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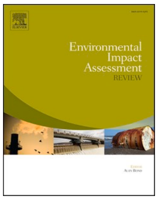

Neutrosophic multi-criteria evaluation of sustainable alternatives for the structure of single-family homes

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ABSTRACT

This paper proposes a methodology for the assessment of the sustainability among three different structural design alternatives for a single-family home. The response associated with each alternative has been measured using 43 indicators considering all stages of the life cycle. A decision-making model is carried out on the basis of a neutrosophic group analytical hierarchy process (NAHP-G) capturing the maximum information in terms of credibility, inconsistency and indetermination. The 9 criteria on which an expert group intervenes are finally evaluated using VIKOR. The results show that non-probabilistic uncertainties influence the weights obtained, with maximum deviations in the criteria between 11.91% and 4.95%, if compared to conventional AHP. From the methodology it is obtained that the technological alternative with non-conventional concrete performs best in sustainable terms. Although the industrialized option has less environmental impact, only the simultaneous consideration of the economic, environmental and social pillars in a project will lead to appropriate sustainable designs.

1. Introduction

Nowadays, the construction industry is constantly changing and evolving. With housing as a basic possession that affects society and people's well-being, residential architecture continues to be the most demanded building typology. Therefore, it is necessary to address the future of the real estate and urban planning sector focused on fulfilling the commitments established for the year 2050 (World Green Building Council, 2019). The methods promoted traditionally by construction companies tend to focus on the optimization of economic aspects, although currently the minimization of costs is not sufficient to satisfy the growing environmental and social demands of the 21st century, which claim for a paradigm shift towards more sustainable action.

In fact, in recent times there has been increasing concern about environmental emissions from the construction sector, considered to be one of the main environmental stressors existing to date. In particular, a major part of these emissions results from the extraction of construction materials. In residential construction, it is estimated that 70% of greenhouse gas emissions are the result of the extraction and manufacture of cement and steel (UAM Observatory - Via Célere for Environmental Sustainability of Residential Building, 2020). For this reason, in construction there has been a tendency to economize by optimizing the consumption of materials (Boscardin et al., 2019), reducing the embodied energy (Martí et al., 2016) and controlling CO_2 emissions (García-Segura et al., 2015). The greatest impacts are precisely on those chapters of the budget that use cement, such as the foundations and the structure itself. However, since the reduction of emissions is not necessarily proportional to the reduction of costs (Yepes et al., 2015), environmental criteria must be explicitly integrated into the evaluation of sustainability (Zhong and Wu, 2015). Economic and environmental design criteria have also been applied to the study of chloride corrosion in reinforced concrete bridge structures (Navarro et al., 2018a), in steel-concrete composite beams (Tormen et al., 2020) or to heuristic optimization techniques in design of pedestrian bridges (Yepes et al., 2019).

The assessment of building structures is essential to ensure a sustainable future, as they are responsible for a large amount of environmental damage and economic costs, but are also fundamental to the social welfare and economic development of cities. The literature review shows that, for years, social aspects have been neglected in favour of the economy and the environment (Liu et al., 2020; Martínez-Muñoz et al., 2020). Several authors consider that the social dimension as a basic pillar influences social sustainability, both in the short term through the

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fair wage potential (Vitorio and Kripka, 2020) and in the long term by increasing participation in the social structure and the economy through the efficient allocation of resources (Sierra et al., 2017b). Social aspects have been studied in civil engineering to evaluate sustainability in railway tracks substructures (Pons et al., 2020), urban housing demolitions (Yu et al., 2017), bridges (García-Segura et al., 2018; Penadés-Plà et al., 2020) and Post-Disasters temporary housing units (Hosseini et al., 2016). However, few studies have evaluated the connection between society and architecture (Josa and Aguado, 2019). Some authors believe that social criteria in construction projects are not clearly defined (Sierra et al., 2017b; Navarro et al., 2020a). It is necessary to select appropriate criteria according to the characteristics of the study to achieve the desired objective, depending on the context, the perspective of the participants and the stages of the life cycle (Valdes-Vasquez and Klotz, 2013). Therefore, and supported by the first principle of the "Rio Declaration on Environment and Development" (United Nations, 1992), in order to evaluate the sustainable development of any construction method, the three basic pillars must be considered together: environmental, economic and social (Veldhuizen et al., 2015).

The construction industry is a business in constant change and evolution, with housing being one of the basic sectors that affect society and people's well-being. According to the "Housing and Land Observatory" (Fomento, 2020), in 2019 the total number of homes completed in Spain experienced a year-on-year increase of 20%, which is the third consecutive year of recovery in the activity. Housing construction continues to be the most popular form of building. Therefore, there is a growing need to review traditional construction systems and seek new approaches. Modern methods of construction (MMC) offer the opportunity to rethink how we conceptualize, design and build homes. MMC can speed up the process, make development viable in more challenging locations, and provide varied and adaptable homes that respond to the nature of local needs (Pellicer et al., 2014). These decisions have long-term social consequences ranging from household economy to macroeconomic stability (Tabner, 2016) when the cumulative effects of individual decisions accumulate throughout the population. Considering that for the average family self-promotion or buying a home may be the most important investment of their life, making the right decision is essential.

The design and sustainable management of a building is a complex problem to solve, with multiple criteria that are usually contradictory. Vague and incomplete information generates uncertainties that can lead to confusion on the part of the decision-maker. In recent years, researchers have examined different methodologies for multi-criteria decision-making (MCDM) to assess the sustainability in construction (Jato-Espino et al., 2014) and structures (Navarro et al., 2019, 2020a). MCDM methods have been applied for the assessment of bridges (García-Segura et al., 2018; Contreras-Nieto et al., 2019), buildings (Sánchez-Garrido and Yepes, 2020; Daget and Zhang, 2020), materials (Zubizarreta et al., 2019) and building elements (De la Fuente et al., 2019), among others. Several methods have been combined in this paper, such as AHP (Saaty, 1990) (Analytic Hierarchy Process), one of the most used methods based on pair-wise comparison; MIVES (Pons et al., 2016) (in Spanish "Modelo Integrado de Valor para Evaluaciones de Sostenibilidad") based on utility or value functions; and unified with VIKOR (Opricovic and Tzeng, 2004) (in Serbian "Vlse Kriterijumska Optimizacija Kompromisno Resenje") based on the distance to the ideal solution.

However, there are always uncertainties that affect a valuation or comparison. Group MCDM (GMCDM) is a complex process involving multiple criteria and requires the consensus of multiple decision makers (DMs) with different interests (Chen et al., 2012). The problem is amplified when qualitative and quantitative variables are involved with respect to the criteria that define each alternative. These judgments end up being vague and contradictory, thus not aiding the decision-making process. Uncertainty in decision making can arise from several sources (Webb and Ayyub, 2017) in which the human factor is essential. The initial data, assumptions or criteria may contain inaccuracies, changes in scenarios or some variability that may influence the decision, especially if the person who finally makes the decision is not aware of these external uncertainties. Additionally, the subjectivity and quality of the judgment of DMs generate so-called non-probabilistic uncertainties, which influence the weighting of criteria (Gervásio and Simões da Silva, 2012). As the complexity of an assessment increases, the individual's ability to make rigorous judgments decreases, while certainty and accuracy are excluded (Zadeh, 1973) by having to choose one or the other. The classic AHP assumes that the values in Saaty's comparison matrix are true and accurate. It does not insist on consensus, but rather synthesizes a representative result of several judgments, and can detect inconsistency biases in DMs' assessments (Saaty, 1990). Although it leads to a full assessment of the desirability of each alternative, the introduction of a new one may alter the preference structure of DMs. The technique has been questioned by some authors (Radwan et al., 2016) who doubt its suitability for capturing the complex and diffuse nature of human thinking.

To avoid these problems associated with uncertainty, scientific research studies include sensitivity analyses to check whether the decisions taken are correct in the face of a certain variation in the hypotheses. Bayesian networks (Sierra et al., 2018), fuzzy logic (García-Segura et al., 2018) and neutrosophic logic (Sodenkamp et al., 2018) are tools that serve this purpose. The most used approach in MCDM is the fuzzy sets (FSs) theory, raised by Zadeh (1965) who introduced the membership grade/ truth (T), defined in the interval [0–1]. Its main advantage over classical logic is that it does not admit gradation between "true" and "not true" (or false). Fuzzy logic allows modeling vague or imprecise concepts mathematically, similar to human reasoning that is not based on a binary classical logic. Atanassov (1986) added the degree of non-membership/falsehood (F) by defining the intuitionistic fuzzy sets (IFSs) that allow for more complex mental constructions and semantic uncertainties. However, FSs and IFSs cannot judge uncertain, incomplete and inconsistent situations such as a metaphor or social phenomena that can be positive or negative depending on the point of view.

New advances in the treatment of uncertainty arise with Neutrosophic Sets (NSs) as a generalization of FSs and especially IFSs. First introduced by Smarandache (1998) the degree of indeterminacy/ neutrality (I) was included as a separate component. The NSs are characterized by assigning each element three independent properties, namely truth, falsity and indeterminacy. The gap closed by neutrosophic models, unlike the fuzzy and intuitionistic ones, is that the sum of the three properties (T, F, I) can be greater than one (up to a maximum of 3), while in the other logics it cannot exceed unity. This formulation allows the modeling of most cases of ambiguity or semantic inconsistencies, such as paradoxes. As a NSs is more difficult to apply to technical or scientific decision making, single value neutrosophic sets (SVNSs) (Wang et al., 2012) and interval neutral sets (INSs) (Ye, 2014) were proposed. This allowed for a better definition of its properties, with the introduction of linguistic variables or the contribution of theoretical aggregation operators (Peng et al., 2015, 2016), increasing the interpretability of the uncertainty generated by the imprecise, inconsistent and incomplete information that characterizes the real world.

Although the origin of the NSs dates back to the end of the 20th century, its theoretical basis has been developed in the first decade of the 21st century. Only recently it has begun to be applied to practical MCDM problems related to Hospital Performance Measurement (Yang et al., 2020), personnel selection (Nabeeh et al., 2019) or Typhoon Disaster Assessment (Tan et al., 2020). The literature review conducted by Navarro et al. (2019) indicates that from 1995 to that date no application of the neutrosophic approach had yet been found to be applied in MCDM related to the infrastructures assessment. To the best of our knowledge, NSs have not yet been applied to the evaluation of the sustainability of structural engineering in general or residential building in particular. In 2020, it appeared for the first time in the field of civil engineering applied to bridges (Navarro et al., 2020b). For this reason, the authors have focused this research on evaluating the sustainability of the structure of a single-family house by applying neutrosophic logic.

The objective of this paper is to evaluate sustainability among three MMC-based alternatives applied to the design of the structure and thermal envelope of a single-family home throughout its life cycle. For this purpose, a methodology based on neutrosophic logic is used to obtain the weights in an Analytical Hierarchy Process (N-AHP) that considers the subjectivity of a group of experts in the decision-making process for complex evaluations. Given the significant impact that the weighting of criteria can have on the outcome of MCDM processes, it is essential to capture as much information as possible to transform the conventional or crisp numbers in their truth-, indeterminacy-, and falsity-membership degrees, especially in real situations inherent to the subjective judgments of the experts involved in the assessment.

2. Problem definition

This paper aims to analyze sustainability in residential building, comparing different options for the design of the structure and the enveloping walls from a life cycle perspective. The problem analysis requires establishing who will act as the DM, previously organizing the system boundaries and stipulating the scope of the project. Initially the problem to be solved is defined which identifies the decision to be made. Then, the possible solutions are delimited, whose number of alternatives will depend on the nature of the problem. This will allow defining the criteria that will evaluate sustainability, deploying a hierarchical structure with the sub-criteria and indicators that are required. This stage is limited to the organization of the context, without quantifying or evaluating any aspect.

2.1. Characterization of the case study

The study focuses on a single-family row house. A typology has been chosen that can be found all over the world, especially in expansion areas of big cities, since it allows an average economic cost and is affordable for a large number of people who prefer to live in single-family homes rather than collective ones. Its elongated and narrow geometry is normally the result of the maximum adjustment of the parameters of building density, surface and occupation in the plot.

This building, in particular, is located in Jaén (Spain), with a rectangular shape of 6.20 m × 20.00 m and access from street level (±0.00) according to Fig. 1. The two-storey house, consists of a semi-basement level (−1.30) with use of garage; level 0 (+1.50) raised on the sidewalk, with living room, kitchen and toilet; level 1 (+4.40) with 3 bedrooms, bathroom and toilet; level 2 (+7.40) with solarium and swimming pool and a small roof for the tower (+11.00).

2.1.1. Definition of design alternatives

The selection of an appropriate MMC allows improving the design, and therefore the building, throughout its life cycle in different aspects (environmental, economic and social) in search of sustainability. Three design alternatives are considered in this study, one conventional as a reference and two disparate MMC for comparison: a traditional solution (REF); an industrialized and prefabricated option with semi-dry assembly (YTN); and, finally, an integral structural system with innovative technology (ELE).

