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Multi-Criteria Decision-Making Method for Sustainable Energy-Saving Retrofit Façade Solutions

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Abstract: The increasing energy consumption levels of buildings within Europe call for controlled consumption and improvements to energy savings and efficiency and effective energy efficiency regulations. However, many aging and energy-inefficient buildings require energetic retrofitting that can employ various façades solutions and insulation materials. The selection of the most sustainable options in each situation therefore requires a decision-making methodology that can be used to prioritize available retrofit solutions based on economic, functional, environmental and social criteria. In this paper, both the methodology and the economic basis of the retrofitting process are presented. The methodology was validated in a case study, and a sensitivity analysis also demonstrated its validity, robustness and stability.

Keywords: façades; sustainability; retrofit; energy efficiency

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1. Introduction

European Directives incorporate thermal requirements with which efficient buildings must now comply, a development that can be explained by the increasingly higher energy consumption levels of buildings. In the European Union, almost 50% of final energy consumption is used for heating and cooling, of which buildings consume 80% [1] and produce 36% of CO_2 emissions [1,2]. At a global level, the construction sector is responsible for the consumption of approximately 36% of total energy and more than 40% of emissions [3]. In 2018, more than 5 billion m2 of buildings were built without fulfilling any type of energy requirement, as there are no regulations on minimum energy efficiency requirements for buildings in almost two-thirds of nation states worldwide [4]. Therefore, since 2000, the use of energy in buildings has only improved by 25% [4]. Likewise, the energy demand of the residential sector in terms of total consumption and electricity consumption has risen in Spain and at a European level (EU27) to 17% and 25% and to 25% and 29% [5], respectively. In addition, consumption habits, thermal improvements within homes and the expansion of teleworking in reaction to the new health emergency situation all point to increased energy demand within the residential sector [5].

The building sector has become a strategic sector because it has the potential to implement energy-saving measures more effectively than other sectors (i.e., the transport sector and industry sectors) [6]. In addition, the Energy Efficiency Directives in Europe must be applied both to new and, above all, to aging buildings in order to retrofit the existing housing stock, prioritizing energy efficiency [1]. Retrofitting shows the best potential for saving energy and reducing emissions [2], given the low rates of demolition and construction of new buildings. The economic and environmental impacts of energetic retrofitting are, moreover, a better option than demolition and new construction [7]. The rate of retrofitting compared to new buildings is 1% to 3% per year [8,9]. Large reductions in energy consumption through retrofitting, which has been proven to reduce energy

consumption and CO_2 emissions [10], are therefore necessary to improve the energy efficiency of these older buildings [10].

The most recent regulations on energy efficiency reflect the commitments acquired in the European Community. Thus, The Spanish Technical Building Code (CTE) that entered into force in 2006 contained quite stringent regulations on energy efficiency. It was, in turn, modified in 2013 following the transposition of European directives and in 2019 due to the obligation for periodical reviews and updates to the minimum energy efficiency requirements [11]. The CTE established minimum requirements for the thermal envelope of a building, taking into account the climate and the location of the building, as well as the presence of thermal bridges and methods for their closure [11].

In Spain, less than 8% of all housing was built after the 2006 regulations, so the stock of energy efficient housing is quite small [12]. Therefore, 92% of residential buildings could be improved through energy saving retrofitting.

However, the percentage of retrofitted buildings in Spain, in relation to total housing stock, is one of the lowest in the European Union, thirteen points below the European average [13]. Spain is, nevertheless, the second country in southern Europe, with the largest stock of buildings over 50 years old [14].

Thermal retrofitting of the envelope makes it possible to reduce both the energy consumption of a building and its CO_2 emissions [15]. The constructive solution, which can reduce the energy consumption of a building, is a fundamental improvement measure that must be properly selected to improve the thermal performance of the façade [16], as approximately 50% of total energy loss is through the envelope [17]. In Europe, façade retrofitting is the most advantageous, and roof retrofitting is the least advantageous energy saving measure, in terms of economic viability and energy savings [18]. In countries such as Ecuador, at a different latitude, the opposite effect occurs, in so far as roof insulation is more energy efficient than façade insulation [19].

There are various façade retrofit methods that can improve the energy efficiency of buildings. These proven techniques are widely used with different materials and construction solutions in retrofitting. External Thermal Insulation Composite Systems (ETICS), Ventilated Façades (VF), Internal Insulation Systems (IIS) and Air-space Insulation Systems (ASIS) are among the leading solutions.

It is necessary to determine the type of thermal insulation and the thickness of the material used in the building envelope in order to reduce energy consumption and to achieve comfortable interior atmospheres [20].

Various decision-making methods have been developed to select the most suitable insulation material or building façade solution for energetic retrofitting of buildings. Different factors are applied in each method such as the scope of application, the location of the building, etc. For example, factors such as primary energy consumption, economic costs and environmental impact were considered in a methodology for selecting an optimal material with emphasis on recycling for use as insulation in residential buildings in Greece [21]. A somewhat similar method that focused on insulation material properties for buildings located in Sarajevo was also proposed in [22]. The methodology in [23] involved the selection of an optimal thickness of insulation material for a Spanish climate based on economic and environmental considerations. Other methods were proposed to select the most suitable retrofit alternative for a structural concrete building. Functional and economic aspects were taken into account for the application of both methods to residential and public buildings located in Lithuania [24,25], although no consideration was given to either social or environmental aspects. Methodologies were also developed to establish the selection process of the most important building elements to improve the energy efficiency of buildings located in Lithuania [26]. A multi-criteria tool was developed to optimize the retrofit of the envelope [27] and to help select materials and emerging technologies [28], but only four criteria were considered: the energy consumption of the building, the cost, the environmental impact of the building life cycle and thermal comfort [27,28]. A tool was proposed in [29] to evaluate the façade retrofit solutions. It was used to guide the choice of

the most appropriate technology in the early design stages, taking into account the LCC (Life Cycle Costing) of the envelope, its characteristics and its installation problems.

The objective of this study is, therefore, to establish a model for evaluating the sustainability of the construction systems used for the energetic retrofitting of buildings. In this decision-making methodology, all aspects of sustainability will be taken into account, including economic, environmental, functional and social aspects. In addition, the model will be of a global character, as it will determine both the constructive solution and the most suitable thermal insulating material. Therefore, this methodology is intended to assist the retrofitting process of the large stock of old and energy-poor buildings that fail to comply with the minimum requirements on energy efficiency, assistance that can serve both building owners and construction companies when selecting the most sustainable façade solution.

2. Materials and Methods

A building façade should be evaluated in terms of economic and environmental aspects in order to consider multiple selection criteria [30]. However, energy and other factors such as economic, environmental, social, technical and regulatory factors should also be considered in an optimal retrofit solution [10]. In addition, selection of the right energy saving measures entails the selection of criteria and the assignment of weighting factors, because it is a multi-objective optimization problem [10].

The methodology proposed in this paper can be used to select a residential building retrofit system. Both the selection of the most suitable insulation material and the façade retrofit solution are based on sustainability considerations. Buildings retrofit solutions are of vital importance, not only because of the immediate consequences such as the reduction of energy consumption and other improvements, such as positive external effects, increased quality of life and climate change mitigation. Buildings are human spaces in which people live and work, for which reason the surroundings around the building and human aspects should also be considered [31].

Sustainable construction is a process that integrates functional, economic, environmental and quality considerations in order to build and to retrofit buildings so that they are functional, accessible, attractive, comfortable and healthy, thus promoting the well-being of the occupants and the environment. In addition, this process implies efficient consumption of energy, materials and water in a way that is respectful of the environment and economically competitive throughout the life cycle of the building.

All these conditions are required for the sustainable retrofitting of buildings, included within the three basic pillars of sustainability: the social pillar, the environmental pillar and the economic pillar. Sustainable retrofitting can, therefore, also bring improvements to environmental, economic and social aspects of the environment and the quality of life of the occupants throughout the life cycle of the building. However, the sustainability evaluation of each solution entails an analysis and comparison of factors that are difficult to describe in similar terms and to quantify in the same units. The use of the MIVES (Integrated Value Model for Sustainability Assessment) multi-criteria methodology is, therefore, proposed in order to select the most sustainable retrofit solution. MIVES is a Multi-Criteria Decision-Making Model (MCDM) that uses value functions and an Analytic Hierarchy Process (AHP) to assess the sustainability of many sorts of processes. It was developed by three different Spanish universities and a research institute (Universitat Politècnica de Catalunya (UPC), Tecnalia, Universidade da Coruña (UdC) and University of the Basque Country (UPV/EHU)) and was initially applied in the field of industrial buildings [32].

