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Multi-criteria assessment of alternative sustainable structures for a self-promoted, single-family home

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Abstract

In the architecture sector, single-family housing projects are often linked to demand from private clients, without arousing very much interest from developers, who seek higher returns on other real estate assets. For any owner, the construction of a home is perhaps the biggest investment of their life, and success or failure will therefore depend on the right decision. This paper presents a study of three different structural alternatives that are applied to a terraced house to facilitate decision making by a self-promoter, based on multiple criteria and taking sustainability into consideration. The methodology used allows us to identify the structure and to evaluate the different alternatives proposed here in order to find the optimal option. A comparison is drawn between a traditional reference solution, a pre-cast design and finally a technological option based on an integral reinforced concrete structural system. Although the technical feasibility of these last two solutions has been proven, they have not yet received enough attention from researchers to allow the thermal envelope of the building to be solved at the same time as the structure itself. The last of these alternatives achieved the best valuation, although it is neither the most widely used alternative or the quickest to build. This study demonstrates the practical versatility of a method that is seldom used in residential construction and only rarely used for single-family homes. We evaluate three alternatives for optimizing the structure and enveloping walls of a self-promoted, terraced house from a sustainability perspective. The study provides a set of indicators for assessing the environmental, economic and social aspects of a building throughout its life cycle. The sustainability index of the structural envelope obtained in this way allows a self-promoter to prioritize solutions to ensure its global sustainability.

Keywords Single-family house; Multi-criteria decision making; Sustainable design; MIVES; Ytong; Elesdopa

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1. Introduction

In professional practice, the optimization of structures and materials has mainly focused on economic aspects due to budgetary constraints (García-Segura et al., 2014, 2018; Payá-Zaforteza et al., 2010). Many other important aspects are neglected, or at least relegated to a secondary involvement. From a sustainability perspective, it seems reasonable that the best choice should take into account aspects other than economic ones in order to design a more rational and efficient building (Griese et al., 2005).

Since the publication of the Brundtland report (1987), it has been accepted that sustainable development is paramount in terms of balancing economic (business) needs, socio-cultural needs and environmental (resources) effects. The construction sector is responsible for a significant proportion of these effects (Cabeza et al., 2014), from the extraction of raw materials through to their use and maintenance during the useful life of the building, and ending with demolition (or, where appropriate, recycling). Waas et al. (2014) have already pointed out that this concept should be integrated into decision-making processes.

The construction sector is one in which many different aspects coexist, and these may be contradictory and conflict with each other. This makes it difficult to manage the decision-making process when more than one criterion is taken into account. In recent years, increasing numbers of developers have begun to integrate new indicators into their project management and to evaluate contracting by implementing a sustainability component. There are different tools and methods for assessing a building, although there is no consensus on the priority of the criteria to be applied in each case (Marjaba and Chidiac, 2016).

In the engineering domain, several studies of economic and environmental factors have already been carried out, including assessments of the environmental impacts of large structures such as bridges (Navarro et al., 2018). In the field of construction, problems arising from energy consumption and pollutant emissions have been characterized, and these can be mitigated using the idea of "green building" by rationalizing the use of energy (Osma and Ordonez, 2010). Activities linked to the production of industrial typologies have aroused more interest as a study model (Cuadrado et al., 2016) than other types of buildings such as residential ones. Residential buildings have usually been constrained by companies that prefer to repeat the same traditional construction instead of innovating.

New systems and materials are constantly being incorporated into a construction industry that does not fully exploit these technological and productivity-related possibilities, especially in more conventional architecture. Beyond energy efficiency, which is based on the "Passivhaus" standard model (Suarez et al., 2017), residential building projects lack holistic criteria that take into account perspectives other than economic ones (Queipo et al., 2009). These criteria can be used to create better designs in an integral way throughout the entire life cycle (Penadés-Plà et al., 2017). At the Bauma 2019 trade fair (Munich, April 2019), innovation awards were presented to companies who best represented worldwide technological trends in machinery, with a clear focus on "smart construction" and the digitization of equipment. At the Barcelona Building Construmat fair (May 2019), McKinsey & Company (2019) presented a report detailing how data-based technology could help Spanish infrastructure companies make smarter decisions, reduce risk and improve project results.

The technological transformation of construction has already become a reality thanks to modern construction methods (MMC) (Dowsett et al., 2019) or "smart construction". By involving all interested parties, it is possible to incorporate the latest technological trends into residential buildings in the form of digitization, automation and electrification in the fields of machinery and project construction processes. The aim is to increase the productivity of the available resources by improving the quality, business efficiency, customer satisfaction, environmental performance, sustainability index and control of delivery deadlines (Yepes et al., 2012; Pellicer et al., 2014, 2016). These improvements are usually associated with benefits to real estate businesses, but are rarely taken into account by individuals who simply want to build their own homes. There are many countries in which the culture is still rooted in ownership, and where people would rather buy or build a house than rent it if the economic situation is favorable (Liu et al., 2017). The cumulative effect of these individual decisions has long-term consequences for household economy, and influences macroeconomic stability to a certain degree (Tabner, 2016). Since for the average family, this is probably the biggest investment of their lives, making the right decision is vitally important.

There are numerous precedents for the application of multi-criteria decision-making methods (MCDM) to sustainable infrastructure development (Navarro et al., 2019), and traditional economic approaches have been widely studied (Kazimieras and Turskis, 2011; Liou and Tzeng, 2012). Environmental aspects related to LCAs have been studied to a lesser extent (Chithambaranathan et al., 2015; Ilangkumaran et al., 2015), followed by social aspects (Sierra et al., 2016, 2018). The latter are currently less developed because they are more difficult to evaluate. In view of the above, the objective of the present research is to employ an MCDM methodology (Zavadskas et al., 2016) with a holistic approach, applying it step by step to a practical example of a self-promoted, single-family house. This approach compares sustainability criteria within a conventional system and two completely different MMC alternatives, including building systems that are seldom studied (Fisarova et al., 2016; Rojas Fernández-Fígares et al., 2016). The methodology used is MIVES (in Spanish, "integrated value model for sustainable assessments"), in which assessments of the alternatives are converted into the degree of satisfaction of the decision makers for each indicator, by means of utility or value functions. This method has been previously tested for subway lines (Ormazabal et al., 2008), road pavements (Villegas-Flores, 2009), industrial buildings (Alarcón-Nunez, 2006; San-José and Cuadrado, 2010; Alarcón et al., 2011), building projects for educational use (Pons and Aguado, 2012), the evaluation of constructive elements, concrete columns (Pons and De la Fuente, 2013), hydraulic infrastructure (Pardo and Aguado, 2015), sanitation networks (De la Fuente et al., 2016), post-disaster emergency housing planning (Hosseini et al., 2016) and wind turbines (De la Fuente et al., 2017). The Spanish Structural Code (Fomento, 2018), which is expected to be approved imminently, includes complementary documents that are not covered by the Eurocodes for the evaluation of sustainability, and are based on this precise method. The most recent research in this field has been carried out on urban pavements in the city of Barcelona (Pujadas et al., 2019) and for the evaluation of trenches, including a new eco-trench (Casanovas-Rubio et al., 2019).

This study demonstrates the advantages and limitations of this method when used as a one-person evaluation tool for a self-promoted single-family home. To the best of our knowledge, there are no models in the field of residential construction that can be used to evaluate both the sustainability of a resistant structure and the thermal envelope at the same time, and which consider the economic, environmental and social aspects. For this reason, we have developed a sustainability index for the structural envelope (SISE), which integrates the aspects of a construction that have the greatest impact. Research, analysis and a comparison are carried out for three alternatives: a traditional construction (A) as a reference, involving a conventional in-situ concrete structure and brick wall enclosures; a precast solution (B) with autoclave-cured, aerated concrete as the only material for both block walls and slabs; and a "technological" system (C) with integral construction (including foundations and retaining walls) consisting of two sprayed, reinforced concrete wall elements separated by a support and joined by connectors.

The scenario chosen is so everyday, but a minority one in the construction sector that it has rarely been studied. Each decision may have a social influence on a global model of sustainable self-construction, beyond the economic benefits linked to the real estate business and extended to the promotion of n-housing.