REF consists of a conventional reinforced concrete structure and brick walls. YTN is based on the use of Ytong as a unique material for the construction of walls, partitions and slabs with prefabricated elements. It is made of autoclaved aerated concrete, manufactured with densities between 350 and 700 kg/m^3. Its lightness provides a very high performance (35–50 m^2/day for blocks and 150–200 m^2/day for slabs). It does not require props, formwork or concrete pouring, except for joint filling and edge beams. It is a fireproof material composed of 100% recyclable minerals (silica sand, cement, lime and an expansion agent), with an environmental product declaration (EPD) according to European standards (ISO 14025). ELE is known as Elesdopa (in Spanish, double wall structural element). It works as an integral system to create a building with a unique plate type element. In addition to the enclosure, this element provides the necessary rigidity to support the structural function by increasing the moment of inertia of the H section. The folded and continuous shell is achieved by forming two sheets of projected and reinforced concrete, with thicknesses between 5 and 10 cm, bracing them with keys that absorb the shear forces. The inner chamber between the plates is materialized with hollow boards for the passage of installations or lost formwork made of expanded polystyrene that also fulfils the function of thermal insulation.

In the life cycle assessment, the impacts of the construction elements with the greatest impact on the budget have been analyzed. The description of the alternatives and their breakdown by elements is detailed in Table 1. Although the study focuses on the foundation and structural elements, facades and partition walls have been included to compare the reference solution with those where the resistant support shares the function of the building envelope.

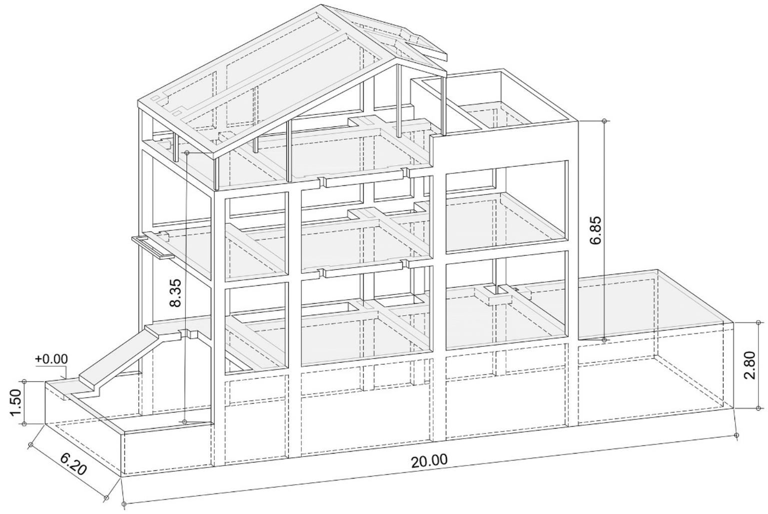

Fig. 1. General view of the structure of the single-family house.

Table 1
Main features of the alternatives.

Alternative	Elements	Description
REF "Traditional" [a]	Foundation	Piles CPI-7 Ø35cm HA-35/F/12/IIa + Qc and steel quantity 7.38 Kg/m up to 8.80 m deep. Foundation beams HA-30/B/20/IIa + Qb and steel quantity 100 kg/m^3.
	Floor slabs	Reinforced concrete slab HA-25/B/20/IIa (24 cm type floor, 26 cm solarium), steel quantity 26 kg/m^2 and HA-30/B/20/IV in swimming pool area.
	Sloping floor slab	Reinforced concrete slab HA-25/B/20/IIa (22 cm); 10 cm PUR (0.035 m^2K/W).
	Supports	Concrete columns and metal profiles (only in props of the roof). Reinforced concrete basement perimeter wall (25 cm).
	Building enclosure	Brick outer wall (11.5 cm); air chamber insulated with 9 cm MW (0.031 m^2K/W). Interior brick partition wall (7 cm).
YTN "Industrialized" [b]	Foundation	Same to alternative "A".
	Floor slabs	Reinforced plates (30 cm type floor, 17.5 cm solarium); Density 600 kg/m^3. Thermal conductivity 0.16 W/(mK), steel quantity 2 kg/m^2, in plate joints. Passable deck not ventilated, fixed flooring; 8 cm XPS (0.032 m^2K/W). Pool bottom with 30 cm plates (live load 1100 Kg/m^2); "O" block anchored to the bottom and "U" block at the top and half height.
	Sloping floor slab	Reinforced plates (12 cm); 12 cm XPS (0.032 m^2K/W).
	Supports	There are no columns. Reinforced concrete basement wall is maintained.
	Building enclosure	Structural load-bearing walls with tongue and groove aerated concrete blocks (20–30 cm) with densities (400–350 Kg/m^3).
ELE "Technology" [c]	Foundation	Mat foundation 7/46/7 on 1.00 m deep compacted soil improvement. HRA-30/B/12/IIa + Qb with a steel quantity 85 kg/m^3. 46 cm interior gravel filling.
	Floor slabs	Sprayed reinforced concrete lightened slab HRA-25/B/12/IIa (6 + 18 + 6 cm type floor, 7 + 26 + 7 cm solarium), steel quantity 26 kg/m^2 and HRA-30/B/12/IV in pool. Passable deck not ventilated, fixed flooring; 26 cm XPS (0.042 m^2K/W).
	Sloping floor slab	Sprayed reinforced concrete lightened slab (5 + 5 + 5 cm). 5 cm XPS (0.025 m^2K/W).
	Supports	Reinforced concrete basement wall is maintained.
	Building enclosure	Structural walls in façade and dividing walls (6 + 13 + 6 cm); interior air chamber formed with 13 cm EPS (0.029 m^2K/W).

[a] Reference: Conventional on-site reinforced concrete structure and brick enclosure walls.
[b] Ytong: Prefabricated blocks and industrialized slabs, autoclaving aerated concrete manufactured with densities 350–700 kg/m^3.
[c] ELESDOPA©: Double Wall Structural Element, of Projected Reinforced Concrete.

3. Materials and methods

This section proposes a complete method that integrates the neutrosophic logic in the weighting of the criteria involved in the decision making of the GMCDM with the aim of discretizing between several constructive alternatives based on the MMC from a sustainable point of view. The methodology for selecting the best alternative is divided into the four stages shown in Fig. 2. It consists of a rigorous process based on the definition of the criteria, obtaining the weights of each one, their evaluation, and discriminating between the alternatives using a multiple-criteria technique.

3.1. Stage 1: indicators for the sustainability assessment of alternatives

Sustainability must be assessed by simultaneously considering its three dimensions, namely, economy, environment, and society. For this case, a set of 9 criteria has been selected. The quantitative assessment of these criteria relies on the evaluation of 43 concrete indicators, which are grouped into 20 sub-criteria. Table 2 shows the assumed decision criteria and displays the evaluation tree. The proposal of sustainable optimization in the structures of single-family homes, is based on the evaluation of the impacts of the life cycle resulting from the different phases or constructive activities associated with the project during its entire life, considering a so-called "cradle-to-grave" approach. Consequently, impacts resulting from the conception, materialization, use and maintenance, demolition and re-use life cycle stage are taken into account.

To evaluate the economic dimension, cost has been considered as the only unit of impact, quantifying the economic resources used in each phase of the life cycle. All impacts are expressed in the same unit of measurement, so the inventory data do not need to be normalized. The criteria C1, C2 and C3 correspond to the following life cycle stages: conception-construction, including fees, licenses, taxes, construction and waste management budget; service life, with prevention, protection, use and maintenance costs; and end-of-life (EoL) which refers to the costs resulting from dismantling and waste treatment for reuse.

Two criteria have been considered for the environmental dimension, evaluating the possible impacts to the environment as a consequence of human activities. On the one hand, it shall be noted that over 50% of construction and demolition waste in Europe goes to landfill. Consequently, criterion C4 accounts for the usage proportion of recycled materials. By using this criterion, both the use of recycled materials (Zhong and Wu, 2015) and the reintegration of surplus materials in construction (Sánchez-Garrido and Yepes, 2020) are assessed. This process avoids impacts on the environment and the waste of mostly non-renewable energy. On the other hand, criterion C5 evaluates the environmental impacts, both in the short term (construction) and in the long term (demolition). Three end point indicators are selected to characterize criterion C5, namely damage to human health, depletion of natural resources and damage to ecosystems (Huijbregts et al., 2017).

The criteria that justify the social field are defined so as to evaluate the impacts on the main stakeholders proposed by the "Methodological Sheets for the Subcategories of Social Life Cycle Assessment" (United Nations Environment Programme and SETAC, 2013). According to the

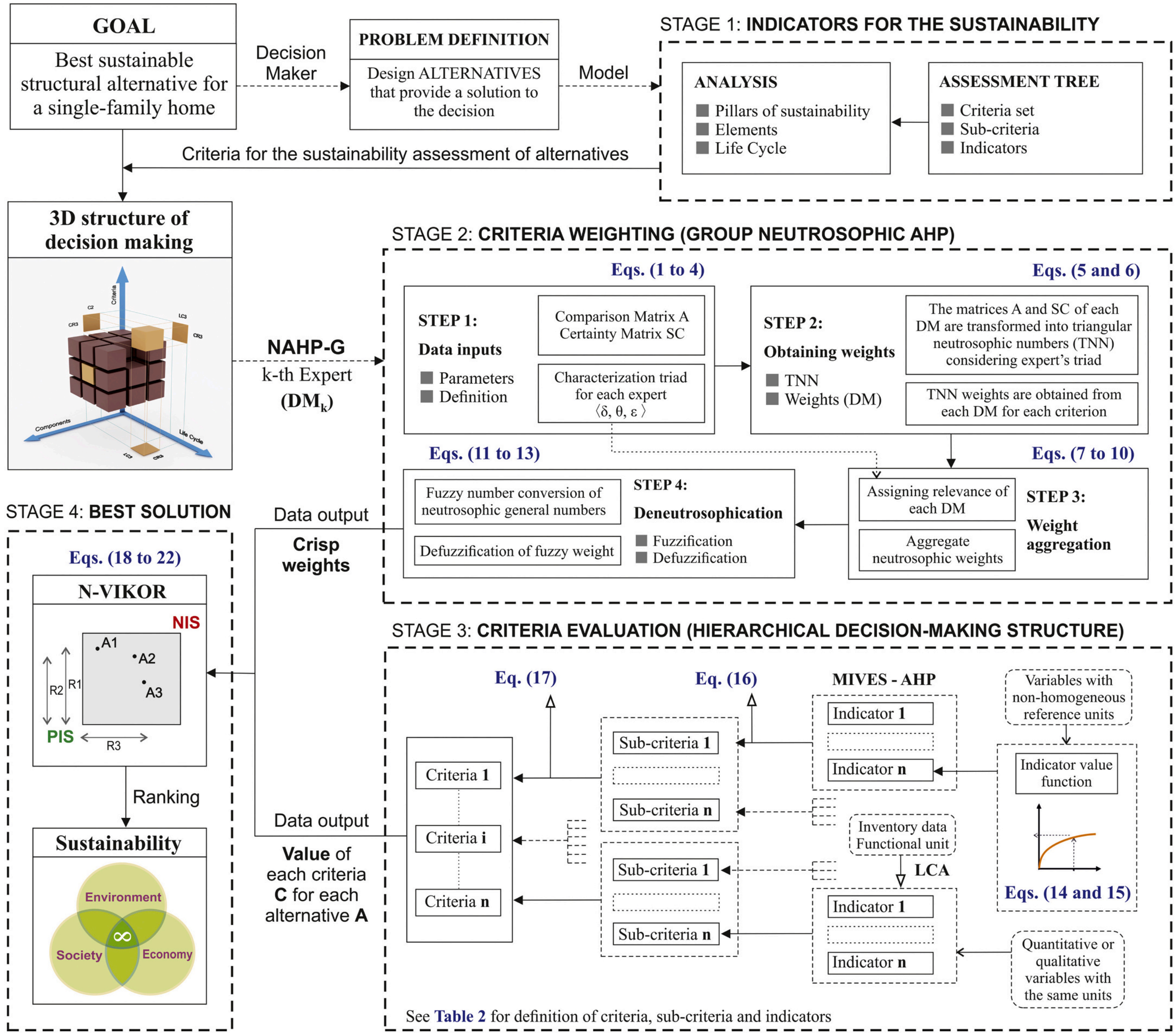

Fig. 2. Overview of the methodology.

Methodological Sheets referred above stakeholders are defined, namely the local community, value chain actors, consumers, workers and society. All the proposed indicators have been chosen specifically to characterize the social impacts on the five stakeholders based on a hotspot analysis according to the "Guidelines for Social Life Cycle Assessment of Products" (United Nations Environment Programme, 2009), taking into consideration the social context of the site and of the production centers involved in the system of the product under consideration. The assessment of the social impacts has been divided into four criteria. C6 corresponds to the design, construction and demolition times required by each design alternative, measured in terms of working hours. C7 covers prevention of occupational risks, worker health and safety, as well as structural reliability both during the construction phase and during the service stage. C8 takes into account the preferences that construction agents manifest about each construction system, based on the ease to access the particular construction materials involved, as well as on the trust that construction companies have in the structural solution. Additionally, the generation of local employment is also accounted for, both in the short- and in the long-term. Finally, C9 focuses on functionality related to user comfort throughout the service life of the building (safe and healthy living condition).

3.2. *Stage 2: Criteria weighting through NAHP-G*

AHP is a technique widely used in the decision-making process to help select alternatives based on some criteria. The method is suitable for problems that can be broken down into a hierarchical structure. For this process, comparison matrices are constructed using the fundamental scale proposed by Saaty (1990), thus obtaining weights through the subjective importance of each element with respect to the others. This matrix complies with the properties of reciprocity (if $a_{ij} = x$, then $a_{ji} = 1/x$); homogeneity (if i and j are equally important, $a_{ij} = a_{ji} = 1$, and furthermore, $a_{ii} = 1$ for all i); and consistency. Consistency is obtained by means of the Consistency Index:

$$CI = (\lambda_{max} - n)/(n - 1) \tag{1}$$

where λ_{max} is the maximum eigenvalue and n the dimension of the

Table 2
Deployment of the assessment tree and defuzzified crisp weights.

