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Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction

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Abstract

Since the establishment of the Sustainable Development Goals, great concern has arisen on how to diminish the impacts that result from construction activities. In such context, Modern Methods of Construction (MMC) rise as a powerful way to reduce life cycle impacts through optimizing the consumption of materials. This paper focuses on the sustainability assessment of different modern construction techniques applied to concrete structures of single-family houses. The life cycle performance in terms of sustainability is compared between a conventional reference design, a precast design, a lightweight slab design with pressurized hollow discs, and a design based on double-wall structural elements. The sustainability is assessed through a set of 38 indicators that address not only the economic and environmental response of the designs, but also their social impacts as well. Five of the best known Multi-Criteria Decision-Making (MCDM) techniques (SAW, COPRAS, TOPSIS, VIKOR and MIVES) are applied to derive the life-cycle performance of each design into a single sustainability score. Since there is no consensus on which MCDM method works best in sustainability assessments, a Global Structural Sustainability Index (GSSI) combining and weighting the above is proposed here to aid the analysis of the results obtained. The results show that consideration of the three dimensions of sustainability leads to balanced designs whose preference need not coincide with those derived from each one-dimensional life cycle approach.

Keywords: Sustainability; Construction; Structural Design; Life Cycle Cost; Life Cycle Assessment; Social Life Cycle; Multi-Criteria Decision-Making; Modern Methods of Construction

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1. Introduction

The global climate emergency is a reality that threatens the planet, with the construction sector being one of the main culprits. By 2050, half of CO_2 emissions in construction will come from new buildings, up from 28% today. The Ellen MacArthur Foundation (2019) predicts that if this trend continues, global consumption of material resources would grow to 90 billion tons by 2050 (up 125% since 2010), exceeding all levels that the planet can sustainably provide. The construction industry must make important decisions for the future as soon as possible in order to design buildings that promote our cities in a socially and environmentally responsible way. To achieve the climate targets, designers should direct efforts towards the circular economy, trying to improve aspects such as embedded energy, materials, waste and resource management, water cycle, rehabilitation and recyclability, and use management. To this end, philosophies such as Lean Construction have appeared to improve the management of construction projects (Mellado and Lou, 2020) by eliminating activities that do not add value (losses). New technologies such as Building Information Modeling (BIM) have made it possible to collaboratively generate and manage the data of a building or infrastructure through a digital model shared between the different construction agents (Van Eldik et. al, 2020). And also objective methodologies such as Life Cycle Analysis (LCA), which seeks to evaluate the environmental impacts related to an activity, process or product during all stages of its existence (Borghi et al., 2018; Marinkovic et al., 2021) by quantifying and identifying the use of matter and energy as well as emissions to the environment.

Structures are among the construction activities that generate the greatest economic and environmental impact. Structural projects often use more materials than they actually need. Very recent studies indicate that it is possible to increase the mechanical capacity and durability of structures by using recycled concrete aggregates, granulated blast furnace slag and silica fume (Habibi et al., 2021). But it is also possible to achieve the same structural strength of concrete with recycled aggregates and low cement content (Robalo et al., 2021). Designing buildings with less material can be achieved by reducing excessive project specifications, optimizing the design and using high strength materials. In this context, Modern Methods of Construction emerge not only as economically preferable alternatives to conventional construction methods (Lopes et al., 2018), but also as a powerful way to reduce life-cycle environmental impacts by optimizing material consumption. MMCs favor the reduction of the carbon footprint, the production of higher quality housing without necessarily making it more expensive. They also contribute to improving the working conditions of the construction workforce through the implementation of safer, more comfortable and controlled environments with reduced occupational risks (Yepes et al., 2012; Pellicer et al., 2014). But at present there are obstacles to achieve such social benefits, such as a lack of skilled labor force, shortage of supplies or the absence of specific regulations (Rahman, 2014).

Civil engineering has traditionally focused on the study of the reliability of structures in terms of strength and durability with restrictive budgets imposed by construction companies. Public administrations have a preference for strengthening environmental issues. Architecture preferences have usually been of a social nature, promoting spatial design and functionality but relegating economic control to a secondary role. To date, both the environmental (Penadés-Pla et al., 2017) and the economic (Younis et al., 2018) impacts of structures have been extensively investigated. In recent years, designs have also been analyzed from an economic-environmental perspective (Yepes et al., 2015; Zastrow et al., 2017). However, very few publications on the social assessment of building structures throughout their life cycle have been found in the literature (Sierra et al., 2017; Navarro et al., 2018). This is because the technique S-LCA for estimating the social life cycle impacts of a product is relatively recent compared to LCC (Hunkeler et al., 2008) or E-LCA (ISO, 2006a; ISO, 2006b). Some authors, such as Jørgensen (2013), consider that in order to be a solid and consistent methodology like the previous ones, it still has some way to go to prove its validity. Growing cities, ageing populations, climate change and the lack of natural resources mean that the construction, management, and life cycle design of buildings need to be rethought in order to be as sustainable as possible. Therefore, it is necessary to address research that studies modern construction techniques to design building structures in terms of sustainable criteria. And sustainability implies considering the simultaneous nature of its three dimensions, namely the economy, the environment and society.

2. Brief state of the art of MCDM methods

The sustainable design of structures, along with their management, is a complex problem to solve due to the conflicting nature of multiple stakeholders involving generally conflicting criteria. The literature review revealed the existence of a wide variety of conventional and novel Multi-Criteria Decision Making (MCDM) techniques developed to evaluate multifaceted options, including sustainability strategies (Zavadskas et al., 2016a, 2016b).

In recent years there has been a boom in the application of MCDM methods to almost all aspects of construction. Classical methods have been used in construction to evaluate the sustainability of infrastructure planning (Salas and Yepes, 2020), bridges (García-Segura et al., 2018), maintenance of public buildings (Ighravwe and Oke, 2019), residential building structures (Sánchez-Garrido et al, 2021), or materials such as recycled concrete (Rashid et al., 2020), among many others. From the analysis of the relevant literature of the last two decades (Zhu et al., 2021), a change of trend towards cross-integration is detected, with novel hybrid MCDM methods being developed to address construction problems that every day need to adapt to more complex environments. Sivilevičius et al. (2008) presented an original additive model for determining quality attributes and for a complex evaluation of an computerized asphalt mixing plant, which are one of the most expensive and complicated equipment for road pavement construction. Although not cited as such, it refers to the QUALIFLEX (QUALItative FLEXible) method, which is very useful for selecting viable sustainable options under all possible permutations of alternatives (Turskis, 2008). Models have also been developed where decision makers could describe problems using accurate and different fuzzy models. In this regard, Medineckiene et al. (2010) used an integrated model based on AHP and SAW-G (SAW with gray numbers) to investigate sustainable construction, taking into account the life cycle impact of a block house on the environment as well as its financial and social conditions. Subsequently, Turskis et al. (2015) presented a hybrid model based on fuzzy AHP and fuzzy WASPAS for construction site selection.

During these years, some studies have shown a novel use of applications of mathematical models and strategies, such as Game Theory, to assess sustainability in construction (Peldschus et al., 2010). Other researchers have introduced new methods for solving multi-criteria decision making problems. For example, Keshavarz Ghorabaee et al. (2016) presented the CODAS (COmbinative Distance-based Assessment) method that uses Euclidean distance as the primary measure and taxonomic distance as the secondary measure, both calculated from the negative ideal point. This is also the case for the CoCoSo method (COmbined COmpromise SOlution), introduced by Yazdani et al. (2019). In any case, each new technology and strategy needs to adapt management to provide the right skills to the managers. This is true for the selection of the right contractor, one of the most risky tasks in construction (Erdogan et al., 2017).

There is no specific MCDM model to solve all the multifaceted problems encountered in the construction industry. Requirements, standards, and aims depend on a wide variety of characteristics, such as construction site location (Turskis et al., 2012), materials and construction elements (Zavadskas et al., 2013), technologies used (Ruzgys et al., 2014) as well as stakeholders' aims (Zavadskas et al., 2017). In this study, we focused on the five most commonly used methods for construction in general and structures in particular (Jato-Espino et al., 2014; Zavadskas et al., 2016a; Navarro et al., 2019), namely SAW, COPRAS, TOPSIS, VIKOR and MIVES. They all share the same decision process whose steps consist of: standardization and weighting, calculation of the sustainability index and construction of the ranking. Their choice aims to cover the most representative methods according to Hajkwociz and Collins (2007) and De Brito and Evers (2016) classification for Multi-Attribute Decision Making (MADM) methods.

The simple additive weighting (SAW) technique was introduced by MacCrimmon (1968) being the most widely used method multi-criteria decision making problems. However, it is limited to dealing with maximizing and positive definite criteria, while minimizing evaluation criteria must be converted into maximizing ones. The complex proportional assessment method (COPRAS) is an evolution of the previous one developed by Zavadskas et al. 1994). Based, like SAW, on direct scores the authors eliminated the limitation by separately evaluating the influence of both maximizing and minimizing criteria. For more complex criteria, more sophisticated distance-based MCDM methods have been preferred in recent years. The Technique of Order Preference by Similarity to the Ideal Solution (TOPSIS) method, presented by Hwang and Yoon (1981), is the first and most widely used technique to address MCDM issues in the sustainability assessment of buildings and structures. The ideal point is obtained from the optimal value among the scores obtained for each criterion of any alternative, while the least preferred point is deduced from the worst value. The Multicriteria Optimization and Compromise Solution (VIKOR) technique, based on the shortest distance to the ideal solution, was introduced by Opricovic (1998). VIKOR provides for the set of alternatives one or several compromise solutions. There are other methods in which it is of interest to obtain the best alternative from a given group based on the degree of satisfaction they provide. The Integrated Value Model for Sustainable Evaluation (MIVES) methodology, developed by Aguado et al. (2006), is based on providing the equations that define the different satisfaction functions of an alternative with respect to a criterion.

For more than 50 years, researchers have developed and presented many subjective methods for determining the weighting of criteria. Eckenrode (1965) used and compared up to six different methods without finding a significant difference between them. Subsequently, Saaty (1977) presented the well-known AHP (Analytic Hierarchy Process) method, introducing years later the ANP (Analytic Network Process) method (Saaty, 1996), as an evolution of the previous method that allows the use of mutually dependent criteria. Keršuliene et al. (2010) proposed the SWARA (Step-wise Weight Assessment Ratio Analysis) method. Stanujkic et al. (2017) developed the PIPRECIA method (PIvot Pairwise RElative

Criteria Importance Assessment method) as two extensions of SWARA when it is not possible to reach consensus on the expected importance of the evaluation criteria. Finally, Turskis et al. (2019) recently presented a technique that includes the Delphi method and fuzzy extensions of the Eckenrode criteria ranking method. Despite the many methods available to determine the weightings of the criteria, this study adopts the AHP method, being one of the most widely used (Zavadskas et al., 2016c).

In short, MCDM methods have been widely used in recent years in the study of infrastructures, as well as in different constructive elements or facilities. However, in the absence of a universal technique to evaluate all problems, a hybrid model composed of several MCDM tools has rarely been used to obtain the most consensual results possible (Turskis and Juodagalvienė, 2016). And to the authors' knowledge, a combined model using several MCDM techniques has not been used to assess the sustainability of the envelope and structure of a residential building by integrating the three dimensions during its life cycle.

3. Materials and Methods

To solve the knowledge gap previously detected, the present paper provides a holistic sustainability life cycle assessment of different MMC-based building alternatives, taking into consideration different MCDM techniques. In addition, a Global Structural Sustainability Index (GSSI) is finally proposed to overcome the singularities and differences between the most frequently used decision making techniques. The sustainability performance of the different housing alternatives presented in this study is analyzed based on the life cycle assessment methodology introduced in ISO 14040 standard. According to ISO 14040, any life cycle assessment should consist of four steps: the definition of the goal and scope of the study, the presentation of the impact assessment methodology to be followed, an analysis of the inventory that the assessment will account for, and finally the results with their interpretation.

