Declaration of interest: None
8710 words

Decision matrix methodology for retrofitting techniques of existing buildings

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Abstract

The building sector is the highest energy consumer (38.1%) in the European Union. This consumption has to be reduced in both new and existing buildings. Respect to the existing ones, they need an effective energy renovation as the current European Directives reflect. Specifically, according to these Directives, all countries have had to retrofit 3% of their public buildings per year since 2014. There are dozens of retrofitting measures that can be applied to each building, and selecting the most appropriate ones is not an easy task. In this paper, a decision matrix is proposed as a tool to identify the most appropriate retrofit measures of an existing building. This decision matrix is calculated using dynamic simulation tools. Furthermore, a sensitivity analysis is carried out and the energy deviations produced modifying the input variables are quantified. The outputs obtained by this decision matrix are the building loads of each retrofit measure and the associated cost. After obtaining this decision matrix, a multi-variable optimization has been made considering different cost functions. This methodology has been applied to an educational building at Oviedo University, located in Gijón (Spain). According to the climate classification of Gijón, the Spanish normative and the building layout, three upgrading measures have been studied: addition of insulation on the envelope, windows renovation and shading devices. It has been observed that the influence of the cost function selected is relevant, and for the educational building, the case with the best glazing but only intermediate façade insulation is the best retrofitting choice according to the majority of cost functions compared.

Keywords: decision matrix, retrofitting, dynamic simulation, energy demand, office building.

1. Introduction

In the European Union (EU-28), the building sector (including residential and service ones) is the highest energy consumer (38.1%) according to the last data published by Eurostat (2016) [1], above transport (33.3%) and industry (25.9%).

By 2020 the European Union intends to reduce its greenhouse gas emissions by at least 20%, increasing the use of renewable energy at least 20% and achieving energy savings of 20% or more. Therefore, the energy consumption of the building sector must be reduced in both new and existing buildings. Regarding new buildings, all countries have modified their regulations in order to build low-energy ones and also, to implement renewable energy systems. With respect to existing buildings, a lot of them have very high energy consumption –the older the higher, usually- so an effective energy renovation of these buildings is necessary, as the European Directives [2-4] reflect. These Directives are applied to both residential and office buildings. Specifically, about office buildings, they state that all countries have to refurbish 3% of the total surface of their public buildings (those belonging to Central Administration) per year from 2014 on. The refurbished buildings have to fulfil, at least, the minimal energy performance requirements according to the Directives [2,3]. Although this normative does not specify the concrete measures, there are several techniques such as adding insulation in façades, floor or roof, windows renovation, use of renewable energy, modifications in the heating, ventilation and air conditioning systems, and so on, which can be implemented. Therefore, it is necessary to look for the most appropriate ones, analysing different strategies.

In general, the priorities of these strategies have been identified by the European Union and appear in the Winter Package [5] presented in 2016. This package proposes to lead the energy transition in European countries, considering three main goals: putting energy efficiency first, achieving global leadership in renewable energies and providing a fair deal for consumers. Once the objectives have been selected, they must be applied to each case and the effect of the refurbishment measures has to be analysed in function of these goals. Both the analysis and decision making process are very complicated due to the high number of different options, the multiple variations of each one and the complexity of the numerical calculation of each case [6,7]. In this task, a decision matrix can be very helpful because it allows an expert (or "decision maker") to identify, analyse and assess the performance of the relationships among sets of measures and evaluation criteria. In general, a decision matrix consists of the decision alternatives against the relevant factors affecting the decisions (such as, cost, effectiveness, and so on); the simplest ones are bi-dimensional, as rows and columns. In the present case, the decision matrix is a multi-dimensional matrix, where different retrofit measures (each one has also several options) have been assessed according to different evaluation criteria (cost, energy consumption reduction, etc.). The selection of the retrofit measures depends on many aspects such as meteorological conditions, thermal characteristics, indoor requirements, energy-end uses, total cost and even local normative restrictions. All these variables should be considered as input information into the decision matrix, setting constrains and limitations on the final results. Also, the knowledge of the impact produced by possible uncertainties on the building energy performance could be useful to identify which deviations could be critical in the renovation process.

In this paper, a refurbishment of an existing building is used as an example of this methodology. The decision matrix for this case will mainly consist of the different measures proposed and the evaluation criteria. Furthermore, other elements can be added, such as installation and operating cost, cost of conserved energy (CCE), environmental factors, normative restrictions, uncontrolled variables (weather conditions), probabilities or uncertainties. Table 1 shows an example of some parameters of this decision matrix.

Table 1. Some parameters of the decision matrix in this case

Elements	Evaluation criteria					
	Energy consumption reduction (%)	Energy saving (%) or (€)	Implementation Cost (€)	Payback period	CCE	Others
Cases analysed: different scenarios or operating cost	Influencing in all measures					
Uncontrolled variables: weather conditions, operating conditions, etc.	Influencing in all measures					
Probabilities or uncertainties	Influencing in all measures					
Retrofit measure 1: Adding insulation on façade inside. This measure has several possibilities in function of the insulation thickness.						
Retrofit measure 2: Adding insulation on façade exterior. This measure has also several possibilities in function of the insulation thickness.						
Retrofit measure 4: Windows replacement. In this case, there are several possibilities in function of the glazing and the frame.						
Retrofit measure 5: Adding insulation on ground with different options in function of the insulation thickness.						
And so on….						

The novelty of this article is the methodology developed to create the decision matrix and the analysis technique. It is also noteworthy the quantification of the energy deviations produced by the simulation model when there are certain uncertainties in the input information. These uncertainties can lead to solutions far away from the real consumption of the existing building. The quantification of these uncertainties has been carried out through different sensitivity analyses, helping designers to identify the influence of different input variables on the thermal energy loads of a building. Once the multi-dimensional decision matrix has been obtained, a multi-variable optimization is employed considering different dimensionless or homogenous cost functions based on energy saving, the installation and operational cost, the payback period, etc. Finally, the methodology has been applied to a real case, an educational building at Oviedo University.

2. Literature review

Building retrofitting has been widely investigated in recent years due to its crucial role in reduction of green-house gas emissions and energy consumption. Allouhi et al. [8], analysed the current status and future trends of buildings energy consumption, stating that it is necessary to implement measures to reduce this energy consumption as the building sector is considered as the biggest single contributor to world energy consumption and greenhouse gas emissions. Ma et al. [9] estimated that between 1% and 3% of old buildings are being retrofitted every year. In their work, the authors list different factors influencing energy consumption, remarking that Owens and Wilhite [10] had noticed that human behaviour can affect up to 20% in energy savings. The relation between human behaviour and energy consumption has also been analysed by Yohanis [11], confirming its relevance.