MCDM methods can be based on different algorithms such as fuzzy logic [33,34]. Nevertheless, not all the methods allow for the application of fuzzy evaluation as it happens with the Weighted Sum Method [35,36]. The proposed MCDM method has several advantages over other optimization methods, and that is why it has been selected. One of the advantages is that the approach of the entire valuation model is prior to the creation of the alternatives. This makes the methodology different from others, being one of the most

important characteristics of the methodology. Decision making is done at the beginning, when defining and assessing the aspects to take into account. This approach is an advantage because, since the alternatives are not defined, there is no influence of the evaluations of the alternatives, and therefore, a certain subjectivity is avoided [37]. In addition, a comparison criterion can be generated from the results, which is useful for conducting sensitivity analyses [38].

Another advantage is that the sustainability of the different retrofit solutions can be evaluated with MIVES, taking into account environmental, economic and social sustainability aspects throughout the life cycle of each solution. In this way, the most sustainable energy retrofit solution can be selected from all the alternatives.

The limitations of MIVES appear when applied outside the context for which it was designed. The databases with which we work must be modified in order to evaluate a specific context and to achieve a homogeneous evaluation [37].

MIVES has been used in different applications due to its versatile nature [39] such as building [40,41], electricity generation systems [42], wind-turbine systems [43] and urban planning [44], among others. It is also referred to in Spanish regulations on the sustainability of concrete and steel structures as a means of estimating the degree of sustainability of both concrete and steel structures [45–47].

It consists of an MCDM method with which each alternative solution can be evaluated by means of a value index. A value indicator reflects the degree of satisfaction with an indicator, each of which may have different units. A weighted sum of the values of the criteria under consideration yields the value index. This methodology is based on multi-attribute utility theory [37] and employs the Analytic Hierarchy Process (AHP) technique in the weight assignment phase so as to try to reduce subjectivity when establishing the weights [48].

The indicators involved in decision making are usually expressed in different units. MIVES uses value functions to standardize the units for comparison, which will transform the measurement units of the indicators into dimensionless units between 0 and 1, depending on their degree of adequacy.

The evaluation model must first be defined before the different alternatives are evaluated. The evaluation model consists of establishing the decision-making tree, assigning the weights to each part of the tree and determining the value function of the tree indicators. This model predates the creation of the alternatives. The decision making is, therefore, performed at the outset when defining the aspects to take into account and their assessments. In this way, subjective decision making is avoided, as the weights are assigned before the alternatives are evaluated.

The aspects for consideration when making each decision are branches of the decision-making tree that have several levels, and each level is, in turn, subdivided into different sub-levels (Figure 1) [49]. Thus, the alternatives are defined following an evaluation of their characteristics at each level and sub-level: the Requirements, which are the most general aspects; the Criteria, specific concepts that are analyzed within a requirement; and the Indicators, which are the most specific and generally quantifiable aspects with tangible characteristics, which will be directly evaluated and quantified.

The indicators are defined using value functions so that the valuations of different measurement units may be compared. In this way, the different variants can be compared with each other, and a weighted sum of the different valuations of each indicator can be calculated.

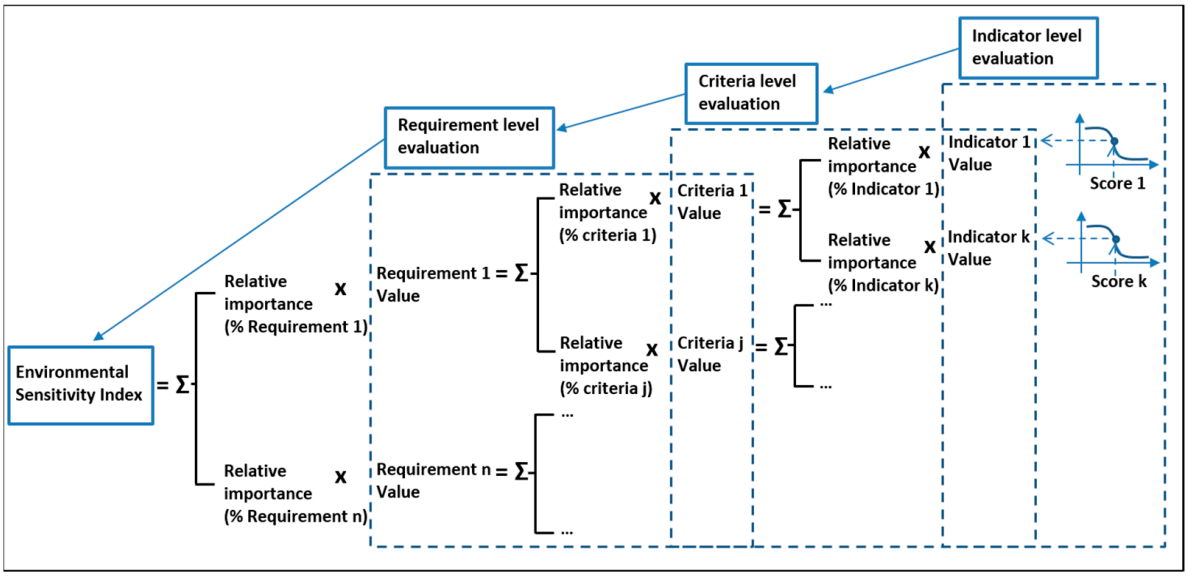


Figure 1. General diagram of the MIVES methodology and its operation.

The score of the value functions (V_{ind}) is obtained using Equations (1) and (2) [32]. The value of factor B in Equation (1) is obtained by Equation (2). This factor B allows the function to remain in the value range from 0 to 1 (a minimum value of 0 and a maximum value of 1 that can be obtained for each indicator).

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

where, V_{ind} is the Indicator response; X_{ind} is the response of the alternative evaluated with respect to the corresponding indicator (indicator abscissa value); X_{min} and X_{min} are the minimum and maximum reference points on the indicator scale, respectively; A is the value of the response X_{min} where A will usually be equal to 0 (A = 0); Pi is the shape factor that determines whether the curve will be concave, convex, straight or S-shaped. (Concave curves imply Pi < 1. Convex or S-shaped curves imply Pi > 1. Straight lines imply Pi ≈ 1); Ci is the abscissa value at the inflection point on the curves where Pi > 1; Ki is the ordinate value of point Ci; B is the factor that maintains the value function within the range (0–1), obtained with Equation (2).

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

Different value functions are defined, one for each indicator, each between 0 and 1. To do so, the trend of the value function is defined, the points of minimum and maximum satisfaction and the shape of the value function are determined, and finally, the value function is mathematically computed.

The value function curves assume different shapes: S-shaped, concave, convex or linear increasing or decreasing (Figure 2) [50].

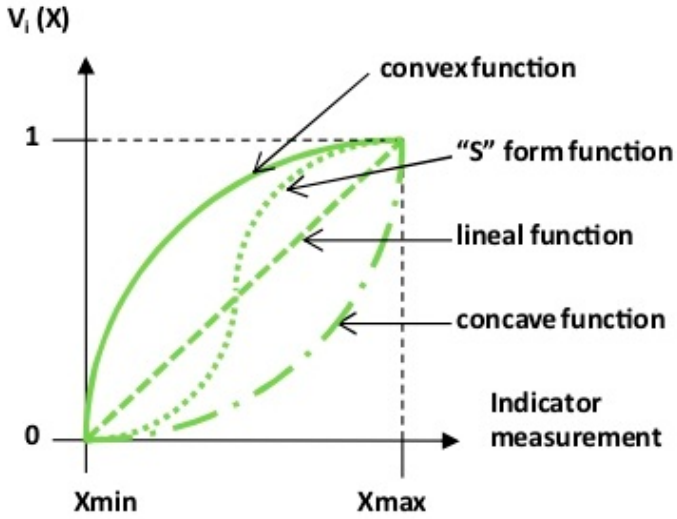


Figure 2. Indicator value functions.

The weights are assigned to different variables within the same group, weighting the decision tree in accordance with its hierarchical level. The weights, therefore, determine the level of importance of each requirement, criterion and indicator. In this study, the weights were directly assigned using the Delphi method, which involves a panel of experts with proven experience in this field [51]. The Delphi method is a research technique with which an opinion is obtained from a panel of experts. The formation of a panel of experts was based on the guide defined by Hallowell and Gambatess [52]. The panel of experts consisted of 12 professionals with over 25 years of experience in building retrofit and energy efficiency projects: 4 architects and engineers with past experience of various retrofit projects affecting residential buildings and architectural heritage; 3 university professors with investigative roles in various national and international projects in the field of energy efficiency and retrofit; representatives of 3 building retrofit companies; and, finally, 2 agents of a public company in charge of managing the promotion and maintenance of council housing. The questionnaire can be found in Appendix A.

The experts were consulted at least twice on each question so that they could reconsider their responses within an iterative process. The questions were formulated so that the responses could be quantitatively processed for their statistical treatment to ensure robust results.

The following flow chart shows how the study was conducted (Figure 3).

