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DEFINITION OF THE ENERGY PERFORMANCE REQUIREMENTS IN REHABILITATION PROJECT

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Summary

Building rehabilitation is essential to achieve the targets defined by the EPBD-recast regarding energy efficiency, reduction of carbon emissions and use of on-site renewable energy sources.

To propose an effective building rehabilitation it is necessary to study the best combination of available options in terms of construction solutions, technical building systems (hot water, ventilation, heating, cooling and lighting), their cost, but also their impact on the thermal and acoustic comfort and indoor air quality of the building. Also, the definition of the cost-optimal level is essential, which is the minimum lifecycle cost (including investment costs, maintenance and operating costs, energy costs, earnings from energy produced and disposal costs) of each individual measure.

In this work the multi-criteria decision analysis method ELECTRE III will be applied to balance all these aspects, during the design phase of a refurbishment project, in order to assist the design team on the selection of construction solutions and technical building systems.

A simple case study is presented to demonstrate the feasibility of this approach in what concerns the definition of the energy performance requirements (e.g. thickness of insulation and efficiency of the heating system/air-conditioning system etc.), of a rehabilitation project. In this example several retrofit alternatives were studied, their implementation could lead to the reduction of the energy needs of the building from 13% to 83%. With this approach it was also possible to identify the alternative with the best global performance considering the investment costs, energy needs, indoor air quality, thermal comfort, and CO_2 emissions.

Keywords: rehabilitation, cost-optimal, EPBD-recast, building energy efficiency, life-cycle cost

1. Introduction

Energy efficiency and indoor environmental quality of buildings are nowadays major concerns as European Union (EU) buildings account for 40% of the total energy consumption and Men spend a significant amount of their time inside closed spaces (EPBD, 2002). Thus, it is mandatory to control the energy consumption in the building sector, while maintaining, or even improving, the indoor environmental quality (IEQ), to reduce these needs and, consequently, reduce the EU energy dependency as well as the greenhouse gas emissions, in accordance with what is prescribed in the Energy Efficiency in Buildings Directive (EPBD) and reinforced with the "EPBD-recast" (EPBD, 2002; EPBD-recast, 2010).

To achieve the targets defined by the EPBD-recast (2010) regarding energy efficiency, reduction of carbon emissions and use of on-site renewable energy sources it is essential to rehabilitate the existing buildings.

The rehabilitation of the buildings should include: energy conservation measures, increasing the envelope insulation levels; energy efficiency measures, through the selection of more efficient building systems; and should also include greenhouse gas emissions (GHG) reduction measures through the use of on-site renewables.

To propose an effective building renovation it is necessary to find the equilibrium point of these three types of measures, taking into account the cost/benefit of each one of the measures. This equilibrium position should be determined through the study of the best combination of available options in terms of construction solutions, technical building systems (hot water, ventilation, heating, cooling and lighting), respective cost, but also their impact on the thermal and acoustic comfort and indoor air quality of the building. Also, the definition of the cost-optimal level is essential.

The cost-optimal level is the minimum lifecycle cost (including investment costs, maintenance and operating costs, energy costs, earnings from energy produced on-site and disposal costs) of each individual measure. The overall added value achieved by the rehabilitation, the users' disturbance and other on-site impacts may also be included.

To make a conscious selection of the best possible alternative it is necessary to balance the benefits and cost of each solution into the global behaviour of the building trough a multi-objective optimization. It is also important to have in mind that some of the cost and benefits are not quantitatively measurable (users' disturbance, for example).

Multi-criteria decision analysis (MCDA) is, in this way, an important tool in such problems, since it can be used in any location and employs mathematical models that evaluate alternative options, taking into account both their objective - quantitative - characteristics (U-Value, energy consumptions, for example) and also their qualitative aspects (users' disturbance etc.) and also the preferences of the decision makers regarding the objectives and constraints of each project.

In this work the multi-criteria decision analysis method ELECTRE III (Roy, 1978) will be applied to balance all these aspects, during the design phase of a rehabilitation project, in order to assist the design team on the selection of construction solutions and technical building systems.

This method allows, in an easy and quick way, to outrank energy efficiency and conservation measures according to a set of criteria pre-established and based on criteria weights and thresholds assigned to each one. The criteria, criteria weights and thresholds are selected by the design team according to the objectives and constraints of each project, which enable the use of this methodology to a vast set of possibilities (selection of materials, construction solutions, design alternatives, rehabilitation scenarios etc.), based on different criteria, (U-value, heating and cooling needs, efficiency of the heating system/air-conditioning system and the costs associated to each ones).