Among the possible retrofitting measures, Pombo et al [12] made an exhaustive review of energy efficiency measures applied to different kind of houses, showing that envelope insulation, window replacement, and air sealing are the most common strategies under consideration. In a similar way, Cao et al. [13] and Sun et al. [14] provided a comprehensive review of different measures that can be applied in order to obtain zero-energy buildings. Recently, Uriarte et al. [15] analysed the use of vacuum insulation panels in different climate conditions. With a different approach, Yang et al. [16] studied the influence of anthropogenic heat on total building energy consumption, and therefore, the interest of controlling it in building retrofitting.

In order to analyse the influence of different factors, such as, weather conditions, operating conditions, constructive elements, human behaviour and so on, dynamic simulation techniques should be applied [17,18]. There are several options available such as EnergyPlus, TRNSYS, CENED+, eQUEST, etc., as shown different studies [19-25]. The use of these simulation tools in combination with experimental measurements can reduce the gap between theoretically predicted and real life energy performance of buildings [26,27]. To obtain high accuracy in the calculation of the energy consumption of buildings validated and calibrated models are needed [28,29]. This approach develops precise building models to predict the lifecycle of the building that can be used as predictive control applications [30].

Currently, there are many buildings with poor energy performances, so the application of dynamic simulation tools has a great potential for increasing the energy savings and reducing their environmental impact. Sensitivity analyses can be done to optimize the energy response of buildings when different refurbishment strategies have been applied. When all measures are analysed and simulated, then it is necessary to select the best option. In this task, the decision-making tools are very useful. Nielsen et al. [31] made a review of these tools applied to the building retrofits in the different phases (pre-design, design and execution).

In the building modelling task, Rysanek and Choudhary [32] proposed a different methodology based on independent models coupled together. They obtained more than 6,000 possibilities, taking into account the construction elements and installations, and they also considered technical and economic uncertainty in the analysis, in a similar way to Ma et al. [9], who also stated about the relevance of assigning weights to each factor analysed in a multi-objective problem like this. Nielsen et al. [31], also considered the assignment of weights and established a procedure with 6 steps to evaluate the different options, always considering a dynamic simulation step. More recently, Jafari and Valentin [33] suggested a decision matrix relating retrofitting benefits to investor benefits. The optimization of investment decision-making can change under financing budgetary restriction, as it has been analysed by He et al. [34] for 27 buildings in United States.

In recent months, Rose et al. [35] pointed out that economic benefit is not the main advantage of energy retrofitting of buildings. The authors considered other different benefits classified in three groups (tenants, house association and society) and exposed the case of two retrofitting actions in Denmark with poor economic benefit, but with increased thermal comfort and related benefits. In relation to this, Brom et al. [36] analysed thousands of retrofitted dwellings in The Netherlands, concluding that usually energy savings were lower than expected, in agreement with Pallis et al. [37] who stated that the relationship between cost-optimality and energy performance has not been properly studied.

This paper aims at proposing a methodology for choosing among different retrofitting alternatives on an existing building. The methodology has been applied to the case of an educational building owned by the regional administration. Different retrofitting benefits have been analysed such as environmental and economic.

3. Methodology

A theoretical methodology has been developed in order to build a decision matrix for the energy refurbishment of existing buildings. This methodology can be structured in the following steps as shown in Fig. 1.

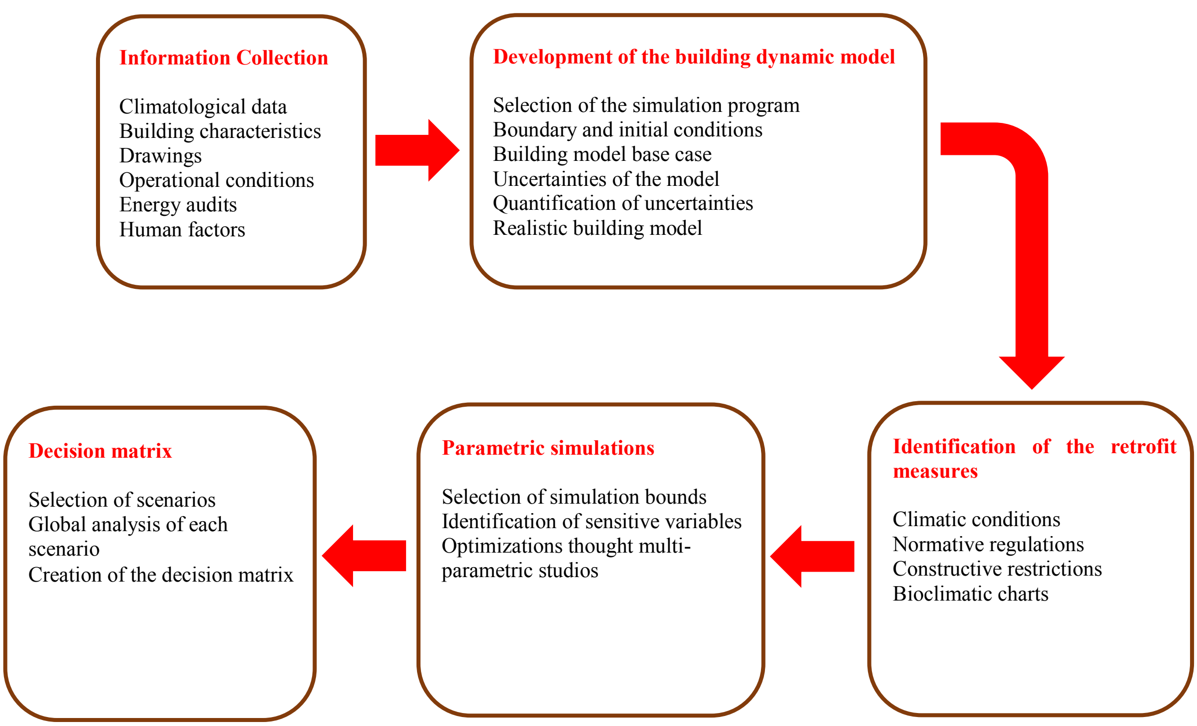

Fig. 1. Steps of the theoretical methodology.