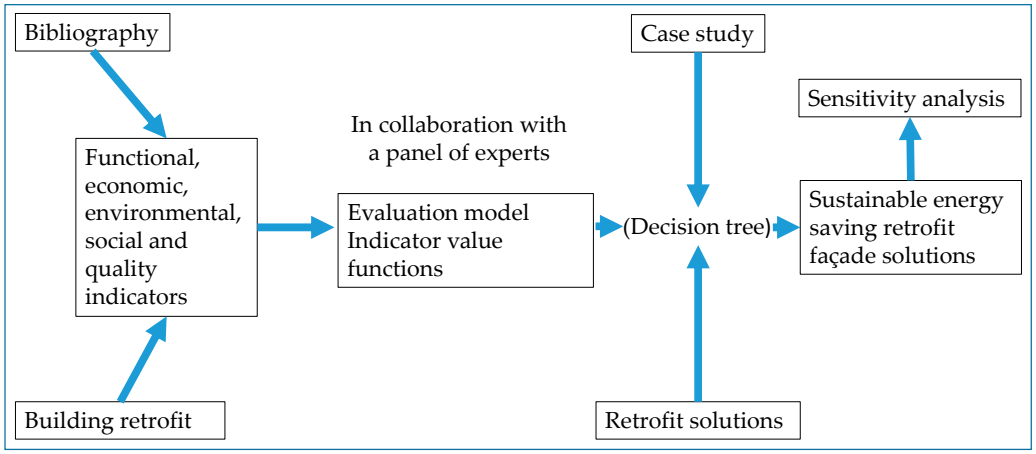


Figure 3. Flow chart of the study.

2.1. Evaluation Model

2.1.1. Decision Tree

The decision-making tree, defined below in Figure 4, represents the aspects under study to produce the sustainability index: the requirements, criteria and indicators [53].

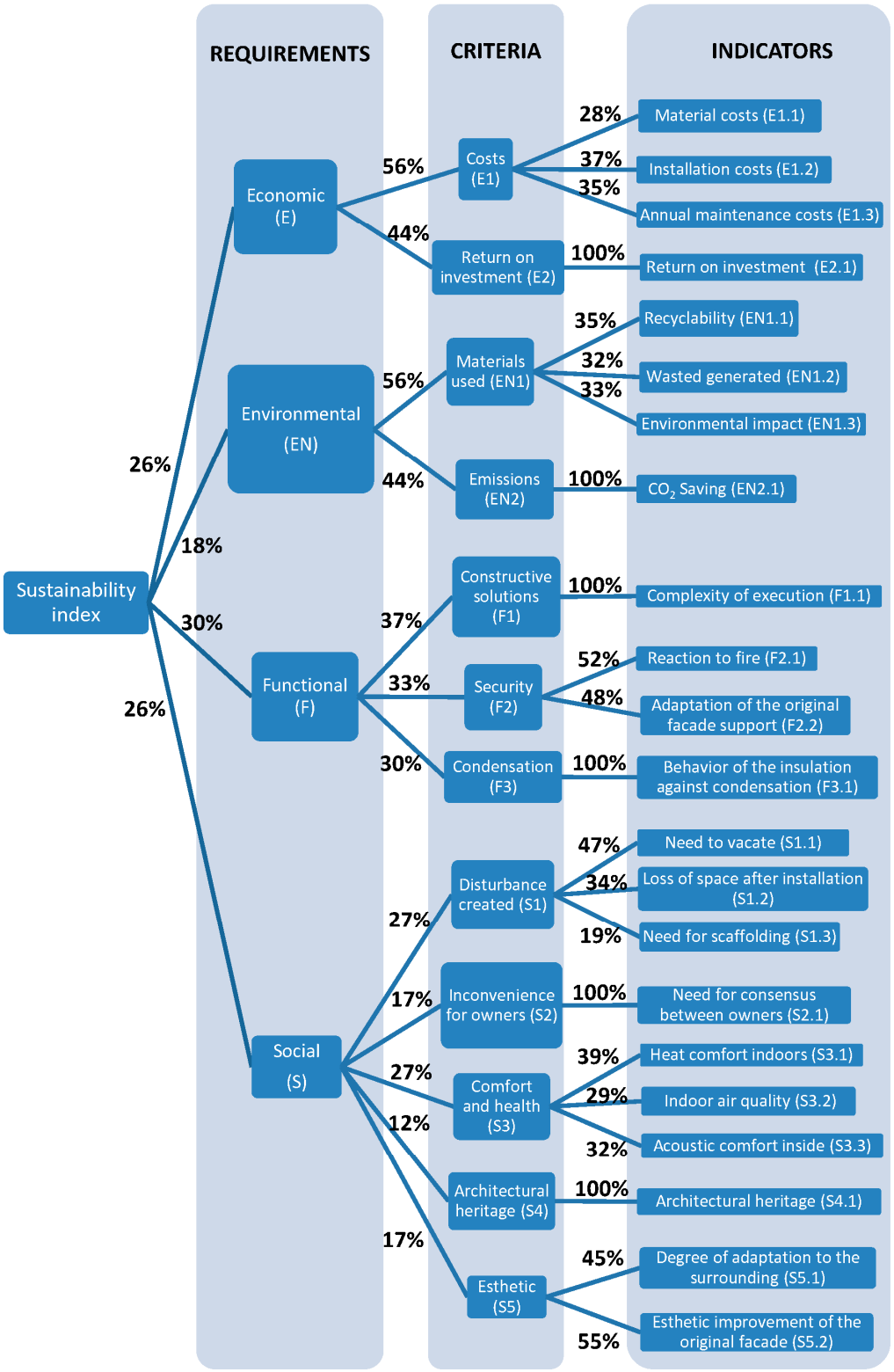


Figure 4. Decision tree [53].

2.1.2. Requirements

The requirements are the main characteristics to consider when evaluating the life-cycle sustainability of the various retrofit solutions. The sustainability of each solution will be measured by the economic, environmental, social and functional requirements.

Each requirement of the tree is in turn subdivided into one or more criteria. Each criterion is used to compare the different alternatives that are proposed and is in turn subdivided into one or more indicators, in order to evaluate the criterion and compare it with others. The criteria are not measurable parameters but represent a way of grouping the parameters that each indicator represents. The indicators are associated with parameters for the quantification of the different criteria, thereby offering a picture of the different alternatives in terms of sustainability.

The economic requirement takes into account initial costs and maintenance costs throughout the life cycle of the building. It assumes great importance when considering that the maintenance costs are borne by the homeowners who represent 80% of the population in Spain and over 50% of the population of each EU Member State [54]. Furthermore, the different alternatives were compared with this requirement, taking into account the total cost generated throughout all the life-cycle phases and the energy savings that may be obtained.

The various alternatives were compared in terms of the environmental impact generated throughout the life cycle. In this way, it is possible to minimize the environmental impact that the façade retrofit may generate.

Each alternative has a degree of complexity for installation, as new materials and structures are added to the building in the retrofit process that can affect fire safety or/and the stability of the building throughout its life cycle. The functional requirement is used to compare the different alternatives from these points of view in order to select the most sustainable alternative according to its functionality.

The social requirement is linked to the urban environment and the tenants living in the building that is to be retrofitted. It should be recalled that, in most cases, the building will be occupied during the renovation process and throughout its life cycle.

2.1.3. Economic Requirement: Definition of Criteria and Indicators

The economic requirement is analyzed in this sub-section so as to give an example of the proposed methodology. The cost criteria and the return-on-investment criteria are subdivided into one or more indicators, each with its own value function according to the parameters needed for its calculation (Table 1). The panel of experts also recommended this value function for the evaluation of the indicators.

Table 1. Type of function and necessary data for each indicator.

Indicator	Parameter	Data for Each Alternative							
		Xmax	Xmin	C	K	P	Function Type	Units	References
Material costs (E1.1)		5.22	472.20	90	0.001	3	Parabolic/Decrease	€/m^2	CYPE. Index price generator
Installation costs (E1.2)		6.84	56.40	90	2	2.5	Parabolic/Decrease	€/m^2	CYPE. Index price generator
Annual maintenance costs (E1.3)	Durability	107.23	1.86	100	0.3	2.5	Parabolic/Decrease	€/m^2 the first 10 years	CYPE. Index price generator
	Susceptibility to vandalism	-	-	-	-	-	Step	-	-
	Maintenance against vandalism	-	-	-	-	-	Step	-	-
Return on investment (E2.1)	Total cost	527.24	14.09	150	0.01	3	Parabolic/Decrease	€/m^2	CYPE. Index price generator
	Energy saving	55	6	40	5	1	Parabolic/Increase	%	CEX v2.3 software
	Payback	30	5	50	0.1	3	Parabolic/Decrease	years	CYPE. Index price generator CEX v2.3 software. Energy Agency of the Basque Government

The expenditure needed to carry out the retrofit project is considered under the first criterion, "costs". Within these costs, the initial costs and annual maintenance costs analyzed over a 10-year period must be estimated. The return-on-investment criterion evaluates the return on the investment in terms of the energy savings of each alternative solution.