2. Problem characterization

The construction industry is an environment that is constantly changing and evolving, and housing is one of the basic sectors that affects society and the welfare of its citizens. According to the "Observatory on Housing and Land" (Fomento, 2018), in Spain the total number of homes completed in 2018 was 64,544 (including free market and subsidized housing), representing a year-on-year increase of 19%. This indicates a second consecutive year of recovery after the continuous downturn during the crisis years of between 2007 and 2016. Residential construction continues to be more highly in demand than other forms of construction. Hence, there is a growing need to review conventional construction systems and to seek new approaches to decision making in project development. The selection of a suitable construction system allows the design, and therefore the building, to be improved throughout its life cycle in different respects (environmental, economic and social) in search of sustainability. Despite this, construction systems for residential buildings continue to be selected intuitively or on the basis of conventional solutions sanctioned by practice; there is a lack of a rigorous decision support tool that allows each project to select the construction system that is best suited to its needs from a holistic management perspective.

Our aim in this work is to study the optimum design of the structure and enveloping walls of a terraced house from a sustainable point of view. The plot is located in the town of Jaén (Spain). It has a single access at street level

(±0.00) and is a rectangular plot 6.20 m wide by 20.00 m deep, with a main façade and interior organization as shown in the section in Figure 1. The house consists of a basement that is used as a garage (-1.30), a ground floor with living/dining room, kitchen and toilet (+1.50), a first floor with three bedrooms, a bathroom and a toilet (+4.40), a second floor with a terrace and swimming pool (+7.40) and a small rooftop tower (+11.00).

According to the geotechnical report, the soil is very unfavorable, with a low bearing capacity due to the presence of loams and expansive clay. The soil is also highly aggressive, due to its sulfate content. In addition to this, it would be essential to preserve the level of the current "active zone" during the works, and to avoid excavation tasks in the warmer months, since Jaén has very hot summers that would cause loss of moisture from the material when exposed to the weather.

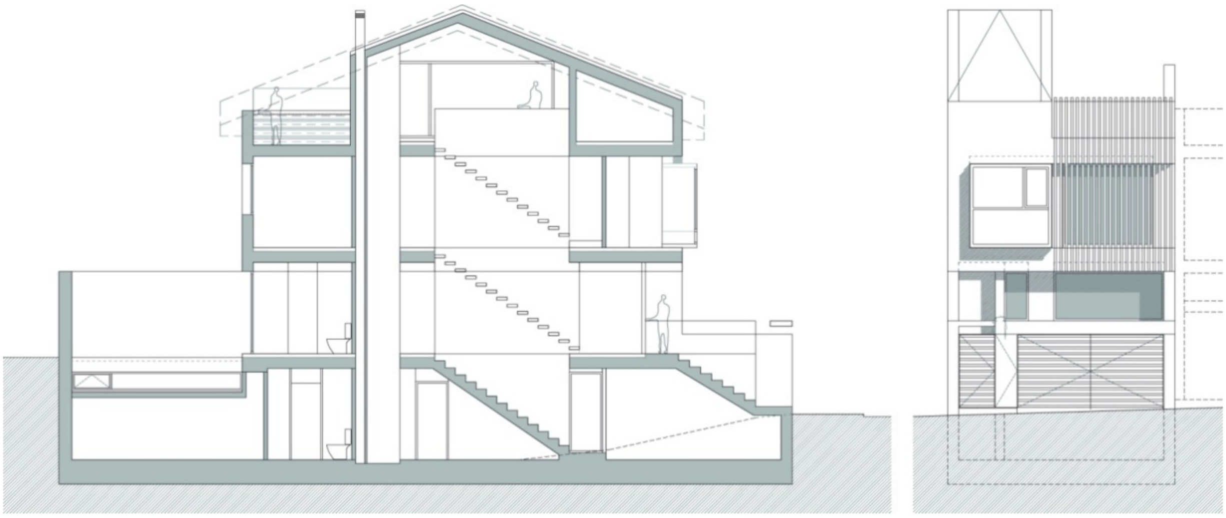

Fig. 1. Housing cross-section and main elevation.

The distribution of floors in the dwelling has not been considered, as these form the input data for the project. The facilities and services will be subcontracted separately, and the interior partitions, carpentry and cladding will be the same in all of the alternatives to preserve the aesthetic image of the project. Since it is a self-promotion for habitual residence, budget limitations are important.

3. Methods

This project uses the MIVES methodology (Pons et al., 2016), which is based on MCDM and evaluates different alternatives using a utility value index. This multi-attribute utility theory method (Keeney et al., 1979) supports decision making by using different satisfaction or value functions. The best alternative of the proposals is chosen on an objective basis via a rigorous process of evaluation, assessment, weighting and aggregation (see Figure 2). During the analysis period, the scope or objectives of the decision are defined, and then in the creativity phase, the possible alternatives that can be presented for later evaluation are defined. In the next phase, these alternatives are assessed, and finally, in the control phase, the degree of compliance with all aspects related to the previous phases is verified.

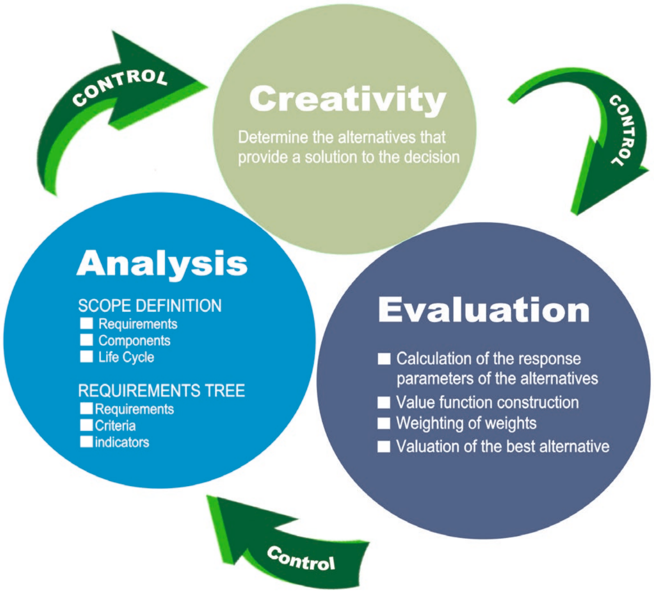

Fig. 2. Decision-making process for a single-family home (authors' diagram based on Alarcón, 2005).

3.1. Analysis

Our analysis defines the boundary conditions and the circumstances affecting the decision to be taken, including the scope of the project and the organization of all aspects to be evaluated. The limits of the system are structured along three axes (requirements, components and life cycle) and the contour conditions are stipulated. This approach to modeling allows us to gain a global vision of the scope of the project based on the intersection of these three planes. In addition, it provides a detailed perspective for each of the axes, thus allowing the decision maker to control the problem from different points of view. In order to apply this model, it is necessary to formulate a decision tree. This is a hierarchical diagram in which the general aspects or requirements are ordered in a branched manner; the criteria are then located at the intermediate layers and the more specific aspects or indicators at the last levels. The latter are then evaluated directly (Saaty, 2006). It is essential to have the minimum number of representative and independent indicators required to adequately ensure the scope of the decision under consideration.

3.1.1. Axis of requirements

Four requirements are proposed (Table 1) corresponding to the needs of the decision maker. In this case, we aim to reach a compromise between the self-promoter/user and the architect, taking into account its impact on the project. In this way, the fundamental levels that define a sustainable evaluation are obtained: the environmental, economic and social aspects. The last of these can be split into temporary (short-term) and functional (long-term) factors for a self-promotion dwelling, based on which the requirements tree will be designed. The requirements are of a general nature, allowing specific plans to be assigned to each project and adjusted according to the expected level of performance. Note that the objectives for a residential building differ from those for any other type of architecture. Each level of requirements is divided into specific strata called criteria that express a qualitative grouping, and these are in turn subdivided into other so-called 'indicators' that are quantitatively measurable. This hierarchy structures the information and facilitates the orderly evaluation of decision making. It is advisable to develop a dimension that is understandable and sufficiently perceptible. Each additional branch does not guarantee greater precision in the results, and involves mathematical effort that makes the method tedious.

