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MULTI-CRITERIA ANALYSIS OF OCCUPANTS' PERCEPTIONS ON THE BENEFITS OF ENERGY RETROFITTING OF BUILDINGS

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ABSTRACT

The awareness of users about the benefits provided by the energy retrofitting of buildings is mostly related to the measurable return on investment in each energy efficiency measure. The environmental and economic assessment of the benefits depends on the quality of information (which usually has to be collected for each case). However, in the absence of data decisions tend to be postponed or taken on a subjective level. This paper assesses the preference of occupants about energy efficiency measures applied to Portuguese residential buildings, following cost optimality criteria. Six alternatives were created for the reference building and presented to twenty-five interviewees. These alternatives encompass different combinations of energy efficiency measures arrived at by changing four elements (insulation, glazing, equipment and renewable energy systems). The reference building is representative of the housing stock built between 1961 and 1990 which has high potential for improving energy efficiency. Two Multi-Criteria Decision-Aiding (MCDA) methods were applied: one

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additive method based on Multi-Attribute Value Theory (MAVT) and an outranking method (PROMETHEE). These methods enabled decision-makers' preferences to be established and gave a final ranking of the alternatives being assessed. Moreover, this study also looks at the results from four rankings of building conservation measures: Spontaneous (obtained through simple sorting of alternatives by interviewees), MAVT, PROMETHEE and Cost-Optimal (sorting given by interviewees after knowing the cost-optimal analysis).

Key words: Multi-criteria, MAVT, PROMETHEE, Energy Retrofitting, Cost Optimality, Buildings

Introduction

The decision process to invest in energy retrofit of buildings can be complex since it comprises multiple criteria and objectives, sometimes conflicting. This complexity can discourage the building owners to invest or take decisions in a not very thoughtful way. So, there are advantages in performing analysis that can improve the consistency of the decisions at the same time as promote the social, environmental and economic sustainability of energy retrofit measures.

Residential buildings are a very important source of carbon dioxide emissions with long-term impact in the energy use due to its long life-time [1]. The residential sector in Portugal accounts for about 18% of the total energy use in 2010. Buildings constructed between 1961 and 1990 accounts for 44% of the total number of buildings and can present a high contribution to an economy of energy due to its current high levels of heating energy use [2]. According to the Portuguese Census 2011, there are about two million households needing retrofit works, which accounts for about 34% of the Portuguese building stock [3], which can represent a high economy of energy.

The Delegated Regulation (EU) n ° 244 [4] published in 2012 define rules to perform economic and environmental assessments of energy efficiency measures in buildings, such as initial costs definition, energy savings and primary energy impacts reduction. Since these type of assessments can results in a large number of combinations between variables [5], several authors have proposed a multi-objective optimization approach to minimize global costs and to reduce the associated primary energy needs [6],[7].

The goal of this study is to assess the preference of occupants about energy efficiency measures applied to Portuguese residential buildings, following cost optimality criteria. Six alternatives were created for the reference building and presented to twenty-five interviewees. The retrofit alternatives combine building envelope components (exterior walls and roof), windows (frames), efficient heating systems and renewable energy systems.

Methodology

The methodology followed in this work was: (1) to identify alternatives of retrofitting packages for the reference building assuming a lifecycle of 30 years [8]; (2) to assess its thermal and energy performances following ISO 13789 [9], ISO 13790 [10] and the Portuguese standard [11]; (3) to evaluate the criteria performances for each assessed alternative under a cost-optimal perspective [4] and (4) to perform 25 interviews to assess the preference of occupants about energy efficiency measures applied to the reference building.

The criteria and performance values for each alternative was based on Keeney [12]. The interviews were performed to generate four rankings: **Spontaneous**, **MAVT**, **PROMETHEE** and **Cost-Optimal**.

Phase 1 of the interviews qualified the interviewees profile and the goal of the study was explained. The energy retrofit alternatives for the building were presented, including criteria and corresponding performances. The interviewees were asked to sort the alternatives according to their preferences and the first ranking was created (**Spontaneous**). Phase 2 applied the MAVT method to assess the different energy retrofit packages to find the best fitting solution. The method created automatically the second ranking once the trade-offs from the bisection and indifference processes were defined (**MAVT**). Phase 3 used the VISUAL PROMETHEE 1.4 software to parameterize the scale coefficients (k_i) of the indifference process and the intermediate values ($x_{0.5}$) of the bisection process (obtained from phase 2). A third ranking was created from the results of this phase (**PROMETHEE**). The profitability plot created according to [4] is presented at the end of the third phase of interviews. This plot shows the performance of the alternatives once subjected to two objective functions: minimize initial global costs of the packages and reduce primary energy needs. Finally, the interviewees are asked to establish a last ranking after seeing the results of the last plot (**Cost-Optimal**).

