concept.

Case studies within the field of fibre reinforced concrete tunnel linings and precast concrete wind turbine supports were included aiming at emphasizing the versatility and applicability of the model to deal with the sustainability analyses of concrete structures.

References

- [1] B. Alarcón, A. Aguado, R. Manga y A. Josa, A. Value Function for Assessing Sustainability:
- [2] T. Saaty. How to make a decision: The analytic hierarchy process. *Eur J Oper Res*, vol. 48, pp. 9-26, 1990.
- [3] T. Saaty. *Fundamentals of decision making and priority theory with the Analytic Hierarchy Process*. Vol. VI, Pittsburgh: RWS Publications, 2006.
- [4] E. Kazimieras, J. Antucheviciene, Z. Turskis y H. Adeli. Hybrid multiple-criteria decision-making methods: A review of applications in engineering. *Sci Iran*, vol. 23, n° 1, pp. 1-20, 2016.
- [5] J. San-Jose y I. Garrucho. A system approach to the environmental analysis industry of buildings. *Build Environ*, vol. 45, n° 3, pp. 673-683, 2010.
- [6] J. San-Jose y J. Cuadrado. Industrial building design stage based on a system approach to their environmental sustainability. *Constr Build Mater*, vol. 24, n° 4, pp. 438-447, 2010.
- [7] J. Reyes, J. San-Jose, J. Cuadrado y R. Sancibrian. Health & Safety criteria for determining the value of sustainable construction projects. *Safety Sci*, n° 62, pp. 221-232, 2014. J. San-José,
- [8] R. Losada, J. Cuadrado y I. Garrucho. Approach to the quantification of the sustainable value in industrial buildings. *Build Environ*, vol. 42, n° 11, pp. 3916-3923, 2007. G. Ormazabal, B.
- [9] Viñolas y A. Aguado. Enhancing value in crucial decisions: Line 9 of the Barcelona Subway. *Manage Eng J*, vol. 24, n° 4, p. 265-272, 2008. 2008.
- [10] F. Pardo y A. Aguado. Investment priorities for the management of hydraulic structures. *Struct Infrastruct E: Maint Manag Life-Cycl Design and Perform*, vol. 11, pp. 1338-1351, 2014.
- [11] F. Pardo y A. Aguado. Sustainability as the key to prioritize investments in public infrastructures. *Environ Impact Asses. Review*. Vol. 60, September 2016, 40-51.
- [12] A. de la Fuente, J. Armengou, O. Pons y A. Aguado. Multi-criteria decision-making model for assessing the sustainability index of wind-turbine support systems. Application to a new precast concrete alternative. *J Civ Eng Manag*, In Press.
- [13] A. de la Fuente, O. Pons, A. Josa y A. Aguado. Multi-Criteria Decision Making in the sustainability assessment of sewerage pipe systems. *J Clean Prod*, vol. 112, n° 5, pp. 4762-4770, 2016.
- [14] S. Hosseini, A. de la Fuente y O. Pons. Multi-criteria decision-making method for sustainable site

- location of post-disaster temporary housing in urban areas. *J Constr Eng M ASCE*, In Press.
- [15] S. Hosseini y A. de la Fuente. Multi-criteria decision-making method for assessing the sustainability of post-disaster temporary housing units' technologies: A case study in Bam. *Sustainable Cities and Society*, vol. 20, pp. 38-51, 2016.
- [16] O. Pons y A. Aguado. Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia. Spain. *Build Environ*, vol. 53, pp. 49-58, 2012.
- [17] O. Pons y A. de la Fuente. Integrated sustainability assessment method applied to structural concrete columns. *Constr Build Mater*, vol. 49, p. 882–893, 2013.
- [18] CPH 2008. Spanish Structural Concrete Standard. Annex 14: Recommendations for the use of fiber reinforced concrete, Madrid, 2008.
- [19] Aguado, A. del Caño, P. de la Cruz, P. de la Cruz, P. Gómez y A. Josa. Sustainability assessment of concrete structures. The EHE approach Rev., *J Constr Eng M ASCE*, vol. 138, nº 2, pp. 268-276, 2012. Doi: 10.1061/(ASCE)CO.1943-7862.0000419
- [20] A. Caño, D. Gómez y M. de la Cruz. Uncertainty analysis in the sustainable design of concrete structures: A probabilistic method. *Constr Build Mater*, vol. 37, p. 865–873, 2012.