A simple case study is presented to demonstrate the feasibility of this approach in what concerns the selection of the most adequate option to be adopted during a rehabilitation project.

2. Methodology

To propose an adequate rehabilitation of the buildings it is necessary to consider energy efficiency and conservation measures as well as GHG mitigation and indoor environmental quality measures. It is then essential to optimize the building envelope, by improving construction solutions and insulation levels, glazing type, optimizing the thermal and acoustic behaviour, the natural ventilation and daylighting techniques, through an appropriate design and selecting materials with low environmental impact. Then it is necessary to carefully select the technical systems to install in the building (hot water, ventilation, heating, cooling and lighting systems) and also the on-site renewables production systems. All this principles must be considered since the first moments of the rehabilitation process.

2.1 Existing Building Envelope and Systems Characteristics

To test this integrated approach, a detached single family house (Figure 1), from the 1980's, undergoing a rehabilitation study was selected. The building, with one floor, 54.42 m^2 and a floor to ceiling height of 2.44 m, is located in a rural area of Braga, Portugal. The building, with a low cost construction system, is a detached residential unit and has two bedrooms (Figure 1, left).

Figure 1 Floor plan, left, northeast perspective view, center and simulation model, right, of the building.

Table 1 lists the main characteristics of the building envelope.

Table 1 building characteristics

Building element	Construction solution	U-value ($W/m^2.ºK$)
Structure (pillars and beams)	Concrete	-
Floor	Concrete	-
Roof	Pitched roof	-
Ceiling	Beam and pot slab	3.08
Façade walls	Single pane hollow concrete block	2.00
Thermal bridges (roller shutter boxes)	concrete	2.37
Walls separating the building from the technical area	Single pane hollow concrete block	1.97
Partition walls	Hollow brick	-
Windows	Single clear glass with aluminium frame	5.14

The building systems consist of a diesel boiler (performance of 72%) and a gas water-heater (performance of 50%). The air change rate (ACH) of the existing building, measured using a blower-door, according to ASTM E 1827 standard, is of 1.05 h^{-1}(ASTM E 1827, 1999). According to the Portuguese thermal regulation the minimum air change rate in a residential building is 0.6 h^{-1} (RCCTE, 2006).

2.2 Multi-criteria Decision Analysis

The MCDA defines flexible approach models to help the decision makers perform a multi-objective optimization to select the most adequate solutions to optimize the building IEQ and energy efficiency among a large number of options and possibilities. The problem of the decision makers is a multi-objective optimization problem (Ehrgott et al., 2005) characterized by the existence of multiple, and in several cases competitive, objectives that should be optimized, taking into account a set of criteria and constraints.

This kind of analysis is able to reflect the objectives and limitations of each one of the alternatives to be studied. The selection of criteria should be exhaustive but not redundant (no more than 12 criteria should be used, representing an acceptable compromise between feasibility and detailed description) and must be coherent (which criteria to be maximized and to be minimized) (Roy et al., 1993; Roulet et al., 2002).

ELECTRE III model was the MCDA method selected in this work as it may be considered as a decision-aid technique suited to the appraisal of complex civil engineering projects (Papadopoulos et al., 2008).

2.2.1 The ELECTRE III method

ELECTRE III is a multi-criteria decision analysis method (Roy, 1978) that takes into account the uncertainty and imprecision, which are usually inherent in data produced by predictions and estimations. The construction of an outranking relation amounts at validating or invalidating, for any pair of alternatives (a, b), the assertion "a is at least as good as b". This comparison is grounded on the evaluation vectors of both alternatives and on additional information concerning the decision maker's preferences, accounting for two conditions: concordance and non-discordance.

This method is based on the axiom of partial comparability according to which preferences are simulated with the use of four binary relations: I, indifference; P, heavy preference; Q, light preference and R, non-comparability. Furthermore, the thresholds of preference (p), indifference (q) and veto (v) are defined so that relations are not expressed mistakenly due to differences that are less important (Roy, 1978).