Parameterization of additive model - MAVT

MAVT (Multi-Attribute Value Theory) assumes that a value function is based on the maximization of the utility. Thus, the preferences of each interviewee were quantified by a value function and by the scale coefficients assigned to each criterion [12]. Equation 1 presents the additive aggregation model.

$$V(a) = \sum_{i=1}^{n} k_i \, v_i \, (a_i) \tag{1}$$

where,

$V(a)$ represents the total value of alternative a;
$v_i\ (a_i)$ represents the simple value function which shows the value of alternative a related to an attribute i;
k_i represents the scale coefficients (weights) assigned by the decision-makers.

This approach defines a value function, $v_i\ (a_i)$, which allows an analytical assessment of the preferences and value judgments [13]. The value functions assessment is a complex task, so the attributes chosen for the assessment and corresponding scales should be clear to the decision-maker. The bisection process is one of the most used techniques to assign a value function scale. This method gives the option to the decision-maker to choose between two extreme values from a certain scale assigned to each criterion. The attractiveness relative scale for this method is defined by an interval that quantifies the attractiveness of each alternative, based on subjective judgments from an ordinal scale. However, it is necessary to account that the values assigned to each alternative in each criterion should be associated with reference values. This study assumed the reference values as zero for the worst value, 10 for the best value and intervals of 2.5. Following that, each interviewee was asked to give an intermediate value ($x_{0.5}$) between the two values based on criteria's performances. This value represents the same level of satisfaction of the decision-maker moving from the worst value to the intermediate or from the intermediate to the best value. The same procedure was followed to obtain levels $x_{0.25}$ and $x_{0.75}$. The scale values given resulted in a curve which allows the decision-maker to fit his values according to the preferences [13].

Another important phase of the decision process is the definition of the scale coefficients (k_i), which can be estimated by different methods. MAVT assumes that all alternatives are comparable and that there is transitivity in preference and indifference relationship [14]. This study used the indifference method which assesses trade-offs. This technique shows to the decision-maker two options between two alternatives: one presents the maximum value and the other the minimum value, to present a trade-off problem to the decision-maker. So, the decision-maker had to adjust the values for the two options until reaches a balance, which corresponds to the level of indifference of the decision-maker. However, this process was used to all alternatives, the investment alternative was always used as base to the comparison. The swings equivalents to the trade-offs were determined between the alternatives and the sum of all swings. The scale coefficients were calculated by the ratio between the equivalent swings of each alternative and the sum of all swings.

Parameterization of the prevalence model - PROMETHEE

PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) is a multi-criteria assessment method based on the concept of prevalence (outranking) [15]. The VISUAL PROMETHEE 1.4 software that was used in this study applies the

ELECTRE III (*ELicitation Et Choix Traduisant la REalité*) method, which integrates indifference and preference thresholds to model the decision-maker opinion.
Sensitivity analyses are used by this method, particularly in the assignment of criteria weights, allowing the decision-maker to assess if changes in the criteria weights have impact on the rankings produced by the multi-criteria assessment method. The use of a single agreement index led to establish an order of preference. Three types of relationship arise from the comparison of two alternatives, a and b:

- Preference: a P b or b P a
- Indifference: a I b
- Incomparability: a R b

The PROMETHEE method requires additional information related to the decision-maker priorities and preferences, besides the performance of the alternatives for each assessed criterion. To model the preferences ratios of the decision-maker is necessary to assign weights to the criteria assumed by the decision-maker. Additionally, preference functions (or value functions) are applied to represent the perception of scale of the decision-maker in relation to the indifference and preference thresholds for each assessment criterion.

There are six types of preference functions which can be used in the scope of PROMETHEE method. Usual, U-shape and Level functions are used for qualitative criteria while Linear, V-shape and Gaussin functions are more commonly used in quantitative criteria. Preference functions are built considering a pairwise comparison taking into account the performances and their differences in each criterion. These functions show the difference between the assessment of two actions in a certain criterion in terms of degree of preference (measure between zero and one, where zero represents no preference and one represents an unquestionable preference. The value function is defined by the value Q (indifference thresholds) and the value P (preference threshold). A function π defined by a preference P_j and a weight w_j is given for each criterion j. This function represents the multi-criteria preference relationship from a over b (see Equation 2). As a result, the software presents a ranking from the answers provided by the interviewees.

$$\pi(a,b) = \sum_{j=1}^{k} w_j \; P_j(a,b) \tag{2}$$

The variable "weight of preferences" (w_j) from the PROMETHEE method was parameterized in order to use the same weights (k_i) assigned previously by the interviewees in the MAVT method. Intermediate values ($x_{0.5}$) obtained in the bisection process of the MAVT were adopted in PROMETHEE to equalize the P (preference thresholds) values. Moreover, the function V-shape was adopted since all the assessment criteria studied are quantitative, which makes the value Q (indifference threshold) not applicable.