Table 1. Deployment of the requirements tree

Requirements	Criteria	Indicators

Environment (29.30%)[1]	R1	Energy consumption	C1R1 (83.33%)	Energy consumed by building materials in the manufacturing process (MJ/m2)	I1C1R1 (100%)
		Improving environmental impact	C2R1 (16.67%)	Recycling of construction waste (%)	I1C2R1 (100%)
Economic (41.18%)[1]	R2	Cost	C1R2 (66.67%)	Construction budget (€/m2)	I1C1R2 (83.33%)
				Maintenance (€/m2 in first 10 years)	I2C1R2 (16.67%)
		Certainty of the final cost	C2R2 (33.33%)	Risk of cost deviation due to external factors (score)	I1C2R2 (100%)
Temporary (10.80%)[1]	R3	Period of construction	C1R3 (50%)	Construction period by work output (days)	I1C1R3 (100%)
		Responsiveness	C2R3 (50%)	Availability of materials and equipment (score)	I1C2R3 (100%)
Functional (18.72%)[1]	R4	Added value	C1R4 (25%)	Degree of ease in the construction process (scale)	I1C1R4 (25%)
				Flexibility to introduce reforms (score)	I2C1R4 (75%)
		User comfort	C2R4 (75%)	Thermal insulation (transmittance W/m2ºK)	I1C2R4 (66.67%)
				Acoustic insulation (overall noise reduction index Ra,tr)	I2C2R4 (33.33%)

[1] Weights are in percentage between brackets, calculated as indicated in section 3.3.1.

3.1.2. Components

The components that define the project are focused on the foundations and structural elements. We have also added the facades and party walls, although these obviously form part of the thermal envelope in a traditional solution. We were interested in including these in order to compare them with other solutions at a later stage, where the resistant support also has the function of building envelope. This allows us to eliminate one of these components to evaluate the global computation for that alternative. A comparison is made of those items that are not typically known as being "perceived qualities" by a user but which still constitute the bulk of the volume of the construction, and are therefore the most relevant at all levels. The components studied were the foundations, floor slabs, sloping roof slabs, supports (columns, basement walls) and enclosures.

An advantage of this methodology is that it avoids any kind of subjectivity in evaluation. Indeed, alternative valuations can be carried out after the stages described above, if they were not initially fixed, including even the functions for value and weight assignment.

3.1.3. Life cycle

The life cycle starts with the extraction and processing of raw materials to their manufacture, distribution, use, repair, maintenance, and finally to disposal or recycling, as illustrated in Figure 3, which shows the "cradle to grave" cycle (Evangelista et al., 2018). We wanted to give the life cycle the relevance it deserves in this project, since it allows us to obtain a wider perspective for decision making. It has an important impact in the initial stages (Josa et al., 2007) and can improve the project to a greater degree the earlier it is taken into account. In our project there are four phases: conception, materialization, usage and re-integration.

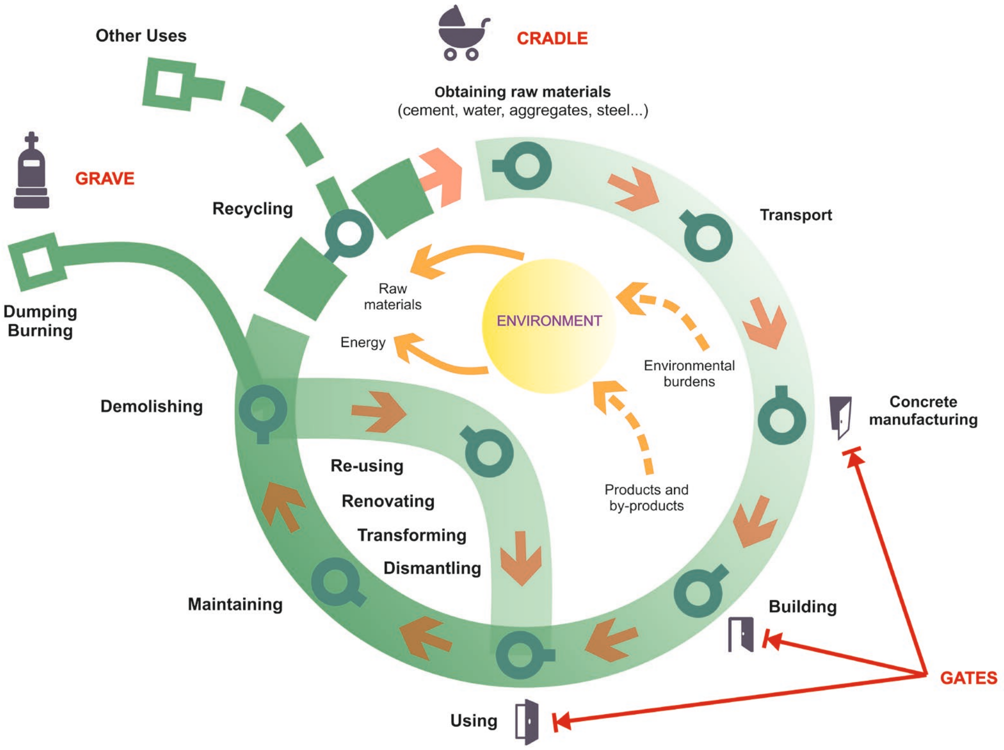

Fig. 3. The life cycle of a building (authors' diagram based on Josa, 2007).

3.2. Creativity

In this stage, we define the alternatives (Table 2) that will be included in the decision-making process. Three entirely different options are considered: a "traditional" reference solution (A); a solution with prefabricated elements and dry assembly (B); and, finally, an integral structural system using innovative technology (C).

Table 2. Main features of the alternatives

Alternative	Components	Description
A "Traditional"	Foundation	Piles CPI-7 of Ø35cm up to 8.80 m deep and foundation beams.
	Floor slab	Reinforced concrete slab (24 cm type floor, 26 cm solarium / pool). Passable deck not ventilated, fixed flooring; XPS insulation (8 cm).
	Sloping floor slab	Reinforced concrete slab (22 cm); XPS insulation (6 cm).
	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 XPS (8 cm). Interior brick partition wall (7 cm);
B "Precast"[2]	Foundation	Same to alternative "A".
	Floor slab	Reinforced plates (30 cm type floor, 17.5 cm solarium); XPS insulation (9 cm). Pool bottom with 30 cm plates (1100 Kg/m^2) and "O" block anchored to the bottom and "U" block at the top and half height.
	Sloping floor slab	Reinforced plates (12 cm); XPS insulation (12 cm).
	Supports	There are no columns. The reinforced concrete basement perimeter wall is maintained.
	Building enclosure	Load-bearing structural walls with tongue and groove aerated concrete blocks (20 cm).
C "Technology"[3]	Foundation	Mat foundation 7/46/7 on soil improvement.
	Floor slab	Sprayed reinforced concrete lightened slab (6+18+6 cm type floor, 7+26+7 cm solarium / pool). Interior air chamber with XPS (10 cm).
	Sloping floor slab	Sprayed reinforced concrete lightened slab (5+5+5 cm).

	Supports	Same to alternative "B".
	Building enclosure	Structural walls in façade and dividing walls (6+13+6 cm). Interior air chamber with XPS (10 cm).

The traditional alternative (A) consists of a conventional reinforced concrete structure, developed based on the practical experience of the designer. The solution does not need to be the optimal one, and of course can be improved towards a more sustainable construction.

The precast alternative (B) using Ytong is based on the use of a single material with a high load-bearing capacity for the construction of walls, partitions, slabs and roofs. Autoclave-cured and aerated concrete is used, which is manufactured with densities of between 350–700 kg/m^3. Its lightness and maneuverability help to give a very high placement performance (35–50 m^2/ day for blocks and 200 m^2/ day for slabs). As the system does not require struts, formwork or concrete pouring, delivery times are also much shorter. In terms of properties, it is a fireproof material that is made up of 100% recyclable minerals (sand, lime, cement and water). In addition, it offers good thermal insulation (increasing savings in terms of air conditioning) and acoustics (with a high capacity for the absorption of airborne noise). Finally, it provides comfort, as it contributes to the natural regulation of temperature and humidity.