The indifference threshold (q) defines the value beneath which the decision maker is indifferent to two option valuations, the preference threshold (p) defines the value above which the decision maker shows a clear strict preference of one option over the other, and the veto threshold (v) where a ‘discordant’ difference in favour of one option greater than this value will require the decision maker to negate any possible outranking relationship indicated by the other criteria. The indifference (q) and preference (p) thresholds of any criterion can also be interpreted as the minimum imprecision and the maximum margin of error respectively (Maystre et al., 1994).

This method does not allow for compensation, which may occur when using methodologies based on performance indexes, due to the use of the veto threshold. Using this method, an option which shows too poor results in one criterion cannot be ranked in a higher position (Roulet et al., 1999). The model permits a general ordering of alternatives, even when individual pairs of options remain incomparable or when there is insufficient information to distinguish between them (Rogers, 2000). Also, the technique is capable of dealing with the use of different units, the mix of both quantitative and qualitative information and when some aspects are “the higher the better” and others are “the lower the better”.

2.3 Energy Conservation and Energy Efficiency Measures

To select the adequate energy conservation and efficiency measures to be implemented during the rehabilitation process the behaviour of the existing building was assessed using a dynamic energy simulation code. The software applied in this study was eQuest (The Quick Energy Simulation Tool), which combines a building creation, an energy efficiency measure wizard and a graphical results display module with an enhanced DOE-2.2-derived building energy use simulation program (Crawley, 2005).

This study was performed using the internal heat gains and the heating and cooling set points (20ºC in winter and 25ºC in summer) in accordance with the Portuguese thermal regulation for residential buildings (RCCTE, 2006). The energy consumption was estimated considering the heating and cooling needs of the building and also the energy necessary for the production of domestic hot water, the household appliances consumption was not considered and the ACH was calculated according to the methodology defined in the Portuguese thermal regulation for residential buildings (RCCTE, 2006). As the building does not have a cooling system the reference system (a chiller with a COP of 3) defined in the Portuguese thermal regulation for residential buildings was used to estimate the building’s cooling needs. When defined the actual HVAC systems characteristics were used to estimate the energy needs.

With the results of the existing building performance nine optimization options, covering the most common rehabilitation measures adopted in Portugal, with increasing level of performance, for the envelope and systems were defined.

The rehabilitation project followed the two steps approach proposed by the EPBD-recast (2010). First the thermal quality of the envelope and of the systems was improved to an optimal level (to be defined). The second step was to cover the low amount of energy required by energy from on-site renewable sources.

Using the multi-criteria decision analysis method ELECTRE III the rehabilitation options were outranked considering five criteria. The criteria selected were the ones that were considered as most relevant for the target audience of ECBCS Annex 56 (IEA, 2011): total final energy (kWh/m^2.year); CO_2 emissions (tons); total final cost (€), that encompass the energy consumption and the investment due to the implementation of the measures to optimize the building behaviour, considering a 20 years period (remaining lifetime span of the building); indoor air quality (IAQ), considered in this study by the air change rate (ACH); and thermal comfort conditions, represented here by the U-value (weighted averaged values).

Once selected the most adequate rehabilitation option the on-site renewables production measures were implemented and the CO_2 emissions of the building were calculated.

The energy conservation and energy efficiency measures that were studied (and respective costs) were:

- Measure 1 - Application of 10 cm of expanded polystyrene in the façade walls (ETICS system) (U-Value = 0.30 W/m^2.K, 4880 €);
- Measure 2 - Application of 10 cm of expanded polystyrene in the walls separating the building from the technical area, where the boiler was installed (U-Value = 0.29 W/m^2.K, 594 €);
- Measure 3 - Insulate the roof with 12 cm of mineral wool (MW) placed in a plasterboard suspended ceiling (U-Value = 0.25 W/m^2.K, 2999 €);
- Measure 4 - Replacement of the existing windows by windows with aluminium frame with thermal cut and low-e double glass (4 mm low-e glass + 10 mm argon filled air gap + 8 mm low-e glass) and good acoustic insulation level (U-Value = 1.45 W/m^2.K, 372 €);
- Measure 5 - Correction of the thermal bridges of the roller shutters boxes, through the injection of 4 cm of mineral wool (U-Value = 0.68 W/m^2.K, 25 €);
- Measure 6 - Installation of a mechanical ventilation system (91 m^3/h) in the kitchen and in the bathroom and placement of grids in the interior doors (ACH = 0.6, 362€);
- Measure 7 - Installation of a mechanical ventilation with heat recovery system (180 m^3/h, efficiency of 70%) and placement of grids in the interior doors (ACH = 1.2, 2469 €);
- Measure 8 - Replacement of the existing diesel boiler (heating) and gas water-heater (for domestic hot water (DHW) production) with a condensation boiler for heating and for DHW production (25 kW and efficiency of 110%, 2296 €);
- Measure 9 - Replacement of the existing diesel boiler with a heat pump for heating and cooling (heating – 22.4 kW, COP = 3.86; Cooling – 20 kW, EER = 3.03; 14160 €).