Case Study

Reference building

The reference building was based on statistical data obtained from the Portuguese Energy Agency (ADENE). Statistical data was also obtained from the Portugal Statistics and the General Office for Energy and Geology [2].

The reference building is a 3-bedroom apartment with 100 m², a heating system with efficiency of 1 and a domestic hot water (DHW) system with efficiency of 0.64. The climate data is from a place with 1500 °C heating degree days (HDD) and total radiation of 850 [kWh/m²] was used to calculate the needs for the heating season. This study assumed a reduction factor of 0.2 for the energy needs simulating the occupants' heating habits.

An economic assessment was performed for the most used solutions in Portugal. The life-cycle costs for the 30-year life span (materials, equipment and labor costs) and 6% discount rate were assumed for the financial perspective.

Criteria and their performances

The criterion "investment costs" represents the capital expense in euros when the retrofit measure is implemented, i.e. initial investment. This criterion represents the willingness to invest by the interviewee. The "energy bill" represents the monthly expenses in euros with heating and DHW. The energy bill shows a negative value (see table 1) in the Feed-in alternative due to the contribution of photovoltaic panels (PV) which allows the consumer to sell energy to the grid. The Feed-in alternative represents the saving concerns of the interviewee. The "carbon emissions" are represented in kilograms of CO_2 per month produced by the reference building.

The production of "renewables" is presented to the interviewee in euros of produced energy. These costs do not compete with energy bills or emissions since it aims assessing the relative importance given by the interviewees to an environmentally conscious attitude and how others perceive that attitude (for instance, neighbors). This criterion comply with what Keeney [12] proposes.

Alternative energy retrofitting packages

An energy performance assessment of the building was performed which is based in a dimensional survey, building geometry, envelope thermal parameters, heating and DHW equipment, as well as renewable energy systems. The same reference building can assume different hydrothermal behaviors and energy use depending on the climate conditions and location.

Energy performance simulations were performed for each alternative applying the seasonal method described in ISO 13790 [10]. A profitability assessment following the Delegated Regulation (EU) n. ° 244 [4] was carried out after the energy needs were calculated for each energy retrofit package. This study only assumed a financial perspective for the cost optimal assessment (return of the investment).

The alternatives assessed by the interviewee were:

- *Reference*: represents the business as usual alternative (no improvements). The equivalent cost of the investment is 3078 €. The monthly energy bill is 71 €, only for heating and DWH. This monthly energy use represents an average of 127 kg CO_2eq;
- *Insulation*: represents the reference building improved with thermal insulation. The initial investment cost is 10476 €. The monthly energy bill is 45 €. This monthly energy use represents an average of 86 kg CO_2eq;
- *Envelope*: represents the reference building improved with thermal insulation and windows. The initial investment cost is 11157 €. The monthly energy bill is 43 €. This monthly energy use represents an average of 82 kg CO_2eq;
- *InGlaSys*: represents the reference building improved with thermal insulation, windows and heating and DWH systems. The initial investment cost is 12821 €. The monthly energy bill is 29 €. This monthly energy use represents an average of 57 kg CO_2eq;
- *RES*: represents the reference building improved with thermal insulation, windows, heating and DWH systems. Solar collectors' annual production of 1557 kWh. The initial investment cost is 14888 €. The monthly energy bill is 12 €. This monthly energy use represents an average of 23 kg CO_2eq. The renewable energy produced locally converted in €.month is equivalent to 9 € (according kWh price, if it were sold to the grid at subsidized regime);
- *Feed-In*: represents the reference building improved with thermal insulation, windows and heating and DWH systems. Solar collectors and photovoltaic panels annual production of 1557 kWh and 5705 kWh, respectively. The initial investment cost is 24818 €. The monthly energy bill is -18 €. This monthly energy use represents an average of 18 kg CO_2eq. The renewable energy produced locally converted in €/100m^2.month is equivalent to 40 € (also considering the electricity sold to the grid at subsidized regime [16]).

Table 1. Shows the four quantitative criteria that were chosen (initial investment costs, reduction in energy bill, renewable energy production and emissions) for each assessed alternative of energy retrofitting (Feed-in, RES, InGlaSys, Envelope, Insulation and Reference).

Figure 1 clearly presents the relative position of each alternative in the environmental impacts vector (represented by the primary energy needs) and economic vector (represented by the global costs).

Table 1 : Criteria performances for each assessed alternative.