The technological alternative (C), known as Elesdopa (in Spanish, "double-walled structural element"), was chosen as an integral system to create a building with a single plate-type element. In addition to performing the function of enclosing, this element provides the rigidity necessary to support the structural function by increasing the moment of inertia of the wall section (thereby distancing the mass from the neutral axis). A continuous and folded facing is achieved by forming two sheets of sprayed, reinforced concrete. This wall has a low thickness that is normally between 5 and 10 cm, depending on the element. In addition, it is strengthened with an electro-welded mesh or grid which forms a reinforced base inside each of the concrete sheets. These reinforced concrete slabs are joined with bracing "keys" which support the two slabs and absorb the shear forces produced inside the elements. The interior void of the plates can be filled with insulating material such as gravel.

3.3. Evaluation

The objective at this stage is to select which of the three alternatives described above generates the greatest value to the project, according to the limiting conditions identified at the analysis stage. Table 3 shows a summary of the indicators that must be assessed for each component. Note that not all of them are applied in the evaluation, which follows the steps described in the subsections below.

Table 3. Indicators evaluated for each component

Indicators	**Components**				
	Foundation	Floor slab	Sloping floor slab	Supports	Building enclosure
I1C1R1	☒	☒	☒	☒	☒
I1C2R1	☒	☒	☒	☒	☒
I1C1R2	☒	☒	☒	☒	☒
I2C1R2		☒	☒		☒
I1C2R2	☒	☒	☒	☒	☒
I1C1R3	☒	☒	☒	☒	☒
I1C2R3	☒	☒	☒	☒	☒
I1C1R4	☒	☒	☒	☒	☒
I2C1R4		☒	☒	☒	☒
I1C2R4	☒	☒	☒		☒
I2C2R4		☒	☒		☒

3.3.1. Weighting

[2] Ytong: Prefabricated blocks and slabs, autoclaving aerated concrete manufactured with densities 350-700 kg/m3.

[3] ELESDOPA©: Double Wall Structural Element, of Projected Reinforced Concrete.

This stage involves the assignment of weights at each level of the hierarchy in order to establish preferences that will allow for a comparison between all of the elements. This weighting is carried out for each branch of the tree, and the relevance of each element with respect to those on the same level is determined. The process starts at the indicators and is then applied to the criteria, ending with the requirements. A mathematical theory called an analytical hierarchy process (APH) is used as a comparison system in this project (Saaty, 1990). A fundamental scale of comparison between pairs is used in which intermediate and inverse situations are considered, giving weights based on the subjective importance of each element to the others. In Table 1 above, we show the weights in brackets.

3.3.2. Construction of utility or value functions

The value function transforms the indicators with physical units into common units (values). For each indicator, a specific function is defined, and its mathematical expression depends on the parameters adopted. Equation (1) is a general expression of the value function used to assess satisfaction with respect to the indicator:

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

The variable B, defined in Equation (2), maintains the range of the function {0–1} depending on five parameters (see Table 4). P_i ($0<P<\infty$) is a factor that defines the shape of the curve; the parameters C_i represent n curves with $P_i>1$, the value of the abscissa for the inflection point; K_i ($0<K<1$) is the value of the ordinate for the inflection point; X_{min} is the abscissa whose response is equal to zero for increasing functions (for decreasing functions, the minimum value is X_{max}); and, finally, X is the abscissa of the evaluated indicator that generates a V_i value (variable for each alternative).

$$\boldsymbol{B = 1/\left[1 - e^{-k_i}(|x_{max} - x_{min}|/c_i)^{P_i}\right]} \qquad (2)$$

Table 4. Parameters of the value function

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

A common value function is created for each of the indicators (Alarcón et al., 2011; Pons et al., 2016). This function is used to transform the quantification 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 properly establish the points of maximum and minimum satisfaction. Conceptually, the strategy consists of transforming subjective measurements into objective ones. The construction procedures for the indicators are given in Tables 5 and 6.

Table 5. Parameters of value functions for a single-family home

Indicators		Satisfaction		Function	Trend
		Minimum	Maximum		
Energy consumed in the manufacturing process (MJ/m2)	I1C1R1	1433	0	Linear	Decresaing
Recycling of construction waste (%)	I1C2R1	17	70	Concave	Rising
Construction budget (€/m2)	I1C1R2	777	249	S-Shaped	Decresaing
Maintenance (€/m2 in the first 10 years)	I2C1R2	15.54	0	Concave	Decresaing
Risk of cost deviation due to external factors (score)	I1C2R2	0	100	S-Shaped	Rising

Construction period by work output (days)	I1C1R3	225	138	Convex	Decresaing
Availability of materials and equipment (score)	I1C2R3	0	100	Linear	Rising
Degree of ease in the construction process (scale)	I1C1R4	1	10	Linear	Rising
Flexibility to introduce reforms (score)	I2C1R4	0	100	Linear	Rising
Thermal insulation (transmittance W/m2ºK)	I1C2R4	0.29	0.19	Concave	Decresaing
Acoustic insulation (overall noise reduction index Ra,tr)	I2C2R4	33	60	Convex	Rising

Table 6. References and tools for the calculation of coefficients for each indicator

Indicators	Procedures
I1C1R1	**Energy consumed by building materials in the manufacturing process (MJ/m2):** AZPILICUETA, E. Table of energy content or primary energy of materials. Tectónica: monografías de arquitectura, tecnología y construcción, ISSN 1136-0062, Nº. 31, 2010. Forecast in "new construction" of energy expenditure by chapters (Mardaras y Cepeda, 2004).
I1C2R1	**Recycling of construction waste (%):** Data published in the 2nd national plan for construction and demolition waste 2008-2015 (II PNRCD); % Partial recycled material (Garrucho, 2006; Alarcón, 2006, etc).
I1C1R2, I2C1R2	**Construction budget (€/m2) and Maintenance (€/m2 in first 10 years):** Estimated average construction values 2019 COAMA; Prices bank: (PREOC, BCCA and Generador de precios. España - CYPE Ingenieros, S.A.). Prices offered by specialized companies: ("Plataforma Logística YTONG Sur BigMat Multipio" and "ELESDOPA© international")
I1C2R2	**Risk of cost deviation due to external factors (score 1-100):** Several questionnaires for scoring indicator. Own elaboration: Construction company offers (no previous study, lump sum price, closed price...); Site management (alterations during the work, indefinite project, Project management, permanent construction manager...); Technical control of the work (professional association visa only, supervision report by independent technician, Technical Control Body (OCT)...); Concrete pouring machine (concrete pump, stationary spraying pump, pails, manual means,...).
I1C1R3	**Construction period by work output (days):** Estimated on the basis of experience, contrasted with the return provided by construction companies: ("Plataforma Logística YTONG Sur BigMat Multipio" and "ELESDOPA© international").
I1C2R3	**Availability of materials and equipment (score 1-100):** Several questionnaires for scoring indicator. Own elaboration. Accessibility to equipment and materials (dependence on specialized technology, part of unusual equipment, locally available machinery and materials...); Sourcing (constant conflict with supplies, temporary supply problems, local supplies or delivered on time...); Distance in the transport of goods (local <10 Km, municipal<50 Km, provincial<100 Km, state >100Km...); Need for lifting aids: high (mobile cranes), medium (boom truck), low (only possible with manual means).
I1C1R4	**Degree of ease in the construction process (scale 1-10):** Several questionnaires for scale indicator. Own elaboration: Quality control and/or necessary tests (reduced, normal, intense); Sensitivity of the construction company (maximum legal subcontracts, only economic or time criteria, quality management in safety and health); Prefabrication / Industrialized assembly (wet work, mixed system, dry assembly); Assembly time (slow, normal, fast); Need for auxiliary means (special equipment and machinery, formwork and struts, self-supporting); Adapting to building solutions (innovation, own building system, conventional).
I2C1R4	**Flexibility to introduce reforms (score 1-100):** Several questionnaires for scoring indicator. Own elaboration: Technical complexity (difficulty in the system with loss of time, intermediate degree to adapt to changes, optimization of time in reforms...); Degree of acceptance of the client / user (annoyances and high cost due to difficulty in the work, intermediate degree of interference and cost in each modification,

	maximum adaptability with minimum cost in the unforeseen...); Labor performance (lack of knowledge or commitment, basic efficiency, maximum capacity to adapt the construction system...).
I1C2R4	**Thermal insulation (transmittance W/m2ºK):** Calculated and verified for each type of building enclosure with the computer application CEXv2.3. DB-HE: Technical building code. Basic document - Energy conservation (https://www.codigotecnico.org) Catalogue CTE components (https://www.codigotecnico.org)
I2C2R4	**Acoustic insulation (overall noise reduction index Ra,tr):** YTONG 2018 Technical Guide and DAU YTONG-SIPOREX 03/012 F DB-HR: Technical building code. Basic document - Noise protection (https://www.codigotecnico.org) Catalogue CTE components (https://www.codigotecnico.org)

3.4. Control (optional)

3.4.1. Sensitivity analysis

When some data are not precisely known, a sensitivity analysis is carried out to determine the influence of the different parameters on the value index obtained for each of the alternatives. Sensitivity studies of this type have been carried out on the sustainability evaluation model of the current Structural Concrete Spanish Instruction (EHE-08). Interesting conclusions have been obtained due to a certain inconsistency of the life cycle analysis (LCA) between the weightings and the value functions used in the Concrete Code (Mel et al., 2015). This indicates the need for a revision to the Structural Code, which will probably be approved this year. The analysis allows us to identify the most important parameters in order to select the solution that responds best to as many values as possible, as well as reinforcing the reliability of the results (see Section 4).