3.1. Definition of goal and scope

This study aims to compare the life-cycle sustainability performance of four structural design alternatives for the construction of a residential building. The functional unit on which the comparative analysis is based consists of a single-family row house located in Jaén (Spain) consisting of two floors occupying a rectangular area of 20.00 m × 6.20 m and a built-up area of 384.69 m^2. The plot has a single access from the street, typical of this typology, as shown in Figure 1. This typology has spread all over the world, especially in the expansion areas of large cities, because it allows an average and affordable economic cost for a large number of people who prefer to live in single-family dwellings rather than in collective dwellings. The housing solution consists of a garage on the semi-basement floor; on the second floor there is a living room, a toilet and a kitchen; on the first level, three bedrooms and a bathroom; a swimming pool located on the second floor solarium and, finally, a small turret with a sloping roof. Figure 2 shows the general structure of the building.

Fig. 1. Elevation of the single-family row house

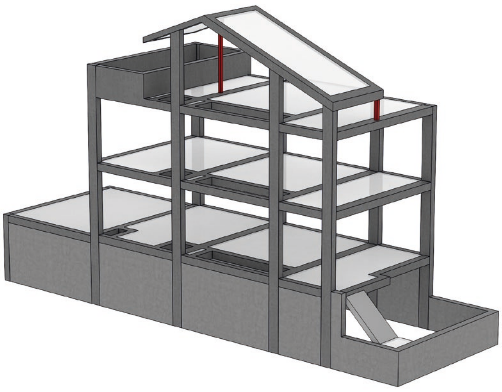


Fig. 2. 3D model of the reference structure.

The four construction solutions to be analyzed are presented in Table 1. The baseline solution (called REF hereafter) consists of a traditional construction system for a concrete building, in which the main structural elements are made of 25 MPa reinforced concrete, and the partition walls are built with conventional bricks. In the retaining walls and foundations 30−35 MPa reinforced concrete is used, respectively, with sulfate resistance characteristics due to the high aggressiveness of the soil. The second construction alternative (called YTN hereafter) consists of a more industrialized and prefabricated solution, based on the semi-dry assembly of the structural elements, which are mainly composed of special precast reinforced plates and confined masonry blocks. Both are made of autoclaved aerated concrete. Due to the strong emphasis on the use of prefabricated elements, this alternative is free of formwork or fresh concrete pouring except for the joint between plates. The third construction alternative to be evaluated (called PRE hereafter) is based on the use of ultra-light concrete structural slabs. This lightness is achieved through the use of pressurized recycled polyethylene discs or spheres that provide discontinuous voids, allowing a considerable reduction of the slabs selfweight while ensuring sufficient inertia. The latest modern construction alternative (hereafter referred to as ELE) is based on the use of double-walled structural elements. A continuous projected concrete shell based on this system can be folded to achieve the desired shape for the building. The hollow boards are used to materialize the space inside the double walls, allowing the passage of installations and the inclusion of expanded polystyrene (EPS) as lost formwork and thermal insulation.

Table 1.
Constructive description of the alternatives.

Design option	Elements	Main features
REF “Conventional” [a]	Foundations	Piles CPI 7 (Ø35cm) HA-35/F/12/IIa+Qc (8.80 m). Beams HA-30/B/20/IIa+Qb.
	Floor slabs	Reinforced concrete slab HA-25/B/20/IIa (24 cm) and HA-30/B/20/IV (26 cm) in the swimming pool area. Passable deck, not ventilated; 10 cm XPS (0.032 m^2K/W).
	Pitched roof slab	Reinforced concrete slab HA-25/B/20/IIa (22 cm); 10 cm PUR (0.035 m^2K/W).
	Supports	Concrete and metal columns. Reinforced concrete basement wall.
	Facades / Party walls	Exterior brick wall (11.5 cm); 9 cm MW (0.031 m^2K/W); interior brick wall (7 cm).
YTN “Prefabricated” [b]	Foundations	Same as alternative “REF”.
	Floor slabs	Reinforced plates on floors (30 cm) and solarium (17.5 cm); Density 600 kg/m^3 and thermal conductivity (0.16 W/mK). Passable deck; 8 cm XPS (0.032 m^2K/W). Pool bottom plates; “O” block anchored to the bottom and “U” block at the top.
	Pitched roof slab	Reinforced plates (12 cm); 12 cm XPS (0.032 m^2K/W).
	Supports	No columns are required. Reinforced concrete basement walls are maintained.
	Facades / Party walls	Aerated concrete blocks walls (20-30 cm), densities 400-350 Kg/m^3; 6 cm MW (0.031 m^2K/W) and self-supporting plasterboard wall paneling.
PRE “Lightweight” [c]	Foundations	Piles CPI 7 (Ø35cm) HAR-35/F/12/IIa+Qc (8.80 m). Beams HAR-30/B/20/IIa+Qb.
	Floor slabs	Reinforced recycled concrete slab HAR-25/B/20/IIa (18 cm) and HA-30/B/20/IV in pool, lightened with pressurized recycled polyethylene discs (27x12 cm). Passable deck not ventilated; 10 cm XPS (0.032 m^2K/W).
	Pitched roof slab	Reinforced recycled concrete slab HAR-25/B/20/IIa (16 cm) lightened with pressurized recycled polyethylene discs (22x10 cm); 10 cm PUR (0.035 m^2K/W).
	Supports	Concrete and metal columns. Reinforced concrete basement perimeter wall.
	Facades / Party walls	Exterior brick wall (11.5 cm); 9 cm MW (0.031 m^2K/W); interior brick wall (7 cm).
ELE “Technology” [d]	Foundations	Mat foundation (7/46/7) HRA-30/B/12/IIa+Qb on deep compacted soil improvement (1.00 m). Interior gravel filling (46 cm).
	Floor slabs	Double-wall slab with sprayed reinforced concrete HRA-25/B/12/IIa on type floors (6+18+6 cm), solarium (7+26+7 cm) and HRA-30/B/12/IV in pool. Passable deck, not ventilated; 26 cm XPS (0.042 m^2K/W).
	Pitched roof slab	Double-wall slab with sprayed reinforced concrete (5+5+5 cm). 5 cm XPS (0.025 m^2K/W).
	Supports	No columns are required. Double-walled reinforced concrete basement walls (6+13+6 cm) HRA-30/B/12/IIa+Qb.
	Facades / Party walls	Double-wall with sprayed reinforced concrete (6+13+6 cm); interior air chamber formed with 13 cm EPS (0.029 m^2K/W).

[a] Reference: Solid slab, columns and brick enclosure walls.
[b] YTONG: Industrialized plates and prefabricated blocks of autoclaving aerated concrete manufactured.
[c] PRENOVA: Flat concrete slab (20% recycled aggregates) lightened with pressurized hollow discs, columns and brick enclosure walls.
[d] ELESDOPA©: Double-walled structural element made with sprayed reinforced concrete (20% recycled aggregates).

The functional unit includes the construction, maintenance and demolition works over a service life of 50 years. Maintenance is assumed to be needed every ten years. A gate-to-grave approach has been adopted for the definition of the product system of the present analysis, covering from the production activities of the different construction materials to the decommissioning of the building at the end of its service life. As is usual in comparison-oriented life cycle analyses, processes that are considered common among the alternatives have been excluded from the product system (Martínez-Blanco et al., 2014; Navarro et al., 2020).

3.2. Life cycle impact assessment

An indicator-based evaluation is proposed for the evaluation of the life-cycle sustainability performance of each of the building alternatives analyzed, covering the three dimensions on which sustainability is based, namely economy, environment and society.

3.2.1. Assessment of the economic dimension

The economic assessment of each alternative accounts for the economic costs associated to the construction, the maintenance, and the demolition phase. The construction costs include those derived from the design and management stage, from the construction itself and from the management of the materials waste generated during this stage, including costs resulting from transport activities and different authorization fees. Regarding the costs associated to the service life stage, two categories have been considered, namely the costs derived from use and minor maintenance activities over time, and those resulting from maintenance prevention. In particular, the costs from five prevention treatments are considered, namely protection against reinforcement corrosion, treatments against concrete carbonation, hydrophobic surface treatments for concrete, façade waterproofing, and fire protection of the different building elements. The economic cost of the ten-year maintenance has been passed on according to the conservation operations foreseen in the maintenance program of the building after its construction. The costs associated to the End of Life (EoL) are divided into three categories: the costs associated to the activities needed for the complete demolition of the structure; the costs derived from the pre-treatment of waste materials resulting from the demolition (classification of waste and crushing of stone waste); and finally, the costs derived from the waste management, including transport costs and authorization fees.

A total of 3 economic criteria, 8 categories and 19 subcategories are included in the economic assessment of the different construction alternatives to be analyzed. Table 2 presents the considered assessment criteria, as well as the weights assigned to each sub-criterion. It shall be noted that future costs, namely costs derived from maintenance and demolition, are discounted and converted into present values. There is no clear consensus on which discount rate is more adequate for each assessment. Considering that sustainability-oriented decisions must take into account the minimization of burdens for future generations, the use of low discount rates, also called social discount rates in the literature, is desirable. In the present analysis, a social discount rate d=2% is chosen (Allacker, 2012). The equation that obtains the future costs converted into present costs is as follows:

$$LCC = \sum_{t=t_0}^{t_{SL}} C_i \times 1/(1+d)^{t-t_0} \tag{1}$$

where LCC is the Life Cycle Cost of the structure, C_i is the economic costs linked to time t, t_0 is the time corresponding to the beginning of the evaluation period (in our case is 0), t_{SL} is the expected number of years, and d is the value of the discount rate.

Table 2.
Deployment of the economic criteria tree and weights (local and global).

Field	**Criteria [C]**		**Sub-criteria (G)**		**Indicators {I}**	
Economy	Construction cost [12.78%] [a]	C1	Production	G1	Design + project management fees (€/m^2)	I1
					Construction management fees (€/m^2)	I2
					License and taxes (€/m^2)	I3
			Materialization	G2	Construction cost - bill of quantities (€/m^2)	I4
			Waste management	G3	Transport of the land by truck (€/m^2)	I5
					Landfill fee to authorized manager (€/m^2)	I6
					Transport of inert waste by truck (€/m^2)	I7
					Fee for delivery of inert waste (€/m^2)	I8
	Service life cost [8.65%] [a]	C2	Prevention	G4	Corrosion protection (€/m^2)	I9
					Prevention of carbonation (€/m^2)	I10
					Water-repellent for concrete (€/m^2)	I11
					Facade waterproofing (€/m^2)	I12
					Protection against fire (€/m^2)	I13
			Use and maintenance	G5	Ten-year maintenance (€/m^2 first 10 years)	I14
	End of life cost [2.51%] [a]	C3	Demolitions	G6	Full building demolition (€/m^2)	I15
			Pre-treatment of waste	G7	Classification of construction and demolition waste (CDW) generated (€/m^2)	I16
					Crushing of stone residues (€/m^2)	I17
			Inert waste management	G8	Transport of inert waste by truck (€/m^2)	I18
					Fee for delivery of inert waste (€/m^2)	I19

[a] Crisp weights in criteria in percentage between square brackets, calculated according to Eq. (17).

3.2.2. Assessment of the environmental dimension

The assessment of the environmental impacts of each alternative is based on two criteria, namely the impacts derived in the short term, which result from the construction activities, and those derived in the long term, resulting from the EoL. The assessment of these impacts conforms to the ReCiPe methodology (Huijbregts et al., 2017), which calculates the result based on three environmental endpoint indicators, namely damage to ecosystems, depletion of natural resources and damage to human health. These three endpoint indicators are constructed based on 18 midpoint indicators that consider a variety of environmental aspects such as climate change, ozone layer depletion, ionizing radiation, marine and freshwater eutrophication, land use and others. The direct impacts on these midpoint categories shall then be translated into direct effects on human health, measured in terms of the Disability Adjusted Life Years (DALY) scale. This scale represents the number of years that a person is disabled because of disease. The impacts on the environment are measured in terms of the number of local species lost each year due to the effects of the abovementioned midpoint impacts. At last, the endpoint impacts on the availability of natural resources is measured as the extra monetary costs required for the extraction of fossil and mineral resources in the future due to the present extraction. Here, the ReCiPe method is applied from a hierarchist perspective, where similar relevance is assigned to both the short- and the long-term impacts.