Pillars	Criteria (C)		Sub-criteria (G)		Indicators {I}	
Economy	Construction cost [9.63%][a]	C1	Production	G1	Design + project management fees (€/m^2)	{1}
					Construction management fees (€/m^2)	{2}
					License and taxes (€/m^2)	{3}
			Materialization	G2	Construction cost - bill of quantities (€/m^2)	{4}
			Waste management	G3	Transport of the land by truck (€/m^2)	{5}
					Landfill fee to authorized manager (€/m^2)	{6}
					Transport of inert waste by truck (€/m^2)	{7}
					Fee for delivery of inert waste (€/m^2)	{8}
	Service life cost [6.78%][a]	C2	Prevention	G4	Corrosion protection (€/m^2)	{9}
					Prevention of carbonation (€/m^2)	{10}
					Water-repellent for concrete (€/m^2)	{11}
					Facade waterproofing (€/m^2)	{12}
					Protection against fire (€/m^2)	{13}
			Use and maintenance	G5	Ten-year maintenance (€/m^2 the first 10 years)	{14}
	End-of-life cost [1.36][a]	C3	Demolitions	G6	Full building demolition (€/m^2)	{15}
			Pre-treatment of waste	G7	Classification of construction and demolition waste (CDW) generated (€/m^2)	{16}
					Shredding of non-stone waste (€/m^2)	{17}
					Crushing of stone residues (€/m^2)	{18}
			Inert waste management	G8	Transport of inert waste by truck (€/m^2)	{19}
					Fee for delivery of inert waste (€/m^2)	{20}
Environm.	Resources used [17.16%][a]	C4	Recycling	G9 (100%)[b]	Use of recycled materials (Construction) (%)	{21} (33.33%)[b]
					Reintegrability of surplus materials (EoL) (%)	{22} (66.67%)[b]
	Environmental footprint [15.98%][a]	C5	Endpoint scores (Construction)	G10	Ecosystem quality (Construction) (Points)	{23}
					Human health (Construction) (Points)	{24}
					Resources (Construction) (Points)	{25}
			Endpoint scores (EoL)	G11	Ecosystem quality (EoL) (Points)	{26}
					Human health (EoL) (Points)	{27}
					Resources (EoL) (Points)	{28}
Society	Lead times [5.28%][a]	C6	Conception	G12	Project design development (Days)	{29}
			Construction stage	G13	Building time (Days)	{30}
			EoL	G14	Demolition time (Days)	{31}
	Safety [20.71%][a]	C7	Prevention of occupational risks	G15 (33.33%)[b]	Short-term accident rate (construction site) (% Potential accidents)	{32} (50.00%)[b]
					Long-term accident rate (demolition site) (% Potential accidents)	{33} (50.00%)[b]
			Building process	G16 (66.67%)[b]	Critical load during construction (Index)	{34} (33.33%)[b]
					Probability of pathological processes (%)	{35} (66.67%)[b]
	Degree of acceptance [3.85%][a]	C8	Developer	G17 (25.00%)[b]	Short-term local employment generation (Construction - min. Wage employment hours)	{36} (75.00%)[b]
					Long-term local employment generation (Demolition-min. Wage employment hours)	{37} (25.00%)[b]
			Construction company	G18 (75.00%)[b]	Trust in the building system (scale 1–10)	{38} (16.67%)[b]
					Materials and equipment access (scale 1–100)	{39} (83.33%)[b]
	Functionality [19.25%][a]	C9	Constructability	G19 (14.29%)[b]	Flexibility to make reforms or subsequent renovations (scale 1–100)	{40} (100%)[b]
			User's comfort and health	G20 (85.71%)[b]	Rooftop thermal insulation ($U=W/m^{2\circ}K$)	{41} (33.34%)[b]
					Thermal insulation in facades ($U=W/m^{2\circ}K$)	{42} (33.33%)[b]
					Acoustic insulation (Ra,tr (dBA))	{43} (33.34%)[b]

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[a] Defuzzified crisp weights in criteria are in percentage between square brackets, calculated as indicated in Section 3.2.5.

[b] Weights in group of indicators and indicators are in percentage between brackets, calculated as indicated in Section 3.3.2.

decision matrix. A null value for this index corresponds to a perfect consistency.

This section describes a neutrosophic extension of the traditional (scalar) Analytical Hierarchy Process. Following the proposed methodology, the weights of the criteria are obtained through a neutrosophic group AHP. To facilitate the follow-up, the sequential steps are illustrated in Fig. 2.

3.2.1. Preliminaries on neutrosophic sets

The following is a brief review of some basic concepts about Neutrosophic Sets Theory for a proper understanding of the subsequent sections.

Definition 1. If $N = \{(T, I, F)\text{: } T, I, F \subseteq [0,1]\}$, neutrosophic valuation is a mapping of a group of propositional formulas to *N*, that is, for each *p* sentence we have: $\nu(p) = (T, I, F)$. Henceforth, the following notations are adopted: $\mu_{\bar{a}}\ (x)$, $\nu_{\bar{a}}\ (x)$ and $\lambda_{\bar{a}}\ (x)$ instead of truth (*T*), indeterminacy (*I*) and falsity (*F*), respectively.

Definition 2. Let *x* be a universe of discourse. A single valued neutrosophic set (SVNS) *A* over *x* is an object as follows: $A=\{\langle x, \mu_{\bar{a}}\ (x), \nu_{\bar{a}}\ (x), \lambda_{\bar{a}}\ (x)\rangle\text{:}x \epsilon x\}$ where $\mu_{\bar{a}}\ (x)\text{:}x\rightarrow[0,1]$, $\nu_{\bar{a}}(x)\text{:}x\rightarrow[0,1]$ and $\lambda_{\bar{a}}(x)\text{:}x\rightarrow[0,1]$ with $0 \leq \mu_{\bar{a}}(x) + \nu_{\bar{a}}(x)+ \lambda_{\bar{a}}(x) \leq 3$ for all $x \in x$. The intervals $\mu_{\bar{a}}\ (x)$, $\nu_{\bar{a}}\ (x)$ and $\lambda_{\bar{a}}\ (x)$ denote the truth-membership degree, the indeterminacy-membership degree and the falsity-membership degree of *x* to *A*, respectively.

Definition 3. A single-valued triangular neutrosophic (TNN) number $\bar{a} = \langle(a_1, a_2, a_3); t_{\bar{a}}, i_{\bar{a}}, t_{\bar{a}}\rangle$ is defined as a neutrosophic number on the real number set, whose truth, indeterminacy and falsity membership functions are respectively continuous functions as shown in to Fig. 3 according to those defined by Deli and Şubaş (2017):

3.2.2. Data inputs

The first step is to collect the A_{DMK} paired comparison matrices by each expert. Such comparison matrices are obtained following the conventional AHP procedure. Experts are requested to conduct pairwise comparisons considering a certain number of criteria, manifesting how much more relevant one criterion is with respect to the other following the Saaty scale. The condition is that the A_{DMK} matrix verifies the property of reciprocity and consistency. On the other hand, the uncertainty that the expert manifests in each judgment is collected through the SC_{DMk} matrix, directly assigned by each decision maker (DM$_k$). The second step is to characterize each member in the group of experts, which will be necessary to determine in a later step the relevance of each DM$_k$. Based on the procedure suggested by Sodenkamp et al. (2018), we propose the following expressions to determine the triad $\bar{E}_k = \langle\delta, \theta, \varepsilon\rangle$ associated with the k^{th} expert.

The credibility δ_k of each expert takes into consideration each expert's level of competence, which is based on his or her professional profile, experience in the fields he or she assesses, and research achievements:

$$\delta_{DMk} = \left(\frac{PA_k}{\underset{k=1\ldots p}{max}\{PA_k\}} + \frac{SE_k}{\underset{k=1\ldots p}{max}\{SE_k\}} + \frac{AD_k}{3} + \sum_{i=1}^{6}\frac{Kc_i}{5} + \sum_{i=1}^{3}\frac{Rc_i}{\underset{k=1\ldots p}{max}\{Rck_i\}}\right) \Big/ 12 \tag{2}$$

where PA_k and SE_k are the years of professional activity and experience in sustainability, respectively, of the k^{th} expert among the total number of *p* experts involved in the decision; AD_k is the academic degree (BDs = 1, MSc = 2, PhD = 3). Kc_i are coefficients ≤1 that represent the knowledge in six specific fields (see Table 9) assigning discrete values between 0 and 5. Finally, Rc_i parameters measure in three concepts (JCR Articles, Congresses and Books) the relationship between the scientific production of the k^{th} expert and the maximum Rck_i of the group in each field.

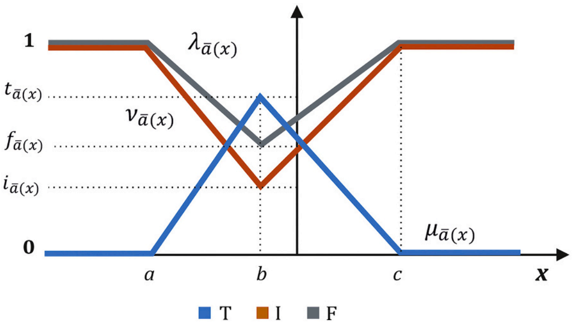

Fig. 3. Functions that define the parameters (T, I, F) in a TNN number.

The indetermination θ_k of each expert is calculated according to Eq. (3) as the complement of the average self-confidence expressed in the SC_{ij} matrix by the DM certainties for each judgment, where *n* is the number of elements to be compared:

$$\theta_{DMk} = 1 - \sum_{i,j=1}^{n}\left(SC_{ij}/n^2\right) \tag{3}$$

The inconsistency ε_k of the expert is obtained with Eq. (4) as the consistency of his judgments measured by the consistency ratio (CR) of his comparison matrix, divided by the maximum consistency allowed in the AHP comparison matrices for the number of elements considered. In our case, for $n = 5$ or more, $CR_{lim} = 0.10$:

$$\varepsilon_{DMk} = CR_k/CR_{lim} \tag{4}$$

3.2.3. Obtaining weights

To reflect the vagueness of the judgments expressed, the matrices of each DM are transformed into TNN matrices. The values (l_{ij}, m_{ij}, u_{ij}) of each trial range from 1/9 to 9 according to Saaty's fundamental scale. The central values (m_{ij}) correspond to the judgments issued by the DM. The lower and upper values (l_{ij},u_{ij}) depend on the *SCij* certainty that the DM has manifested, calculated as:

$$l_{i,j} = m_{i,j} - \Delta V_{i,j};\ u_{i,j} = m_{i,j} + \Delta V_{i,j} \tag{5}$$

where ΔV_{ij} is the number of steps on the Saaty scale between the central m_{ij} value and the corresponding extreme, defined according to Navarro et al. (2020b) and whose ranges are shown in Table 3.

To construct the neutrosophic parameters of each decision maker's judgment (T, I, F), the credibility δ is different for each cell of the matrix, with specific values for the sub-matrices that compare criteria of the same dimension. So, three different credibility levels are defined for the economic (δ_{EC}), the environmental (δ_{EN}) and the social (δ_{SO}) sub-matrices. The rest of the comparisons are governed by the "sustainability contribution" coefficient (δ_{SC}), which takes into account general and research knowledge averaged with professional experience. From the latter and the combination with the different dimensions of sustainability, the specific coefficients of economic-environmental credibility (δ_{EE}), environmental-social (δ_{ES}) and social-economic (δ_{SE}) are obtained, thus completing the rest of the sub-matrices. The indetermination of each judgment is obtained as the complementary value to the

Table 3
Range of triangular numbers according to the expressed uncertainty.

Uncertainty in judgment a_{ij} (SC_{ij})	Definition of the interval (ΔV_{ij})
$SC_{ij} = 1$	0
$0.8 \leq SC_{ij} < 1$	1
$0.6 \leq SC_{ij} < 0.8$	2
$0.4 \leq SC_{ij} < 0.6$	3
$0.2 \leq SC_{ij} < 0.4$	4
$0 \leq SC_{ij} < 0.2$	5
$SC_{ij} = 0$	6

certainty that the expert has stated when making it ($I_i = 1\text{-}SC_i$), and that the inconsistency of each judgment is considered equal to the incoherency of the expert ($F_i = EDM_k$). Table 9 shows in bold all the resulting coefficients that form the matrix of neutrosophic parameters.

The neutrosophic weights (TNNW) are obtained as the normalized components of the eigenvector associated with the highest eigenvalue of the comparison matrix. Obtaining weights and eigenvalues is very complex when working in a diffuse environment, and much more so in a neutral environment. Therefore, when working with logics such as the neurosophical one, it is usual to resort to the approximate method proposed by Buckley (1985). According to Buckley, the weights can be obtained as:

$$\overline{w}_i = \frac{\left(\prod_{J=1}^{n} \overline{a}_{ij}\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{J=1}^{n} \overline{a}_{ij}\right)^{1/n}} \tag{6}$$

where $\bar{w}_i$ is the triangular neutrosophic weight of element *i*, *n* is the number of elements to be compared, and $\bar{a}_{ij}$ is the neutrosophic comparison value between elements *i* and *j*.