	Investment cost €/100m²	Energy bill €/100m².month	Renewables €/100m².month	Emissions kg/100m².month
Feed-in	24818	-18	40	18
RES	14888	12	9	23
InGlaSys	12821	29	0	57
Envelope	11157	43	0	82
Insulation	10476	45	0	86
Reference	3078	71	0	127

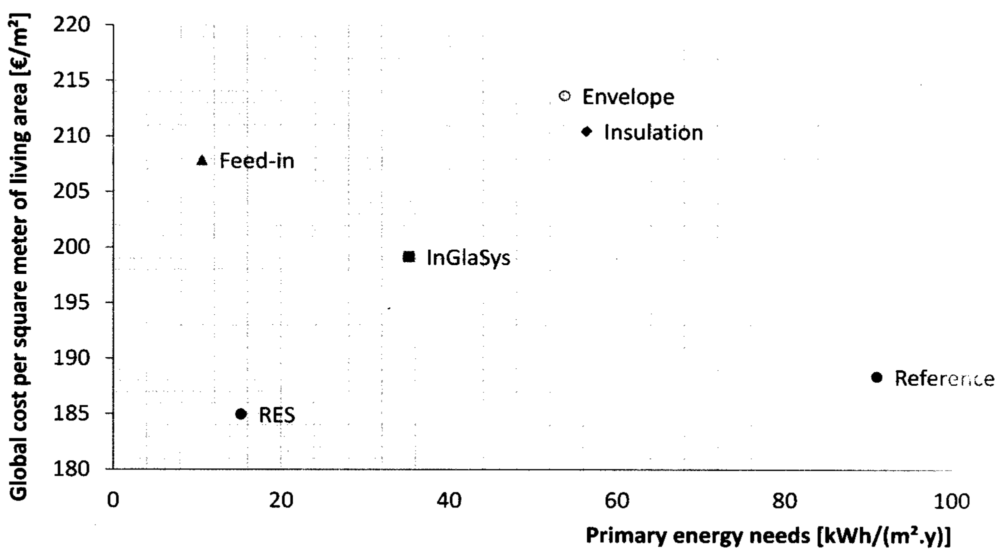

Figure 1 : Profitability assessment of the alternatives according to the Delegated Regulation (EU) n ° 244 [4]

Results

Table 2 presents the results of the rankings according to each method (**Spontaneous**, **MAVT**, **PROMETHEE** and **Cost-Optimal**) for each alternative (Feed-in, RES, InGlaSys, Envelope, Insulation and Reference). The results show that a change in the preferences occurs when comparing the first interviewees' ranking (**Spontaneous**) with the second ranking (**MAVT**), calculated after the results from the first method. The alternatives that incorporate renewable energy are preferred, especially the Feed-in, which lead the preferences in the second ranking. The remain alternatives are least preferred (with a reduced percentage over the total points) and the alternative Reference ranks fourth.

The **PROMETHEE** and **MAVT** method present very similar results, based on the percentage over the total points, with a reduction in attractiveness of the alternative Reference from MAVT to PROMETHEE.Finally, the last ranking **(Cost-Optimal)** devolved by the interviewees after the profitability results, shows an increase in preferences of RES alternative. The change in preferences shows the importance of the profitability assessment defined by the Delegated Regulation (EU) n ° 244 [4], which clearly presents cost-optimal alternative.

Table 2 : Contribution (% in the total of points) of each alternative for each assessment method (Spontaneous, MAVT, PROMETHEE and Cost-optimal).

Alternatives	Spontaneous	MAVT	PROMETHEE	Cost-Optimal
Feed-in	17.1	**32.3**	**31.7**	17.1
RES	**23.2**	27.5	28.3	**30.9**
InGlaSys	22.7	18.1	19.7	21.9
Envelope	14.1	8.0	10.4	9.1
Insulation	13.9	5.3	6.4	10.6
Reference	9.0	8.8	3.5	10.4

Conclusion

This study assessed the users' perceptions of six energy retrofit alternatives for a reference building, using MAVT and PROMETHEE methods as well as a Cost-Optimal approach. According to the preferences from the 25 interviewees (decision-makers), the preferred alternative in both methods was Feed-in (which includes improvements in thermal insulation, windows, heating and DWH systems and the installation of solar collectors and photovoltaic panels) followed by RES (similar to Feed-in but without photovoltaic panels). The preferred alternative for the Cost-Optimal approach was RES followed by InGlaSys (which includes improvements in thermal insulation, windows, heating and DWH systems). It was concluded that:

- The use of ***MAVT*** or ***PROMETHEE*** methods helps in the decision process of energy retrofit by highlighting the benefits of each energy efficiency measure, but the interviewees showed a tendency to favor the alternatives which included renewables.
- The cost-optimality assessment defined by the Delegated Regulation (EU) n ° 244 [4] allows a better understanding of the decision options from an environmental and economic point of view. The ***Cost-Optimal*** ranking shows that the interviewees assign more value to the economic than the environmental criteria once faced with the global costs in a 30-year period, although they have penalized the less energy efficient alternative.
- ***Spontaneous*** and ***Cost-Optimal*** rankings present very similar results which can mean that the interviewees realize the benefits of retrofitting of buildings.

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