3.1. Information collection

In order to build the decision matrix it is necessary to collect all the information of an existing building such as representative climate data, detailed drawings, constructive and operational data, etc. These data will be obtained from technical audits, normative building certificates, real measurements or building projects, provided by national or local administrations as well as by particular owners. They will be used as input data in the simulations.

3.2. Development of the building dynamic model

The technical core of the method is a building dynamic model which allows evaluating different retrofit actions as well as the energy deviations produced by uncertainties in the initial variables.

In this study, the dynamic simulation tool Visual Doe 4.1[38] has been used to model the base case and the retrofit measures. This software executes numerical calculations in a transient regime until the convergence is reached at each time step.

In order to develop the specific model of the building, besides the geometrical data, it is necessary a set of information that has to be collected, such as, human factors, climate, boundary conditions and thermal behaviour. The main fact at this stage is to make sure that all relevant information is considered in the model and the uncertainties related with these data are analysed and taken into account.

There are many sources of uncertainty when using simulation tools to evaluate the energy performance of the buildings, which significantly influence the final results [39,40]. In order to minimize them and adjust the base case to the real situation, real databases of meteorological variables, building components or building uses are employed. One of the most critical uncertainty sources is the meteorological values used in the simulations causing high dispersions regarding the real building energy performance. These climatic data should be representative of the studied area and the best option is to use long time series of meteorological measurements of the analysed area [41]. If this is not possible, existing Typical Meteorological Years can be used. However, in this case the uncertainty in the modelling process could lead to important deviations into the final results.

Another source of uncertainty is the definition of the constructive walls and openings in the dynamic simulation tool [42]. These elements represent the thermal resistance layers of the building to solve the energy balances and heat transfer between inside and outside. The best option is to specify each element, describing the constructive walls as a set of material layers and the openings as a combination of windows and frames. By using these parameters, the simulation tool calculates the heat transfer coefficients (U-values) and solar heat gain coefficients in windows (SHGC). If the exact definition of the walls and openings is not possible, both approximate U-values for each constructive wall and SHGC values for windows can be introduced, although this will increase the uncertainty of the modelling process. It must be noticed that an intrinsic uncertainty always remains, due to the difference between designed and executed walls and openings.

Finally, the influence of people on the energy performance of the buildings is also very important. This consideration can produce one of the highest uncertainties into the modelling process due to the difficulty to quantify human behaviour [43]. Factors such as occupancy profiles, windows and doors positions (open/close), shadings or set point of temperatures can modify the annual thermal loads of the building. The knowledge of the correct values for these factors reduces the model uncertainties. In this case, the best approximation can be to do an exhaustive monitoring of the building in real conditions of use [44]. But, unfortunately, this is very difficult and expensive. There is a simple approximation, a normalised energy audit of the building, but it is not always available [45]. The windows positions or set point of temperatures in offices or classrooms can be adjusted by a technician, not allowing occupants to regulate (or change) these conditions. Also, the selection of optimal indoor temperatures in function of the season of the year can be made using a control system, reducing the influence of the users into the annual thermal loads [46].

In this step, the model for the building under study will be developed using the simulation environment and adjusting the uncontrolled variables: climate data, thermal parameters of the building envelope and set point of temperatures.

3.3. Identification of retrofit measures

The main objective of an efficient refurbishment of buildings is the reduction of their energy consumption through a sustainable design and the improvement of the existing conditioning systems. To implement energy efficient measures on the envelope of a building, it is necessary to take advantage of the local natural resources. An available tool is the use of bioclimatic charts that represents the environmental air properties computed over a period of time. The use of these charts allows quantifying the climate severity as well as the thermal comfort levels achieved inside the building [25].

The starting point of an efficient refurbishment is the definition of the base case. The following step consists on evaluating climatic data and highlights the best conditioning strategies. This assessment has been done using Givoni bioclimatic charts. These diagrams are created with a psychrometric chart in which the thermal comfort zone and different passive and active conditioning strategies are overlaid [47]. These areas have been defined based on human thermal requirements and local climatic conditions. Internal heat gains produced by the use of the building, solar active collectors, thermal inertia, evaporative cooling, shading devices or natural ventilation are some of the thermal conditioning techniques considered [48-51]. Maximum, minimum and mean values of temperature and humidity have been drawn to identify the most suitable strategies according to the climate conditions. These points highlight different retrofit measures related to the reduction of heating and air-conditioning needs. Finally, the real proposal for an efficient building design has to take into account normative and constructive restrictions to select the possible retrofit measures for a building.

3.4. Parametric simulations

The energy performance of the retrofit actions previously proposed will be evaluated with a sensitivity analysis using parametric simulations. First, the range of each retrofit measure has been analysed. This study sets the possible values for each measure using both normative and constructive criteria. For example, the windows glass can be used with different thicknesses, but only a few discrete values are built and available on the market. Among these values, the lowest ones (1, 2 mm) are not practical constructively because they are too brittle and do not fill the thermal requirements demanded by the normative. After this analysis, a multi-parametric study is made sweeping the entire range of all measures, both individually and in combination.

In these simulations, two outputs have been obtained for each case. On one hand, the annual thermal loads (heating and cooling) have been calculated. These results allow the quantification of the annual energy savings with respect to the initial situation and highlight those measures with a higher influence on the final thermal behaviour of the building. On the other hand, the operation cost (or installation) has been obtained from the available products.

3.5. Decision matrix

The main objective of this methodology is to obtain the decision matrix according to the retrofit measures selected. In this case, the decision matrix is composed of both energy savings and operation cost for these measures, or even some other values derived from the previous ones like the payback period and the cost of conserved energy (CCE) computed with the methodology proposed by Martinaitis et al. [52]. Once the decision matrix is obtained, it is necessary to select a cost function, which allows the mathematical optimization process. This cost function will assign different weights for the data in function of the objectives established (energetic performance, environmental factors…). For example, the building owner will prefer a cost function where the energy savings have a higher weight, whereas the building company will prefer a cost function centred on the installation cost of the retrofit measures. When the cost function considers non-homogeneous variables (such as energy in kWh and cost in €), it is also necessary to include appropriate conversion factors or use normalized variables.

4. Application of the methodology: case of study

The objective of this section is to study a real case and analyse the applicability of the methodology. It aims to recreate the complete process: to obtain the specific decision matrix (which identifies the retrofit measures), to evaluate the energy savings and operational cost and finally, to quantify the energy deviations on the initial case reached by each measure proposed.