The cost criterion is divided into three indicators (material costs, installation costs and maintenance costs). These are measured in terms of the economic costs of the material (€/m^2), the cost of its installation and the annual cost of maintenance during the entire use phase after the retrofit. In this way, the most and the least expensive alternative is determined, taking into account the materials used, the installation and the maintenance costs. In this last indicator, in addition to the annual maintenance cost, the susceptibility of the building retrofit to vandalism is considered.

Indicator 1, "material costs": specifies the price of each alternative, taking into account the material costs in €/m^2 based on market construction prices in Spain. The lower the price, the higher satisfaction of the owners, so a descending value function is proposed to evaluate this indicator. The shape of the curve is concave, because the level of value decreases significantly as it moves away from the value of maximum satisfaction, as can be seen below in Figure 5.

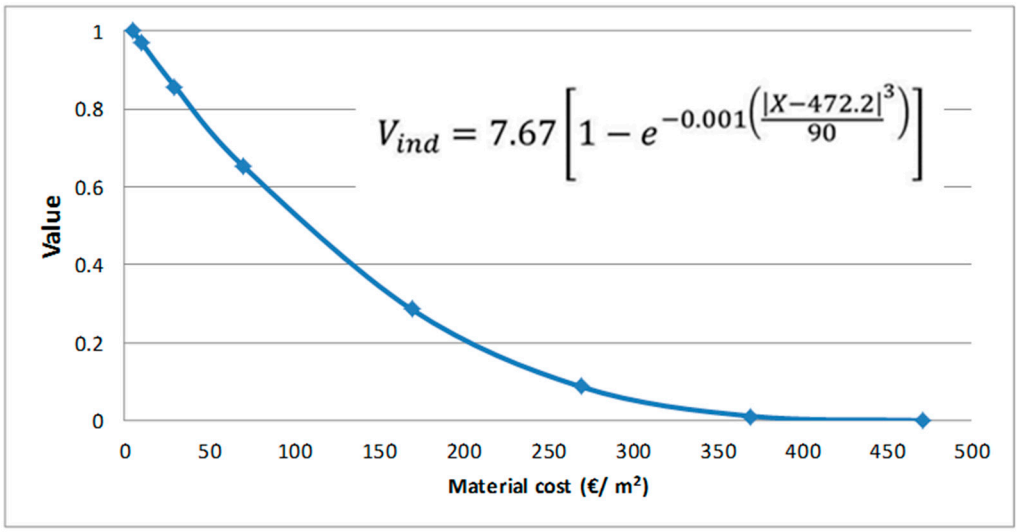


Figure 5. Value function of the material costs indicator.

The maximum satisfaction value of this indicator is defined by the lowest price, considering the costs of the material in use, and the minimum by the most expensive price of all the possible solutions that were proposed.

Indicator 2, "installation costs": for the same insulation material, the installation cost may differ depending on the size of the pieces or their manufacture. This indicator reflects an evaluation of the price in €/m^2 according to the costs during the execution process of the selected alternative using the same price base. As with the previous indicator, a concave descending value function was generated, the extremes of which are defined by the most and the least expensive cost function (Figure 6).

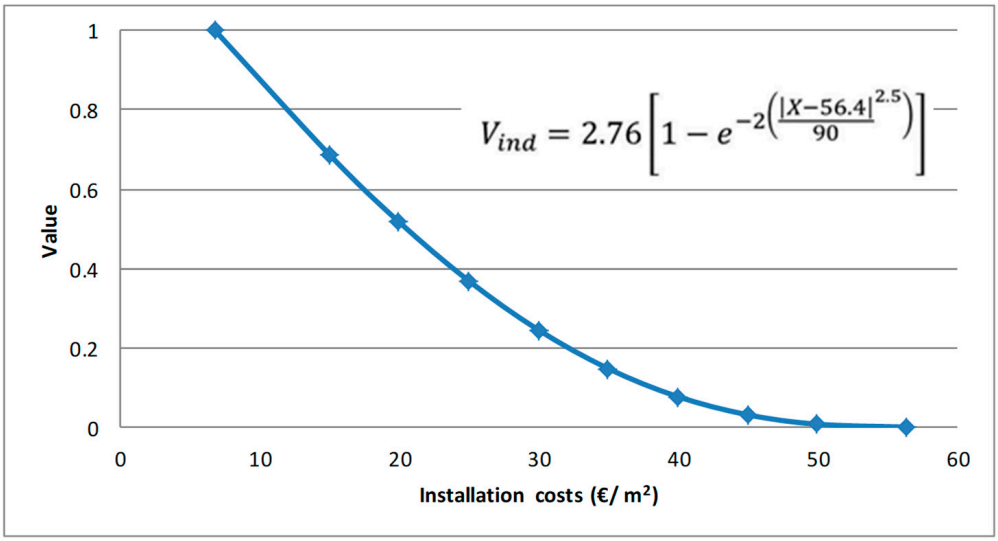


Figure 6. Value function of the installation costs indicator.

Indicator 3, "maintenance costs": represents the evaluation of the annual maintenance cost over a 10-year period of the use phase, both in interventions on the exterior building façade and within the building. The same price base was used to calculate the annual cost as a function of material durability (especially exterior finishing) and any aggressive agents present in the urban environment.

Likewise, the interventions on the exterior building façade improve the external finish of the façade. Façade reform, depending on the location and accessibility of the building, includes susceptibility to vandalism, deterioration of the esthetic appearance and, therefore, increased annual maintenance costs. Among the different external claddings, materials that are easier to maintain against vandalism will reduce annual maintenance costs. In addition, the accessibility of the building façade must be taken into account when assessing any damage caused by vandalism.

Three parameters must, therefore, be defined for the valuation of this indicator: durability, susceptibility to vandalism and maintenance resulting from vandalism. According to the panel of experts, 56% of the indicator weight was conditioned by the durability of each alternative in relation to the maintenance cost (€/m^{2}year), because the parameter establishes the durability of each alternative as a function of the annual maintenance costs. The esthetic maintenance of the façade, therefore, conditions 44% of the indicator weight, which is defined by the parameters, susceptibility to vandalism and maintenance against vandalism. This indicator value, established by Equation (3), must be between the values 0 and 1.

The maximum satisfaction value of this indicator was defined by the maximum value calculated with Equation (3): the least expensive annual maintenance cost, the least susceptibility to vandalism of the façade and an esthetic external cladding that is easy to maintain. The minimum satisfaction value was, in turn, defined by the minimum value of the equation: the alternative with the most expensive annual maintenance cost, the highest susceptibility to vandalism on the façade and an esthetic external cladding that is difficult to maintain.

$$V_{ind} = 0.56 \times Y_{maintenance\ cost} + 0.22 \times Y_{accessibility} + 0.22 \times Y_{esthetic} \quad (3)$$

where Ymaintenance cost = Satisfaction value of each alternative, considering maintenance costs; Yaccessibility = Satisfaction value of each alternative, considering accessibility to the façade; Yesthetic = Satisfaction value of each alternative, considering esthetic maintenance of the façade. "The durability" parameter, obtained with the price generator, determined the maintenance cost of each alternative over the first 10-year period. At a lower price, greater satisfaction is obtained, so the parameter showed a descending function, and the

shape of the curve was concave, as the value level decreased significantly as it moved away from the maximum satisfaction value (Figure 7). The lowest annual maintenance cost over the first 10 years defined the maximum satisfaction value, and the minimum defined the most expensive cost.

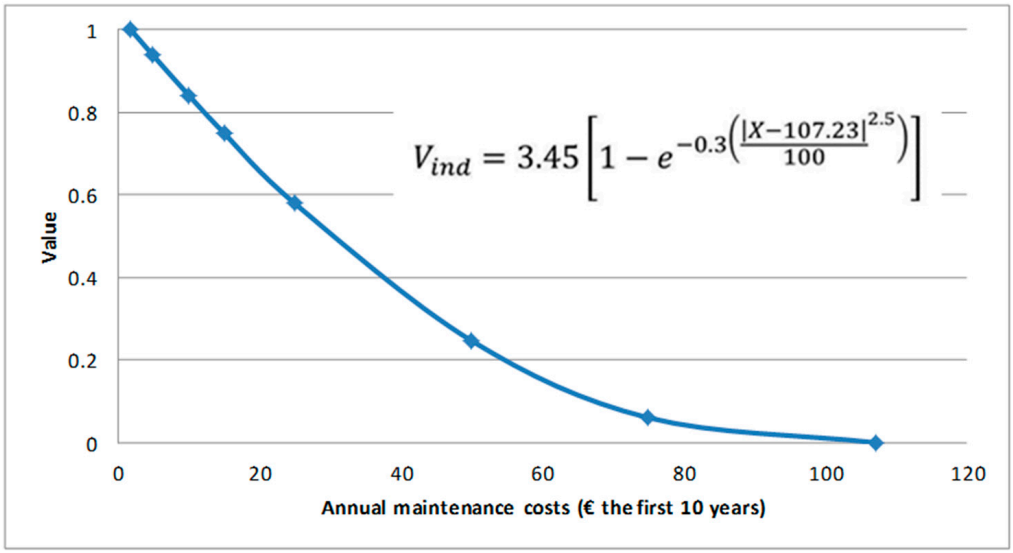


Figure 7. Value function of the durability parameter.