3.4.2. Contrast

The contrast stage allows us to control for deviations and unforeseen uncertainties during the development of the methodology. This allows corrections to be made and both the validity of the model and the results of the alternatives to be checked later against the values that were initially expected. This control provides very useful information that enriches the robustness of the system with each experience. In this way, learning is introduced into the next cycle of decisions, allowing for continuous improvement of the system.

4. Results

The purpose of this section is to describe the results of this research, although these may vary depending on the decision maker. This study seeks to determine the optimum structural and envelope design by comparing the three alternatives proposed as the axis of the analysis.

4.1. Response for each alternative

The responses for the alternatives are recorded after each component has been assessed for each specific indicator. Table 7 summarizes each indicator for the three alternatives studied. The values shown in Table 6 were obtained from the development of our own projects, the scientific literature, the Spanish Building Codes, expert opinion and documentation provided by the bidding companies.

Table 7. Responses for alternatives A, B and C with respect to the indicators evaluated

Comp.	**Foundation**			**Structure**			**Sloped roof**			**Columns Concrete walls**			**Facade Party walls**		
Altern.	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
I1C1R1	1244	1244	746	1008	214	670	902	96	586	799	597	187	1107	171	567
I1C2R1	0.18	0.18	45.64	35.87	11.54	40.35	36.59	8.94	42.85	46.05	36.22	36.22	61.98	16.92	43.19

I1C1R2	128.98	128.98	63.60	75.46	154.14	76.24	75.52	75.79	60.47	60.30	45.95	77.65	43.60	56.84	77.65
I2C1R2	-	-	-	3.77	7.71	3.81	3.78	3.79	3.02	2.24	2.30	3.88	2.18	2.84	3.88
I1C2R2	40	40	65	30	60	65	30	60	65	30	30	65	50	60	65
I1C1R3	49	49	28	72	12	68	10	4	10	24	17	16	18	10	34
I1C2R3	50	50	65	30	50	65	100	15	35	100	100	35	100	40	35
I1C1R4	4.67	4.67	3.83	5.17	9.17	3.83	5.17	9.17	3.83	5.17	5.17	3.83	4.67	9.17	3.83
I2C1R4	-	-	-	100	35	15	100	35	15	100	100	15	100	35	15
I1C2R4	0.41	0.41	0.22	0.21	0.23	0.19	0.29	0.23	0.22	-	-	-	0.26	0.29	0.23
I2C2R4	-	-	-	59	47	51	55	41	47	-	-	-	47	43	47

4.2. Calculating the value for each alternative

To obtain the value index for each alternative, the indicators must first be evaluated. These are the only aspects that can be quantified using the value function previously defined in Section 3.2 and parameterized in Tables 4 and 5. The value of the criteria is then calculated, as well as the requirements based on which the value index of each alternative is finally obtained. The calculations applied to each level of the requirements tree are explained below.

- *Values of indicators (I)*

The values of the indicators are obtained from the value function and the quantification of the indicators for each alternative (Table 8). The quantification of the alternative is the abscissa of the point of the value function, whose ordinate is the value of the indicator for the studied alternative. For alternatives A, B and C, all the indicators are shown in the left hand column for each requirement, together with their answers (X_{ind}) and their transformations via the value function from physical to common units ("Value"), in the order described in Section 3.3. The quantification or response of the indicator is the abscissa for the value function, while the ordinate is the value of the indicator for the evaluated alternative.

Table 8. Values of indicators for a single-family home

R1	**ENVIRONMENT**						
Indicator	**Components**	**Alternative A "Traditional"**		**Alternative B "Precast"**		**Alternative C "Technology"**	
		X_{ind}	Value	X_{ind}	Value	X_{ind}	Value
Energy consumed by building materials in the manufacturing process (MJ/m2)	Foundation	1244	0.13	1244	0.13	746	0.48
	Structure	1008	0.30	214	0.85	670	0.53
	Sloped roof	902	0.37	96	0.93	586	0.59
	Columns-Concrete walls	799	0.44	597	0.58	187	0.87
	Facades-Party walls	1107	0.23	171	0.88	567	0.61
	TOTAL		**0.29**		**0.67**		**0.62**
Recycling of construction waste (%)	Foundation	0.18	0.00	0.18	0.00	45.64	0.81
	Structure	35.87	0.69	11.54	0.00	40.35	0.75
	Sloped roof	36.59	0.70	8.94	0.00	42.85	0.78
	Columns-Concrete walls	46.05	0.82	36.22	0.70	36.22	0.70
	Facades-Party walls	61.98	0.95	16.92	0.00	43.19	0.79
	TOTAL		**0.63**		**0.14**		**0.77**

R2	**ECONOMIC**						
Indicator	**Components**	**Alternative A "Traditional"**		**Alternative B "Precast"**		**Alternative C "Technology"**	
		X_{ind}	Value	X_{ind}	Value	X_{ind}	Value

Construction budget (€/m2)	Foundation	128.98		128.98		63.60	
	Structure	75.46		154.14		76.24	
	Sloped roof	75.52		75.79		60.47	
	Columns-Concrete walls	60.30		45.95		77.65	
	Facades-Party walls	43.60		56.84		77.65	
	TOTAL	**383.86**	**0.56**	**461.70**	**0.20**	**355.61**	**0.72**
Maintenance (€/m2 in the first 10 years)	Foundation	-		-		-	
	Structure	3.77		7.71		3.81	
	Sloped roof	3.78		3.79		3.02	
	Columns-Concrete walls	2.24		2.30		3.88	
	Facades-Party walls	2.18		2.84		3.88	
	TOTAL	**11.97**	**0.60**	**16.64**	**0.37**	**14.60**	**0.66**
Risk of cost deviation due to external factors (score)	Foundation	40	0.38	40	0.38	65	0.87
	Structure	30	0.18	60	0.80	65	0.87
	Sloped roof	30	0.18	60	0.80	65	0.87
	Columns-Concrete walls	30	0.18	30	0.18	65	0.87
	Facades-Party walls	50	0.60	60	0.80	65	0.87
	TOTAL		**0.30**		**0.59**		**0.87**

R3	**TEMPORARY**						
Indicator	**Components**	**Alternative A "Traditional"**		**Alternative B "Precast"**		**Alternative C "Technology"**	
		X_{ind}	Value	X_{ind}	Value	X_{ind}	Value
Construction period by work output (days)	Foundation	49		49		28	
	Structure	72		12		68	
	Sloped roof	10		4		10	
	Columns-Concrete walls	24		17		16	
	Facades-Party walls	18		10		34	
	TOTAL	**173**	**0.36**	**92**	**1.00**	**157**	**0.61**
Availability of materials and equipment (score)	Foundation	50	0.50	50	0.50	65	0.65
	Structure	30	0.30	50	0.50	65	0.65
	Sloped roof	100	1.00	15	0.15	35	0.35
	Columns-Concrete walls	100	1.00	100	1.00	35	0.35
	Facades-Party walls	100	1.00	40	0.40	35	0.35
	TOTAL		**0.76**		**0.51**		**0.47**