However, in the fuzzy field it was found that the direct application of Buckley's method for deriving weights from AHP matrices defined according to Saaty's fundamental scale results in fuzzy weights with unreasonably high and asymmetric ranges of uncertainty. Enea and Piazza (2004) suggested a weighting method to derive a fuzzy weight range with appropriate constraints using a scalar mathematical programming model, considering that the upper and lower matrices should be reciprocal. An adaptation of this method has recently been proposed by Navarro et al. (2020b).

3.2.4. *Weights aggregation*

The relevance φ_k of the k^{th} expert is obtained as the normalized Euclidean distance between the point $\bar{E}_k = \langle \delta_k, \theta_k, \varepsilon_k \rangle$ representing the neutrosophic triad (obtained in Section 3.2.2) and the neutrosophic ideal point representing maximum reliability ⟨1,0,0⟩:

$$\varphi_k = \frac{1 - \sqrt{\left\{(1-\delta_k)^2 + {\theta_k}^2 + {\varepsilon_k}^2\right\}/3}}{\sum_{k=1}^{p}\left(1 - \sqrt{\left\{(1-\delta_k)^2 + {\theta_k}^2 + {\varepsilon_k}^2\right\}/3}\right)} \tag{7}$$

With the relevance φ_k of each expert, the neutrosophic weights of each element shall be aggregated as follows:

$$W_{m,i} = \sum_{k=1}^{p} \varphi_k \bullet w_{m,i}^k \tag{8}$$

$$W_{l,i} = W_{m,i} - max_{k=1\dots p}\left\{w_{m,i}^k - w_{l,i}^k\right\} \tag{9}$$

$$W_{u,i} = W_{m,i} + max_{k=1\dots p}\left\{w_{u,i}^k - w_{m,i}^k\right\} \tag{10}$$

where $W_{m,i}$, $W_{l,i}$ and $W_{u,i}$ are the center value, the lower and the upper bound, respectively, of the group aggregated neutrosophic weight of element *i*. Here, triangular neutrosophic weights obtained are transformed into general neutrosophic weights. According to Navarro et al. (2020b) the resulting generalized neutrosophic weights are represented as $\bar{W}_i = \langle (W_{l,i}, W_{m,i}, W_{u,i}); t_i, i_i, f_i \rangle$, with $t_i = \sum \varphi_k \cdot t_{ik}$; $i_i = \sum \varphi_k \cdot i_{ik}$ and $f_i = \sum \varphi_k \cdot f_{ik}$ being the maxima of the group aggregated weight membership functions defined within the range $x \in [W_{l,i}; W_{u,i}]$.

3.2.5. *Deneutrosophication technique*

First we proceed to the Fuzzification of the general neutral numbers. The neutrosophic weights $\hat{W}i = \langle (W_{l,i}, W_{mi}, W_{ui}); t_i, i_i, f_i \rangle$ are transformed into diffuse generalized weights $Wi = \langle (W_{l,i}, W_{mi}, W_{ui}); \eta_i \rangle$. The fuzzy function η_i (x) for the weight W_i is obtained as the Euclidean distance between each point and the ideal point of maximum reliability ⟨1, 0, 0⟩:

$$\eta_i(x) = 1 - \sqrt{\frac{\left\{\left(1 - \mu_i(x)^2\right) + \upsilon_i(x)^2 + \lambda_i(x)^2\right\}}{3}} \; ; \forall \mathrm{x} \in [Wl, i; Wu, i] \tag{11}$$

The second step consists of the defuzzification of the fuzzy weights obtained. The most used technique is the one based on the center of gravity (CoGx) of the fuzzy membership function η_i (x). Chu and Tao (2002) presented an alternative that improved its use in generalized fuzzy numbers by proposing a defuzzification based on the area between the centroid point (x,y) of a fuzzy number and the origin of the coordinate system considered. An area index is defined as:

$$S_{\widehat{W}i} = CoG_x\left(\widehat{W}i\right) \bullet CoG_y\left(\widehat{W}i\right) \tag{12}$$

The crisp weights of each element *i* are obtained by normalizing the resulting area indices for each element considered:

$$W_i^* = S_{\widehat{W}i} \Big/ \sum S_{\widehat{W}i} \tag{13}$$

3.3. *Stage 3: criteria evaluation through the hierarchical decision-making structure*

Decision-making becomes more complex as the number of criteria increases and various stakeholders with different views participate. In Section 3.1, up to 43 indicators have been defined to characterize the sustainability of a single-family home, which is not a manageable number for an expert. In fact, to calculate the Consistency Index of Saaty's decision matrix, it is usual not to exceed 10 criteria. For this reason, In order to minimize the subjectivity of individual decision makers caused by the dispersion among the large number of indicators defined, the expert group has focused on the evaluation of the 9 first level criteria. Then, in order to assess the relevance of each of the 43 indicators considered, MIVES method is used. This method is an approach that combines MCDM and the Multi-Attribute Utility Theory (MAUT), derived from methods that incorporate the concept of the utility or value function, providing the equations that define the different functions of satisfaction (Pons et al., 2016).

3.3.1. *Impacts inventory*

Regarding the economic inventory, construction costs for the three alternatives and for each phase of the building life cycle (design, construction, service and demolition stages) were gathered from national construction-specific databases. Additional costs, ten-year maintenance costs and weight/volume of waste generated have been considered as well. The overheads and industrial benefit are not included. Tables 4 and 5 present, respectively, the construction and the demolition costs of each of the materials involved in the design of each alternative, as well as the amount of materials consumed by each. The costs of the design life cycle stage have been obtained from professional associations of architects.

The functional unit of this problem corresponds to the 364.68 m^2 built area of the structure, guaranteeing housing safety and functionality conditions in accordance with national standards over a 50-year lifespan. The environmental impact analysis has been carried out using OpenLCA software. Inventory data relevant to the environmental characterization of the different activities that have been evaluated has been gathered from the environmental database Ecoinvent 3.3. Environmental impacts along the service life of the building have been assessed following the ReCiPe methodology (Huijbregts et al., 2017). This method converts 18 mid-point indicators into 3 end-point indicators, namely damage to ecosystems, damage to human health and depletion of natural resources. The advantage of this approach is that it provides an overview of the environmental footprint at the construction stage (G10) and the EoL (G11) and, on the other hand, allows a more detailed analysis of the indicators {23} to {28}. The use of recycled materials and

Table 4

Inventory data with yields of construction materials used in the economic-environmental assessment of the alternatives.

Construction stage		**REF** (0.53%) [a]		**YTN** (17.85%) [a]		**ELE** (30.82%)[a]	
Concept	Unit	Material quantity	CRM [a]	Material quantity	CRM [a]	Material quantity	CRM [a]
Ytong tile 62,5×25×7 cm (450 Kg/m^3)	kg	–	–	833.34	0.00%	–	–
30×62,5 cm Ytong reinf. Plate (600 Kg/m^3)	kg	–	–	29,568.60	0.00%	–	–
17,5×62,5 cm Ytong reinf. Plate (600 Kg/m^3)	kg	–	–	5255.25	0.00%	–	–
12,5×62,5 cm Ytong reinf. Plate (600 Kg/m^3)	kg	–	–	2041.20	0.00%	–	–
Ytong block 62,5×25×20 cm (400 Kg/m^3)	kg	–	–	29,245.15	0.00%	–	–
Ytong block 62,5×25×30 cm (350 Kg/m^3)	kg	–	–	2982.53	0.00%	–	–
Mortar	kg	6074.20	0.00%	1873.97	0.00%	–	–
Cement	kg	22.26	0.00%	3794.83	0.00%	257.38	0.00%
Concrete block	kg	–	–	3346.73	0.00%	–	–
Concrete (fck $\leq$ 30 Mpa; exposure class II-IV)	m^3	174.74	0.00%	116.49	10.00%	152.23	20.00%
Gravel (1650 Kg/m^3)	kg	40,450.91	0.00%	40,450.91	95.00%	207,055.20	95.00%
Aggregate	kg	64.52	0.00%	10,281.36	20.00%	–	–
Compacted granular sub-base	kg	–	–	–	–	272,800.00	0.00%
Bricks (2.30 Kg/unit)	kg	36,110.41	0.00%	–	–	–	–
Polyethylene	kg	–	–	–	–	48.35	0.00%
9 cm EPS; (25 Kg/m^3)	kg	–	–	–	–	2.285,72	50.00%
Rebar steel	kg	13,588.18	16.99%	6816.37	71.50%	12,587.15	88.49%
Wire and tips	kg	151.96	25.00%	82.67	60.75%	151.20	85.75%
Wire mesh	kg	480.17	16.99%	480.17	71.50%	–	–
Steel armor for blocks	m	–	–	43.01	71.50%	–	–
Steel reinf. for Ytong plates (2 kg/m^2)	kg	–	–	483.08	71.50%	–	–
Timber	m^3	8.06	0.00%	1.47	0.00%	0.93	0.00%
22 mm formwork board (25 applications)	m^3	0.32	–	0.07	–	13.63	–
Sand	kg	64.52	0.00%	5120.20	50.00%	–	–
Structural steel (S275JR)	kg	474.11	15.48%	230.81	73.50%	–	–
Shoring and % of props (150 applications)	kg	130.98	–	11.57	–	98.75	–
Pillar formwork (50applications)	kg	52.50	–	5.59	–	–	–
Water (excluding concrete mix component)	dm^3	3025.44	–	1920.47	–	–	–
Priming, resins, de-coating (0.9 kg/l)	kg	50.64	–	11.73	–	53.93	–

[a] Content % of recycled materials (CRM).

Table 5

Construction waste generated assumed in each of the design alternatives according to the LCA.

	REF (72.22%)[a]			**YTN** (82.66%)[a]			**ELE** (74.23%)[a]		
	Building	RSM[a]	EoL	Building	RSM[a]	EoL	Building	RSM[a]	EoL
Soil[c] and stones[b]	37,040.85	0%	–	37,040.85	0%	–	342,240.00	0%	–
Gravel and rocks[b]	384.77	70%	–	442.44	70%	–	5109.17	70%	–
Iron and steel	769.62	80%	13,041.00	464.30	80%	13,586.31	689.06	80%	11,731.15
Concrete	3893.63	85%	366,033.00	6088.79	85%	360,046.82	1154.24	85%	358,900.83
Wood	635.97	85%	–	1259.74	85%	13.23	216.98	85%	–
Paper and cardboard	161.77	60%	–	145.24	60%	4.07	106.41	60%	–
Plastic	15.72	15%	4.50	97.26	15%	4.45	44.51	15%	4.47
Materials from plaster	–	–	2663.88	–	–	–	–	–	–
Ceramic materials	4923.32	60%	31,089.96	–	–	–	–	–	–
Sand and clay waste	–	–	–	15.70	50%	–	–	–	–
Insulation materials[d]	–	–	–	–	–	–	101.65	100%	1187.64

[a] Recovery rate for recycling % (RSM: Reintegrability of surplus building materials).

[b] 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.

[c] Soil not suitable for recycling as it is very expansive clay soil with a high sulphate content.

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

their reuse benefits the environment by reducing the consumption of raw materials, as well as the consumption of primary energy and water needed for their production. Table 4 contains the materials required for the construction of the building, as well as the percentages for the indicator {21} with the recycled materials that can be integrated in each design alternative. Table 5 presents the waste generated in both the construction and demolition phases, with the percentages for the indicator {22} of surplus recyclable materials.

The social pillar is usually the most difficult to assess. In order to obtain the social performance of the alternatives for each of the categories or criteria considered, the resulting indicator values for each subcategory are calculated according to the transfer functions and questionnaires described in Table 6, assigning a relative importance to each subcategory (Table 2) according to Section 3.3.2.

3.3.2. *Weighting*

The assignment of weights determines the relevance of each element with respect to others included in the same branch. In MIVES the process begins by weighting the lower level of the indicators and ends up by ascending to the level of the criteria. In this study, the local weights have been determined in 14 (of 43) indicators and in 7 (of 20) sub-criteria that need to be standardized to be able to add the variables with different reference units. The remaining elements share units in the different branches until reaching the level of criteria that encompasses them, with each local weighting corresponding to 100%. A direct weighting has been ruled out due to the high number of indicators and in order to concentrate the intervention of the experts on the evaluation of the 9 final criteria. Sensitivity studies have shown that weight variations at the indicator level do not contribute significantly to the determination

Table 6
Social indicators for the subcategories considered in the study.