The parameter "susceptibility to vandalism" takes into account the accessibility of the building's façade in relation to the pedestrian traffic zone. The maximum satisfaction value of this parameter was defined by the façade that was least susceptible to vandalism of terms of accessibility, and the minimum satisfaction value was for the façade that was most susceptible to vandalism in terms of its accessibility. The value function of this parameter is dichotomous, as the evaluative response is all or nothing (yes or no), defined by the tabulated function. The function form of this parameter is a stepped function, as the satisfaction value can only be 1 or 0, as shown below in Figure 8.

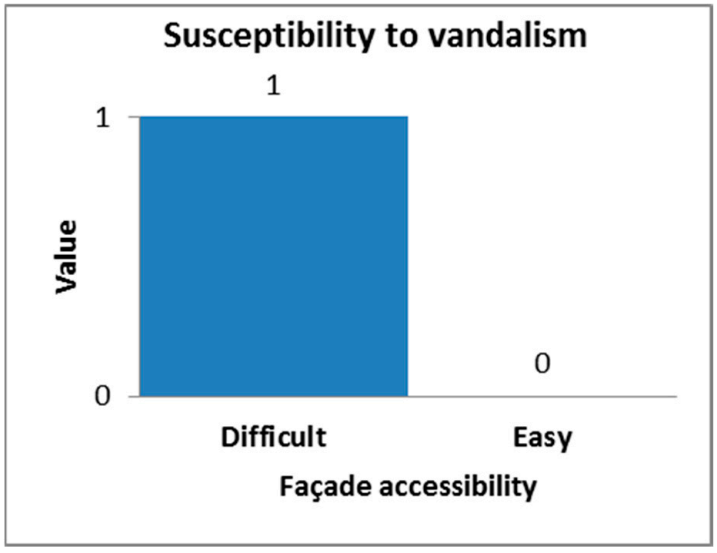


Figure 8. Value function of the susceptibility to vandalism parameter.

Vandalism was not taken into account for Internal Insulation Systems and Air-Space Insulation Systems, as these systems involve no modification of the building façade, and

the susceptibility of the building to vandalism is not increased with respect to its current situation. Therefore, in these cases, the value of "esthetic maintenance" will be 1.

Finally, the parameter "maintenance against vandalism" distinguishes between either simple or difficult maintenance against vandalism in accordance with the cladding proposed in each alternative and the façade esthetics. One sort of façade cladding may be easier to clean following vandalism than another. Two examples are an exterior cladding with acrylic mortar used in ETICS and a ceramic cladding with anti-graffiti protection used in VF. Maintenance of façade esthetics is less costly with easily cleanable materials. The maximum satisfaction value of this parameter is determined by the material that requires the least maintenance to maintain the esthetic appearance of the façade against possible acts of vandalism. The minimum satisfaction value is determined by the material that needs the most maintenance to maintain the esthetic appearance of the façade against possible acts of vandalism. A difficult-to-clean exterior cladding is the natural stone cladding used in VF.

As with the previous parameter, this parameter is a step function that is defined by the tabulated function. The function of this parameter is represented in Figure 9.

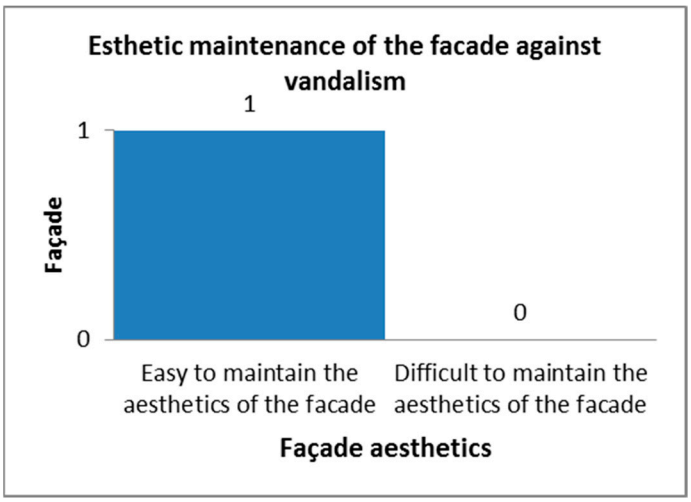


Figure 9. Value function of the parameter "Aesthetic maintenance of the façade against vandalism".

The indicator "Return on investment (E2.1)" corresponds to the criterion with the same name "Return on investment (E2)". Three parameters must, therefore, be defined for the valuation of this indicator: total cost, energy saving and payback. Each parameter will have a weight that is defined by the following Equation (4):

$$V_{ind} = 0.27 \times Y_{total\ cost} + 0.41 \times Y_{energy\ saving} + 0.32 \times Y_{payback} \quad (4)$$

where $Y_{total\ cost}$ = Satisfaction value of each alternative, considering total costs; $Y_{energy\ saving}$ = Satisfaction value of each alternative, considering energy saving; $Y_{payback}$ = Satisfaction value of each alternative, considering payback of the investment which is obtained using Equation (5).

$$\text{Payback (years)} = \frac{\text{Investment cost (€)}}{\text{Energy saving}\left(\frac{\text{KWh}}{\text{years}}\right) \times \text{Energy cost}\left(\frac{€}{\text{KWh}}\right)} \quad (5)$$

where Investment cost = Investment cost of each alternative; Energy saving = energy saving in each alternative; Energy cost = The average price of energy, which is the same for all alternatives.

2.2. Building Features of the Practical Case

A building (Figure 10) that had been built before the entry into force of CTE (2006) in Spain was used to validate the methodology. The building under study is located in

an historic city center next to other blocks of flats with the same characteristics. A high percentage of the apartments were occupied by older homeowners, in some cases living alone with reduced mobility and with few economic resources, as well as some low-income family groups.

Figure 10. Case study.

With no thermal insulation, the building is energy poor and requires an energetic renovation to improve its energy efficiency. In this way, the building will comply with the energy-saving requirements set forth in the new CTE.

The building is located in Bilbao, in the north of Spain and within the Autonomous Community of Euskadi (CAE). The housing stock of this Autonomous Community is among the oldest of Southern Europe [55] and within the European Union, behind only the United Kingdom [56]. In addition, 90% of all houses within the CAE have homeowners [57].

The climate of the CAE is mild with relative humidity values between 65–76% and temperatures between 8 °C and 22 °C [58], environmental conditions that compare favorably with other climatic zones in Spain that have more severe winter and summer weather, which explains why only 1.7% of homes have installed air conditioning [59].

With reference to the CTE, the climatic zone of the building is C1 (Figure 11). In this climatic zone, the minimum thermal transmittance requirement for façade walls and envelope in contact with the ground is 0.49 W/m^2K. Likewise, the standard also establishes optimal thermal transmittance to obtain the optimal cost solution, taking into account the overall cost and energy consumption. In this climatic zone the optimum thermal transmittance is 0.29 W/m^2K.

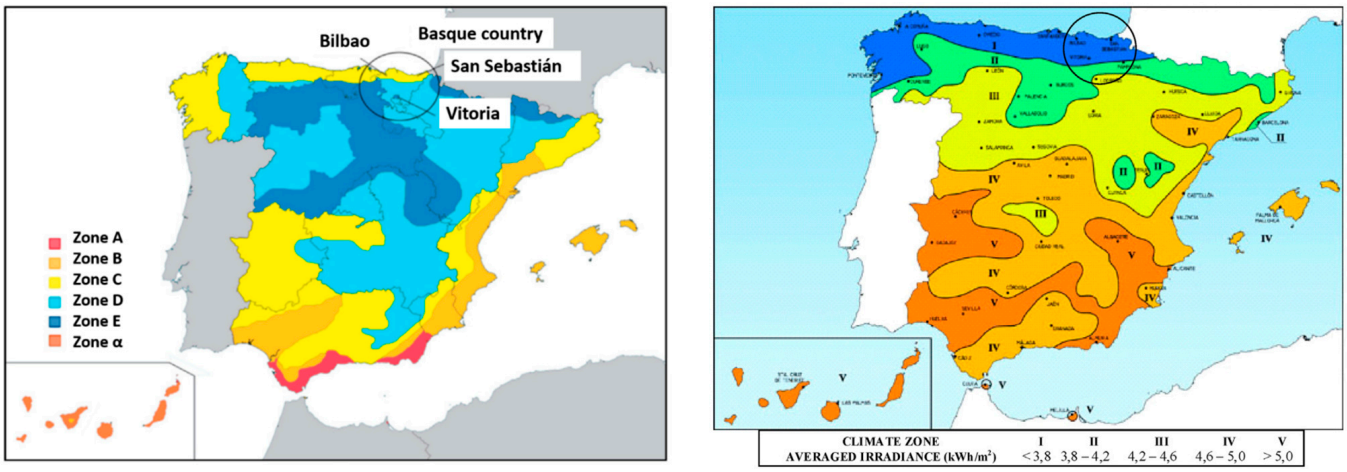


Figure 11. CTE climatic zones according to winter and summer severity in Spain.