4.1. Information collection

The case of study is an educational building at Oviedo University Campus in Gijón (Asturias, Spain). It is a rectangular building with two constructive bodies separated by two external patios and connected by three towers. Both bodies have most windows and openings north-south oriented (see Fig. 2). The building consists of classrooms, offices and laboratories. On the back, five north-south rectangular modules, perpendicular to the main bodies, have been constructed for large industrial laboratories.

Fig. 2. Educational building at Oviedo University Campus in Gijón (Asturias, Spain).

The external envelope of the building is made of concrete walls with big windows at the façades, ceramic slab with insulation and cement mortar. The ground consists of a heavy concrete slab and gravel without insulation. The roof is composed of waterproof clays, gypsum plaster, insulation, reinforced concrete and cement mortar. These constructive configurations have been set as nominal values of the base case to obtain the thermal loads. With these data, the overall heat transfer coefficients for each element are shown in Table 2.

In Spain, the implementation of the European conditions for the buildings retrofit has been carried out from 2006 according to the Spanish Building Code [53], whose energy requirements have been updated in 2013 and 2018 [54]. The application of this normative depends on the climate classification of the location and the final use of the building. Gijón is placed in the northwest coast of Spain characterized by mild temperatures and a lot of precipitations along the year. The normative climatic label is C1 corresponding to a temperate oceanic climate (Cfb) by the Köppen-Geiger classification [55,56]. Taking into account the Spanish constructive conditions for the climatic zone C1, the maximum values of the overall heat transfer coefficient required since 2013 for new buildings are also shown in Table 2.

Table 2. Initial U-values for different constructive elements and maximum U-values taking into account the Spanish normative for new buildings

Constructive Element	**Initial U-value (W/(m^2·ºC))**	**Maximum U-value (W/(m^2·ºC)) according to the normative**
External walls	0.52	0.29
Ground	1.58	0.29
Roof	0.57	0.23
Double windows	3.16	3.3

Regarding the climate database, the experimental data collected in the meteorological station placed at University Campus in Gijón (MS Viesques) have been used in the simulation of the base case.

And finally, respect to the interior air temperature, it has been fixed in 21ºC in winter and 26ºC in summer, according to the thermal regulations established by the Spanish Government in 2009, following the principles of energy savings and promoting the efficiency in public buildings [57].

4.2. Development of the building dynamic model

As discussed in section 3.2, in this study the dynamic simulation tool Visual Doe 4.1 [38] is used in order to model the energy performance of the base case as well as the influence of the selected retrofit actions. This software performs numerical calculations in a transient regime to solve the coupled and time-dependent equations with a time step of 1h [58]. The final results are cooling, heating and annual thermal loads of the building. Fig. 3 shows a view of the building model using this software.

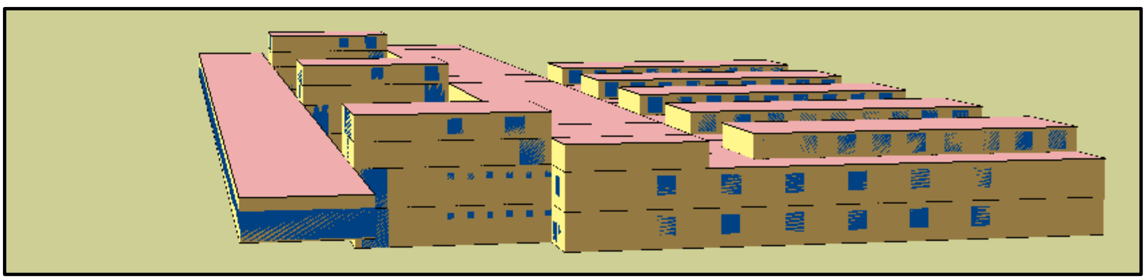

Fig. 3. A view of the building model to study.

The results of the base case (BC) simulation have been annual thermal loads of 55.5 kWh/m^2, with a heating percentage on the annual value of 88% and a cooling percentage of 12%.

After the simulation of the base case, it is necessary to quantify the influence of some uncertainties in the input information before starting the refurbishment process of the building envelope. In this case three possible deviations have been quantified (as mentioned in section 3.2): climate databases, constructive characteristics and occupational data. The knowledge of the impact of these uncertainties on the building energy performance could be useful to identify which deviations with respect to the design process could be critical to optimize the retrofit process.

To evaluate the influence of these uncertainties, a sensitivity analysis has been performed with the execution of three batteries of simulations. The first step was the definition of the base case regarding the real performance of the existing building (climate measurements, real building construction parameters and normative set point temperatures). The second step consisted on the definition of the simulation range for each variable, varying between a lower and an upper bound. Finally, the energy loads obtained by each battery of simulations quantify the energy deviations achieved. This sensitivity analysis enables the estimation of the most influential variables when input parameters have been modified with respect to the base case.

<u>*Uncertainty produced by climate database*</u>

To quantify the energy deviation obtained by the modification of the real weather of Gijón, three climate databases have been tested for this case:

- Meteorological station placed at University Campus in Gijón: Viesques (MS Viesques - BC).
- EnergyPlus weather files for Asturias [59]: Oviedo (EPW Oviedo).
- Spanish Building Code (CTE) considering the climatic restrictions for Gijón: Zone C1 [60] (CTE Zone C1).

The first one has been determined using the climatic measurements provided by the meteorological station placed at Gijón University Campus [61] and it has been used as reference data. The comparisons among the databases give an idea about the climatology of the area and allow the quantification of the mean deviation. Fig. 4 represents the annual thermal loads obtained in the studied building by using the available climatic files.

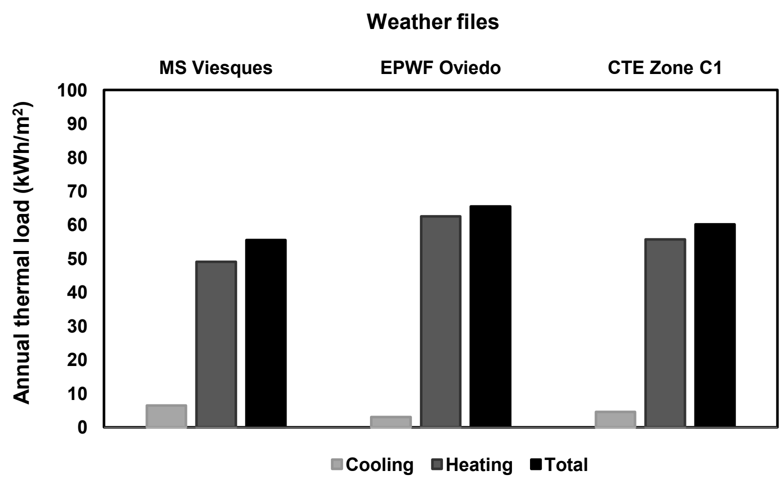

Fig. 4. Cooling, heating and annual thermal loads obtained with three different climatic files: Viesques (BC) (reference case), Oviedo (E+) and Zone C1 (CTE).