Indicator	Parameters	Transference function/questionnaire	References
{29}	**T_W = Work time (days)** F = fees (€) K = complexity index [1–2] I_u = update rate in 2020 [1.63]	$T_w = \frac{F}{42 \cdot K \cdot I_u \cdot 8}$	https://www.cacoa.es/calculo-de-costes-de-proyectos/ http://coamalaga.es/
{30}	**T_{SC} = Construction time (days)** * *Precast housing* C_c = construction cost (€)	$T_{sc} = (30.9 \cdot \log_{10} C_c - 130.8) \cdot 5$ $T_{sc}{}^* = (37.4 \cdot \log_{10} C_c - 158.8) \cdot 5$	Martin et al. (2006)
{31}	**T_{SC} = Demolition time (days)** Y_{em} = yield equipment + machinery (hours) m_0 = No. of activities with machinery Y_w = yield of working (hours) a_0 = No. of activities with workers	$T_{sc} = \frac{Y_{em} \cdot \sqrt{m_0} + Y_w \cdot \sqrt{a_0}}{8 \cdot (m_0 + a_0)}$	Own elaboration based on: Valderrama (2009)
{32} {33}	**X_{AC} = Probability of accidents in building (%)** a_p = No. potencial accidents on site construction 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 = accidents rate per sector/day in ref. period Y_{em} = yield equipment + machinery (h) Y_w = yield of working (h) T_{SC} = time on site construction (months) {30}{31}	$I_r = \frac{a_r}{w_a} \cdot 100,000$ $e_s = \frac{Y_{em} + Y_w}{168 \cdot T_{sc}}$ $a_p = \frac{e_s \cdot I_r}{Y_{em} + Y_w}$ $x_{AC} = \frac{a_p}{e_s} \cdot 100$	Own elaboration based on data from: 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
{34}	**X_{CL} = Critical load (safety factor)** P_k = total service loads (KN/m^2) G = Self weight of the affected slab Dl + Ll = dead + live loads (service) P_{ck} = total construction loads(KN/m^2) K = worst load factor on props and slabs 10% G^1 = formwork and shoring weight Tl = transitory loads (workers + accumulation) ^{1} Increase +10% when no.of floors shored up >1	$x_{CL} = \frac{G + (Dl + Ll)}{K \cdot G + (0.1G + Tl)} \geq 1.00$ $If \left\{ x_{CL} = \frac{P_k}{P_{ck}} < 1 \right\} \rightarrow re - shoring$	Grundy and Kabaila (1963) AFECI - Formwork - shoring guide https://www.afeci.es/ UNE 180201:2016
{35}	**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 {38}	$x_{PR} = \frac{\sum I_e \cdot I_c \cdot [(100 - (T_{BS} \cdot 10)]}{3}$	Own elaboration based on data from: National statistical analysis on building pathologies MUSAAT (2013, 2016) https://fundacionmusaat.musaat.es/
{36} {37}	**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)	$\Delta x_{LE} = \left(\frac{E_{Smin}}{P_m + P_w} - 1 \right) \cdot 100$ $E_{Smin} = \frac{\left(P_m \cdot \frac{1}{n} \sum_{i=1}^{n} s_o \right) + \left(P_w \cdot \frac{1}{n} \sum_{i=1}^{n} s_w \right)}{s_{min}}$	Own elaboration based on: Navarro et al. (2018b) Sierra et al. (2017a)
{38}	**T_{BS} = Trust in the building system (scale 1–10)** Self-made qualitative questionnaire	Q1. Quality control and testing required; Q2. Management of the construction co.; Q3. Industrialized assemblies; Q4. Installation time; Q5. Need of auxiliary means; Q6. Usual construction solutions.	
{39}	**A_{EM} = Availability equipment /materials (1−100)** Self-made qualitative questionnaire	P1. Accessibility to equipment and materials; P2. Supplies; P3. Transport distances; P4. Need for auxiliary lifting machinery for structure; P5. Same for walls.	
{40}	**F_R = Flexibility to introduce reforms (1–100)** Self-made qualitative questionnaire	P1. Technical complexity; P2. Customer Satisfaction; P3. Labour Efficiency	
{41} {42}	**U_T = Transmittance ($W/m^{2\circ}K$)** 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
{43}	**$R_{a,tr}$ = 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

of the value of each alternative since their influence is diluted at higher levels in the tree hierarchy (Sánchez-Garrido and Yepes, 2020). In this case, the weighting has been done through working groups with the AHP methodology (described in Section 3.2). The resulting weights for these indicators and sub-criteria are shown in brackets in Table 2.

3.3.3. *Construction of utility or value functions*

MIVES method is based on utility or value functions that determine the degree of satisfaction of an alternative with respect to a criterion. These functions present different forms depending on the relation between the valuation and the degree of satisfaction. In the environmental {21,22} and social {32–43} indicators, specific functions are defined that convert physical units into common units (values), and whose mathematical expression depends on the parameters adopted. Eq. (14) shows the general expression of the value function used to evaluate satisfaction with respect to the indicator:

$$V_i = B \cdot \left[1 - e^{-k_i}\left(|x - x_{min}|/c_i\right)^{P_i}\right] \tag{14}$$

Variable B is defined according to Eq. (15) to maintain the range of the function {0–1} according to the five parameters described in Table 7:

$$B = 1/\left[1 - e^{-k_i}\left(|x_{max} - x_{min}|/c_i\right)^{P_i}\right] \tag{15}$$

where $X_{\min}$ is the abscissa whose response is equal to zero for increasing functions (for decreasing functions, the minimum value is $X_{\max}$); and X is the abscissa of the evaluated indicator that generates a V_i value (variable for each alternative); P_i ($0 < P < \infty$) defines the shape of the curve; C_i in curves with $P_i > 1$, sets the value of the abscissa for the inflection point; and K_i ($0 < K < 1$) the value of the ordinate for the inflection point.

This function is used to transform the quantification or qualification of an attribute into a dimensionless variable between 0 and 1. It is important to assign a correct form to the value function and, above all, to correctly establish the points of maximum and minimum satisfaction. As in the assignment of weights in Section 3.3.2, MIVES has been used in 14 of the 43 indicators to normalize those whose higher levels of sub-criteria do not allow to sum the scores between indicators with heterogeneous units. Table 8 summarizes the parameterization of all the value functions used in this study, as well as the value of the indicators once they are weighted.

Once the alternatives in each of the proposed indicators have been evaluated, each sub-criterion is evaluated. The evaluation is carried out according to Eq. (16), based on the values obtained for the indicators multiplied by their respective weights, obtaining through the sum of all the results of the indicators the value of each sub-criteria:

$$V_{GkCn} = \sum\nolimits_{i=1}^{j} W_{IiGkCn} \cdot V_{IiGkCn} \tag{16}$$

where V_{GkCn} represents the value of sub-criterion *k* of criterion *n*, W_{IiGkCn} stands the weight of indicator *i* of sub-criterion *k* of criterion *n* and V_{IiGkCn} is the value of indicator *i* from sub-criterion *k* of criterion *n*.

Similarly, the values of the criteria are formed following Eq. (17) from the sum of the values of the sub-criteria associated with a given criteria multiplied by their weights:

$$V_{Cn} = \sum\nolimits_{k=1}^{z} W_{GkCn} \cdot V_{GkCn} \tag{17}$$

where V_{Cn} represents the value of criterion *n*, W_{GkCn} stands for weight of sub-criterion *k* of criterion *n* and V_{GkCn} is the value of sub-criterion *k* of criterion *n*.

3.4. Stage 4: Selection of the best alternative

The objective in this stage is to select which of the alternatives perform best along their life cycle from the perspective of sustainability, according to the boundary conditions identified in the analysis phase.

Table 7
Typical ranges of parameters defining value functions.

Shape of function	P_i	K_i
Concave / Essential	< 0.75	> 0.9
Linear / Proporcionate	1	0
Convex / Normative	> 2	< 0.1
S-Shaped (soft)	$2 < P_i < 4$	$0.1 < K_i < 0.2$
S-Shaped (steep)	$4 < P_i < 10$	$0.1 < K_i < 0.2$

Once the final criteria scores are obtained in the hierarchical assessment structure, the VIKOR technique (Opricovic and Tzeng, 2004) is applied to compare sustainability among the different design options. The method ranks and determines a compromise solution from a finite set of viable alternatives that have conflicting criteria measured with different units. Once the decision matrix that makes up the problem has been composed, the positive ideal solution PIS (A*) and the negative ideal solution NIS (A^-) of the *n* criteria are identified for each alternative, and each score is then normalized:

$$r_{ij}' = \left(r_i^* - r_{ij}\right)/\left(r_i^* - r_i^-\right) \tag{18}$$

The crisp weights (w_i) for each criterion, obtained from the neutrosophic group AHP described in Section 3.2.5, are then assigned. The VIKOR method considers the Manhattan (L_1) and Chebyshev (L_∞) distances, according to the *S* and *R* indices, respectively. *S* is the aggregation of the values of the alternatives according to the *L1* metric, which takes into account the group utility of the criteria. *R* uses the metric L_∞, which takes into account the individual minimum of each criterion to find the maximum distance from the alternative to the ideal solution, i.e. the worst possible case:

$$S_j = \sum_{i=1}^{m} w_i\left(r_i^* - r_{ij}\right)/\left(r_i^* - r_i^-\right) \tag{19}$$

$$R_j = max\left[w_i\left(r_i^* - r_{ij}\right)/\left(r_i^* - r_i^-\right)\right] \tag{20}$$

The final ranking is obtained by determining the relative distance of each Q_j alternative according to the equation:

$$Q_j = \nu \cdot \frac{\left(S_j - S^*\right)}{S^- - S^*} + (1 - \nu) \cdot \frac{\left(R_j - R^*\right)}{R^- - R^*} \tag{21}$$

where $S^* = \min S_j$, $S^- = \max S_j$, $R^* = \min R_j$, $R^- = \max R_j$, weighted through the variable [0,1] that determines the importance of each distance, balancing the indexes *S* and *R*. For comparative purposes, the *Q* values have been calculated as well with crisp value of Q_j, $j = 1,2, \ldots,n$, as:

$$Q_j = \left(Q_{j1} + 2Q_{j5} + Q_{j9}\right)/4 \tag{22}$$

As the compromise solution depends on the value that the decision-maker wants to give to each criterion, the combined use of VIKOR and the NAHP-G provides a powerful tool for obtaining the closest trade-off to the ideal point of decision-makers' judgments (Chatterjee and Chakraborty, 2016), since the vagueness of human thinking and the uncertainties inherent to experts' subjective judgments have previously been integrated into the multi-criteria decision process through the use of neutrosophic logic.

4. Results and discussion

4.1. Neutrosophic group AHP results

This section examines the results of the neutrosophic group weighting methodology described in Section 3.2. A seminar composed of three experts has been consulted. In order to maximize the DM contribution while minimizing subjectivity, a very simple data inputs procedure has been implemented. The intervention of each expert is limited to making pairwise comparisons, assigning values in relation to the Saaty scale, among the nine impact categories that constitute the decision criteria initially defined. The process shall be repeated as many times as necessary until the resulting comparison matrix becomes consistent, i.e. $CR < 10\%$. It should be noted that in the comparison matrix A_{DMk} each a_{ij} element represents the judgment emitted by the DM_k decision maker when comparing the relevance of decision criterion *i* with criterion *j*. The identification number of each criterion from C1 to C9 is according to Table 2. Each DM_k must also complete a matrix SC_{DMk}

Table 8
Calculator of the MIVES method based on utility or value functions.

Indicator[a]	Trend	Graphs and parameters of the value function						Alternatives response		Weighted indicator values				
	Optimal	Function	P_i	K_i	C_i	X_{min}	X_{max}	REF	YTN	ELE	Weights	REF	YTN	ELE
{21}	Max.	Concave	0.75	0.9	50	0	70	0.53	17.85	30.82	33.33%	0.01	0.17	0.23
{22}	Max.	Concave	0.3	0.9	73	70	100	72.22	82.66	74.23	66.67%	0.36	0.55	0.43
{32}	Min.	S-Shaped	4	0.2	50	0	100	30.73	42.15	39.60	50.00%	0.27	0.16	0.18
{33}	Min.	S-Shaped	4	0.2	50	0	100	26.44	22.43	31.10	50.00%	0.32	0.36	0.27
{34}	Max.	Convex	2	0.1	0.5	0	1	0.77	1.12	0.86	33.33%	0.21	0.40	0.26
{35}	Min.	S-Shaped	6	0.2	50	0	100	39.77	29.01	30.70	66.67%	0.30	0.54	0.51
{36}	Max.	Concave	0.4	0.9	1603	1512	2427	2248	1635	1631	75.00%	0.71	0.40	0.40
{37}	Max.	Concave	0.4	0.9	2197	2072	3325	2540	2984	2163	25.00%	0.19	0.23	0.11
{38}	Max.	Linear	1	0.01	1.9	1	10	3.83	7.00	5.17	16.67%	0.05	0.11	0.08
{39}	Max.	Linear	1	0.01	10	0	100	80	45	15	83.33%	0.67	0.39	0.13
{40}	Max.	Linear	1	0.01	10	0	100	100	10	40	100%	1	0.10	0.41
{41}	Min.	Concave	0.6	0.9	0.23	0.19	0.25	0.25	0.24	0.12	33.33%	0.03	0.14	0.47
{42}	Min.	Concave	0.6	0.9	0.27	0.23	0.29	0.29	0.29	0.22	33.33%	0.03	0.03	0.36
{43}	Max.	Concave	0.5	0.9	35	33	53	45	38	41	33.34%	0.28	0.19	0.24

[a] Indicators 21 and 22 belong to the environmental dimension and indicators 32 to 43 to the social dimension.