Table 2 lists the studied rehabilitation options and the total investment costs associated.

Table 2 List of the rehabilitation options studied

Rehabilitation option	Rehabilitation measures implemented	Total Investment Costs (€)
Option 1	1	4880
Option 2	1 + 2	5474
Option 3	1 + 2 + 3	8473
Option 4	1 + 2 + 3 + 4 + 5	8870
Option 5	1 + 2 + 3 + 4 + 5 + 6	9232
Option 6	1 + 2 + 3 + 4 + 5 + 7	11340
Option 7	1 + 2 + 3 + 4 + 5 + 7 + 8	13636
Option 8	1 + 2 + 3 + 4 + 5 + 7 + 9	25500
Option 9	1 + 2 + 3 + 4 + 5 + 6 + 8	11528

3. Results

In the study performed the ELECTRE III method was applied to evaluate nine alternative rehabilitation options for the envelope and systems of the building on the basis of five criteria: total final energy, CO_2 emissions, total final cost, IAQ (represented by the ACH) and thermal comfort conditions (considering the weighted averaged U-value). Table 3 lists the different criteria, criteria weights and thresholds that were considered in the use of ELECTRE III method for this case-study.

The definition of criteria weights and thresholds must take into account the objectives and constraints of the project and capture the points of view of the decision makers. Thus, to select them, a sensitivity analysis was performed and the visualization of the outcome impacts was assessed.

The criteria weights were defined taking into account the relative importance of each one of the criteria. The criteria weighting established for the ACH and U-Value, related with the IAQ and thermal comfort conditions, for example, was defined according to the relative importance of each one to the occupants of the building based on studies performed in Portugal and according to literature (Monteiro Silva, 2009; Rohles, 1987; Kim et al., 2005; Rogers, 1998). The thresholds were defined according to the criteria characteristics.

Table 3 Criteria, criteria weighting and thresholds (criteria to: ↓ - minimize; ↑ - maximize).

Criteria	Units		Criteria Weight	Threshold		
				Preference	Indifference	Veto
Total final energy consumption	kWh/(m^2.year)	↓	30	150	50	300
CO_2 emissions	tons	↓	30	0.20	0.10	0.40
ACH	h^{-1}	↑	25	0.40	0.10	0.80
U-Value (weighted averaged values)	W/m^2.K	↓	25	0.20	0.05	0.30
Total final costs	€	↓	25	10000	5000	25000

The total final energy consumption, CO_2 emissions, U-value and total final costs are criteria that should be minimized. The ACH is a criterion that should be maximized to ensure an adequate IAQ.

The criteria values for the existing building and for the different rehabilitation options are listed in Table 4.

Table 4 Criteria for the existing building and for the nine rehabilitation options proposed

Options	Total final energy consumption (kW/m^2.year)	CO_2 emissions (tons)	ACH (h^{-1})	U-Value (weighted averaged values) (W/m^2.K)	Total final costs (20 years) (€)
Existing	455	0.68	1.05	2.50	44889
Option 1	393	0.64	1.05	1.69	43243
Option 2	364	0.63	1.05	1.52	40731
Option 3	330	0.61	1.05	0.45	40031
Option 4	278	0.58	1.05	0.32	34952
Option 5	159	0.51	0.60	0.32	22591
Option 6	114	0.49	1.20	0.32	19965
Option 7	58	0.23	1.20	0.32	17378
Option 8	89	0.48	1.20	0.32	31651
Option 9	87	0.24	0.60	0.32	17138

The credibility degree matrix and the results of the outranking using ELECTRE III method are presented in Table 5. The credibility degree matrix gives a quantitative measure to the force of the statement “a outranks b” or “a is at least as good as b”. Number 1 indicates the full truthfulness of the assertion and 0 indicates that the assertion is false. The ranking of the alternatives can then be determined based on the credibility degree matrix through a distillation procedure, where the alternatives are located firstly following their qualification going from the best to the worse one and then inversely, from the worse to the best one, defining two pre-ranks. Finally, the final ranking is achieved by using the results of these two pre-ranks.