The semi-basement area of the building with stone slab cladding has a different esthetic appearance from the residential part. The exposed brick façade rests on the floors of different heights, breaking its vertical continuity and highlighting its horizontal lines.

The energy certification of the building was calculated using CEX v2.3 software. From these calculations, the heating demand (97.4 KWh/m^2) and the global emissions (38.9 KgCO$_2$/m^2 year) of the building before retrofitting were obtained. An "E" energy certification was obtained, as may be seen in the following Figure 12.

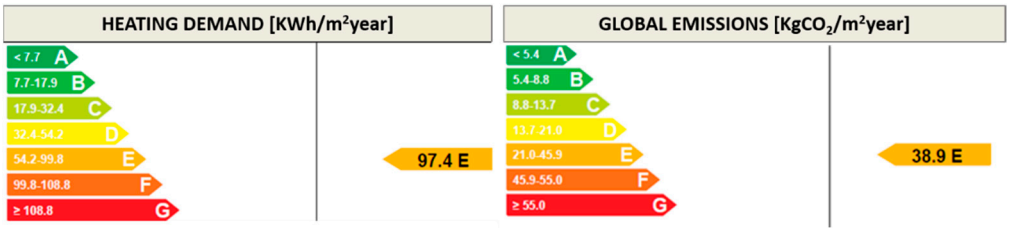
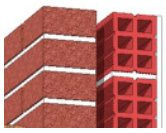
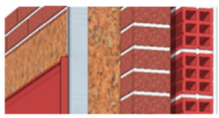
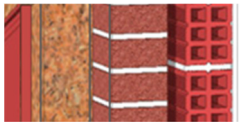
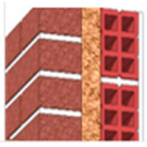


Figure 12. Energy certificate of the case study.

2.3. Retrofit Alternatives

Four alternatives were proposed (Table 2) in order to evaluate the most sustainable façade retrofit alternative for the building under study. These alternatives correspond to the most widely used energy retrofit systems in use today: ETICS, VF, IIS and ASIS. Moreover, improving insulation efficiency is an efficient way to reduce energy demand by reducing heat losses through the envelope [60]. Reductions in energy demand of 64% in summer and 37% in winter through appropriate use of insulation have been reported [61]. Insulating materials commonly used in industry are: mineral wool, expanded polystyrene (EPS), extruded polystyrene (XPS), cellulose, cork and polyurethane (PUR) [62]. Among those materials, mineral wool was the chosen insulation for use in the four systems proposed above in order to carry out a comparative analysis without adding another variable such as the use of different insulation materials. Mineral wool is one of the most widely used insulation materials today due to its thermal, acoustic and fire resistance properties in addition to its versatility. This type of insulation can be used in the four retrofit systems [63]. Furthermore, mineral wool is one of the most widely used insulation materials in Spain together with EPS and polyurethane [61].

Table 2. Characteristics of the existing building and alternatives.

Description	Materials	Characteristics
Existing building 	Insulation: None. External cladding: Facing brick. Internal cladding: Gypsum boards, paint.	Thermal bridges.
Internal Insulation System (IIS) 	Insulation: Mineral wool. External cladding: None. Internal cladding: Gypsum boards, paint.	Does not avoid all thermal bridges. Loss of space inside.
Ventilated Façade (VF) 	Insulation: Mineral wool. External cladding: Extruded ceramic plates. Internal cladding: None.	Avoids all thermal bridges. High installation costs. High energy savings. Esthetic modification of the façade.
External Thermal Insulation Composite System (ETICS) 	Insulation: Mineral wool. External cladding: Decorative mortar. Internal cladding: None.	Avoids all thermal bridges. High energy savings. Esthetic modification of the façade.
Air-Space Insulation System (ASIS) 	Insulation: Mineral wool. External cladding: None. Internal cladding: None.	All thermal bridges not avoided. Less expensive installation costs. Complex execution.

Each proposed alternative will have a value function between 0 and 1. The response of the alternative evaluated with respect to the corresponding indicator (Xind, Equation (1)) that are shown in Table 3 must be ascertained in order to establish the value functions.

Table 3. Response of each alternative for each indicator.

Indicator	Parameter	Alternatives			
		IIS	VF	ETICS	ASIS
Material costs (E1.1) (€/m^2)		30.52	66.53	42.46	6.87
Installation costs (E1.2) (€/m^2)		10.33	39.15	25.59	22.06
Annual maintenance costs (E1.3)	Durability (€/m^2 the first 10 years)	9.66	18.5	4.35	1.86
	Susceptibility to vandalism	1	0	0	1
	Maintenance against vandalism	1	0	1	1
Return on investment (E2.1)	Total cost (€/m^2)	41.59	108.85	69.42	31.04
	Energy saving (%)	7.2	48.4	48.3	7.1
	Payback (years)	27.5	10.7	6.8	20.8

2.4. Sensitivity Analysis

The sustainability index is directly related to the weights of the requirements. Minimal variations of the relative weights of these requirements can cause great alterations in the final value [64,65]. These weights that represent the consensus of a panel of experts might

present a certain degree of subjectivity, which explains the need for a sensitivity analysis that can demonstrate the validity of the value functions and their stability and robustness. This sensitivity analysis was performed by modifying the weights of the requirements compared to modifying the weight of the indicators [66], as the influence they have on the final results is much lower than modifying the weights of the requirements.

OAT (One-at-a-Time Sensitivity Analysis) was used to conduct the sensitivity analysis [67]. From a simple perspective, it is one of the most widely used AHP-based methodologies that requires few resources and produces easily interpretable results [68].

The sensitivity analysis of the results provided information on the validity and stability of the proposed methodology. In cases where the results are sensitive to small changes in the relative weights of the requirements and the criteria, a review of the defined weights is recommendable. It was, therefore, decided to vary the relative weights, regardless of the criteria and the requirements. First, the relative weights of all the decision tree criteria were modified by ±30%, ±50% and ±80%, respectively. Then, the relative weights of all the tree requirements were also modified by ±30%, ±50% and ±80%, obtaining the results in percentages, and new sustainability indexes were calculated for each alternative. Finally, the results of having modified the relative weights of both the criteria and the requirements were evaluated, and the results of the analysis were shared with the expert panel in case they wished to modify any relative weight. It is important to examine and to validate the results obtained in the sensitivity analysis with the panel of experts that assigned the weights to the decision-making tree [65].

Eight new scenarios were defined (four scenarios for positive percentages and another four for negative percentages), to perform the analysis at the requirement level (Figure 13). In each of these scenarios, three cases will be defined with each of the percentages for each alternative considering the positive percentages. Likewise, it must be taken into account that when modifying the weight of a requirement, it will also be necessary to modify the weight of the other requirements so that it adds up to 100% and yields a final result.