A total of two environmental criteria, 2 categories and 6 subcategories are included in the environmental assessment of the different construction alternatives to be analyzed. Table 3 presents the considered assessment criteria, as well as the weights assigned to each sub-criterion.

Table 3.
Deployment of the environmental criteria tree and weights (local and global).

Field	Criteria [C]		Sub-criteria (G)		Indicators {I}	
Environment	Envir. Footprint (Short term) [17.28%] [a]	C4	Endpoint impacts (Construction)	G9	Ecosystem quality (Construction) (Points)	I20
					Human health (Construction) (Points)	I21
					Resources (Construction) (Points)	I22
	Envir. Footprint (Long term) [15.50%] [a]	C5	Endpoint scores (EoL)	G10	Ecosystem quality (EoL) (Points)	I23
					Human health (EoL) (Points)	I24
					Resources (EoL) (Points)	I25

[a] Criteria weights in percentage between square brackets, calculated as according to Eq. (17).

3.2.3. Assessment of the social dimension

To assess the social impacts resulting along the life cycle of each construction alternative, a set of criteria is selected based on the stakeholder approach suggested by UNEP/SETAC (2009) for the social life cycle analysis. Here, four stakeholders are considered, namely the local community, the consumers, the workers, and the society. The mathematical construction of the social indicators follows the methodology suggested in Navarro et al. (2018) is presented in Table 4.

Table 4.
Social indicators for the sub-criteria involved in the assessment.

Criteria	Subcategory	Ind.	Transfer function / questionnaire	References
Local community	Local employment	I26 I27	**E = Generation of local employment (hours)** EM = Equipment and machinery (hours) LL = Local labor (hours) $E_S = \sum EM_C + \sum LL_C$ (short term→construction) $E_L = \sum EM_D + \sum LL_D$ (long term→demolition)	OECD Navarro et al. (2018) http://www.generadordeprecios.info/
	Access to material resources	I28	**A_{EM} = Availability equipment /materials (qualitative scale 1-100)** Q1. Accessibility to equipment and materials; Q2. Supplies; Q3. Transport distances; Q4. Need for auxiliary lifting machinery for structure; Q5. Need for auxiliary lifting machinery for walls.	
Consumer	User safety	I29	**X_{PR}= Probability of pathology risk (%)** I_e = incidence on construction *n*-elements (%) I_c = incidence according to construction type (%) T_{BS} = trust in the building system (scale 1-10) $X_{PR} = \frac{\sum I_e \cdot I_c \cdot [(100 - (T_{BS} \cdot 10)]}{3}$	Sánchez-Garrido et al. (2021) National statistical analysis on building pathologies MUSAAT (2013, 2016) https://fundacionmusaat.musaat.es/
	User's health	I30 I31	**U_T= Transmittance ($W/m^{2o}K$)** R = thermally layer resistance (m^2K/W) e = layer thickness (m) λ = material thermal conductivity (W/mK) $R = \frac{e}{\lambda}$; $U_T = \frac{1}{\sum_{i=1}^{n} R_i}$	Computer application CEXv2.3. https://www.efinova.es/complementos/ UNE-EN ISO 10456:2012 - AENOR

		I32	**$R_{a,tr}$ = overall sound reduction index (dBA)** R = noise reduction index of a constr. element $L_{Atr,i}$ = A-weighted standard vehicle noise spectrum value in the *i*-frequency band $R_{a,tr} = -10 \cdot \log \sum_{i=1}^{n} 10^{\left(L_{Atr,i}-R_i\right)/10}$	DB-HR: Noise protection - CTE Catalogue CTE components
Workers	Occupational health and safety	I33 I34	**X_{AC} = Probability of accidents in building (%)** a_p = No. potencial accidents on construction site or demolition e_s = No. site employees I_r = average monthly incidence rate x 100,000 h w_a = No. workers per sector affiliated (monthly) a_r = accident rate by sector/month in the reference period Y_{em} = yield equipment + machinery (h) Y_w = yield of working (h) T_{SC} = time on construction site or demolition (months) $I_r = \frac{a_r}{w_a} \cdot 100{,}000\,; \quad e_s = \frac{Y_{em} + Y_w}{168 \cdot T_{sc}}$ $a_p = \frac{e_s \cdot I_r}{Y_{em} + Y_w}; \quad X_{AC} = \frac{a_p}{e_s} \cdot 100$	Statistics on Accidents at Work. INSHT (National Institute for Occupational Safety and Health). https://herramientasprl.insst.es/ Ministry of Labour and Social Economy. Spanish Government
	Fair wage	I35 I36	**X_{LE} = Generation of quality local employment** Es_{min}= Employment equivalent to min. salary P_m = equipment/machinery performance (h) s_o = salary of *n*-machine operators (€/h) P_w = workers performance (hours) s_w = salary of *n*-trades (€/h) s_{min} = official minimum salary (€/h) $\Delta X_{LE} = \left(\frac{E_{Smin}}{P_m + P_w} - 1\right) \cdot 100$ $E_{Smin} = \frac{\left(P_m \cdot \frac{1}{n}\sum_{i=1}^{n} s_o\right) + \left(P_w \cdot \frac{1}{n}\sum_{i=1}^{n} s_w\right)}{s_{min}}$	OECD Navarro et al. (2018) Sánchez-Garrido et al. (2021)
Society	Technology Development	I37	**F_R = Flexibility to introduce reforms (qualitative scale 1-100)** Q1. Technical complexity; Q2. Customer Satisfaction; Q3. Labor Efficiency	
	Public Commitment to Sustainability Issues	I38	**B_{CM} = Benefits of each construction method (qualitative scale 1-100)** Q1. Use of recycled materials; Q2. Reinstatement of surplus materials; Q3. Construction time performance; Q4. Energy consumption; Q5. Savings in logistics and transportation costs; Q6. Material savings (building weight); Q7. Labor yield; Q8. Construction method certification	

The positive impact on the local communities is quantified considering the employment generated both during construction and over the long term, as well as the ease to access the material resources. The impacts on the consumer are evaluated during the use and maintenance stage taking into account user safety, which is related to the probability that the structure develops any type of deterioration that could compromise the integrity of the building, and the users' health and well-being. This last subcategory is assessed in terms of three different indicators, measuring both the thermal and the acoustic comfort of the user. The social impact affecting the workers is assessed by considering the short- and long-term accident rates during construction and demolition activities, as well as to what extent their wages are fair or not. At last, the impact on the society is evaluated considering two subcategories, related to technological development and public commitment to sustainability issues. Both are measured in a qualitative scale ranging from 1 to 100. The first subcategory accounts for the flexibility of a construction alternative to admit alterations and modifications during the course of its service life. On the other hand, the second subcategory aims to regard the benefits of each construction method by integrating aspects such as the use of recycled materials, the savings in logistics and transportation costs, or the performance in the construction time.

The standardization of the social indicators is achieved by applying utility functions to each of them, which allows for the conversion of the different measurements into values included within the unit interval. The shape functions assumed for each of those criteria, together with the parameters defining them are presented in Table 10. It is preferred to optimize the contribution of the experts by avoiding diluting the judgments to focus their attention only on the evaluation of the 9 criteria. Sensitivity studies have shown that weight variations at the indicator level do not significantly alter the preference for each alternative, since their influence is lost as one moves up to the criteria level (Sánchez-Garrido and Yepes, 2020). When no information is available to define the relevance attributed to each subcategory, it is preferable to consider an equal weighting to prevent biased results. This achieves the lowest level of disagreement among the wide variation in the weights of the individuals involved (Hagerty and Land, 2007). A total of 4 social criteria, 8 categories and 13 subcategories are included in the social assessment of the different construction alternatives to be analyzed. Table 5 presents the considered assessment criteria, as well as the weightings assigned to each sub-criterion and indicator.

Table 5.
Deployment of the social criteria tree and weights (local and global).

Field	**Criteria [C]**		**Sub-criteria (G)**		**Indicators {I}**	
Society	Local community [6.64%] [a]	C6	Local employment {50.00%}[b]	G11	Short-term local employment generation (construction hours)	I26 {50.00%}[b]
					Long-term local employment generation (demolition hours)	I27 {50.00%}[b]
			Access to material resources {50.00%}[b]	G12	Materials and equipment access (scale 1-100)	I28 {100%}[b]
	Consumer [23.72%] [a]	C7	User safety {50.00%}[b]	G13	Probability of pathological processes (%)	I29 {100%}[b]
			User's health {50.00%}[b]	G14	Thermal insulation in rooftop (U=W/m^{2}ºK)	I30 {33.34%}[b]
					Thermal insulation in facades (U=W/m^{2}ºK)	I31 {33.33%}[b]
					Acoustic insulation (Ra,tr (dBA))	I32 {33.33%}[b]
	Workers [7.13%] [a]	C8	Occupational health and safety {50.00%}[b]	G15	Short-term accidentability (construction) (% Potential accidents)	I33 {50.00%}[b]
					Long-term accidentability (demolition) (% Potential accidents)	I34 {50.00%}[b]
			Fair wage {50.00%}[b]	G16	Wage quality in the short term (construction) (Increase with respect to minimum wage)	I35 {50.00%}[b]
					Wage quality in the long term (demolition) (Increase with respect to minimum wage)	I36 {50.00%}[b]
	Society [5.81%] [a]	C9	Technology Development {50.00%}[b]	G17	Modifiability and flexibility to introduce reforms (scale 1-100)	I36 {100%}[b]
			Public Commitment to Sustainability Issues {50.00%}[b]	G18	Benefits of each construction method (scale 1-10)	I36 {100%}[b]

[a] Criteria weights in percentage between square brackets calculated according to Eq. (17).
[b] Equal weightings in the sub-criteria and indicators considered according to Hagerty and Land (2007).

3.3. Inventory analysis

Table 6 presents the different materials required by each of the four analyzed solutions for the functional unit under study, as well as the quantities consumed by each one. The economic costs for each construction material required by each construction, maintenance or demolition activity, are gathered from national construction-specific databases. Cost values considered here for each construction material include the costs the machinery and labor force involved in the manufacture and installation of those materials. Every cost is referred to year 2021 and is provided in Euro (€).

Table 6.
Inventory data with material quantities used in the economic-environmental assessment (construction stage).