R4	**FUNCTIONAL**						
Indicator	**Components**	**Alternative A "Traditional"**		**Alternative B "Precast"**		**Alternative C "Technology"**	
		X_{ind}	Value	X_{ind}	Value	X_{ind}	Value
Degree of ease in the construction process (scale)	Foundation	4.67	0.42	4.67	0.42	3.83	0.32
	Structure	5.17	0.47	9.17	0.91	3.83	0.32
	Sloped roof	5.17	0.47	9.17	0.91	3.83	0.32
	Columns-Concrete walls	5.17	0.47	5.17	0.47	3.83	0.32
	Facades-Party walls	4.67	0.42	9.17	0.91	3.83	0.32
	TOTAL		**0.45**		**0.72**		**0.32**
Flexibility to introduce reforms (score)	Foundation	-		-		-	
	Structure	100	1.00	35	0.35	15	0.15
	Sloped roof	100	1.00	35	0.35	15	0.15
	Columns-Concrete walls	100	1.00	100	1.00	15	0.15
	Facades-Party walls	100	1.00	35	0.35	15	0.15
	TOTAL		**1.00**		**0.51**		**0.15**
Degree of ease in the construction process (scale)	Foundation	0.41	0	0.41	0	0.22	0.81
	Structure	0.21	0.88	0.23	0.73	0.19	1
	Sloped roof	0.29	0	0.23	0.73	0.22	0.81
	Columns-Concrete walls	-		-		-	
	Facades-Party walls	0.26	0.46	0.29	0	0.23	0.73

	TOTAL		**0.34**		**0.37**		**0.84**
Flexibility to introduce reforms (score)	Foundation	-		-		-	
	Structure	59	0.93	47	0.27	51	0.45
	Sloped roof	55	0.67	41	0.09	47	0.27
	Columns-Concrete walls	-		-		-	
	Facades-Party walls	47	0.27	43	0.14	47	0.27
	TOTAL		**0.62**		**0.17**		**0.33**

- *Values for criteria (C)*

The values for the criteria (Equation (3)) are obtained from the values of the indicators associated with a given criterion multiplied by their respective weights, with *n* being the number of indicators associated with that criterion (Table 9).

$$V_{Criteria}=\sum_{i=1}^{n} V_{Indicator\ i} \times W_i \qquad (3)$$

Table 9. Values for criteria for a single-family home

	Alternative A "Traditional"				**Alternative B "Precast"**				**Alternative C "Technology"**			
Indicator	V_{ind}	W_{ijk}	V_{alt-A}	ΣV_{crit}	V_{ind}	W_{ijk}	V_{alt-B}	ΣV_{crit}	V_{ind}	W_{ijk}	V_{alt-C}	ΣV_{crit}
I1C1R1	0.29	100%	0.29	**0.29**	0.67	100%	0.67	**0.67**	0.62	100%	0.62	**0.62**
I1C2R1	0.63	100 %	0.63	**0.63**	0.14	100 %	0.14	**0.14**	0.77	100%	0.77	**0.77**
I1C1R2	0.56	83.33%	0.47	**0.57**	0.20	83.33%	0.17	**0.23**	0.72	83.33%	0.60	**0.71**
I2C1R2	0.60	16.67%	0.10		0.37	16.67%	0.06		0.66	16.67%	0.11	
I1C2R2	0.30	100%	0.30	**0.30**	0.59	100%	0.59	**0.59**	0.87	100%	0.87	**0.87**
I1C1R3	0.36	100%	0.36	**0.36**	1.00	100%	1.00	**1.00**	0.61	100%	0.61	**0.61**
I1C2R3	0.76	100%	0.76	**0.76**	0.51	100%	0.51	**0.51**	0.47	100%	0.47	**0.47**
I1C1R4	0.45	25.00%	0.11	**0.86**	0.72	25.00%	0.18	**0.57**	0.32	25.00%	0.08	**0.19**
I2C1R4	1.00	75.00%	0.75		0.51	75.00%	0.38		0.15	75.00%	0.11	
I1C2R4	0.34	66.67%	0.22	**0.43**	0.37	66.67%	0.24	**0.30**	0.84	66.67%	0.56	**0.67**
I2C2R4	0.62	33.33%	0.21		0.17	33.33%	0.06		0.33	33.33%	0.11	

- *Values for requirements (R)*

Similarly, the values of the requirements (Equation (4)) are formed from the sum of the values of the criteria associated with a given requirement multiplied by their weights, with *n* being the number of criteria associated with the requirement (Table 10).

$$V_{Requirement}=\sum_{i=1}^{n} V_{Criteria\ i} \times W_i \qquad (4)$$

Table 10. Values for requirements for a single-family home

	Alternative A "Traditional"				Alternative B "Precast"				Alternative C "Technology"			
Criteria	V_{crit}	W_{ijk}	V_{alt-A}	ΣV_{req}	V_{crit}	W_{ijk}	V_{alt-B}	ΣV_{req}	V_{crit}	W_{ijk}	V_{alt-C}	ΣV_{req}
C1R1	0.29	83.33%	0.24	**0.35**	0.67	83.33%	0.56	**0.58**	0.62	83.33%	0.51	**0.64**
C2R1	0.63	16.67%	0.11		0.14	16.67%	0.02		0.77	16.67%	0.13	
C1R2	0.57	50.00%	0.28	**0.44**	0.23	50.00%	0.11	**0.41**	0.71	50.00%	0.35	**0.79**
C2R2	0.30	50.00%	0.15		0.59	50.00%	0.30		0.87	50.00%	0.44	
C1R3	0.36	66.67%	0.24	**0.49**	1.00	66.67%	0.67	**0.84**	0.61	66.67%	0.41	**0.56**
C2R3	0.76	33.33%	0.25		0.51	33.33%	0.17		0.47	33.33%	0.16	
C1R4	0.86	25.00%	0.22	**0.54**	0.57	25.00%	0.14	**0.37**	0.19	25.00%	0.05	**0.55**
C2R4	0.43	75.00%	0.32		0.30	75.00%	0.22		0.67	75.00%	0.50	

- *Value indexes for the alternatives: Determination of the optimum*

The value index for each alternative (Equation (5)) is obtained by adding the values of the requirements multiplied by their weights, where n is the number of requirements. As shown in Table 11, the optimal alternative is the one with the highest SISE.

$$SISE_{Alternative} = \sum_{i=1}^{n} V_{Requirement\ i} \times W_i \qquad (5)$$

Table 11. Calculation of the best alternative

Requirements	Alternative A "Traditional"			Alternative B "Precast"			Alternative C "Technology"		
	V_{req}	W_{ijk}	V_{alt-A}	V_{req}	W_{ijk}	V_{alt-B}	V_{req}	W_{ijk}	V_{alt-C}
R1 Environment	0.35	29.30%	**0.10**	0.58	29.30%	**0.17**	0.64	29.30%	**0.19**
R2 Economic	0.44	41.18%	**0.18**	0.41	41.18%	**0.17**	0.79	41.18%	**0.33**
R3 Temporary	0.49	10.80%	**0.05**	0.84	10.80%	**0.09**	0.56	10.80%	**0.06**
R4 Functional	0.54	18.72%	**0.10**	0.37	18.72%	**0.07**	0.55	18.72%	**0.10**
SISE		**0.44**			**0.50**			**0.68**	

In short, based on the global application of our methodology for a terraced house, it appears that the best of the alternatives is C. This corresponds to a structure that is designed and executed with a technological system involving structural elements composed of a double wall of reinforced concrete and interior thermal insulation. In order to determine which alternative was more susceptible to changes in the input conditions, a sensitivity study was conducted to investigate whether the choice made based on these data used was robust. With this in mind, the parameters influencing the values of the alternatives were analyzed from two perspectives. Firstly, to examine the range of variation in the results for the alternatives, the input values were randomly increased and decreased by a maximum of ±30%. This interval was set because exceeding it would mean invalidating certain indicators, reckless reductions in the cost of the work, setting deadlines requiring planning that would be impossible to comply with, or using unrealistic values of thermo-acoustic insulation. The discrete indicators determined based on semantic results (scales or scores) remain unchanged. Secondly, for modeling purposes, we examined the modification of weights and the effects of variation in the parameters of the value function (P_i, K_i, C_i). In this case, the adjustments in the weights were determined based on a variation not exceeding ±15%, as a larger value would result in inconsistent matrices in the AHP method. In both studies, random values were obtained by applying a Monte Carlo method with 1000 iterations for each of the three alternatives. Based on the sensitivity of the values, alternative C was the best solution 99.60% of the time. Solution B was the best option for the remaining 0.40%, and in no case did alternative A surpass option C. Of the lower scoring alternatives, A only surpassed B 11.60% of the time, while B was better 88.40% of the time. On the other hand, in the sensitivity study of the model, the variations in weights of the indicators and criteria did not make a significant contribution to determining the value of each alternative, since their influence becomes diluted at higher levels in the hierarchy of the tree. Accordingly the results for the variation in the weightings fundamentally affected the level of the requirements, with alternative C being optimal in 100% of the cases. Of the two remaining solutions, option B was preferred over A in 97.40% of the cases, well above the 2.60% in which the A option was preferred. Based on a comparison between these two analyses, it can be concluded that the proposed method is robust, coinciding with the conventional AHP-MIVES approach for the preferred alternative.