The highest differences have been obtained with the EnergyPlus file with an annual variation from the real case (Viesques-BC) of 18%. This is mainly because it considers the same climatic zone for all the regions of Asturias, without taking into account if the studied areas are coastal (Gijón) or inland (Oviedo). However, the Spanish Building Code (CTE) [60] divides Asturias in three climatic zones: D1 (Oviedo), C1 (Gijón) and E1 (mountain), reducing the annual difference to 8.5%, smaller but still significant.

Uncertainty produced by constructive characteristics

To quantify the influence of the constructive characteristics on the thermal load, three batteries of simulations have been executed, modifying only one U-value of the constructive elements (façades, ground and roof) while the rest are kept constant. The batteries have a variation range of ±50%, which is too high for an uncertainty study, but it has been established due to the large differences between the actual values and the values demanded by the normative. The results are shown in Fig. 5 as variations with respect to the base case (at the centre).

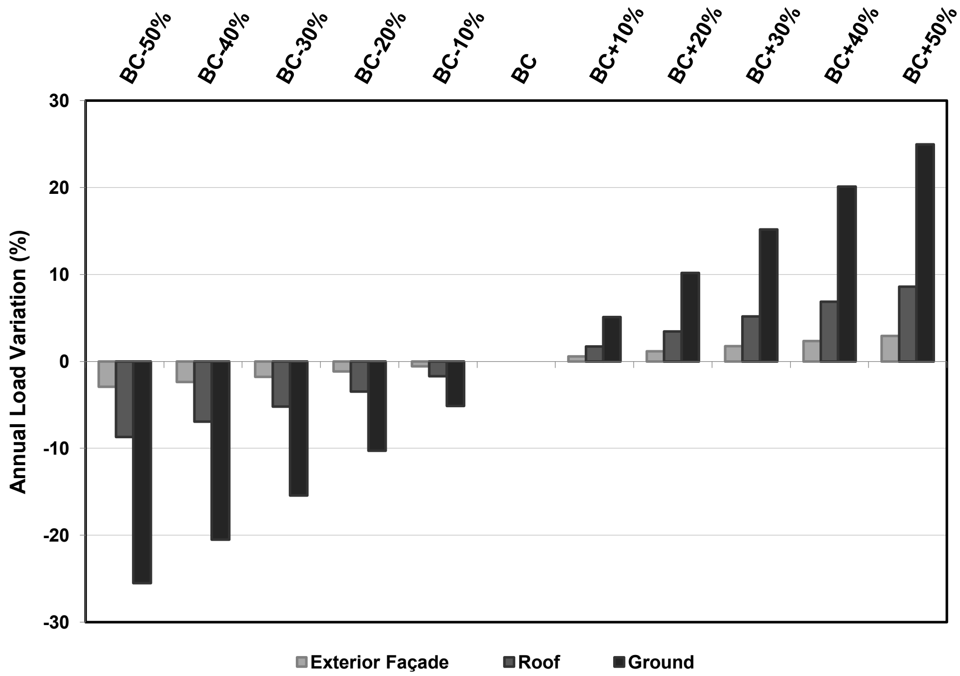

Fig. 5. Annual thermal load variations obtained modifying the nominal U-values of the external façades, roof and ground for a variation range of ±50%.

As it can be seen, the most sensitive constructive surface is the ground, with deviations from the base case up to 25% with a ±50% change in the U-value. This is due to the poor thermal characteristics of this element, with a U-value of 1.58W/m^{2}K, which falls quite short of the actual Spanish requirements for a ground surface in a climatic Zone C1, U=0.29W/m^{2}K [53]. The second constructive surface in order of influence of the annual loads is the roof, with deviations from the base case up to 8%. Finally, the massive construction of the external façades makes this element less sensitive to the variation of the U-value. The percentages of variation oscillate close to 3%.

Uncertainty produced by occupational characteristics

According to the Spanish regulations for Thermal Installations [57], following the principles of energy savings and promoting the efficiency in public buildings, the Spanish Government has established that the interior air temperature will not exceed 21ºC in winter conditions and in summer conditions, this value will not be below 26ºC.

Taking into account these limits, temperature variations have been analysed to quantify the energy deviation produced by their modification. It has been considered both a little more comfortable temperature values (a bit warmer in winter and a bit cooler in summer) and a little more uncomfortable (with lower energy consumption). Fig. 6 represents the annual thermal load variations obtained if the normative set point temperatures have been modified and considering more comfortable values. The annual deviation from the base case is close to 80% if the indoor air temperatures for summer and winter are reversed.