Material description	Properties	Alternatives				Unit
		REF	**YTN**	**PRE**	**ELE**	
Ytong tile (62,5×25×7 cm)	450 Kg/m^3	-	939.16	-	-	kg
Ytong reinforced plate (30×62,5 cm)	600 Kg/m^3	-	29568.60	-	-	kg
Ytong reinforced plate (17,5×62,5 cm)	600 Kg/m^3	-	5255.25	-	-	kg
Ytong reinforced plate (12,5×62,5 cm)	600 Kg/m^3	-	2041.20	-	-	kg
Ytong block 62,5×25×20 cm	400 Kg/m^3	-	29245.15	-	-	kg
Ytong block 62,5×25×30 cm	350 Kg/m^3	-	2982.53	-	-	kg
Mortar	2000 Kg/m^3	6074.20	1873.97	6074.20	-	kg
Cement (ground)	1500 Kg/m^3	22.26	3958.40	22.26	257.38	kg
Concrete block	14.5 kg/unit	-	3346.73	-	-	kg
Concrete (fck≤30 Mpa; exposure class II-IV)	2500 Kg/m^3	176.07	109.47	141.17[a]	152.23[a]	m^3
Gravel	1650 Kg/m^3	40450.91	40450.91	40450.91	207055.20[b]	kg
Aggregate	1750 Kg/m^3	64.52	10716.82	64.52	-	kg
Compacted granular sub-base	1850 Kg/m^3	-	-	-	272800.00	kg
Bricks	2.30 Kg/unit	36110.41	-	36110.41	-	kg
Polyethylene (high density)	980 Kg/m^3	-	-	−185.39[c]	189.90	kg
EPS (9 cm)	25 Kg/m^3	-	-	-	2151.00	kg
Rebar steel	7850 Kg/m^3	13111.33	6870.80	11810.55	12587.15	kg
Wire and tips	7850 Kg/m^3	149.57	75.57	134.89	151.20	kg
Wire mesh	7850 Kg/m^3	92.34	92.34	92.34	-	kg
Steel armor for blocks	0.31 kg/m	-	13.12	-	-	m
Steel reinforcements Ytong plate (30×62,5 cm)	2 kg/m^2 (quantity)	-	328.54	-	-	kg
Steel reinforcements Ytong plate (17.5×62,5 cm)	2 kg/m^2 (quantity)	-	100.10	-	-	kg

Steel reinforcements Ytong plate (12.5×62,5 cm)	2 kg/m^2 (quantity)	-	54.43	-	-	kg
Timber (pine)	420 Kg/m^3	8.06	0.66	8.06	0.93	m^3
formwork board (22 mm)	25 applications	0.32	0.05	0.32	13.63	m^3
Sand (dry)	1700 Kg/m^3	64.52	5377.93	64.52	-	kg
Structural steel (S275JR)	7850 Kg/m^3	474.11	3144.26	474.11	-	kg
Shoring and % of props	150 applications	130.98	7.46	133.80	98.75	kg
Pillar formwork	50applications	52.50	-	54.09	-	kg
Modular concrete walls formwork	50applications	-	-	-	0.42	kg
Water (excluding concrete mix component)	-	3025.44	2083.76	3025.44	-	dm^3
Priming, resins, de-coating	0.9 kg/l	50.64	7.99	49.54	53.93	kg

[a] Recycled concrete with a maximum percentage of recycled aggregates of 20%.

[b] It is considered 75% recycled gravel only when it is used as a soil improvement for the foundation.

[c] Polyethylene discs are introduced as negative production because they come from 100% recycling of plastic waste.

The inventory data to perform the environmental assessment according to the ReCiPe methodology have been gathered from Ecoinvent 3.3 database. The wastes generated both during the construction and the demolition stage of the life cycle of each alternative are summarized in Table 7. The environmental impact resulting from the transport of waste materials to landfill is included in the assessment. For each alternative, an average transport distance of 20 km from the construction site to the landfill is assumed. The inventory data required to quantify the social indicators proposed in this study have been gathered from the Spanish National Statistics Institute and OECD official databases. The material properties required to characterize the indicators related to the consumer well-being have been obtained from national standards.

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

Waste generated	REF		YTN		PRE		ELE	
	Building	EoL	Building	EoL	Building	EoL	Building	EoL
Soil and stones [a]	37040.85	-	37040.85	-	37040.85	-	228160.00	-
Gravel and rocks [a]	384.77	-	442.44	-	385.00	-	3077.93	-
Iron and steel [c]	580.81	13041.00	393.80	13586.31	519.83	11520.97	533.94	11731.15
Concrete	3,897.65	366033.00	6088.79	360046.82	3678.30	291081.91	1135.53	358900.83
Wood	635.97	-	1259.74	13.23	627.99	-	214.78	-
Paper and cardboard	161.99	-	145.24	4.07	159.79	-	106.41	-
Plastic	15.72	4.50	97.26	4.45	15.72	4.43	41.68	4.47
Materials from plaster	-	2,663.88	-	-	-	2663.88	-	-
Ceramic materials [a]	4923.32	31089.96	-	-	4923.32	31089.96	-	-
Sand and clay waste	-	-	15.70	-	-	-	-	-
Insulation materials [b]	-	-	-	-	-	-	94.22	1187.64

[a] Transport by truck of the materials coming from the excavation of any type of land to a specific landfill, construction and demolition waste treatment facility outside the worksite or waste recovery or disposal center, located at a maximum distance of 20 km.

[b] EPS is computed for formwork purposes for the execution of the structure in the ELE alternative, not for thermal insulation needs.

[c] Steel can always be recovered at a rate of up to 89% thanks to its magnetic properties.

4. Multi-Criteria Decision-Making process

The final step for a holistic assessment is to aggregate the results of the impact assessment of each of the three dimensions of sustainability into a single index so that the results are comparable. The conversion of the obtained results for the economical, the environmental and the social dimension as a whole is made using Multi-Criteria Decision-Making techniques. Here, five of the most widely used classical MCDM methods in civil engineering and construction according to the literature (Jato-Espino et al., 2014; Zavadskas et al., 2016a) are applied to obtain the most sustainable solutions. Then, a sustainability overall index is proposed that considers the results from each of the methods mentioned above. Among the wide set of available methods and extensions, the study focuses on multi-attribute decision making methods (MADM) as they are oriented to solve discrete problems. They have been selected among the most representative groups of the classification proposed by Hajkwociz and Collins (2007) and De Brito and Evers (2016). In particular, SAW and COPRAS (scoring methods), TOPSIS and VIKOR (distance-based methods) and MIVES (utility/value methods) are used. AHP (pairwise comparison methods) is one of the most widely used methods in decision making, being used here to obtain the weights of the different criteria and to evaluate the subjective criteria by comparing the alternatives with each other. The so-called outranking methods (e.g., PROMETHEE and ELECTRE) have not been included because the results would not be useful in this evaluation by obtaining a dominance ranking among the proposed solutions instead of an index as in the other techniques.

4.1. SAW

The Simple Additive Weighting (SAW) method is a direct scoring technique that consists of the direct summation of the standardized results for each criterion (c_{ki}') multiplied by its relative weight (w_k). The obtained indices S_i for each alternative are then compared in order to determine the best solution.

$$S_i = \sum_{k=1}^{m} w_k \cdot c_{ki}' \tag{2}$$

Depending on the problem, the best solution can be the one that maximizes or minimizes the resulting index. If the desired solution is the one that maximizes the index, the standardization of each criterion is made by dividing the actual values of each criterion (c_{ki}) by the maximum value for that criterion considering every alternative ($max_k\{c_{ki}\}$). If the desired solution is the one that minimizes the obtained index, standardization of criteria is done by dividing by the minimum value for this criterion ($min_k\{c_{ki}\}$) between all alternatives.

4.2. COPRAS

The Complex Proportional Assessment (COPRAS) method can be included under the scoring MCDM methods. It allows obtaining the best performing solution by considering the relative significance of each alternative as a function of the positive and negative (beneficial and hindering) attributes expressed in a previous step. This method allows simultaneous consideration of the maximization and minimization criteria, being the index for each alternative formulated as:

$$S_i = S_{i+} + S_{i-} \tag{3}$$

Here, S_{i+} accounts only for those criteria c_{ki+} that need to be maximized, and is formulated as the SAW method:

$$S_{i+} = \sum_{k=1}^{m} w_{k+} \cdot c_{ki+}' \tag{4}$$

The term S_{i+} is the formulated equally to S_{i+} but taking into consideration those criteria c_{ki-} that need to be minimized.

$$S_{i-} = \frac{\sum_{k=1}^{m} w_{k-} \cdot c_{ki-}'}{w_{k-} \cdot c_{ki-}' \cdot \sum_{j=1}^{n} \frac{1}{w_{k-} \cdot c_{ki-}'}} \tag{5}$$

The resulting index is consequently proportional to the maximizing criteria and inversely proportional to the minimizing criteria.

4.3. TOPSIS

The best performing alternative according to the distance-based Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is the nearest to the positive ideal solution (PIS), and the furthest from the negative ideal solution (NIS). The first step consists in normalizing the scores c_{ij} of each alternative i and for each criterion j as:

$$c_{ij}' = c_{ij} \Big/ \sqrt{\sum_{j=1}^{m} c_{ij}^2} \tag{6}$$

Where m is the number of criteria involved in the decision problem. The standardized scores c'_{ij} are then multiplied by the corresponding criteria weights w_i to obtain the standardized, weighted score v_{ij}. The distance to the positive ideal solution (D_i^+) and to the negative ideal solution (D_i^-) is then obtained as:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \tag{7}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \quad (8)$$

Where v_j^+ and v_j^- are, respectively, the best and worst score for the criterion *j* considering every alternative *i*. Finally, an index C_i^* is defined that represents the final performance of each alternative *i* considering its relative position to the positive and negative ideal solutions:

$$C_i^* = D_i^- / (D_i^+ + D_i^-) \quad (9)$$

4.4. VIKOR

This MCDM distance-based technique considers, similarly to TOPSIS, the relative position of each alternative in relation to the positive and negative ideal solutions for each criterion. The score c_{ij}' for each alternative *j* and each criterion *i* is standardized as:

$$c_{ij}' = \left(c_i^+ - c_{ij}\right) / \left(c_i^+ - c_i^-\right) \quad (10)$$

The final score Q_j of each alternative *j* is then obtained as a function of two indices S_j and R_j based on the Manhattan and the Chebyshev distance, respectively, of alternative *j* to the ideal solution:

$$S_j = \sum_{i=1}^{m} w_i \left(c_i^+ - c_{ij}\right) / \left(c_i^+ - c_i^-\right) \quad (11)$$

$$R_j = max\left[w_i\left(c_i^+ - c_{ij}\right) / \left(c_i^+ - c_i^-\right)\right] \quad (12)$$

The score Q_j of each alternative *j* is then defined as:

$$Q_j = v \cdot \frac{\left(S_j - S^+\right)}{S^- - S^+} + (1 - v) \cdot \frac{\left(R_j - R^+\right)}{R^- - R^+} \quad (13)$$

Where v is a parameter defined between 0 and 1 that considers the relevance of each index S and R in determining the final score.

4.5. MIVES

This technique is a utility-based MCDM technique that determines the performance of each alternative *j* with respect to each criterion *i* considering a degree of satisfaction assuming particular value functions for each criterion. The value functions V_i are defined as:

$$V_i = K_i \cdot \left[1 - e^{-m_i}\left(\left|x_{ij} - x_{i,min}\right| / n_i\right)^{P_i}\right] \quad (14)$$

Where x_{ij} is the score of alternative *j* with respect to criterion *i*, P_i is the shape factor assigned to criterion *i* that determines whether the value function is concave ($P_i < 1$), convex ($P_i > 1$) or linear ($P_i = 1$), m_i is the ordinate value for point n_i, and K_i is a standardization factor defined as:

$$K_i = 1 / \left[1 - e^{-m_i}\left(\left|x_{i,max} - x_{i,min}\right| / n_i\right)^{P_i}\right] \quad (15)$$

4.6. Sustainability overall index

There is no consensus on which MCDM technique provides the most accurate results. Consequently, literature reviews on the application of MCDM methods always bring to light a wide variety of methods being used. Here, and to complement the latter discussion of the obtained results, an overall index is presented to measure the sustainability performance of each alternative along its life cycle. This Global Structural Sustainability Index (GSSI) is constructed as a weighted aggregation of the scores obtained for each alternative attending to the abovementioned five MCDM techniques.

The relative importance assigned to each method shall take into consideration the advantages and limitations of its application. The weights are assumed to be proportional to its frequency of use to solve civil engineering related MCDM design problems, as this frequency of use is considered to be representative of the advantages and drawbacks of each method. Those have been obtained from the literature review conducted by Zavadskas et al. (2016a) on the use of MCDM techniques in the field of Construction Building Technologies, which is representative of the decision problem to be solved in the present paper. According to this literature review the assumed weights Φ_{MCDM} (see Table 14) are 52% for TOPSIS, 26% for COPRAS, 9% for VIKOR and MIVES, and 4% for SAW.