5. Discussion

The evolution of the market, and hence the demand in the construction sector, has made it increasingly necessary to find suitable approaches to project management. The success of a project depends on a multiplicity of factors, and in the current globalized market, these change so quickly that it is essential to involve specialists who can apply appropriate construction methods so that uncertainties are transformed into certainties. However, even this is not sufficient, since the factors most affecting the results of a project often apply in the early stages of its life cycle. Those responsible for planning, design or construction may ignore or only partially consider the perspectives of the experts in charge of controlling operations or maintenance, thus putting the viability of the real estate investment at risk in its later stages.

As we have seen in previous sections, based on a clear definition of the scope of the decision and the MCDM process, specific tools can be used to evaluate the overall suitability of a given type of construction from the point of view of sustainability. However, this is conditional on the variability in stakeholders' opinions of the importance of the sustainability criteria used (García-Segura et al., 2018). Uncertainty is also an inherent factor in the process and depends on the decision maker. It has therefore been addressed in this case by considering expert seminars linked to the specialization of constructive solutions. The assignment of weights and value functions during these sessions brings rigor and objectivity to the evaluation (Casanovas-Rubio et al., 2019; Pujadas et al., 2019). These functions quantify the subjectively assigned value of each variable according to the specific point of view of the decision maker (promoter, technical, owner, user or sales representative, for example) in relation to location and time. Both the value function and the evaluation are typically susceptible to variation due to these aspects (Pons and Aguado, 2012).

By rigorously following all of the steps in the procedure described in Sections 3 and 4, a total of 11 indicators were evaluated for each alternative via qualitative and quantitative variables that were both discrete and continuous. Using the value functions and a weighting system, these variables were transformed into a one-dimensional numerical value representing the SISE based on the three axes of environmental, economic and social factors. In the last of these, a distinction was made between the time requirements, which apply until the end of the construction process, and the functional requirements, which apply during the use, maintenance and repair stages. Value functions were also used to control any possible nonlinearity in the assessment process (Mel et al., 2015). Finally, of the three alternatives proposed, our procedure determined that the technological option C had a higher SISE (0.68) than the prefabricated option B (0.50), and the traditional structure A (0.44) was the least preferred. The optimal choice was a structure and enclosure formed of an integrated system of two projected, reinforced concrete wall elements. This includes the foundations and the retaining walls, which were separated by a support and joined by connectors, unlike the rest of the components.

Table 11 shows that alternatives B and C obtained the highest scores of 0.17 and 0.19, respectively, for the environmental requirements. For the prefabricated option, this was due to the use of autoclaved, aerated concrete with a very low primary energy content, while for the technological alternative, this was due to the greater recycling of construction waste through the use of a type of concrete containing 20% recycled aggregates and 90% recycled steel; thanks to its magnetic properties, the latter can be recovered for reuse without losing its properties. In economic terms, alternative C (with a value of 0.33) was clearly the best based on the final price of the work. In contrast, the maintenance costs were very similar for all three alternatives, without constituting a differentiating indicator. The temporal plane with the best classification (0.09) corresponds to alternative B, as construction of all components is estimated to take place within only 92 days, compared to 157 days for C and 173 days for A. However, for the prefabricated option, time has a low weight compared to other issues that are more important to the owner. In an evaluation of a real estate development on a larger scale, in which the deadlines are essential criteria, alternative B would be a strong candidate for an optimal SISE. Finally, the functional requirements of alternatives A and C are equal (0.10). The comfort criteria act to balance both alternatives, since they have more weight than the complexity of the project for the self-promoter. This is because although an owner may overlook the cost and time of construction, the quality remains important throughout the useful life of the building.

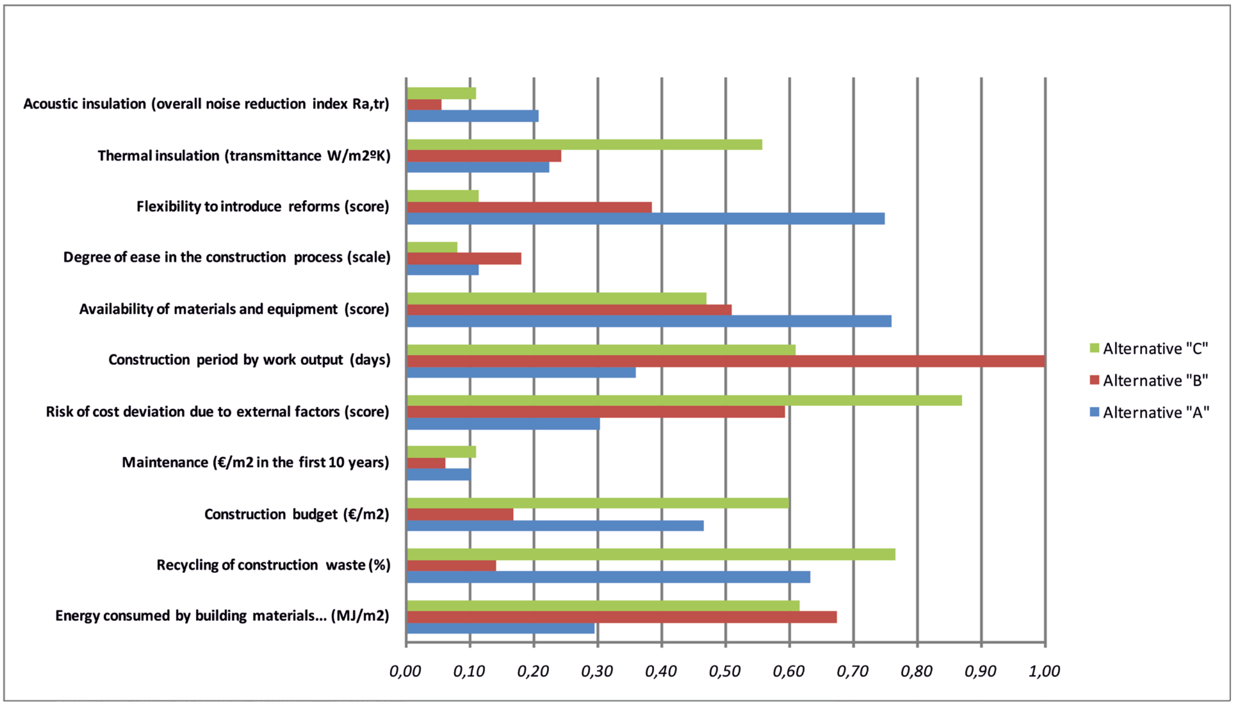

Fig. 4. Comparison of the normalized values of all indicators for the three alternatives

Figure 4 shows that alternative A gives the best short-term social performance (temporary plane) in terms of the availability of materials and equipment, due to the local facility to find usual technical means. The long-term social plane (functional) has the highest value in terms of flexibility to introduce reforms, as expected in a conventional construction system and widely known in the sector. The user's comfort in terms of acoustic insulation is consistently the best in this alternative, as it is the most massive (none of the others are multi-layered). This is because one of the factors on which the rate of acoustic reduction depends is the mass of the construction elements, since this mass dampens the shock of sound waves and improves attenuation. However, its main disadvantage is that it gives the worst thermal insulation. This is explained by the fact that materials with greater density, and therefore greater thermal mass, have a high capacity to store heat but are also better conductors, and therefore require greater thicknesses to provide the same level of insulation as another system with less thermal mass. In economic terms, this is also the alternative with the highest energy consumption in its manufacture, the highest risk of deviation cost and the option with the worst deadlines.