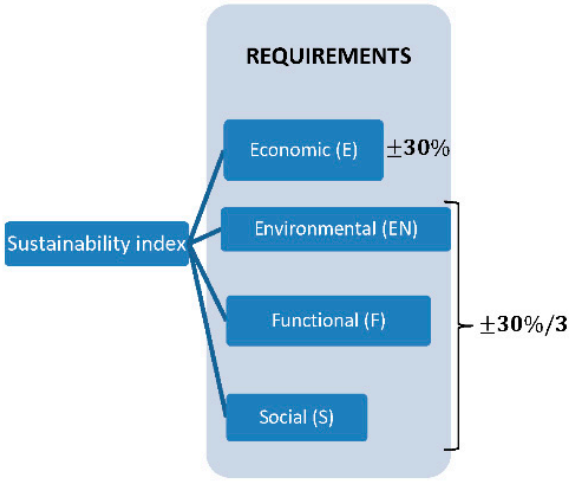


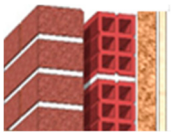
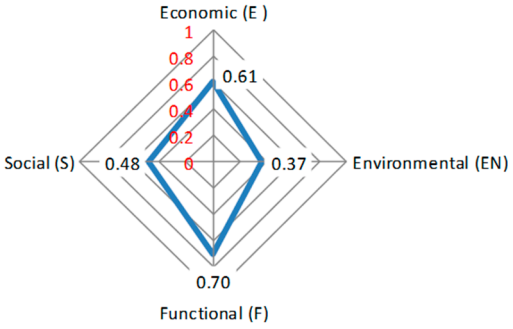
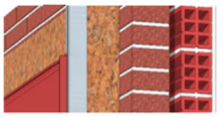
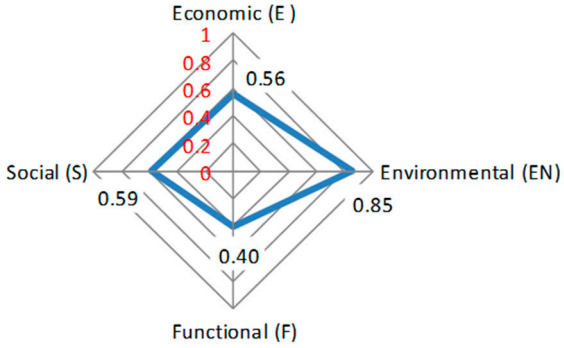
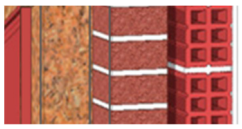
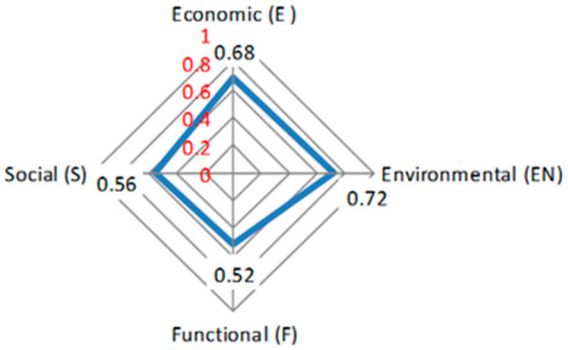
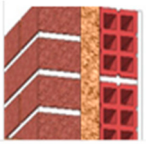
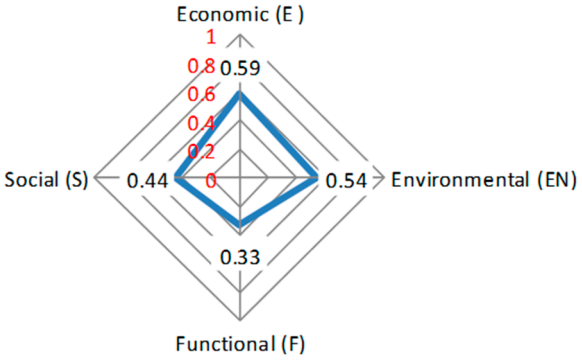
Figure 13. Sensitivity analysis at the requirement level.

3. Results

3.1. Requirement Values of the Retrofit Alternatives

The requirement values obtained for each alternatives are shown in Table 4. The results are shown in spider graphs. In this way, the area of the sum of all the requirements may be obtained, from which the most sustainable alternative may be elucidated, considering the economic, environmental, functional and social requirements. The values of each requirement are between 0 and 1, where 1 is the maximum and 0 the minimum satisfaction value. These values were obtained by evaluating the four requirements set out in the decision tree (Figure 4).

Table 4. Requirement values of each alternatives.

Alternatives	Results
Alternative 1: IIS 	
Alternative 2: VF 	
Alternative 3: ETICS 	
Alternative 4: ASIS 	

3.2. Economic Indicators

The indicator values of each alternative proposal are shown in Table 5. The value function takes a value between 0 and 1, where 0 is the minimum satisfaction value and 1 is the maximum satisfaction value. These values were obtained by taking into account Equations (1)–(5) and the data in Tables 1 and 3.

Table 5. Values of the indicators and the criteria of the economic requirement for each alternative.

Criteria	Indicator	Alternative			
		IIS	VF	ETICS	ASIS
Costs (E1)	Material costs (E 1.1)	0.86	0.67	0.79	0.99
	Installation costs (E1.2)	0.86	0.09	0.35	0.45
	Annual maintenance costs (E1.3)	0.85	0.61	0.53	1.00
		0.86	0.43	0.54	0.79
	Return on investment (E2.1)	0.29	0.72	0.87	0.32
Return on investment (E2)		0.29	0.72	0.87	0.32

3.3. Results of the Sensitivity Analysis

Table 6 shows the results obtained in the sensitivity analysis. The variations of the sustainability index can be observed for each alternative and scenario. It must be recalled that the proposed scenarios correspond to how the variation of one requirement influences the other three requirements. Hence, eight scenarios were proposed (the first four were for positive percentages and the other four for negative percentages) for variations between ±30%, ±50% and ±80%.

Table 6. Variation in the values of the sustainability index due to the modifications made in the weights of the requirements.

	Scenario							
	1	2	3	4	5	6	7	8
Alternative 1 ±30%	1.32%	−2.19%	3.50%	−1.19%	−1.32%	2.19%	−3.50%	1.19%
Alternative 1 ±50%	2.21%	−3.66%	5.84%	−1.98%	−2.21%	3.66%	−5.84%	1.98%
Alternative 1 ±80%	3.53%	−5.85%	9.34%	−3.17%	−3.53%	5.85%	−9.34%	3.17%
Alternative 2 ±30%	−1.22%	2.71%	−4.47%	1.17%	1.22%	−2.71%	4.47%	−1.17%
Alternative 2 ±50%	−2.03%	4.52%	−7.45%	1.96%	2.03%	−4.52%	7.45%	−1.96%
Alternative 2 ±80%	−3.25%	7.24%	−11.92%	3.13%	3.25%	−7.24%	11.92%	−3.13%
Alternative 3 ±30%	0.64%	0.82%	−2.45%	0.31%	−0.64%	−0.82%	2.45%	−0.31%
Alternative 3 ±50%	1.06%	1.36%	−4.09%	0.52%	−1.06%	−1.36%	4.09%	−0.52%
Alternative 3 ±80%	1.70%	2.18%	−6.54%	0.83%	−1.70%	−2.18%	6.54%	−0.83%
Alternative 4 ±30%	1.71%	0.47%	−4.22%	1.27%	−1.71%	−0.47%	4.22%	−1.27%
Alternative 4 ±50%	2.85%	0.78%	−7.03%	2.12%	−2.85%	−0.78%	7.03%	−2.12%
Alternative 4 ±80%	4.55%	1.25%	−11.25%	3.40%	−4.55%	−1.25%	11.25%	−3.40%

4. Discussion

4.1. The Requirements

Considering the values obtained in Table 4, alternative 3 (ETICS) obtained the best results. Comparing the areas of the four graphs, this alternative has a greater area than the others. It easily exceeded the average value (0.5) in almost all the requirements: the average in the four requirements for this alternative yielded a value of 0.65 over 1. It is the alternative that obtained the highest score for the economic requirement, mainly because it is the most economically advantageous alternative and is not among the most expensive.

In addition, as with VF, the generation of discomfort from a social point of view that may be caused to the tenant is minimal. As it is an external intervention, there is no need to vacate the home, and no interior space is lost once the intervention has been completed. The ETICS system is, therefore, the most sustainable solution.

At the opposite extreme, we find alternative 4 (ASIS) that has a lower score and that never exceeded the average value of 0.5 in the functional requirement, a requirement that had the greatest weight (30%) with respect to the others (Figure 4) due to the complexity of its execution. From an economic point of view, it is the least expensive system, as it practically generates zero waste, and only insulation material is used.

However, the energy savings and thermal comfort achieved indoors will be less than in continuous solutions, such as the ETICS and the VF system that offer a needs-based insulation thickness. Moreover, depending on the thickness of the chamber, the energy savings achieved may also be less than an IIS system.

Alternative 2 (VF) obtained the second-best results. When compared with the best alternative (ETICS), this alternative obtained weaker results, mainly as a consequence of its low scores for the economic and the functional requirements, which have the greatest weight, 26% and 30%, respectively (Figure 4). It is the most expensive alternative, considering both the installation costs and materials. In addition, it is one of the most complex solutions to install, ahead of alternative 4 (ASIS). However, it obtained the highest score for the social and environmental requirements, followed closely by ETICS. From the social point of view, alternative 2 produced somewhat better results than alternative 3, mainly because the degree of adaptation to the surrounding of this alternative was better, although those results also affected its final cost.

Finally, the Internal Insulation Systems (alternative 1) was better than the worst construction solution, the Air-space Insulation Systems (alternative 4). Alternative 1 is the simplest constructive solution to execute, which is why it obtained the best score in the functional requirement compared to the other alternatives: a value of 0.7 out of 1. Economically, it is one of the cheapest thermal insulation systems, as the investment cost is approximately 50% lower when compared to an external insulation system. In addition, the intervention is within the interior of the building, so it is not susceptible to vandalism. However, it is a non-continuous solution, and the insulation is not placed continuously on the envelope; therefore, not all thermal bridges are avoided. Thus, the energy savings and the indoor thermal comfort levels will be less than they might be in continuous solutions, such as ETICS and VF. From the social point of view, it has no effect on the surroundings, no scaffolding is ever erected and the façade is unaltered. In addition, a consensus among the owners is not necessary to carry out the work, and it is a system that can be applied to any type of façade. There is, nevertheless, inconvenience to the tenants, who have to vacate the house either totally or partially throughout the building work and move furniture to access the walls. It also implies loss of useful space within house.