5. Results and interpretation

5.1. Life cycle cost assessment results

This section analyzes the life cycle economic impacts of each design option on the 384.69 m^2 of built area of the house and the impact per m^2 of structure. Table 8 presents the responses for each economic indicator (I1 to I19) expressed in €/m^2 and evaluated in the life cycle phases described as criteria (C1 to C3) and hierarchized through the sub-criteria (G1 to G8).

Table 8.
Responses for alternatives according to the economic indicators evaluated.

Dimension	Criteria	Sub-criteria	Alt.	REF	YTN	PRE	ELE
			Ind.	x_{ij}	x_{ij}	x_{ij}	x_{ij}
Economy	C1	G1	I1	13.36	29.43	13.53	41.15
			I2	5.72	12.61	5.80	13.72
			I3	8.93	10.93	8.22	8.56
		G2	I4	203.00	248.45	186.91	194.58
		G3	I5	0.26	0.26	0.26	1.76
			I6	0.12	0.12	0.12	0.83
			I7	0.11	0.08	0.10	0.03
			I8	0.16	0.14	0.15	0.05
	C2	G4	I9	0.12	0.87	0.12	0.00
			I10	5.98	3.91	5.98	5.98
			I11	3.25	1.46	3.25	3.25
			I12	0.85	4.32	0.85	0.85
			I13	0.89	6.57	0.89	0.00
		G5	I14	7.16[a]	4.77[a]	6.32[a]	7.65[a]
	C3	G6	I15	32.35[b]	28.60[b]	29.73[b]	28.02[b]
		G7	I16	4.02[b]	3.57[b]	3.29[b]	3.58[b]
			I17	1.74[b]	1.71[b]	1.39[b]	1.71[b]
		G8	I18	1.59[b]	1.44[b]	1.30[b]	1.43[b]
			I19	1.95[b]	1.72[b]	1.60[b]	1.73[b]

[a] Discount rate of 2% considering maintenance during the first 10 years.
[b] Discount rate of 2% considering a 50-year service life.

Figure 3 shows the results of the LCCA through the cumulative present cost of value (CPV) for entire life span. On average, the design, materialization and construction waste management phase contributed to more than 80% of the total cost over the entire life of the building. The results indicate that the design with the greatest economic impact is the prefabricated alternative (YTN). Compared to the conventional reference design (REF), it has been more expensive by 30.4% and 20.1% in the construction and maintenance stages, respectively. In the EoL stage, the three MMCs have shown similar performance, between 11-13% better than REF. In contrast, the lightened alternative (PRE) has had the least impact, reducing the cost over the REF by 7% in construction, 5% in maintenance and 11% in EoL. In fact, the second lowest cost is represented by REF. The technological alternative (ELE) is the design with the third lowest economic impact, below REF, with 12.5% more cost in the construction stage and 3% less in the prevention and maintenance stage.

The environmental impacts and economic costs of materials are not proportional, as can be seen in Section 5.2. This issue was already reported by García-Segura et al. (2016) detecting different studies with optimal cost solutions and satisfactory environmental results, while others experienced cost increases when CO_2 emissions decreased. In conclusion, PRE with 269.83 €/m^2 represents the lowest cost option, while YTN with 360.98 €/m^2 represents the worst economic alternative. The main reason for the lower cost is the structural efficiency of the PRE slab. Its 18 cm cross-section is optimized by lightening it with pressurized plastic discs to achieve an inertia equivalent to that of a 12 cm solid concrete slab. This represents half the material for the same structural stresses compared to the REF option, whose slabs have an average thickness of 24 cm.

In terms of use stage, the ten-year maintenance cost has been evaluated to compare the degree of economic viability of the building during the first ten years after its construction. A building with a low construction budget implying a high maintenance cost could far exceed the capital invested in another building with a higher construction cost but a low maintenance cost. Even its maintenance could become economically unsustainable.

In this case study, the PRE and ELE alternatives reduce the service life costs by about 5% compared to the baseline REF option. As all three designs use mainly reinforced concrete as material, the preventive treatments against carbonation and waterproofing are very similar. In particular, in ELE, the maintenance cost represents only 6.8% of the construction costs, compared to 8.0% in PRE. However, the YTN prefabricated alternative, despite having the lowest maintenance at ten years, the total costs in the use phase are the highest, with an increase of 20% compared to the reference design. This is justified by the difference due to the preventive waterproofing treatments of the Ytong blocks, as well as the passive fire protection and the anti-rust painting of the metal structure required for the industrialized assembly of the plates.

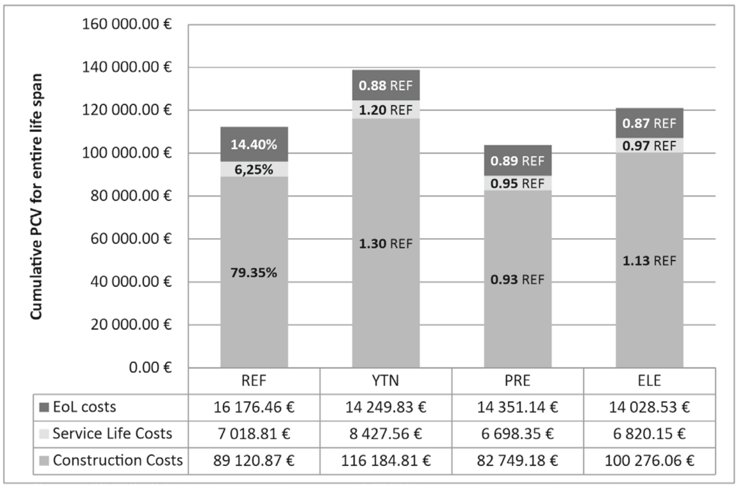


Fig. 3. Life cycle economic impacts.

5.2. Environmental life cycle assessment results

In the analysis of environmental indicators, ReCiPe combines two approaches to show the results of environmental impact. Table 9 presents the responses for each impact indicator (I20 to I25) expressed in points and evaluated in the life cycle phases hierarchized through the sub-criteria (G9 and G10).

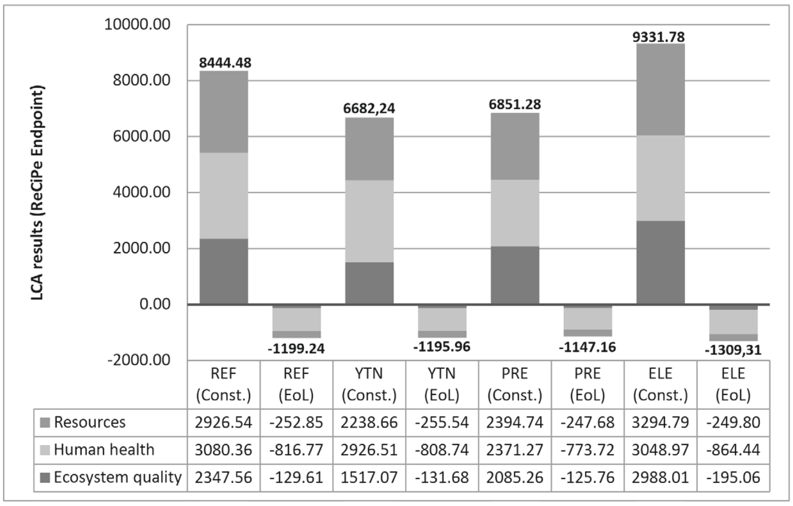
Table 9.
Responses for alternatives according to the environmental indicators evaluated.

Dimension	Criteria	Sub-criteria	Alt.	REF	YTN	PRE	ELE
			Ind.	x_{ij}	x_{ij}	x_{ij}	x_{ij}
Environment	C4	G9	I20	2347.56	1517.07	2085.26	2988.01
			I21	3080.36	2926.51	2371.27	3048.97
			I22	2926.54	2238.66	2394.74	3294.79
	C5	G10	I23	−129.61	−131.68	−125.76	−195.06
			I24	−816.77	−808.74	−773.72	−864.44
			I25	−252.85	−255.54	−247.68	−249.80

Figure 4 shows the scores of the three endpoint impact categories considered in this assessment for both the construction and maintenance phases (positive impact results) and the EoL phase (negative impact results). The negative values represent the positive effects on the environment of recycling waste materials. The graph also includes the overall impact value by stage for each alternative.

In the construction phase the greatest life cycle impacts can be observed. YTN design option obtains the best environmental performance followed closely by the PRE alternative, resulting in environmental impacts ranging from 79.13% to 81.13% with respect to REF. This is explained because the cellular concrete used in YTN is a 100% mineral material that requires only 1 m^3 of raw material (sand, lime, cement, water) to manufacture 5 m^3 of final product. In addition, energy consumption in manufacturing is low because the autoclaving process does not require high temperatures. In the case of the PRE, the good environmental performance is mainly due to the equivalence of the concrete cross-section, since it only requires the production of 50% of the material for the same structural stresses compared to REF. In contrast, the worst environmental results in construction are those of the REF and the ELE options. The latter reduces by 30% the equivalent mass of the conventional concrete design; however, it requires several concreting phases to execute two concrete slabs for each structural element. This design requires a thickness of EPS of 18 cm in floor slabs in standard floors and 27 cm in the solarium as lost formwork. EPS has a primary energy content of around 100 MJ/Kg, which is very high compared to 7 MJ/Kg in cement or 35 MJ/Kg in commercial steel (Cepeda and Mardaras, 2004). This means that in floor slabs alone the ELE causes three times the energy consumption to obtain EPS than that required for thermal needs by the reference solution. In addition, the enclosures are executed with the same double concrete wall system, which means 40.54% more concrete in enclosures than the REF. In fact, among the most detrimental to the atmosphere is the grinding of clinker, the main component of Portland cement. This result demonstrates that for a low environmental impact in a material or construction system it is not enough with its energy efficiency once installed, if it is costly to manufacture and not efficient in its production at all.

In the EoL phase, the results of the four alternatives are more balanced, with the PRE design having the lowest environmental impact. This option makes the difference because it requires 20% less concrete than the conventional concrete option. In addition, the lightweight slabs contain 1891 pressurized polyethylene discs that occupy a volume of 9.31 m^3. Both savings mean a total concrete volume of 44.27 m^3 less than that used in REF, which translates into the same waste reduction. For their part, the lightening elements come from 100% recycled plastic and are 100% recoverable after demolition.



	REF (Const.)	REF (EoL)	YTN (Const.)	YTN (EoL)	PRE (Const.)	PRE (EoL)	ELE (Const.)	ELE (EoL)
■ Resources	2926.54	-252.85	2238.66	-255.54	2394.74	-247.68	3294.79	-249.80
■ Human health	3080.36	-816.77	2926.51	-808.74	2371.27	-773.72	3048.97	-864.44
■ Ecosystem quality	2347.56	-129.61	1517.07	-131.68	2085.26	-125.76	2988.01	-195.06

Fig. 4. Environmental performance score after the life cycle assessment.

5.3. Social life cycle assessment results

The SLCA based on the methodology presented in Section 3.2.3 results in ELE as the socially optimal design alternative for the case study analyzed, which is followed by PRE, YTN and finally the baseline option REF. Value functions have been used in the 13 social indicators (I26 to I38) to normalize the units of the different attributes. Otherwise, at the higher hierarchical level, scores between sub-criteria with heterogeneous units could not be summed. Eq. (14) expresses the utility function or value used to evaluate satisfaction with respect to each social indicator. Table 10 summarizes the parameterization of all the value functions used. The variable K_i, defined in Eq. (15), keeps the interval of the function with unit value between 0 and 1 according to its five parameters. More detailed information on the construction of value functions with the MIVES method can be found in the studies by Sánchez-Garrido and Yepes, (2020).

Table 10.
Calculator based on value functions for social indicators.