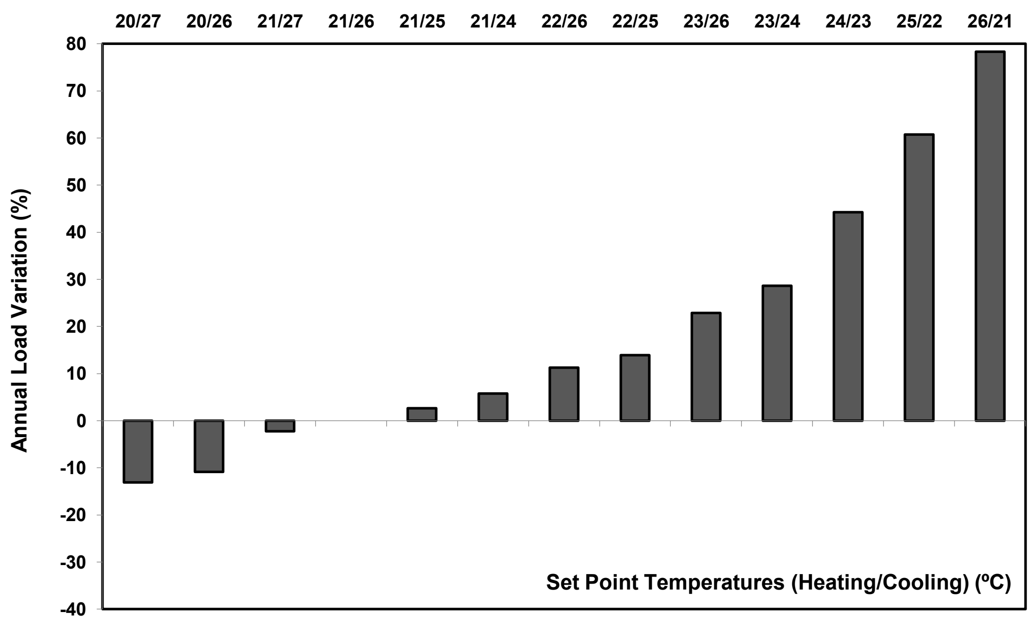

Fig. 6. Annual thermal load variations obtained modifying the Spanish normative set point temperatures (21º/26ºC).

The knowledge of the impact of these uncertainties on the building energy performance could be useful to identify which deviations with respect to the design process could be critical to optimize the retrofit process. In this case, the control of the set point temperatures represents a critical point to calculate the thermal loads of building, being less influential the strict knowledge of the U values of the constructive parameters and the use of the real climate of Gijón. However, the energy deviations with respect to the base case highlight the necessity of adjust the simulation model as much as possible to the real values. This process should be done before developing the decision matrix.

4.3. Identification of the retrofit measures

In order to identify the best retrofit measures to implement in this educational building, Givoni Charts have been used. The points in these diagrams show the hourly combination of ambient air temperature and humidity ratio measured in Viesques during the characteristic summer and winter months (Fig. 7). These climatic diagrams show the most suitable passive and active techniques according to the climate of Viesques in order to reduce the thermal loads of the building.

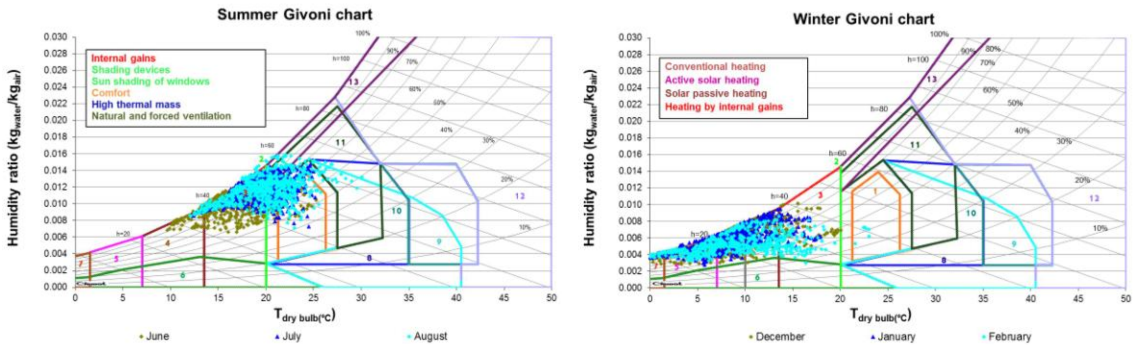

Fig. 7. Summer (left) and winter (right) Givoni charts of Viesques to highlight the best retrofit actions.

During the summertime, as it can be seen and contrary to the usual expectations, there is very little need of cooling to reach the comfort band (orange zone), due to the local climate. In fact, during this period there are many heating needs. So, the implementation of thermal mass, insulation thickness, improvement of windows, shading devices or natural ventilation are the best practices to reach the comfort band. The wintertime is wet and mostly mild, so the combination of passive and active heating with sporadic conventional heating are highlighted to reach the comfort zone. In both seasons, dehumidification techniques and internal gains (produced by the use of the building) are recommended.

Using the guidelines proposed by the Givoni charts and taking into account commercial prices and constructive restrictions of this building as well as the normative limitations, the retrofit measures proposed to be implemented in this building are façade, roof and ground insulation, renovation of windows and shading devices.

4.4. Parametric simulations

Once the base case has been created and the retrofit measures have been selected, several series of simulations have been executed modifying only one retrofit measure along its simulation range. The selections of these values have been done according to the commercial prices [62] and they have been highlighted in Table 3.

Table 3. Upper and lower bounds for the selected refurbishment measures

Retrofit measure	Characteristics	Simulation bounds
Façade insulation	Addition to the inner layer	5, 6, 7, 8, 9 and 10 cm
Façade insulation	Addition to the outer layer	6, 8, 10, 12 and 14 cm
Roof insulation	Addition to the outer layer	8, 10, 12, 14 and 16 cm
Ground insulation	Addition to the inner layer	3, 4, 5, 6, 7, 8, 9 and 10 cm
Window types	Modification of the U-glazing	2.5, 2.1, 1.8, 1.4 and 1.1 W/m^{2}K
Shading devices	Seasonal awnings over the south windows	0.5, 1 and 1.5 m

The outputs of these parametric runs are the annual thermal loads (heating and cooling) for each case. These results have been used to quantify the maximum energy savings associated with its total cost in comparison with the base case. These values have been plotted in Fig. 8, where the cases complying with the minimum constructive requirements for new buildings in Gijón by the

Spanish Building Code (CTE) have been highlighted in green. Seasonal awnings over the south windows have been excluded from the figure due to the low influence on the annual thermal loads, less than 1%.

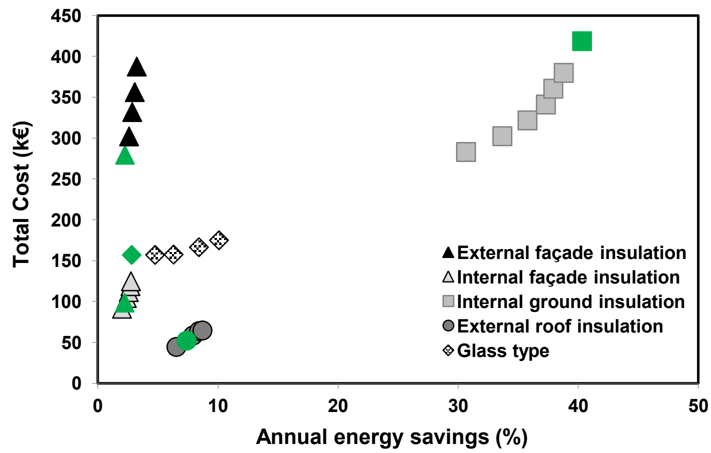

Fig. 8. Total cost versus annual energy savings for each refurbishment measure. The green points represent the minimum constructive requirements for new buildings in Gijón by the Spanish Building Code (CTE).