Alternative B has the highest environmental value in terms of manufacturing energy consumption, as this system uses only one material with very low primary energy content. It also has the best construction time, due to industrialization, and a practically dry assembly. It also gives the best results in terms of the complexity due to the ease of the construction process. It could be expected that the prefabricated, autoclave-cured, aerated concrete alternative (Yurjev and Yurjev, 2001) would obtain a higher score, since it is much more competitive in terms of assembly speed, although it is the most expensive. Timing is a determining factor in development bids or in the management of large real estate corporations, and construction planning has a significant weight in the awarding of contracts. Some European research projects such as the "Industrialization of sustainable housing" (INVISO), led by the Eduardo Torroja Institute of Construction Sciences and the company Dragados, have studied the contributions to sustainability and maximum energy use of modular solutions (Queipo et al., 2009). However, this is not applicable to self-construction, since the owner's goal is unique; the house is often paid for from his or her own resources, and priority is given to economic aspects and social sustainability (Stender and Walter, 2019). These factors will be particularly linked to functionality and comfort during the building's useful life (Janjua et al., 2019).

In other revised evaluation models (Villegas-Flores, 2009; San-José and Cuadrado, 2010; Alarcón et al., 2011), a higher value index was always obtained for alternatives that used assemblies based on open industrialization, as opposed to conventional solutions. In our case, based on the SISE results, alternative C is better than both the prefabricated option and of course the traditional one. This is due to the fact that it is a novel system that uses hollow structures, or insulating fillings, giving maximum material savings in terms of material and minimum weight, with greater use of the mechanical capacity of the concrete and a greater capacity for thermal insulation (Kozlovska et al., 2016). As a result, very rigid reinforced concrete structures are obtained, but at a lower cost than conventional structures, due to the savings on materials. This is one of the most important consequences in this evaluation, not only because of its effect on costs, but also because it generates a smaller ecological footprint. In addition, a specialized system reduces the risk of cost delays due to the additional quality control implemented by the patent itself. The other reason is the balance between the rest of the indicators, since this is an integral solution combining both the structure and the enclosure. This allows for a great deal of flexibility on site, resulting in a sustainable structure with high strength, low consumption of concrete and steel, high functionality in terms of energy efficiency and reasonable acoustic performance. Figure 5 shows how alternative C distributes the largest area across all the criteria without the need to have all the maximum value indices, as some of them are distributed between the other two alternatives. A dominant value of a criterion reduces the probability of selecting an alternative other than the preferred one. Furthermore, the results show that the optimized solution significantly improves some of the indicators without substantially worsening the rest, even when there is uncertainty in the comparison criteria.

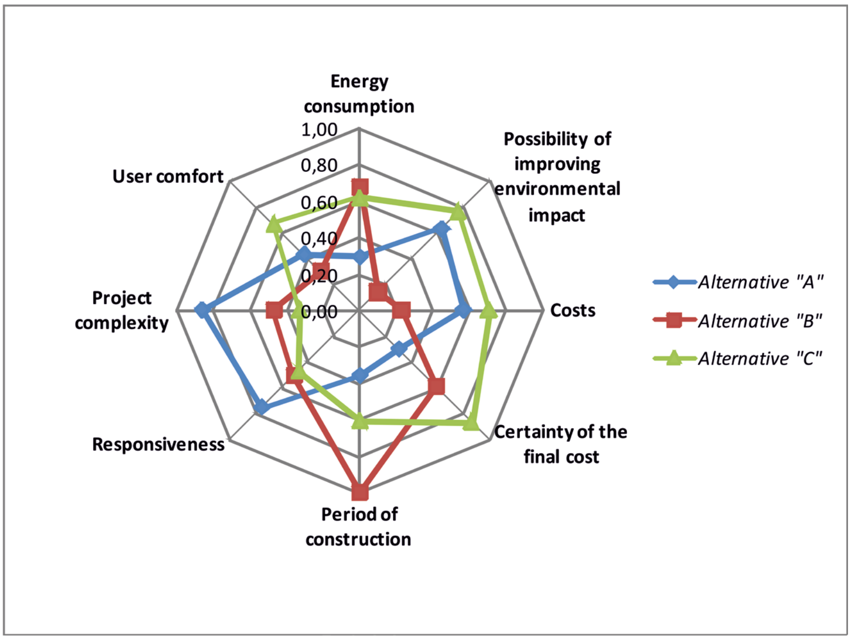

Fig. 5. Comparison between the three alternatives for criteria purposes

We also compared the requirements tree at the indicator level, in order to identify the strengths and weaknesses of the aspects evaluated and compare them for each alternative. This served as a starting point for the sensitivity analysis, which validated the robustness of the methodology, analysing from a double standpoint the influence of the model on the choice of the preferred alternative, as described at the end of Section 4. We considered both the range of variation in the results and the effect on the modification of the weights and parameters of the value functions. In all cases, the consistency of the best solution was higher than 99.60%. Hence, in order for the method to allow for effective pre-selection that reduces the variability of the preferred solution, time and dedication must be invested in the weighting model stage (Navarro et al., 2019). The combination of a specialist seminar ensures a consensus in which all the criteria receive exactly the importance they deserve.

6. Conclusions

From the results of this study, it can be deduced that structure C has an intermediate execution time, due to the reduced setting time, and the lowest material costs. This results in a reduction in the traditional construction time by at least 10%; the enclosure component is also eliminated and the cost of the structure and envelope is reduced by up to 23% compared to the prefabricated system. Some avenues for future work might be to study the improvements in the time and cost when adapting this evaluation to larger projects. This could lead to lines of research that would allow the technological reinforced concrete system to evolve, the leap to modulation and industrialization to be made, and the best of the results achieved by alternatives B and C to be combined.

One contribution of this study is a process for adjusting a set of specific indicators for a self-promoted townhouse. These indicators were measured based on tangible and immaterial attributes using questionnaires to convert the variables into scores and associated scales. Uncertainty and risk factors were also introduced to serve as a decision-making tool for both owners and designers. The model takes into account not only technical and economic issues, which are typical of project management and procurement processes, but also social and environmental issues. Furthermore, due to the flexibility of the decision-making method employed, it can be calibrated by adjusting it to other similar typologies, making it a more versatile tool and enhancing its practical application to various situations.

This tool provides a rigorous and objective framework that can help architects and engineers design and select the most sustainable solution for their client based on contradictory criteria. The decision-making process is applied from the earliest stages of the project and is adjustable to the context, including the geographical location and type of building. However, one disadvantage of this methodology is that it requires considerable time and dedication to compile the data, which must be reliable and obtained from within the same temporal-spatial environment.

As described in Section 1, this method has already been partially used in construction for practical purposes, although seldom in residential buildings and even more rarely in single-family homes. The evaluations are normally carried out in pairs on the basis of two alternatives, thus simplifying the comparison between the options that really constitute a disjunctive on another reference option that has already been tested in practice. In our study, in the face based on dichotomous choices (A or B), we carried out a comparison by providing three simultaneous alternatives. Although it is complicated in terms of data collection and input, this comparison offers a wider perspective on the different constructive solutions, and the sensitivity analysis of the results could be refined using other complementary methodologies such as the Delphi method. On the other hand, there is currently little scientific discussion of systems using autoclaved, aerated concrete blocks and slabs (Ytong), and none of double- or multiple-walled structures of reinforced concrete using connectors and internal thermal insulation (Elesdopa), beyond the internal development of patents or seminars including technical presentations.

This study does not aim to question the weights or the results of the indicators, but instead to apply them to a real case. We use a step-by-step methodology based on an analysis of value with mathematical accuracy. This offers a comprehensive evaluation system allowing a self-promoter, in collaboration with a project architect/designer, to objectively consider the different stages of the life cycle that will undoubtedly affect the design and construction of their home. Future work will address the efficient design of structures with non-conventional concrete, based on multi-objective sustainable criteria through the use of data mining techniques, multi-criteria heuristic optimization algorithms and life cycle analysis.

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