4.2. Economic Indicators

The IIS (alternative 1) in combination with the ASIS system (alternative 4) is the most sustainable solution, from the values obtained for each alternative in the cost criterion indicators, taking into account the material cost indicator and the annual maintenance cost (Table 5), a result that is due to the use of only one material in this system, the insulator, and the risk of vandalism is zero. On the contrary, the least sustainable solution is the VF system (alternative 2), observing the material cost indicator and the installation costs. The explanation is that, unlike the ASIS, the VF system requires external cladding, which raises the installation and material costs.

The "return on investment" indicator is within the "return on investment" criterion, with which the return on investment in years or the payback of one alternative is evaluated against the others throughout the building life cycle. To do so, the annual energy savings generated in the building and the total costs were taken into account. Hence, the most sustainable solution turned out to be the ETICS system (alternative 3) followed by the VF

system, and the least sustainable were the IIS and the ASIS systems. The ETICS solution, even though not the least expensive, obtained the best results, as the energy savings achieved with this system were greater compared to the IIS and the ASIS systems, the two non-continuous alternatives.

4.3. Sensitivity Analysis

Both at the requirements level and at the criteria level, the sensitivity analysis results (Table 6) pointed to a valid methodology that is both stable and robust. Modifications of the requirement weights demonstrated that the variations obtained in the sustainability index were minimal (<12%). These weight variations in the order of 80% all suggested that the proposed alternative was very appropriate so that the results pointed to a valid methodology that is both stable and robust

5. Conclusions

Considering the low construction rates of new buildings and the significant number of buildings that fail to comply with the minimum requirements regarding energy efficiency, energetic retrofitting interventions will be necessary in both the short- and the medium-term. Different measures may be taken to do so, although the energy improvement of the building's façade achieves the highest reductions in energy consumption and CO2 emissions. Nevertheless, the wide variety of retrofit solutions complicates straightforward decision making, hence the presentation in this paper of a decision-making methodology to help select the most sustainable façade retrofit system throughout the building life cycle. To do so, the use of the MIVES methodology has been proposed that is used to evaluate each alternative through a value index obtained through the weighted sum of the different sustainability criteria. The degree of sustainability of each alternative is evaluated, considering economic, environmental, functional and social aspects of the solutions through a series of quantitative indicators.

The practical case presented in this article has shown that the choice of one retrofit system or another varies the sustainability index. The most sustainable construction solution for the practical case that has been analyzed was the ETICS system, closely followed by the VF system, and the least sustainable was the ASIS system, considering the economic, environmental, functional and social requirements of each alternative.

If nothing other than economic aspect is studied, then the alternative that obtained the highest score was the ETICS system, mainly because it is the most profitable alternative. It is not one of the most expensive alternatives, and it achieves higher energy savings. This alternative is followed by the IIS and the ASIS systems. These alternatives are the least profitable, as can be seen from the "return of investment" indicator (E2.1), largely because the energy savings obtained are approximately 40% less (values obtained with the CEX V2.3 program). Even so, both alternatives are less expensive to install and have lower maintenance costs than the VF system, hence their higher values.

The sensitivity analysis results pointed to a valid methodology that is both stable and robust.

Finally, through the methodology set out in this article, our aim has been to increase the knowledge of global social, economic, environmental and functional indicators that must be considered for retrofitting old building. These indicators differ from those for new construction work because the buildings are inhabited while the retrofitting works are in progress during the execution phase. Our intention has been to promote the retrofitting of aging building stocks, in view of current needs, through the use of a decision-making tool. It has been shown how this tool can successfully optimize the retrofitting process and provide a global overview of technical and social aspects as well as their consequences for the building inhabitants.

Author Contributions: Conceptualization, Z.E. and J.C.; methodology, Z.E.; software, Z.E.; validation, A.K. and Z.E.; formal analysis, Z.E. and A.K.; investigation, Z.E.; resources, I.M.; data curation, J.C.; writing—original draft preparation, Z.E.; writing—review and editing, Z.E. and J.C.; visualization, I.M.; supervision, J.C.; project administration, J.C.; funding acquisition, J.C. and I.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The following table shows four rows corresponding to four requirements that are applied with the MIVES methodology to all construction projects: ECONOMIC, ENVIRONMENTAL, FUNCTIONAL AND SOCIAL.

The respondent has to assess the weight that he or she would give to each of these requirements, taking into account that the total sum of all of them has to correspond to 100%. In this way, greater or lesser importance is given to each of the requirements.

Within each requirement (in its corresponding row) it can be seen that both the criteria and the indicators appear alongside their weights. The same process that has previously been followed must be initially repeated for the criteria and then for the indicators that are within each criterion.

In cases where a criterion has only one indicator for its evaluation, its weighting is complete and corresponds to 100%. In cases where there are two or more criteria or indicators for evaluating either a requirement or a criterion, they must be valued, by taking the same previous restriction into account, and the sum of all the values must be 100%.

Please fill in the following table, taking into account both training and experience in the field of building retrofit. Following the above instructions, indicate the corresponding value of the percentage or weight that is considered appropriate [between 0 and 100] in all the boxes that appear in red.

Thank you for your collaboration.

Figure A1. Questionnaire survey.

REQUIRE-MENTS.	Weights	CRITERIA	Weights	INDICATORS	Weights
Economic (E)	% with respect to the total	Costs (E1) [Cost of the retrofit]	% with respect to E	Material costs (€/m2) (E1.1)	% with respect to E1
				Installation costs (€/m2) (E1.2)	% with respect to E1
				Annual maintenance costs (E1.3)	Durability (€/m² the first 10 years) % E1.3 Susceptibility to vandalism % E1.3 Maintenance against vandalism % E1.3 → % with respect to E1
		Return on investment (E2)	% with respect to E	Return on investment (E2.1)	Total costs (€/m²) % E2.1 Energy saving (%) % E2.1 Payback (years) % E2.1 → 100% with respect to E2
Environmental (EN)	% with respect to the total	Materials used (EN1) [New materials used to retrofit, and waste generated in the construction]	% with respect to EN	Recyclability (EN1.1)	Insulation % EN1.1: Recyclable %; With recycled content % Non-insulative material % M1.1 (cladding): Recyclable %; With recycled content % → % with respect to EN1
				Waste generated (waste generated in the construction process of the proposed solution) (EN1.2)	% with respect to EN1
				Environmental quality (the environmental impact of the new materials used) (EN1.3)	% with respect to EN1
		Emissions (EN2)	% with respect to EN	CO2 saving (EN2.1)	100% with respect to EN2
Functional (F)	% with respect to the total	Constructive solutions (F1)	% with respect to F	Complexity of execution (F1.1)	Simple complexity 1 Normal complexity Medium complexity Complex Very complex 0 (rate the intermediary levels) → 100% with respect to F1
		Security (F2)	% with respect to F	Reaction to fire (assesses the fire risk and the inflammability of the new materials) (F2.1)	% with respect to F2
				Adaption to the original façade support (assesses the initial state of the façade that affects the performance of further retrofitting improvement) (F2.2)	Good 1 Regular Unstable 0 (rate the intermediary level) → % with respect to F2
		Condensation (F3)	% with respect to F	Behavior of insulation against condensation (F3.1)	100% with respect to F3
Social (S)	% with respect to the total	Disturbance created (S1)	% with respect to S	Need to vacate (S1.1)	Null 1 For a short period of time Throughout the retrofit 0 (rate the intermediary level) → % with respect to S1
				Loss of space after installation (S1.2)	% with respect to S1
				Need for scaffolding (S1.3)	% with respect to S1
		Inconvenience for owners (S2)	% with respect to S	Need for consensus between owners (S2.1)	100% with respect to S2
		Comfort and health (S3)	% with respect to S	Interior heat comfort (S3.2)	Thermal transmittance % S3.2 (Better insulation at higher transmittance) Thermal bridges % S3.2 → % with respect to S3
				Indoor air quality (the toxicity of the insulative materials and their position in the construction system are measured, to minimize their impact on users) (S3.3)	Eco-indicator % S3.3 Position of insulative materials % S3.3: ETICS; VF; ASIS; IIS → % with respect to S3
				Interior acoustic comfort (S3.4)	% with respect to S3
		Architectural heritage (S4)	% with respect to S	Architectural heritage (S4.1)	100% with respect to S4
		Esthetic (S5)	% with respect to S	Degree of adaptation to the surrounding (S5.1)	Very good 1 Good Regular Null 0 (rate the intermediary levels) → % with respect to S5
				Esthetic improvement of the façade (S5.2)	% with respect to S5

Figure A2. Survey table.

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