Ind.	Parameters of the value function						
	Best	**Graphs**	P_i	K_i	C_i	X_{min}	X_{max}
I26	Max.	Linear ↑	1	0.01	871	739	1763
I27	Max.	Linear ↑	1	0.01	1148	1046	2072
I28	Max.	Linear ↑	1	0.01	10	0	100
I29	Min.	S-Shaped ↓	6	0.2	50	0	100

I30	Min.	Concave ↓	0.6	0.9	0.23	0.19	0.26
I31	Min.	Concave ↓	0.6	0.9	0.28	0.22	0.30
I32	Max.	Convex ↑	2	0.1	47	33	51
I33	Min.	S-Shaped ↓	3	0.2	50	0	100
I34	Min.	S-Shaped ↓	3	0.2	50	0	100
I35	Max	Convex ↑	4	0.1	1.4	1	1.50
I36	Max	Convex ↑	4	0.1	1.4	1	1.50
I37	Max.	Linear ↑	1	0.01	10	0	100
I38	Max.	Linear ↑	1	0.01	1.9	0	10

Table 11 shows the detailed results of the responses for each design option transformed into a common unit (value) for the different social indicators that make up each stakeholder group (local community, consumers or users, workers and society). These stakeholder groups are based on a hotspot analysis according to the Guidelines for Social Life Cycle Assessment of Products (UNEP/SETAC, 2013) which integrates the social context of the location and production sites involved in the product system under consideration. The construction and EoL phases are considered to affect only three main stakeholders: local economies, workers and society, subcategories of which are involved in the production, materialization and demolition processes. The use and maintenance phase incorporates the consumer as a fourth stakeholder. Impact values closer to 1 indicate higher satisfaction of the stakeholder group considered, while values closer to 0 tend to minimal satisfaction.

Table 11.
Responses for alternatives according to the social indicators evaluated.

Dimension	Criteria	Sub-criteria	Alt.	REF		YTN		PRE		ELE	
			Ind.	x_{ij}	V_i [a]	x_{ij}	V_i [a]	x_{ij}	V_i [a]	x_{ij}	V_i [a]
Society	C6	G11	I26	1489.55	0.73	1056.11	0.31	1763.75	1	1162.65	0.41
			I27	1757.78	0.69	2072.43	1	1660.51	0.60	1494.37	0.44
		G12	I28	40.00	0.41	50.00	0.51	30.00	0.31	60.00	0.61
	C7	G13	I29	39.77	0.46	29.01	0.81	32.55	0.70	33.48	0.67
		G14	I30	0.25	0.36	0.24	0.53	0.22	0.71	0.12	1
			I31	0.29	0.33	0.26	0.71	0.29	0.33	0.22	1
			I32	45.00	0.45	38.00	0.08	45.00	0.45	41.00	0.20
	C8	G15	I33	31.21	0.51	44.01	0.31	26.36	0.59	39.98	0.37
			I34	26.44	0.59	22.43	0.66	27.99	0.56	31.10	0.51
		G16	I35	1.49	0.90	1.48	0.85	1.50	1	1.48	0.84
			I36	1.44	0.63	1.40	0.42	1.45	0.64	1.45	0.64
	C9	G17	I37	40.00	0.41	25.00	0.26	50.00	0.51	100	1
		G18	I38	2.13	0.22	7.75	0.78	5.75	0.58	5.13	0.52

[a] Standardization of indicator values with different units, according to the MIVES method, obtained from Table 10.

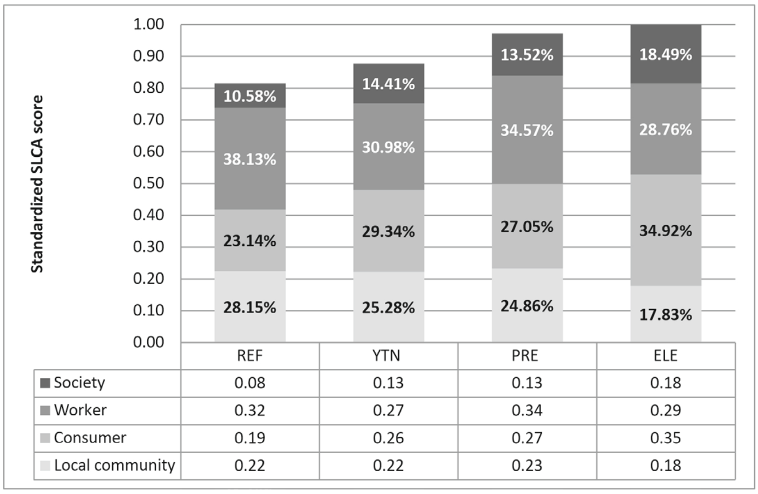
In the local community group, PRE obtained the highest local employment generation for the entire life span, with 3424 machinery and labor hours between the construction and EoL stages. On the other hand, it obtained the lowest priority with respect to the availability of materials and equipment in favor of the ELE alternative. This is because the PRE design requires a relevant volume of lightening discs or spheres that are difficult to find among local suppliers.

In the consumer or user group, YTN has the lowest probability of developing pathological processes which is typical of industrialized and prefabricated construction. The "off site" part of the construction prevents materials from being left out in the open, better controls manufacturing tolerances and reduces errors, resulting in greater safety during construction and use of the building. However, the ELE system is by far the best option in terms of thermal comfort during service life. This system requires a lost formwork of two to three times the thickness of EPS that the others require for thermal insulation reasons. However, closed cell thermal insulation such as EPS or polyurethane (PUR) are not good sound absorbers. Therefore, the best acoustic comfort between the party walls of the semi-detached house is shared by REF and PRE. Both have mineral wool (MW) thermal insulation between two massive brick walls.

In the worker group, PRE reflects the best occupational health and safety performance with the lowest probability of developing accidents in the construction stage. In the demolition phase, the lowest probability is for YTN. In the subcategory measuring the quality of the local salary, the preferred alternative in the short term is PRE with a 50% increase over the minimum wage in the short term (construction). In the long term (demolition) it shares with ELE a 45% improvement.

Finally, in the society group, ELE obtained the best score in terms of modifiability and flexibility. The technical complexity to the project is exactly the same, so the adaptability of the system to possible alterations or reforms is optimized at minimum cost. In contrast, the lowest priority is given to YTN. The most immediate disadvantage of industrialized systems for a developer is the high cost in some countries, as is the case in Spain. But there are other barriers such as the absence of existing regulations, lack of skilled labor, shortage of supplies and logistics centers that lead to cost overruns in transportation. All of this means that any small variation in the initial design can substantially alter the planned production. It is also not easy to consider renovations in such a house during the use stage, since it is a custom-made product that would also require the intervention of specialized labor. In contrast, YTN scores highest on the Public Commitment to Sustainability Issues sub-criterion. Reintegrability >80% of surplus materials, reduced assembly times, material savings or the fact of having certifications such as Environmental Product Declarations (EPD) in accordance with ISO 14025, are issues that demonstrate this preference.

Figure 5 summarizes the social performance scores according to the life cycle assessment of each design. It is observed that the alternatives (PRE and REF) that generate higher economic flows in the local community could be more beneficial for workers by creating more working hours. However, these same designs are at a disadvantage compared to the options (ELE and YTN) that benefit users or society. Precisely in these two categories, ELE stands out with 38% and 29% more satisfaction than the second in the ranking, consolidating itself as the most desirable alternative from a social point of view.



	REF	YTN	PRE	ELE
■ Society	0.08	0.13	0.13	0.18
■ Worker	0.32	0.27	0.34	0.29
■ Consumer	0.19	0.26	0.27	0.35
■ Local community	0.22	0.22	0.23	0.18

Fig. 5. Social life cycle assessment results.

5.4 Group AHP results

This section shows the weights resulting from the evaluation of the criteria performed by a group of experts that takes into account the mathematical theory called Analytical Hierarchical Process (AHP). According to some authors (Daim et al., 2012; Torres-Machi et al., 2015) at least six experts are necessary to stabilize the AHP matrix with credible and reliable results. However, Kendall (1970) previously stated that at least seven experts should be involved in group decisions when ranking criteria. In particular, this study has had a seminar in which seven experts were selected, all of them active professionals with experience between 7 and 33 years in civil engineering, architecture or construction. To optimize the contribution to the decision making of each expert, their intervention is reduced to direct pairwise comparisons between the nine criteria (C1 to C9) defined in Tables 2 to 4, to which values are assigned according to Saaty's fundamental scale. In the square decision matrix A_{DMk}, each element a_{ij} corresponds to the judgment made by each decision-maker (DM_k) when comparing the importance of criterion i with respect to criterion j. It is necessary to review the process by adjusting, if necessary, the assigned values until the consistency of the comparison matrix is acceptable, i.e. CR < 0.10. The weights are obtained by means of AHP from the ADMk comparison matrices. To determine the relevance that each expert has in the group decision, each participant has been characterized in terms of his/her competence in assessing the decision-making problem. The resulting competence of expert i results in a coefficient that can vary between 0 and 1, and is defined as:

$$\delta_i = \left(\frac{PE_i}{max\{PE_k\}} + \frac{ES_i}{max\{ES_k\}} + \frac{AD_i}{max\{AD_k\}} + \sum_{m=1}^{n} Kc_{m,i}/n \right) /9 \tag{16}$$

Where PE_i stands for the years of professional practice of expert i; max$\{PE_k\}$ is the maximum years of experience among all experts involved in the decision-making process; ES_i stands for the years of experience in the field of sustainable design; max$\{ES_k\}$ is the maximum of this parameter among all experts; AD_i characterizes the academic degree of the expert, where

1 stands for a bachelor degree, 2 for a master degree, and 3 for a PhD. At last, parameters $Kc_{m,i}$ represent the expert's knowledge in different fields related to the decision-making problem. Here, n = 5 fields have been chosen, representing his/her expertise in construction engineering, structural design, economic assessments, environmental issues and social analysis. Table 12 shows the profiles with the competencies and fields of knowledge evaluated for each DM$_k$, which translates into the credibility index δ_{DMk} representing the relevance or weight of each expert in the AHP-G.

Table 12
Relevance among the expert group.

Characterization of the *k*-Decision Makers	Attribute	DM$_1$	DM$_2$	DM$_3$	DM$_4$	DM$_5$	DM$_6$	DM$_7$
Expert's Competences								
Years of professional activity	PA$_k$	19	7	33	8	23	21	15
Years sustainability experience	SE$_k$	2	5	11	5	0	0	0
Advanced Degree (BDs, MSc, PhD)	AD$_k$	2	3	3	3	1	1	2
Knowledge in field								
Construction Engineering	K$_{C1}$	4	4	4	4	4	4	4
Structural Design	K$_{C2}$	5	5	4	5	2	2	5
Economic Issues	K$_{C3}$	4	4	4	4	5	5	4
Environmental issues	K$_{C4}$	2	3	4	4	2	1	2
Social Issues	K$_{C5}$	3	3	3	2	3	2	3
Other merits	K$_{C6}$	4	4	5	4	4	3	4
Expert's credibility	$\boldsymbol{\delta}$ **DMk**	**0.647**	**0.696**	**0.867**	**0.700**	**0.559**	**0.486**	**0.613**

With the weights δ_{ij} for each criterion i assigned by each expert j as well as their relevance φ_j, the final weights of the AHP group for each of the 9 criteria are obtained by means of Eq. (17).

$$\boldsymbol{\delta_i = \frac{\sum_j \delta_{ij} \cdot \varphi_j}{\sum_j \delta_{ij}}} \tag{17}$$

The results of which are shown in Table 13. According to the results, the criteria are prioritized as follows: C7 Consumer (23.72%), C4 and C5 Environmental footprint (17.28% short term and 15.50% long term), C1 Construction cost (12.78%), C2 Service life cost (8.65%), C8 Worker (7.13%), C6 Local community (6.64%), C9 Society (5.81%) and, finally, C3 EoL cost (2.51%). All the experts believe that the most important criterion is social C7, except for one who gives it to economic C2. On the other hand, the entire group agrees that the least important criterion is C3. The next three most relevant weights are concentrated by 4 of the 7 experts in criteria C4, C5 and C1. For the rest, the criteria are scored unevenly depending on the preferences and particular knowledge of each expert.