containing the certainty expressed in units between 0 and 1 for each of its judgments. In the same way, each SC_{ij} element of the certainty matrices represents the certainty expressed by the $\mathrm{DM_k}$, when comparing the criterion *i* with the criterion *j*, in the same order as above. The comparison and the certainty matrices of each $\mathrm{DM_k}$ are presented below:

$$\mathbf{A}_{DM_1} = \begin{pmatrix} 1 & 5 & 9 & 1/3 & 1/2 & 3 & 1/3 & 4 & 1/2 \\ 1/5 & 1 & 7 & 1/5 & 1/3 & 1/3 & 1/5 & 3 & 1/4 \\ 1/9 & 1/7 & 1 & 1/7 & 1/5 & 1/6 & 1/8 & 1/5 & 1/6 \\ 3 & 5 & 7 & 1 & 2 & 4 & 1/2 & 5 & 1/2 \\ 2 & 3 & 5 & 1/2 & 1 & 3 & 1/2 & 3 & 1/2 \\ 1/3 & 3 & 6 & 1/4 & 1/3 & 1 & 1/4 & 4 & 1/4 \\ 3 & 5 & 8 & 2 & 2 & 4 & 1 & 3 & 1 \\ 1/4 & 1/3 & 5 & 1/5 & 1/3 & 1/4 & 1/3 & 1 & 1/3 \\ 2 & 4 & 6 & 2 & 2 & 4 & 1 & 3 & 1 \end{pmatrix}$$

$$\mathbf{SC}_{\mathbf{DM_1}} = \begin{bmatrix} 1 & 0.8 & 0.8 & 0.7 & 0.5 & 0.4 & 0.7 & 0.5 & 0.6 \\ 0.8 & 1 & 0.7 & 0.8 & 0.6 & 0.6 & 0.8 & 0.6 & 0.7 \\ 0.8 & 0.7 & 1 & 0.9 & 0.7 & 0.8 & 0.9 & 0.7 & 0.8 \\ 0.7 & 0.8 & 0.9 & 1 & 0.3 & 0.7 & 0.5 & 0.8 & 0.5 \\ 0.5 & 0.6 & 0.7 & 0.3 & 1 & 0.5 & 0.6 & 0.7 & 0.4 \\ 0.4 & 0.6 & 0.8 & 0.7 & 0.5 & 1 & 0.8 & 0.3 & 0.2 \\ 0.7 & 0.8 & 0.9 & 0.5 & 0.6 & 0.8 & 1 & 0.8 & 0.7 \\ 0.5 & 0.6 & 0.7 & 0.8 & 0.7 & 0.3 & 0.8 & 1 & 0.6 \\ 0.6 & 0.7 & 0.8 & 0.5 & 0.4 & 0.2 & 0.7 & 0.6 & 1 \end{bmatrix}$$

$$\mathbf{A}_{\mathbf{DM_2}} = \begin{pmatrix} 1 & 2 & 6 & 1/3 & 1/5 & 3 & 1/3 & 4 & 1/6 \\ 1/2 & 1 & 7 & 1/4 & 1/4 & 2 & 1/3 & 4 & 1/4 \\ 1/6 & 1/7 & 1 & 1/8 & 1/8 & 1/7 & 1/9 & 1/5 & 1/9 \\ 3 & 4 & 8 & 1 & 2 & 4 & 1/3 & 5 & 1/2 \\ 5 & 4 & 8 & 1/2 & 1 & 5 & 2 & 4 & 1 \\ 1/3 & 1/2 & 7 & 1/4 & 1/5 & 1 & 1/4 & 1 & 1/4 \\ 3 & 3 & 9 & 3 & 1/2 & 4 & 1 & 4 & 1/2 \\ 1/4 & 1/4 & 5 & 1/5 & 1/4 & 1 & 1/4 & 1 & 1/4 \\ 6 & 4 & 9 & 2 & 1 & 4 & 2 & 4 & 1 \end{pmatrix}$$

$$\mathbf{SC}_{\mathbf{DM_2}} = \begin{bmatrix} 1 & 0.9 & 0.8 & 0.6 & 0.7 & 0.7 & 0.6 & 0.4 & 0.7 \\ 0.9 & 1 & 0.8 & 0.6 & 0.6 & 0.7 & 0.5 & 0.6 & 0.7 \\ 0.8 & 0.8 & 1 & 0.5 & 0.7 & 0.8 & 0.9 & 0.7 & 0.8 \\ 0.6 & 0.6 & 0.5 & 1 & 0.9 & 0.7 & 0.7 & 0.8 & 0.5 \\ 0.7 & 0.6 & 0.7 & 0.9 & 1 & 0.8 & 0.7 & 0.7 & 0.4 \\ 0.7 & 0.7 & 0.8 & 0.7 & 0.8 & 1 & 0.8 & 0.4 & 0.3 \\ 0.6 & 0.5 & 0.9 & 0.7 & 0.7 & 0.8 & 1 & 0.7 & 0.7 \\ 0.4 & 0.6 & 0.7 & 0.8 & 0.7 & 0.4 & 0.7 & 1 & 0.8 \\ 0.7 & 0.7 & 0.8 & 0.5 & 0.4 & 0.3 & 0.7 & 0.8 & 1 \end{bmatrix}$$

$$\mathbf{A}_{\mathbf{DM_3}} = \begin{pmatrix} 1 & 2 & 9 & 1/3 & 1/3 & 5 & 1/3 & 3 & 1/3 \\ 1/2 & 1 & 9 & 1/3 & 1/3 & 3 & 1/3 & 3 & 1/3 \\ 1/9 & 1/9 & 1 & 1/6 & 1/7 & 1/3 & 1/8 & 1/5 & 1/6 \\ 3 & 3 & 6 & 1 & 1 & 3 & 1/2 & 6 & 1 \\ 3 & 3 & 7 & 1 & 1 & 5 & 1/3 & 3 & 1 \\ 1/5 & 1/3 & 3 & 1/3 & 1/5 & 1 & 1/3 & 3 & 1/3 \\ 3 & 3 & 8 & 2 & 3 & 3 & 1 & 3 & 1 \\ 1/3 & 1/3 & 5 & 1/6 & 1/3 & 1/3 & 1/3 & 1 & 1/5 \\ 3 & 3 & 6 & 1 & 1 & 3 & 1 & 5 & 1 \end{pmatrix}$$

$$\mathbf{SC}_{\mathbf{DM_3}} = \begin{bmatrix} 1 & 0.7 & 0.7 & 0.6 & 0.4 & 0.3 & 0.6 & 0.4 & 0.5 \\ 0.7 & 1 & 0.6 & 0.7 & 0.5 & 0.5 & 0.7 & 0.5 & 0.6 \\ 0.7 & 0.6 & 1 & 0.8 & 0.8 & 0.6 & 0.9 & 0.6 & 0.8 \\ 0.6 & 0.7 & 0.8 & 1 & 0.4 & 0.8 & 0.6 & 0.7 & 0.5 \\ 0.4 & 0.5 & 0.8 & 0.4 & 1 & 0.7 & 0.8 & 0.8 & 0.6 \\ 0.3 & 0.5 & 0.6 & 0.8 & 0.7 & 1 & 0.5 & 0.2 & 0.2 \\ 0.6 & 0.7 & 0.9 & 0.6 & 0.8 & 0.5 & 1 & 0.8 & 0.7 \\ 0.4 & 0.5 & 0.6 & 0.7 & 0.8 & 0.2 & 0.8 & 1 & 0.3 \\ 0.5 & 0.6 & 0.8 & 0.5 & 0.6 & 0.2 & 0.7 & 0.3 & 1 \end{bmatrix}$$

Each expert has been parameterized according to Section 3.2.2 based on experience, preferences, knowledge and achievements both in the architectural and in the engineering field. Table 9 shows the profiles with the evaluated competences of each expert, the resulting characterization triad $\langle \delta, \theta, \varepsilon \rangle$ and their relevance ϕ. To assign the weight or relevance that each DM contributes in the sustainability analysis, the TOPSIS method for multiattribute group decision-making under single-valued neutrosophic environment is used, according to the methodology explained in Section 3.2.4.

From both the comparison matrices A_{DMk} and the certainty matrices SC_{DMk}, the weights are obtained by means of AHP. The matrices of each $\mathrm{DM_k}$ are transformed into TNN matrices defining the intervals of the judgments emitted, according to Table 3, from the $\mathrm{SC_{DMk}}$ certainty matrix resulting from the judgments from each expert. Following the steps of the methodology described in Section 3.2.3, the TNN weights of each $\mathrm{DM_k}$ are obtained for each of the 9 criteria, whose results are presented in Table 10.

After having assigned the particular relevance of each expert's assessment, according to Section 3.2.4, the individual neutrosophic weights resulting from the judgments of each $\mathrm{DM_k}$ are added. To obtain the crisp weights, the deneutrosophization and defuzzification technique described in Section 3.2.5 are applied. Fig. 4 illustrates the resulting fuzzy weights after the deneutrosophication process of the aggregated weights. The methodology allows the mathematical treatment of the semantic values and captures the information implicit in the judgments, considering the uncertainty in the comparisons by pairs in terms of veracity, falsehood and indetermination. The method proposed by Chu and Tao (2002) is applied here to convert the generalized

Table 9
Characterization and relevance among the expert group.

Characterization of the *k*-Decision Makers	Attribute	DM_1	DM_2	DM_3
Expert's Competences				
Years of professional activity	PA_k	18	6	32
Years sustainability experience	SE_k	2	4	10
Advanced Degree (BDs, MSc, PhD)	AD_k	2	3	3
Knowledge in field				
Construction Engineering	K_{C1}	4	4	4
Structural Design	K_{C2}	5	5	4
Economic Issues	K_{C3}	4	4	4
Environmental issues	K_{C4}	2	3	4
Social Issues	K_{C5}	3	3	3
Other merits	K_{C6}	4	4	5
Research work				
Corresponding author JCR	R_{C1}	1	6	12
Lectures at conferences	R_{C2}	2	4	67
Books or chapters	R_{C3}	3	0	9
Expert's credibility	δ_{DMk}	**0.523**	**0.562**	**0.900**
Specific credibility (TNN)				
Economic	δ_{ECk}	**0.800**	**0.800**	**0.800**
Environmental	δ_{ENk}	**0.400**	**0.600**	**0.600**
Social	δ_{SOk}	**0.600**	**0.600**	**0.600**
General knowledge	δ_{GKk}	0.867	0.867	0.867
Research Gate	δ_{RGk}	0.148	0.262	1.000
Sustainability contribution	δ_{SCk}	0.535	0.625	0.898
Economy - environmental	δ_{EEk}	**0.321**	**0.437**	**0.719**
Environmental -social	δ_{ESk}	**0.267**	**0.375**	**0.629**
Social -Economy	δ_{SEk}	**0.374**	**0.437**	**0.629**
Expert's confidence on his/her ability to evaluate sustainability				
Expert's mean self confidence	SC_{DMk}	0.679	0.709	0.640
Expert's mean indeterminacy	θ_{DMk}	**0.321**	**0.291**	**0.360**
Inconsistencies/errors intrinsic to expert's evaluation process:				
Expert's incoherency	ε_{DMk}	**0.875**	**0.827**	**0.766**
Relevance of each DM (δ, θ, ε)				
Weight of each expert	ϕ_{DMk}	**0.296**	**0.325**	**0.380**

resulting fuzzy weights into conventional crisp weights. Table 15 shows the results with the crisp weights for each criterion after applying the defuzzification.

Unlike AHP with conventional logic, the use of N-AHP allows non-probabilistic uncertainties to be considered in the decision-making process. Modeling uncertain preferences as neutrosophic sets allows consideration of truthfulness, falsehood, and member indeterminacy as independent functions of each other. Despite all the mathematical complexity inherent to the internal process, the practical application is relatively simple, as little input is required from respondents. The proposed method for obtaining the crisp weights is characterized by its ease of use for DMs, since they only have to complete a conventional comparison matrix. The only difference with the conventional AHP input procedure is that, additionally, they have to express the certainty (between 0 and 1) of each judgment issued between the criteria compared above.

4.2. Sustainability results

The economic, environmental and social indicators were selected in accordance with the guidelines set out in Section 3.1. The responses to the 43 indicators that value sustainability are evaluated by means of Eqs. (16) and (17) in an ascending hierarchy through the requirements tree until they become 9 criteria belonging to economic (Table 11), environmental (Table 12) and social (Table 13) dimensions. According to the methodology explained, the results obtained for each of the 3 alternatives are as follows:

To aggregate the nine impact categories into a single sustainability score for each alternative, the VIKOR technique is used, which uses the crisp weights (Fig. 4) obtained from the AHP neutrosophic group methodology. With N-VIKOR, the alternative closest to the ideal point is obtained by classifying the solutions according to Eqs. (18) to (22) to select the best of them (Table 14). The results of conventional AHP-VIKOR gives the "technological" ELE alternative as the preferred solution from a sustainable point of view, followed by the "industrialized" YTN option and finally the "traditional" REF design. ELE is based on generating double or multiple wall faces of reinforced concrete, braced by connectors also made of concrete. For its construction, the supports are formworked with lightweight boards joined with steel connectors, and confining the insulation inside. Then the steel meshes are fixed on each side and the concrete covering the reinforcements is projected, forming the wall. The philosophy is to achieve greater resistance with the same amount of material by optimizing the concrete volume needed by increasing the inertia of the sections.

The REF alternative only achieves the best score in the C8 social criterion with a high degree of acceptance because of the possibility of introducing reforms as well as the availability of materials and equipment, due to the local ease of finding the usual technical means. This alternative performs reasonably well economically for a traditional construction system well known in the sector. The economic response of the three alternatives has been similar in the demolition phase, with C3 being a less relevant criterion in this type of structure. Economic criteria show more differentiation between designs as we move closer to the initial stages of the life cycle.

The YTN alternative provides the best response to the environmental requirement with criteria C4 (resources used) and C5 (environmental footprint) which, with a weight of 17.16% and 15.98% respectively, are two of the most relevant criteria. This is due to the manufacture of autoclaved aerated concrete with very low primary energy consumption, using 100% recyclable mineral components. In the social field, this alternative also reaches the maximum score in the criteria C6 (lead times) and C7 (safety), the latter, with 20.71%, being the most important of all. When it comes to lead times, this alternative has no competition in terms of speed, with a construction time of 70 days thanks to

Table 10
Matrices of each expert's judgment (TNN_{DMk}) transformed into neutrosophic triangular weights ($TNNW_{DMk}$).