As it can be seen, the addition of 100 mm of insulation at the internal layer of the ground is necessary to retrofit the building according to the Spanish normative. This measure has the highest influence on the annual energy performance, with annual savings up to 40%, but it supposes the most expensive measure due to the big extension of the ground surface.

The addition of more thickness of insulation in the façade achieves a maximum energy saving about 3%, with a relatively low cost if it is done internally and a very high one if it is applied externally. This is the lowest energy impact action proposed to retrofit the building. The following measures, in ascending order of influence on the annual loads, are the addition of insulation at the roof and the renovation of windows, being more expensive the last one.

To analyse the annual loads combining different refurbishment measures, batteries of simulations have been executed in a multi-parametric evaluation. Taking into account the normative restrictions (the ground insulation has been set to 100 mm) and excluding the addition of insulation at the external layer of the façade, 60 cases have been calculated. Table 4 summarizes all the cases studied.

Table 4. Building cases simulated through the parametric runs

Façade insulation (mm)	60				80				100			
Roof insulation (mm)	100	120	140	160	100	120	140	160	100	120	140	160
Glass type 1	1	2	3	4	5	6	7	8	9	10	11	12
Glass type 2	13	14	15	16	17	18	19	20	21	22	23	24
Glass type 3	25	26	27	28	29	30	31	32	33	34	35	36
Glass type 4	37	38	39	40	41	42	43	44	45	46	47	48
Glass type 5	49	50	51	52	53	54	55	56	57	58	59	60

4.6. Decision matrix

In this study, two basic evaluation criteria have been selected in order to obtain the decision matrix: the annual energy savings and the installation and operational cost. Moreover, two derivative criteria were also used: the payback period and the CCE. This decision matrix has been optimized creating different cost (or objective) functions, assigning weight factors to the evaluation criteria. In general, the proposed cost function can be expressed according to Eq. (1).

$$Cost\ Function = \frac{(AS_{max}-AS)}{AS_{max}} w_{AS} + \frac{(TC-TC_{min})}{TC_{min}} w_{TC} + \frac{(PB-PB_{min})}{PB_{min}} w_{PB} + \frac{(CCE-CCE_{min})}{CCE_{min}} w_{CCE} \quad \text{Eq. (1)}$$

where:

AS_{max} is the maximum annual savings obtained among all the cases analysed.

TC_{min} is the minimum total cost of all the cases analysed.

PB_{min} is the minimum payback period obtained among all the cases analysed.

CCE_{min} is the minimum *CCE* obtained among all the cases analysed.

AS, *TC*, *PB* and *CCE* are the annual savings, total cost, payback period and CCE of each case, respectively.

w_{AS}, w_{TC}, w_{PB}, and w_{CCE} are the weight factors for each criteria, respectively.

In the Eq. (1) the values used for the normalization are the maxima in case of advantageous values (savings) or the minima in case of disadvantageous ones (cost, payback, CCE). This makes that the optimal values of this cost function are the smallest positive ones.

For the computation of both payback period and CCE it has been assumed an energy cost of 100 €/MWh with a 5% rate of energy cost increase, while the interest rate considered was 1.5%. For all the actuations analysed, the life time considered was 35 years.

In this optimization, six cost functions have been proposed. The cost functions 1 and 2 only consider one of the basic evaluation criteria, the annual energy savings (w_{AS} = 1) and the total cost (w_{TC} = 1), respectively. The cost function 3 considers the annual energy savings and total cost equally (weight factor of 0.5 for each criteria). The cost functions 4 and 5 only consider one of the derivative criteria, the payback period (w_{PB} =1) and the CCE (w_{CCE} =1), respectively. Finally, the cost function 6 combines all the evaluation criteria with the following weight factors: 0.4 for annual energy savings, 0.1 for the total cost, 0.4 for the payback period and 0.1 for the CCE. Fig. 9 shows the results obtained with these six cost functions. In each figure, the optimum (highlighted in green) is the case 60 for the first cost function, the case 1 for the second one and the case 52 for the other four cost functions. Analysing these figures, it can be seen that the differences among the 60 cases are relatively small. This is because the normative restrictions imposed by the building regulation are really severe, and it is not easy to improve them.