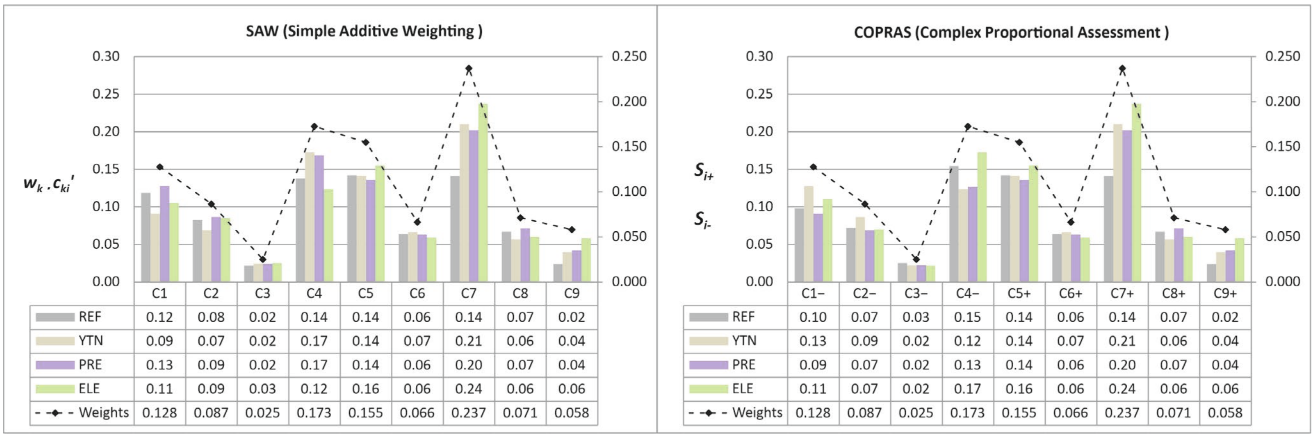
Table 13.
Criteria weighting through AHP-G.

Criterion	Weights resulting from the A_{DMK} pairwise comparison matrices for each expert							**AHP-G**
	DM$_1$	DM$_2$	DM$_3$	DM$_4$	DM$_5$	DM$_6$	DM$_7$	
(C1) Construction cost	0.127	0.068	0.130	0.157	0.225	0.118	0.079	**0.128**
(C2) Service life cost	0.044	0.130	0.053	0.081	0.018	0.039	0.236	**0.087**
(C3) End of life cost	0.018	0.020	0.026	0.024	0.017	0.028	0.043	**0.025**
(C4) Footprint (short term)	0.218	0.104	0.193	0.203	0.057	0.200	0.223	**0.173**
(C5) Footprint (long term)	0.184	0.174	0.161	0.180	0.046	0.245	0.095	**0.155**
(C6) Local community	0.059	0.108	0.068	0.086	0.032	0.052	0.046	**0.066**
(C7) Consumer	0.268	0.270	0.287	0.158	0.337	0.224	0.107	**0.237**
(C8) Worker	0.052	0.060	0.052	0.060	0.145	0.062	0.084	**0.071**
(C9) Society	0.029	0.066	0.031	0.050	0.123	0.032	0.089	**0.058**

5.5. Sustainability results

From the criteria weights obtained in Table 13, the five MCDM techniques that aggregate the 9 impact categories into a single sustainability score are used to compare from a holistic, three-dimensional point of view each of the design alternatives. The criteria to be assessed can be quantitative and qualitative, and within each group the units of measurement can be different. Therefore, the first step is to standardize the decision matrix. To compare the criteria, each method follows its own standardization process, described in Section 4. The matrix scores are transformed into standardized scores to which weights are associated. The summary of the results obtained with the different MCDM methods is shown in Table 14. In general, alternative PRE scores the best except for the case of VIKOR when $v \leq 0.2$. In no case alternative REF obtains the best score in any dimension of sustainability. The individual results with the standardized and weighted criteria scores for each method and for each alternative are illustrated in Figures 6 to 8.

SAW and COPRAS determine very similar final scores. This is because both are direct scoring methods that evaluate the alternatives in a very simple way by summing the standardized value of each weighted criterion. SAW is the older one, designed only to deal with the positive criteria to be maximized. COPRAS is an evolution of the previous one to be able to evaluate the criteria to be minimized, although SAW solves it with a simple standardization. SAW and COPRAS are the simplest and most suitable for applying problems where all variables are quantitative. However, the indicators that define sustainability in building structures have both quantitative and qualitative or semantic variables. Therefore, they are not considered to be the most appropriate, although they are very useful as a first approximation to the problem.



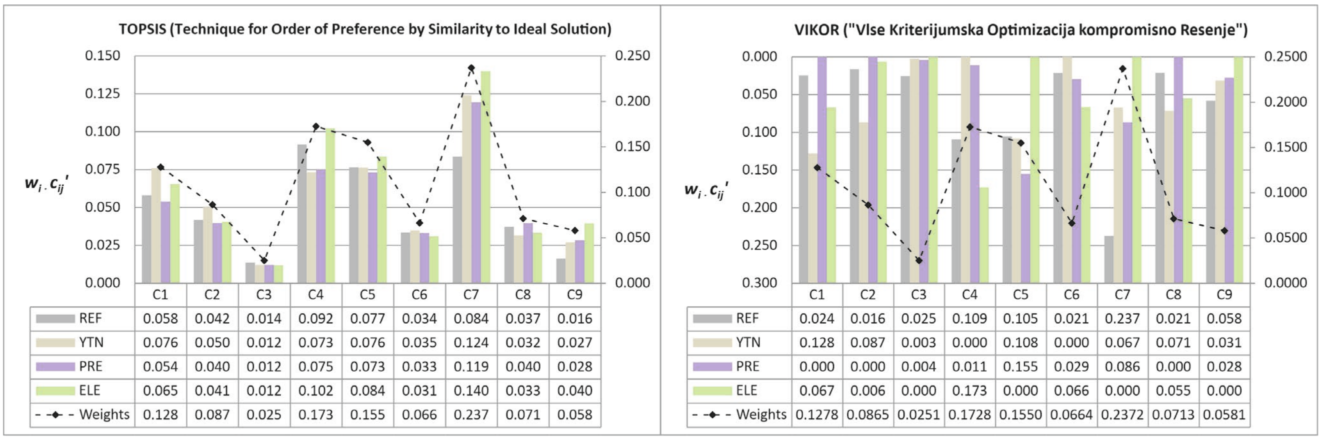
	C1	C2	C3	C4	C5	C6	C7	C8	C9
REF	0.12	0.08	0.02	0.14	0.14	0.06	0.14	0.07	0.02
YTN	0.09	0.07	0.02	0.17	0.14	0.07	0.21	0.06	0.04
PRE	0.13	0.09	0.02	0.17	0.14	0.06	0.20	0.07	0.04
ELE	0.11	0.09	0.03	0.12	0.16	0.06	0.24	0.06	0.06
Weights	0.128	0.087	0.025	0.173	0.155	0.066	0.237	0.071	0.058

	C1−	C2−	C3−	C4−	C5+	C6+	C7+	C8+	C9+
REF	0.10	0.07	0.03	0.15	0.14	0.06	0.14	0.07	0.02
YTN	0.13	0.09	0.02	0.12	0.14	0.07	0.21	0.06	0.04
PRE	0.09	0.07	0.02	0.13	0.14	0.06	0.20	0.07	0.04
ELE	0.11	0.07	0.02	0.17	0.16	0.06	0.24	0.06	0.06
Weights	0.128	0.087	0.025	0.173	0.155	0.066	0.237	0.071	0.058

Fig. 6. Sustainability assessment results: direct scoring methods (SAW and COPRAS).

The TOPSIS and VIKOR pair are distance-based methods trying to find the closest alternative to a hypothetical optimal point. In the case of TOPSIS, although distances to the PIS and NIS are considered, a vector standardization is performed at the end of the procedure. Therefore, a higher score is obtained for the best alternative. TOPSIS has been very useful in confirming that PRE is an ideal optimal solution, as the quadratic standardization metric favors the distancing from the ideal non-optimal solution. In contrast, VIKOR uses a linear standardization obtaining the result as a compromise solution that is as close to the SIP as possible. The results in Table 14 show that as the value of *v* increases, YTN loses importance in favor of PRE. This is due to the fact that the distance from Manhattan (S_j) benefits alternative PRE (S_1=0.62; S_2=0.49; S_3=0.31; S_4=0.37) which becomes preferred from $v \geq 0.3$. The infinite distance (R_j) benefits alternative YTN (R1=0.24; R2=0.13; R3=0.16; R4=0.17) and is preferred for v<0.3. The VIKOR technique is very useful to make a sensitivity study of the results by varying the strategic factor *v* as a function of the preference to its two metrics. In this paper, the Q_j values corresponding to each solution *j* are obtained as:

$$Q_j = \left(Q_{j1} + 2Q_{j5} + Q_{j9}\right)/4 \tag{18}$$



	C1	C2	C3	C4	C5	C6	C7	C8	C9
REF	0.058	0.042	0.014	0.092	0.077	0.034	0.084	0.037	0.016
YTN	0.076	0.050	0.012	0.073	0.076	0.035	0.124	0.032	0.027
PRE	0.054	0.040	0.012	0.075	0.073	0.033	0.119	0.040	0.028
ELE	0.065	0.041	0.012	0.102	0.084	0.031	0.140	0.033	0.040
Weights	0.128	0.087	0.025	0.173	0.155	0.066	0.237	0.071	0.058

	C1	C2	C3	C4	C5	C6	C7	C8	C9
REF	0.024	0.016	0.025	0.109	0.105	0.021	0.237	0.021	0.058
YTN	0.128	0.087	0.003	0.000	0.108	0.000	0.067	0.071	0.031
PRE	0.000	0.000	0.004	0.011	0.155	0.029	0.086	0.000	0.028
ELE	0.067	0.006	0.000	0.173	0.000	0.066	0.000	0.055	0.000
Weights	0.1278	0.0865	0.0251	0.1728	0.1550	0.0664	0.2372	0.0713	0.0581

Fig. 7. Sustainability assessment results: distance-based methods (TOPSIS and VIKOR).

MIVES has the advantage that it allows prioritization of criteria, which is very useful to include common criteria by grouping them under each dimension of sustainability to be analyzed separately. The results are very sensitive to the correct selection of the value function. This is explained by the subjective load introduced by each DM_k, especially when defining the points of maximum and minimum satisfaction. It is observed that PRE has the economic priority (0.200), YTN the best environmental performance (0.262) and ELE socially is the most favorable (0.261). However, the overall rating (0.668) selects PRE as the most sustainable, as it presents the criteria with the most balanced responses.

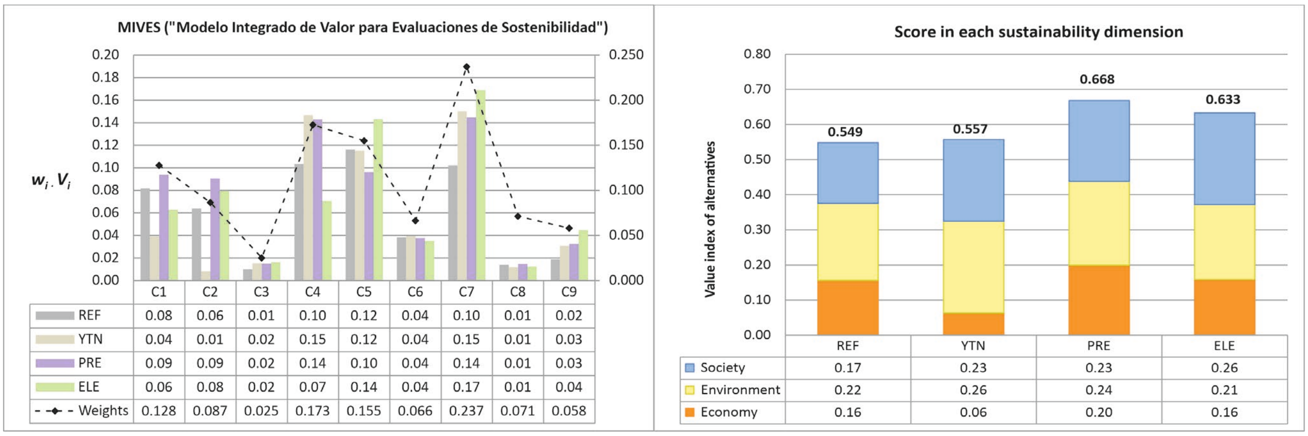


Fig. 8. Sustainability assessment results: utility/value methods (MIVES).