Criterion	Experts (DM_k)		
	DM_1	DM_2	DM_3
(C1) Construction cost	⟨(0.03,0.11,0.52);(0.47,0.36,0.80)⟩	⟨(0.02,0.07,0.24);(0.55,0.31,0.76)⟩	⟨(0.02,0.10,0.52);(0.73,0.46,0.71)⟩
(C2) Service life cost	⟨(0.02,0.05,0.16);(0.47,0.28,0.80)⟩	⟨(0.02,0.06,0.24);(0.55,0.30,0.76)⟩	⟨(0.02,0.08,0.43);(0.73,0.37,0.71)⟩
(C3) End-of-life cost	⟨(0.01,0.02,0.04);(0.47,0.19,0.80)⟩	⟨(0.01,0.01,0.03);(0.55,0.23,0.76)⟩	⟨(0.01,0.02,0.05);(0.73,0.26,0.71)⟩
(C4) Use of materials	⟨(0.05,0.18,0.76);(0.36,0.35,0.80)⟩	⟨(0.05,0.16,0.55);(0.49,0.32,0.76)⟩	⟨(0.04,0.17,0.74);(0.73,0.34,0.71)⟩
(C5) Ecological footprint	⟨(0.02,0.12,0.66);(0.36,0.44,0.80)⟩	⟨(0.06,0.20,0.61);(0.49,0.30,0.76)⟩	⟨(0.04,0.16,0.64);(0.73,0.36,0.71)⟩
(C6) Lead times	⟨(0.02,0.07,0.35);(0.47,0.47,0.80)⟩	⟨(0.02,0.04,0.19);(0.57,0.35,0.76)⟩	⟨(0.01,0.05,0.31);(0.72,0.54,0.71)⟩
(C7) Safety	⟨(0.05,0.22,0.73);(0.46,0.26,0.80)⟩	⟨(0.05,0.17,0.59);(0.52,0.28,0.76)⟩	⟨(0.05,0.21,0.77);(0.65,0.28,0.71)⟩
(C8) Acceptance degree	⟨(0.01,0.04,0.19);(0.46,0.36,0.80)⟩	⟨(0.01,0.04,0.13);(0.52,0.35,0.76)⟩	⟨(0.01,0.04,0.23);(0.65,0.47,0.71)⟩
(C9) Functionality	⟨(0.03,0.20,0.77);(0.46,0.44,0.80)⟩	⟨(0.05,0.23,0.74);(0.52,0.38,0.76)⟩	⟨(0.03,0.18,0.83);(0.65,0.48,0.71)⟩

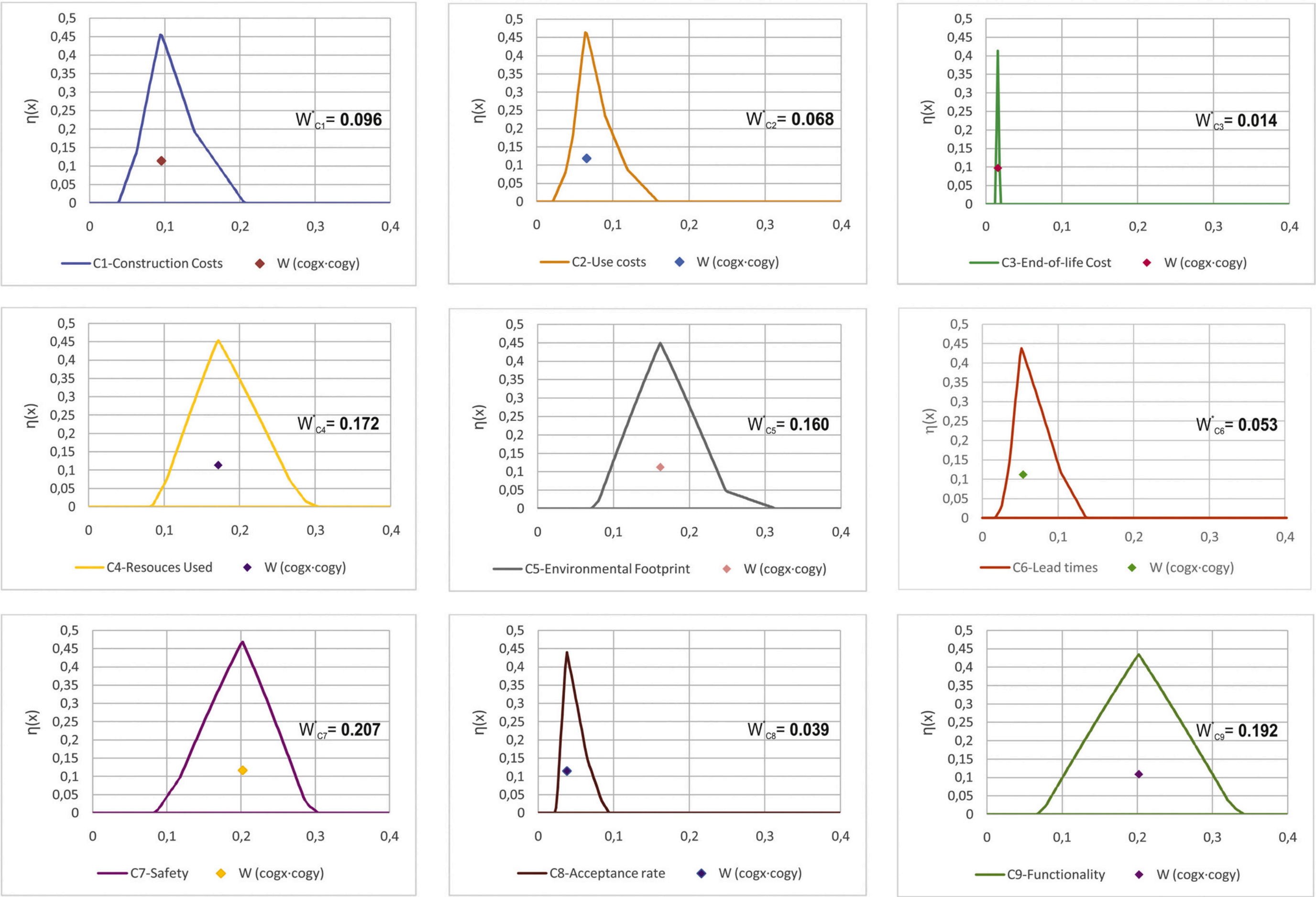

Fig. 4. Aggregated weights of each criterion after deneutrosophication.

Table 11
Responses of the Economic values for the sub-criteria of the single-family house.

	Economic Sub-criteria	**Alt.**	**REF (traditional)**				**YTN (prefabricated)**				**ELE (technology)**			
		Ind.	V_{scrit}	ΣV_{scrit}	W_{ijk}	$\mathbf{\Sigma V_{crit}}$	V_{scrit}	ΣV_{scrit}	W_{ijk}	$\mathbf{\Sigma V_{crit}}$	V_{scrit}	ΣV_{scrit}	W_{ijk}	$\mathbf{\Sigma V_{crit}}$
C1	Production	{1}	16.07				21.74				18.33			
		{2}	6.89				9.32				5.47			
		{3}	8.44	31.39	100%		10.95	42.01	100%		7.02	30.82	100%	
	Materialization	{4}	191.90	191.90	100%		248.86	248.86	100%		159.48	159.48	100%	
	Waste management	{5}	0.26				0.26				1.76			
		{6}	0.12				0.12				0.84			
		{7}	0.11				0.08				0.03			
		{8}	0.16	0.66	100%	**223.95**	0.14	0.60	100%	**291.47**	0.05	2.68	100%	**192.98**
C2	Prevention	{9}	0.12				0.87				0.00			
		{10}	6.49				4.25				6.49			
		{11}	3.25				1.46				3.25			
		{12}	0.79				4.03				0.79			
		{13}	0.87	11.52	100%		6.41	17.02	100%		0.00	10.53	100%	
	Maintenance	{14}	7.40	7.40	100%	**18.92**	5.23	5.23	100%	**22.25**	6.76	6.76	100%	**17.29**
C3	Demolition	{15}	88.14	88.14	100%		76.98	76.98	100%		75.43	75.43	100%	
	Pre-treatment of waste	{16}	10.83				9.61				9.63			
		{17}	0.01				0.00				0.01			
		{18}	4.69	15.54	100%		4.61	4.22	100%		4.60	14.24	100%	
	Inert waste management	{19}	4.27				3.88				3.85			
—		{20}	5.25	9.52	100%	**113.20**	4.62	8.50	100%	**99.70**	4.65	8.50	100%	**98.16**

Table 12
Responses of the Environmental values for the sub-criteria of the single-family house.

	Environmental Sub-criteria	**Alt.**	**REF (traditional)**				**YTN (prefabricated)**				**ELE (technology)**			
		Ind.	V_{scrit}	ΣV_{scrit}	W_{ijk}	ΣV_{crit}	V_{scrit}	ΣV_{scrit}	W_{ijk}	ΣV_{crit}	V_{scrit}	ΣV_{scrit}	W_{ijk}	ΣV_{crit}
C4	Recycling	{21}[a]	0.01				0.17				0.23			
		{22}[a]	0.36	0.38	100%	**0.38**	0.55	0.72	100%	**0.72**	0.43	0.65	100%	**0.65**
C5	Endpoint scores (Construction)	{23}	2398				1505				2798			
		{24}	2957				2574				2353			
		{25}	2744	8099	100%		1627	5705	100%		1770	6921	100%	
	Endpoint scores (EoL)	{26}	129.61				131.67				195.05			
		{27}	816.77				808.73				864.44			
		{28}	252.84	1199	100%	**9298**	255.54	1196	100%	**6901**	249.80	1309	100%	**8230**

[a] Standardization of indicator values with different units, according to the MIVES method, obtained from Table 7 and weighting according to Table 2.

Table 13
Responses of the Social values for the sub-criteria of the single-family house.

	Social Sub-criteria	**Alt.**	**REF (traditional)**				**YTN (prefabricated)**				**ELE (technology)**			
		Ind.	V_{scrit}	ΣV_{scrit}	W_{ijk}	ΣV_{crit}	V_{scrit}	ΣV_{scrit}	W_{ijk}	ΣV_{crit}	V_{scrit}	ΣV_{scrit}	W_{ijk}	ΣV_{crit}
C6	Conception	{29}	9.81	9.81	100%		12.73	12.73	100%		11.70	11.70	100%	
	Building stage	{30}	98.13	98.13	100%		70.21	70.21	100%		85.72	85.72	100%	
	EoL	{31}	39.27	39.27	100%	**147.21**	46.06	46.06	100%	**129.00**	42.09	42.09	100%	**139.51**
C7	Occupation risk prevention	{32}[a]	0.27				0.16				0.18			
		{33}[a]	0.32	0.59	33.33%		0.36	0.51	33.33%		0.27	0.45	33.33%	
	Building process	{34}[a]	0.21				0.33				0.26			
		{35}[a]	0.30	0.52	66.67%	**0.54**	0.54	0.87	66.67%	**0.75**	0.51	0.76	66.67%	**0.66**
C8	Developer	{36}[a]	0.71				0.40				0.40			
		{37}[a]	0.19	0.89	25.00%		0.23	0.63	25.00%		0.11	0.51	25.00%	
	Construction company	{38}[a]	0.05				0.11				0.08			
		{39}[a]	0.67	0.73	75.00%	**0.77**	0.39	0.50	75.00%	**0.53**	0.13	0.21	75.00%	**0.28**
C9	Constructability	{40}[a]	1	1	14.29%		0.10	0.10	14.29%		0.41	0.41	14.29%	
	User's comfort and health	{41}[a]	0.03				0.14				0.33			
		{42}[a]	0.03				0.03				0.33			
		{43}[a]	0.28	0.34	85.71%	**0.44**	0.19	0.36	85.71%	**0.33**	0.24	0.90	85.71%	**0.83**

[a] Standardization of indicator values with different units, according to the MIVES method, obtained from Table 7 and weighting according to Table 2.

Table 14
Multi-criteria optimization and compromise solution with the VIKOR method.

Scope	**Criteria**	Optimum value [+] Lousy value [−]			**Optimal**	Standardized Distance[1]			**Weights NSs**	Weighted standardized distance[a]		
		REF	**YTN**	**ELE**		**REF**	**YTN**	**ELE**		**REF**	**YTN**	**ELE**
Economic	C1	223.95	291.47-	192.98+	Min.	0.314	1	0	0.096	0.030	0.096	0
	C2	18.92	22.25-	17.29+	Min.	0.328	1	0	0.067	0.022	0.068	0
	C3	113.20-	99.70	98.16+	Min.	1	0.102	0	0.013	0.014	0.001	0
Environmental	C4	0.38-	0.72+	0.65	Max.	1	0	0.192	0.171	0.172	0	0.033
	C5	9298-	6901+	8230	Min.	1	0	0.554	0.159	0.160	0	0.089
Social	C6	147.21-	129.00+	139.51	Min.	1	0	0.577	0.052	0.053	0	0.030
	C7	0.54-	0.75+	0.66	Max.	1	0	0.442	0.207	0.207	0	0.092
	C8	0.77+	0.53	0.28-	Max.	0	0.489	1	0.038	0	0.019	0.039
	C9	0.44	0.33-	0.83+	Max.	0.780	1	0	0.192	0.150	0.193	0
				Manhattan distance	S_j	0.808	0.377	0.282				
				∞ distance	R_j	0.207	0.193	0.092				
				FINAL SCORE[a]	Q_j	**REF**	**YTN**	**ELE**	ν			
					Q_{j1}	1	0.804	0	0,10			
					Q_{j5}	1	0.527	0	0,50			
					Q_{j9}	1	0.250	0	0,90			

[a] The shorter the distance, the better.