Table 5 Credibility degrees matrix for the alternative solutions selected for the façade walls.

Options	Existing	Option									Non-Dom		Ranking
		1	2	3	4	5	6	7	8	9	A	μ(A)	Options
Existing	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Existing	0.00	Option 7
Option 1	1.00	-	0.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Option 1	0.00	Option 9
Option 2	1.00	1.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Option 2	0.00	Option 6
Option 3	1.00	1.00	1.00	-	0.89	0.49	0.24	0.03	0.33	0.05	Option 3	0.03	Option 8
Option 4	1.00	1.00	1.00	1.00	-	0.66	0.56	0.13	0.75	0.18	Option 4	0.13	Option 5
Option 5	0.81	0.81	0.81	0.81	0.81	-	0.81	0.45	0.77	0.71	Option 5	0.45	Option 4
Option 6	1.00	1.00	1.00	1.00	1.00	1.00	-	0.76	1.00	0.78	Option 6	0.76	Option 3
Option 7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	1.00	1.00	Option 7	1.19	Options 2, 1 and Existing
Option 8	1.00	1.00	1.00	1.00	1.00	0.85	0.81	0.59	-	0.59	Option 8	0.59	
Option 9	0.81	0.81	0.81	0.81	0.81	1.00	0.81	0.81	0.81	-	Option 9	0.81	

Option 7 was ranked as the best action, as Table 5 shows. This option has the lower total final energy consumption and CO_2 emissions and also has the second lower total final costs. Option 9 that has the lower total final costs and the second lower total final energy consumption and CO_2 emissions was ranked second. Option 6, with the forth lower total final energy consumption and CO_2 emissions was ranked third.

The last ranked options was, as expected, the existing building (0 in all columns indicating that this option is worst than all the others in all criteria). Rehabilitation Options 1 and 2 were also ranked last. These options were the ones with the highest total final costs, more than twice higher than the best ranked options, CO_2 emissions and U-value.

Thus Option 7 was the rehabilitation solution selected to be implemented to optimize the building performance.

3.1 GHG Emissions Reduction Measures

As it is mandatory, according to the Portuguese Thermal Regulation, to install solar thermal collectors in the building (4 m^2) this was the first GHG emission reduction measure that was defined. Additionally due to the easy installation process, adequate orientation of the roof of the building and considering the high levels of solar radiation (about 1800 kWh/m^2.year) and number of sun hours that are available in Portugal, 8.28 m^2 of photovoltaic panels were also installed in the building roof.

These measures will allow the reduction of the total final energy, transforming the building in an energy producer (3.65 kWh/m^2.year), leading to the reduction of the primary energy (0.1 $kgoe/m^2$) and of the CO_2 emissions (0.014 tons). The investment that will be necessary is of 13,650.00 € and the payback is possible in 6.6 years.

4 Conclusion

The use of a multi-criteria decision analysis method allows, in an easy and quick way, to outrank rehabilitation options selected considering a set of criteria pre-established and based on criteria weights and thresholds according to the objectives and constraints of the project.

In this study the total final energy, the CO_2 emissions, the total final cost, the indoor air quality (IAQ), considered in this study by the air change rate (ACH) and the thermal comfort conditions, represented here by the weighted averaged U-value, were the criteria selected to outrank the rehabilitation option.

Several measures were considered, taking into account the construction solutions and technical building systems to be implemented during the rehabilitation of the building.

The implementation of the rehabilitation alternatives could allow the reduction of the energy needs from 13% to 83%. With this study it was also possible to identify the alternative with the best global performance considering the investment costs, energy needs, indoor air quality, thermal comfort, and CO_2 emissions.

Throughout the multi-criteria decision analysis performed, it was possible to verify that with the implementation of rehabilitation Option 7 (application of 10 cm of expanded polystyrene in the façade and in the walls separating the building from the technical area, insulate the roof with 12 cm of mineral wool, installing windows with aluminium frame with thermal cut and low-e double glass, injecting 4 cm of mineral wool in the roller shutters boxes and placement of grids in the interior doors and installing a mechanical ventilation system with heat recovery and a condensation boiler for heating and for DHW), it will be possible to reduce the energy needs in 83%, have a positive energy balance (between the energy produced and consumed), all with a payback period inferior to 7 years.

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