The Global Structural Sustainability Index for each alternative *j* is obtained according to Eq. (19) which, based on Zavadskas et al. (2016a), assigns a relative importance to the score obtained by each MCDM technique used.

$$GSSI_j = \sum \Phi_i \cdot S_{i,j} \qquad (19)$$

Where Φ_i is the weight corresponding to MCDM technique *i*, and $S_{i,j}$ is the score obtained by alternative *j* according to MCDM technique *j*. Table 14 shows PRE as the best alternative with the highest GSSI, followed by ELE, YTN and REF.

Table 14.
Comparison with the results of MCDM methods and best alternative.

MCDM	Summary score		Φ_{MADM} [c]	Alternative 1 "REF"	Alternative 2 "YTN"	Alternative 3 "PRE"	Alternative 4 "ELE"
SAW	Final score [a]		*0.04*	0.800 (D)	0.872 (C)	0.922 (A)	0.909 (B)
COPRAS	Final score [a]		*0.26*	0.784 (D)	0.850 (C)	0.905 (A)	0.892 (B)
TOPSIS	Final score [a]		*0.52*	0.266 (D)	0.606 (C)	0.674 (A)	0.665 (B)
VIKOR	Score [b]	v=0	-	1 (D)	0 (A)	0.249 (B)	0.411 (C)
		v=0.1	-	1 (D)	0.060 (A)	0.224 (B)	0.411 (C)
		v=0.2	-	1 (D)	0.119 (A)	0.199 (B)	0.411 (C)
		v=0.3	-	1 (D)	0.179 (B)	0.174 (A)	0.411 (C)
		v=0.4	-	1 (D)	0.239 (B)	0.150 (A)	0.411 (C)
		v=0.5	-	1 (D)	0.298 (B)	0.125 (A)	0.411 (C)
		v=0.6	-	1 (D)	0.358 (B)	0.100 (A)	0.411 (C)
		v=0.7	-	1 (D)	0.418 (C)	0.075 (A)	0.411 (B)
		v=0.8	-	1 (D)	0.477 (C)	0.050 (A)	0.411 (B)
		v=0.9	-	1 (D)	0.537 (C)	0.025 (A)	0.411 (B)
		v=1	-	1 (D)	0.597 (C)	0 (A)	0.411 (B)
	Eq. (18)	Q_j	-	1 (D)	0.298 (B)	0.125 (A)	0.411 (C)
		$1\text{-}Q_j$	*0.09*	0 (D)	0.702 (B)	0.875 (A)	0.589 (C)
MIVES	Economic rating [a]		-	0.156 (C)	0.063 (D)	0.200 (A)	0.158 (B)
	Environmental rating [a]		-	0.220 (C)	0.262 (A)	0.239 (B)	0.214 (D)
	Social rating [a]		-	0.173 (D)	0.232 (B)	0.230 (C)	0.261 (A)
	Final score [a]		*0.09*	0.549 (D)	0.557 (C)	0.668 (A)	0.633 (B)
GSSI	**Global Structural Sustainability Index**			**0.423 (D)**	**0.684 (C)**	**0.762 (A)**	**0.724 (B)**

[a] The highest score the best.
[b] The shorter the distance, the better.
[c] Relative importance of each MCDM technique.

Sustainability ranking			
1st.	2nd.	3rd.	4th.
(A)	(B)	(C)	(D)

5.6. Sensitivity analysis

Table 15 summarizes eight additional scenarios to analyze the sensitivity in the ranking of alternatives according to the preferences of each multi-criteria method. The scenarios that are proposed cover most of the possible combinations in ranges of variation significant enough to cause changes in the GSSI, with the following conditions. Scenario 1 assigns the same weight (20%) to all five methods. Scenarios 2 to 6 concentrate the highest possible percentage according to the preference of each MCDM group with the condition that the rest have at least 10%. Thus, Scoring methods alternately share 50−20% of weight between the SAW−COPRAS pairs; the same for Distance-based methods with TOPSIS−VIKOR; and finally Utility/value methods concentrate 60% with MIVES alone. Scenarios 6 and 7 combine indistinctly between the groups the weights with values distributed between 10-30%. The results of the sensitivity analysis are presented in Figure 9 with the GSSI scores obtained in the different scenarios for the four alternatives.

Table 15.
Sensitivity analysis on MCDMs weighting.

Methods		Original	Scenario1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Scoring	**SAW**	4%	20%	50%	20%	10%	10%	10%	20%	10%
	COPRAS	26%	20%	20%	50%	10%	10%	10%	10%	30%
Distance-based	**TOPSIS**	52%	20%	10%	10%	50%	20%	10%	10%	30%
	VIKOR	9%	20%	10%	10%	20%	50%	10%	30%	10%
Utility/value	**MIVES**	9%	20%	10%	10%	10%	10%	60%	30%	20%

The analysis shows that the evaluation results do not vary significantly with changes of less than 10% in the weighting factors originally assumed. It can be seen that the PRE alternative is preferable in all cases, increasing the margin with respect to the second in at least 5 of the scenarios or maintaining a similar equidistance to that of the original case study. For its part, the baseline design REF ranks last in the GSSI, although in scenarios 2 and 3 it achieves its best score, around 0.64. However, the rest of the alternatives also increase their value, so no position in the ranking is compromised. As for the second alternative, ELE, it is preferred in scenario 6 with a minimal advantage over the third YTN of no more than 5%. In scenarios 1, 2, 3, 4 and 8, the ELE and YTN designs only differ by 2-3% and even overlap with an index of 0.70 in scenario 7. Scenario 5 (20% TOPSIS−50% VIKOR) is the only case where the YTN alternative is considered more sustainable than ELE.

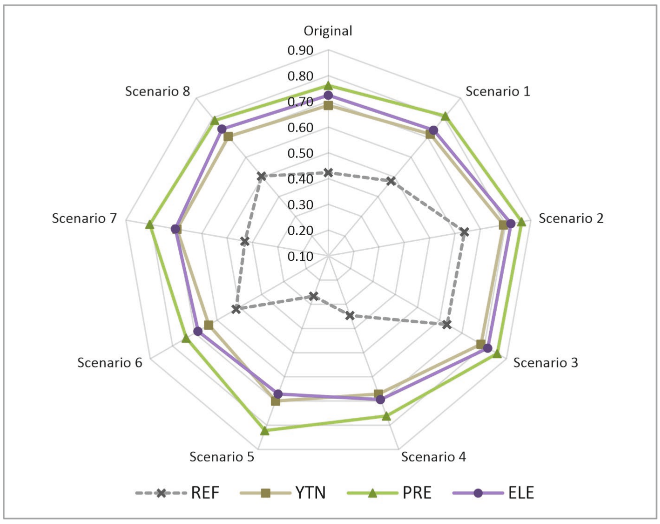


Fig. 9. Sensitivity of the GSSI results according to different scenarios.

Thus, the sensitivity analysis demonstrates that the choice of the multi-criteria method chosen to analyze sustainability influences the results of decision-making. The proposed method is robust, since in all scenarios the best alternative coincides with the original approach, resulting in the PRE design option being the most sustainable. As a second preferred alternative, the balance tips towards ELE or YTN depending on the weighting of each MCDM method used, depending on the dominance of the criterion and the degree of uncertainty in the semantic responses of certain indicators. In this case, the fact that they are solutions oriented from the beginning to the improvement of sustainability makes both designs obtain a very similar GSSI. The fluctuation in the choice of preference increases when the subjectivity of the decision maker intervenes in the method itself. This can be observed in VIKOR through the variable υ to determine the importance of each metric or in MIVES when introducing the parameters of the value functions at the decision maker's discretion. The result of the above occurs with scenario 5 (VIKOR preferred) the second most sustainable option is YTN while in scenario 6 (MIVES preferred) ELE obtains the greatest advantage over YTN.

6. Conclusions

This paper presents a comprehensive methodology for the assessment of sustainability performance among four different design options using concrete, which have been applied to the structure and envelope of a single-family row house in Spain. As alternatives to a traditional construction "REF" (solid slab and brick enclosure walls), three disparate options based on MMCs have been compared, namely: "YTN", (industrialized plates and prefabricated blocks of autoclaving aerated concrete manufactured); "PRE" (flat concrete slab lightened with pressurized hollow discs, columns and brick enclosure walls); and "ELE" (double-walled structural element made with sprayed reinforced concrete). From the same definition of functional unit and product system, the economic, environmental and social impacts of the life cycle of each design alternative are determined.

To assess the sustainability performance associated with the life cycle of each design, several MCDM tools have been used to integrate the different impact categories in the overall assessment. A comparative study is carried out by applying SAW, COPRAS, TOPSIS, VIKOR and MIVES techniques, as well as AHP for the weightings, and results have been discussed. Since there is no agreement among researchers on which MCDM model is the most suitable for solving all multifaceted problems, a GSSI index combining the five techniques used is proposed here. The GSSI index has been designed to overcome the singularities and differences between the different decision techniques and obtain a more consensual result. To determine the specific relevance of each criterion, a group AHP was applied, consisting of 7 experts who were characterized by weighting their importance through a credibility index. Although three different MMCs were designated as optimal according to the individual criteria (PRE: economic, YTN: environmental and ELE: social), the MCDM result indicates that PRE is the most sustainable. In addition, the result of this research indicates that the REF alternative is the worst option in all individual criteria and, consequently, obtains the lowest priority in the characterization of sustainability through the multi-criteria evaluation.

This study has allowed adjusting a set of 38 specific indicators to characterize the sustainability of the thermal envelope and the structure of a row house, measured through quantitative and qualitative attributes that consider uncertainty and risk factors. Besides the economic and environmental issues, this methodology fills a relevant research gap by including the effect of social impacts on the decision-making process of a building structure. A set of criteria based on the stakeholder approach suggested by UNEP/SETAC (2009) is selected for life cycle analysis by providing the mathematical construction of social indicators based on this methodology. In addition, the model can be adapted to other building typologies and locations in countries with similar climatic conditions, enhancing the practical application of this tool. Multiple-criteria decision analysis always follows the same steps, although the process for carrying it out is what differentiates one methodology from another. All tools have their advantages and disadvantages, with no clear preference agreed upon by the authors. And although their choice remains subjective depending on the problem, they are versatile methods capable of admitting modifications or adjustments aimed at achieving the objectives desired by the DM. From the analysis of the criteria presented with any of the methods used, it is concluded that only the simultaneous consideration of the three fields of sustainability applied to the structure and envelope of a building will lead to adequate designs.

Sustainability assessment is a complex and wide-ranging topic, so a single study is not sufficient to answer all the issues. Further work needs to be developed and contrasted to define and refine robust methodologies to assess the sustainable design of building structures. Future lines of research will seek to delve deeper into two aspects. Regarding the influence of experts, it could be investigated which criteria have a higher subjectivity among those that characterize sustainability. Regarding the evaluation of sustainability, this study is limited to the scope of single-family dwellings. It could be extended to evaluate projects with less conventional and more ambitious building structures by optimizing the ratio of spans, thickness and loads (hotels, offices or shopping centers). These lines of research would be aimed at finding the most efficient and sustainable concrete structural solution possible.

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