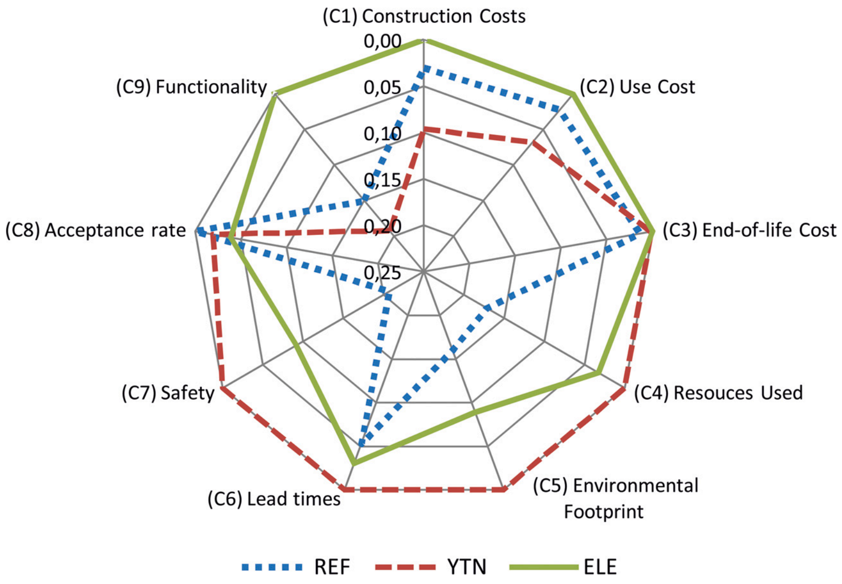

Fig. 5. Results of the sustainability assessment comparing the criteria between the three alternatives.

industrialization and almost dry assembly. However, in this evaluation on a single-family home scale, time has a low weight compared to other more important issues for the group of experts. In terms of safety, it represents with 22.43% the lowest probability of accidents in the long term. This is the only alternative with a construction safety coefficient higher than 1 and only 29.01% statistical possibility of suffering some kind of pathological process.

ELE alternative performs the best in the economic dimension, with a discreet total weight of 17.77%. This is due to the fact that the system uses hollow structures that allow maximum savings in material and minimum weight, with greater use of the mechanical capacity of the concrete. Due to material savings, very rigid structures are obtained but at a lower cost than conventional reinforced concrete structures. From the social point of view, it also reaches the maximum score in the C9 criterion (functionality), with a relevance of 19.25% justified in the search for functional quality throughout the life cycle of the building. Among the three alternatives considered, ELE also performs better in terms of thermo-acoustic comfort. As the system uses EPS as a lost formwork by filling the gap between the double concrete walls, the thermal insulation thickness is much higher than the minimum required by the codes.

Fig. 5 shows how the ELE alternative distributes the area more evenly without having the highest score on most criteria. In terms of area, ELE covers 77.23% of the graph, compared to 71.52% of YTN and 37.64% of REF. It can be concluded that the sustainability performance of a building shall not be based on the sole consideration of its performance in the various sustainability dimensions independently, but shall rely on the simultaneous consideration of the three at a time. Similar conclusions were drawn in the field of bridges design (Navarro et al. (2020b). In this case, a prefabricated and industrialized design with the best environmental performance in the evaluation and the best score in the most relevant criteria with 59.13% of the global weight, has been surpassed by an efficient design using reinforced concrete technology. The reason is that the latter contributes in a more balanced way to the three dimensions of sustainability. In summary, it is necessary that the adequate sustainable design of building structures assumes a holistic design perspective and considers the three dimensions of sustainability simultaneously.

4.3. *Non-probabilistic uncertainty analysis*

To compare with the crisp weights, the midpoints of the TNN are recovered, which are equivalent to the weight according to the traditional AHP (Table 15). This allows the detection of the most subjective criteria among those that characterize sustainability. This is the case of criterion C3 (End of life cost), whose resulting $COG_x{\cdot}COG_y$ weight has a variation of 11.91% with respect to a conventional AHP. Such finding is consistent with the fact that very less attention is usually paid to the impacts associated to the EoL phase in sustainability assessments. Consequently, the uncertainties of the DM when judging the relevance of this particular life cycle stage are greater when compared to other stages. Therefore, special care must be taken when assessing the impacts of the EoL stage on the basis of conventional AHP. In C7 (safety) and C9 (functionality), although the variation is minor (4.57%) the capture of information implicit in the judgments is decisive, since they are the criteria with the greatest weight in the evaluation. At the other extreme, the criteria with less subjectivity are C1 (construction cost), C4 (resources used) and C5 (environmental footprint) with variations of 1.71%, 0.19% and 1.20%, respectively. Such differences in the weights with respect to a conventional AHP are virtually negligible showing that sustainability, among experts, is clearly associated with economic cost and environmental impact. When other different criteria come into play in the assessment, the variations in the weights increase the greater the uncertainty. In view of the results, conventional AHP may fall short

Table 15
Weights resulting from the 9 criteria after defuzzification and comparison with conventional AHP.

Method	Reference	C1	C2	C3	C4	C5	C6	C7	C8	C9
AHP	$m_{\text{criteria }(i)}$	0.095	0.065	0.015	0.171	0.162	0.051	0.202	0.038	0.202
Chu and Tao (2002)	$\boldsymbol{W}^{*}_{(\mathbf{COGx \cdot COGy})}$	**0.096**	**0.068**	**0.014**	**0.172**	**0.132**	**0.053**	**0.207**	**0.039**	**0.192**
$W^{*}_{(\mathrm{COGx \cdot COGy})}$	vs $m_{\text{criteria }(i)}$	−1.71%	−4.95%	11.91%	−0.19%	1.20%	−2.88%	−2.68%	−2.54%	−4.57%

when addressing the relevance of criteria that are highly subjective, such as C2, C3 and C9.

This explains the relevance of characterizing non-probabilistic uncertainties, capturing the maximum of information implicit in the judgments since, in view of the results, subjectivity has a significant influence on the weights obtained. This subjectivity is systematically related to the particular background of the experts involved in the decision-making process and their perception of each dimension of sustainability (Table 9). Therefore, the inclusion of the subjectivity and non-probabilistic uncertainties implicit in DMs judgments results in significant variations of those weights that would result from applying the AHP method using conventional/crisp logic.

The results shown so far are sensitive to the number of indicators and criteria, as well as to the number of experts forming the group of decision makers. This study has defined up to 43 indicators for the evaluation of the sustainability of the three alternatives, a significant number compared to those proposed by many authors. We have taken care that the number of criteria does not exceed 9 in order to avoid excessive comparisons in pairs. The human brain is especially well designed to compare two criteria or alternatives with each other, but less so when it has to make joint comparisons. Note that in the AHP method, the random index (*RI*), which indicates the consistency of a random matrix, is tabulated for matrix orders of at most 10. However, the number of criteria has been maximized in order to represent the three dimensions of sustainability with the highest possible hierarchy of sub-criteria and indicators.

To ensure a greater variety of approaches and different viewpoints, a group of experts and researchers specializing in construction, structural design and sustainability have been consulted. Three DMs have been considered as the minimum according to the ideas of Ciemen and Winkler (1985) who suggest a number of experts between three and five. However, future research is needed by increasing the number of DMs that study the relevance of experts and the variation in the number of criteria to analyze how they influence the design of sustainable building structures.

5. Conclusions

This paper evaluates the sustainability of three different structure and thermal envelope designs for a single-family home according to multiple criteria. A traditional reference solution is compared with two innovative MMC-based alternatives aimed at meeting sustainable needs. This study has made it possible to bring together 43 specific indicators to evaluate the sustainability of the structural envelope through quantitative and qualitative attributes, taking into account uncertainty and risk factors. Most of the indicators are interdependent and are distributed in the four main phases of any construction project: conception-design, construction, use-maintenance and demolition-reintegration. The model covers not only technical and economic issues (specific to project management and tendering) but also environmental and social aspects, as fundamental pillars of sustainable development. In addition, the proposed indicators focus on the participation of professionals experimented in all possible phases of a construction project, to create a comprehensive process with a multidisciplinary team. The flexibility of the methodology allows the integration of several MCDM techniques. MIVES has been used to homogenize the different units of certain indicators in units of value and AHP has been used to weight them. The impacts of the indicators, used in the environmental evaluation of the building during its life cycle, have been obtained from the Ecoinvent 3.3 database using the ReCiPe impact evaluation methodology. The inventory of indicators belongs to a hierarchical structure that converges in 9 final criteria, which are those that an N-AHP group submits to evaluation in order to determine the relevance of each criterion.

However, in sustainability there is uncertainty in evaluations and different interests of the DMs that make evaluation always complex. In these conditions of uncertainty in the decision making process of the multi-criteria groups, it is proposed to integrate the neutrosophic logic, recently formulated as a generalization of the fuzzy and intuitionistic logic. Some expressions have been provided to characterize in detail the expertise of DM in neutrosophic terms to determine their relevance in the decision making process. The end of the process translates into obtaining crisp weights with the importance of each criterion, which will be used in a MCDM process to assess the sustainability of the different alternatives, in our case applying the VIKOR technique. Although most sustainability assessments are based on the crisp approach, researchers are beginning to use intuitively based perspectives to capture the non-probabilistic uncertainties associated with cognitive information in complex decision-making problems. However, a review of the literature has shown that neutrosophic set theory has not yet been used in sustainability assessments.

According to the assumptions adopted in the particular case study evaluated, the specific conclusions drawn are as follows:

- According to the experts' judgments, the relevance of social criteria in the structural design of a residential building represents 49% of the total weight. In particular, safety and functionality have prevailed among its four criteria. Much importance is also given in the decision to the environmental requirement with 33.1% of the weight, considering that there are only two criteria, namely the resources used (C4) and the environmental footprint (C5). The economic dimension is distributed 17.7% of the remaining weight. The economic stage of the EoL (C3), with a 1.36% weight, has little relevance for this type of structure.
- YTN alternative provides the best answer in both environmental criteria, and in two social criteria one of which is safety (C7), the most relevant of decision with 20.7%. On the contrary, the ELE alternative shows the best economic score although they are less relevant criteria, standing out only in the social criterion of functionality (C9) with a 19.2%. However, when considering the impacts on the 9 criteria simultaneously through the application of a MCDM technique, ELE turns out to be the alternative that performs best from the perspective of sustainability. This brings to light that design decisions based on the sole consideration of individual design criteria shall not result in sustainable designs, but only the simultaneous consideration of relevant criteria/ holistic approaches will.
- From the results of the neutrosophic group AHP it can be concluded that integrating subjectivity into MCDM processes can significantly influence criteria weights if compared to conventional approaches. Detecting the most subjective criteria allows us to further refine the relevance of each expert according to their context. In our study, considering the neutrosophic approach suggested here, there have been detected weight differences in some criteria of up to 11.9% when compared to those that would be obtained through a conventional (crisp) approach.
- In view of the results, the inclusion of subjectivity influences the results, reaching conclusions different from those resulting from the use of crisp logic. Sustainability requires a paradigm shift in the way building structures are conceived, requiring a holistic approach of its three pillars intertwined with each phase of the life cycle. An alternative that individually performs best in one or several criteria does not guarantee that it is the most sustainable solution.
- Future work will aim to deepen in two areas. In terms of neutrosophic logic, the influence of experts' subjectivity, with respect to the number of criteria and alternatives. As for the sustainability assessment, this methodology could be extended to evaluate projects with much more ambitious building structures, in terms of spans and

service loads (e.g. hotels, offices or commercial centers). These lines of research would allow implementing the advantages of modulation and prefabrication of the industrialized alternative to the technological system of reinforced concrete.

Author statement

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Declaration of Competing Interest

None.

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Appendix A. List of abbreviations and acronyms used in the study.

AHP	- Analytic Hierarchy Process
CoGx	- Center of gravity
CR	- Consistency ratio
DM_k	- Each decision maker
DMs	- Multiple decision makers
EoL	- End-of-life
EPD	- Environmental product declaration
FSs	- Fuzzy sets
GMCDM	- Group Multi-criteria decision-making
IFSs	- Intuitionistic fuzzy sets
INSs	- Interval neutrosophic sets
MIVES	- Modelo Integrado de Valor para Evaluaciones de Sostenibilidad (in Spanish)
MAUT	- Multi-Attribute Utility Theory
MCDM	- Multi-criteria decision-making
MMC	- Modern methods of construction
N-AHP	- Neutrosophic analytical hierarchy process
NAHP-G	- Neutrosophic group analytical hierarchy process
NIS (A^-)	- Negative ideal solution
NSs	- Neutrosophic Sets
N-VIKOR	- Neutrosophic VIKOR
PIS (A^*)	- Positive ideal solution
RI	- Random Index
S-LCA	- Social life cycle assessment
SVNSs	- Single value neutrosophic sets
TNN	- Single-valued triangular neutrosophic number
TNNW	- Single-valued triangular neutrosophic number weights
TOPSIS	- Technique for Order of Preference by Similarity to Ideal Solution
VIKOR	- Vlse Kriterijumska Optimizacija Kompromisno Resenje (in Serbian)

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