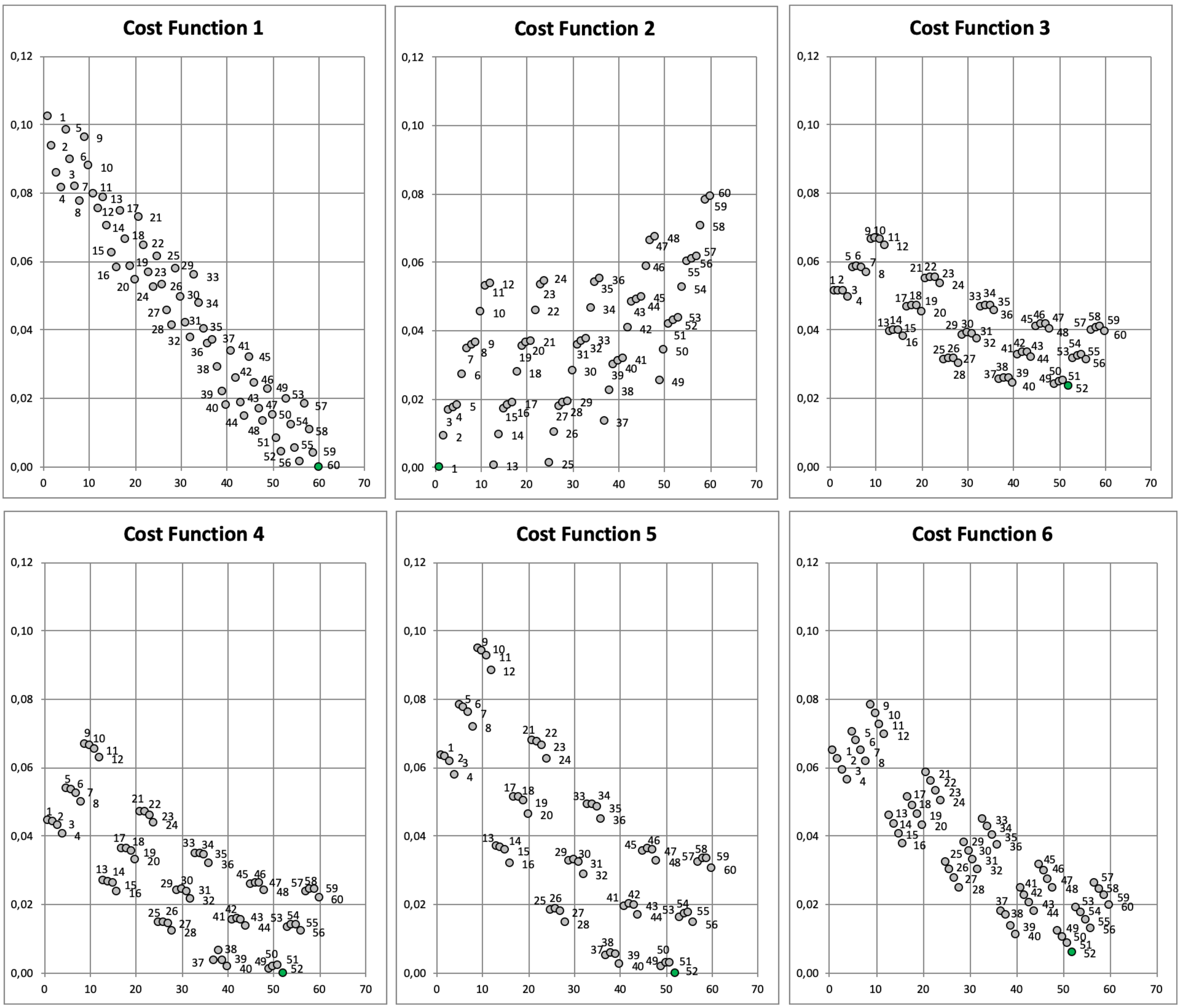

Fig. 9. Results obtained for the six cost functions proposed.

Table 5 shows the results obtained with the six cost functions proposed. For each optimal case, this table gives the specific retrofitted measures, the values obtained with each evaluation criteria and also, the kilograms of CO_2 emissions avoided per year with respect to the initial case [57].

Table 5. Results of the six cost functions proposed

Refurbishment Measures	Cost function 1	Cost function 2	Cost function 3	Cost function 4	Cost function 5	Cost function 6
Savings weight	1	0	0.5	0	0	0.4
Cost weight	0	1	0.5	0	0	0.1
Payback weight	0	0	0	1	0	0.4
CCE weight	0	0	0	0	1	0.1
Best Case No.	60	1	52	52	52	52
Internal façade insulation (mm)	100	60	60	60	60	60
External roof insulation (mm)	160	100	160	160	160	160
Glass type	Type 5	Type 1	Type 5	Type 5	Type 5	Type 5
Annual energy savings (%)	57.6	51.7	57.4	57.4	57.4	57.4
Total cost (k€)	783.14	725.71	756.78	756.78	756.78	756.78
Payback period (years)	20.31	20.76	19.88	19.88	19.88	19.88
CCE (€/MWh)	99.25	102.45	96.32	96.32	96.32	96.32
Avoided CO_2 emissions ($kgCO_2$ year)	61.7	55.4	57.4	57.4	57.4	57.4

As discussed above, there are not many differences among the six cost functions, neither in total cost nor in energy savings. It is evident that the highest energy savings (cost function 1) are achieved with the thickest insulations and the best glazing. And the lowest total cost (cost function 2) with the smallest ones. However, the case 52, which is the best one with the other cost functions, shows that higher roof insulations and better glazing, although with higher installation cost, has a lower long-term cost (due to the financial characteristics). In fact, although this case is a compromise between energy savings and installation cost, it has the smallest payback period of the three.

6. Conclusions

This paper has developed a decision matrix methodology applied to the buildings retrofitting in order to reduce the energy consumption. The retrofitted measures considered are centred in the envelope, not taking into account the heating and cooling systems. The methodology has been structured in several steps. The technical core is the development of the building dynamic model, and the obtaining of the base case for the comparisons. In this step, a dynamic thermal simulation software has been used, and different sources of the input data uncertainties have been identified and taken into account. Once the base case is defined and adjusted to the real situation, all feasible retrofitting measures are identified using the Givoni bioclimatic charts. The energy performance of these actions is evaluated with a sensitivity analysis using parametric simulations. As result of these simulations, the annual energy savings can be obtained, with respect to the initial situation, and also the installation cost for each retrofitting measure. These results and other derived values, such as the payback period and the cost of conserved energy, compose the decision matrix, which is the main purpose of this methodology. Finally, a mathematical optimization is performed, taking into account different cost functions according to the objectives established.

This procedure has been applied to a real case, an educational building at Oviedo University Campus in Gijón (Asturias, Spain). The base case model has been adjusted with real climatic measurements, operational performance and constructive parameters. The uncertainties produced by the lack of information in the input variables to the building model, have achieved significant deviations. The variation of set point temperatures has reached the highest influence on the annual thermal loads (maximum value of about 80%). The variations of the constructive characteristics have obtained the following descending order: ground (maximum value of 25%), roof (maximum value of 8%) and façade (maximum value of 3%). Finally, the maximum deviation obtained by the modification of the climatic input file is about 18%.

Givoni recommendations, commercial prices and constructive restrictions have been considered to identify the most feasible retrofitting measures for the base case. Thermal mass, insulation thickness, improvement of windows, shading devices or natural ventilation have been identified as the best choices to achieve the comfort bands, and they have been analysed and quantified to obtain the specific decision matrix.

Several cost functions have been studied and evaluated to better understand their influence. The results vary between the cheapest to the highest energy saver, although, for this case, the most efficient solution has been shown to be the combination of the best windows with medium façade insulation. This solution not only merges a relatively low cost with high energy savings, but it is also the one with the smallest payback period, and it is the recommended action for the studied building.

7. Acknowledgments

The REHABILITAGEOSOL Project, Reference RTC-2016-5004-3, is a Project funded by the National Program for Research, Development and Innovation in Society Challenges, within the framework of the National Plan for Scientific and Technical Research and Innovation 2013-2016 from the State Research Agency (Ministry of Economy, Industry and Competitiveness), co-financed with FEDER Funds.

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