

Using MCDA to Select Refurbishment Solutions to Improve Buildings IEQ

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ABSTRACT: Due to buildings high energy consumption their refurbishment is essential to achieve the targets defined by the EPBD-recast regarding energy efficiency and reduction of carbon emissions. Besides the energy efficiency, the sustainability and the Indoor Environmental Quality (IEQ) of Buildings must also be considered when planning a refurbishment project. Thus, to propose an effective building refurbishment it is necessary to select the adequate construction solutions taking into account their impact on the energy performance, thermal and acoustic comfort, indoor air quality and environmental impact of the building. In this work a multi-criteria decision analysis method is applied to balance all these aspects in a refurbishment project, in order to assist the design team on the selection of the construction solutions. Throughout the multi-criteria analysis performed, it was possible to verify that the rehabilitation solutions with lower embodied energy were the best refurbishment options.

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 (EPBD 2002) and the population spends about 90% of their time inside closed spaces. Thus, it is mandatory to control the energy consumption in the building sector, while 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).

The rehabilitation of the building stock is an opportunity to achieve these goals. In Portugal, 80% of the building stock was built before 1990 (Census 2011), year of the publication of the first Portuguese thermal regulation, leading to high levels of thermal discomfort and excessive energy consumption, as the majority of the existing buildings was built without any thermal concerns and shows very high energy consumptions even when minimal comfort conditions are required.

To correctly select the rehabilitation construction solutions it is necessary to consider their contribution to the energy efficiency, thermal and acoustic comfort, daylight conditions and the indoor air quality, its environmental impact (considering the embodied energy, for example), but also their contribution to the thermal inertia of the building and the thickness as the useful area might be reduced.

However, these goals are often in conflict and there is not a unique criterion that describes the consequences of each alternative solution adequately and there is not a single solution that optimizes all criteria. In many cases, the best solutions to accomplish different comfort requirements are not compatible, especially in what concerns natural ventilation and daylighting strate-

gies and the acoustic and thermal comfort. For instance, the type of window used can have a strong and opposite influence on the thermal and acoustic performance of the building, just not to mention its interference with the indoor air quality (IAQ). It is, then, necessary to have an integrated approach to ensure the best overall behaviour taking into account all of the, sometimes incompatible, comfort and energy efficiency requirements.

Thus, to propose an effective building refurbishment it is necessary to select the adequate construction solutions and materials taking into account their impact on the energy performance, thermal and acoustic comfort, indoor air quality and environmental impact of the building.

Therefore, thermal quality, acoustic behaviour and energy reduction strategies, that are mandatory, should be meshed at an early stage of the rehabilitation process with the other requirements to ensure the buildings overall comfort conditions and energy efficiency. To do so, it is necessary to select the correct materials, and construction solutions, among a large number of options to improve the occupants overall comfort and, at the same time, reduce the energy costs. Furthermore, to make a conscious selection of the possible alternatives, it is necessary to balance the positive and negative aspects of each solution into the global behaviour of the building through a multi-objective optimization.

The correct comparison of the solutions is difficult as the behaviour of some are affected by imprecision (design phase) and it is also necessary to take into account the constraints of the project and the decision maker point of view.

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 scenarios, taking into account both their objective characteristics (acoustic insulation, U-Value, etc.) and the preferences of the decision makers regarding the objectives and constraints of each project.

The aim of this study was to select the materials and construction solutions to refurbish the façade walls of a building, based on criteria that are mandatory (thermal and acoustic insulation) and the designer must conciliate. The embodied energy, superficial mass and thickness of the construction solutions were also considered as they are a designer concern, affecting the environmental impact, the thermal inertia and the useful area of the building. In this work the MCDA method ELECTRE III (Roy 1978) was chosen to assist the design team in the selection of the most adequate refurbishment solutions.

2 METHODOLOGY

To achieve an adequate behaviour of the buildings it is necessary to consider the indoor environmental quality, the environmental impact as well as the energy efficiency. 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 refurbishment project. In this study several construction solutions for the refurbishment of façade walls were studied.

2.1 *Retrofit Building Characteristics*

The case-study building to be refurbished is a 1980s' single family detached house (Fig. 1).

The building, with two bedrooms, 54.42 m² and 2.44 m of floor to ceiling height, is north oriented. The construction system is a low cost construction system based on a steel reinforced concrete pillars and beams structure, single pane hollow concrete block walls and clear single glass with aluminium frame windows with PVC (Polyvinyl chloride) roller shutters. The window to wall ratio (ratio between the area of the window and the area of the wall) is approximately 20%. Table 1 lists the main characteristics of the building envelope.

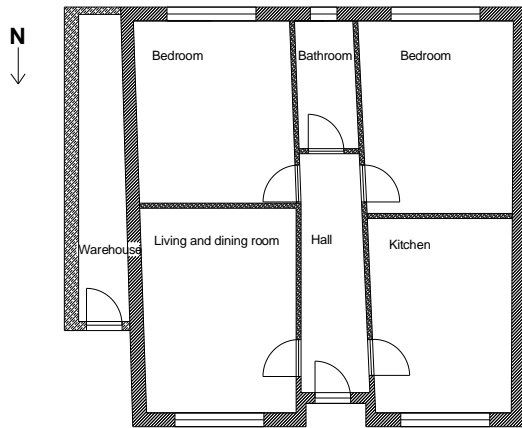


Figure 1. Floor plan of the building

Table 1. Characteristics of the building

Building element	Construction solution	U-value [W/(m ² °C)]
Structure	Concrete pillars and beams	-
Floors	Concrete	-
Roof	Pitched roof	2.35
Ceiling	Beam and pot slab	3.08
Façade walls	Single pane hollow concrete block	1.90
Roller shutter boxes	concrete	2.85
Windows (window to wall ratio of 20%)	Single clear glass and aluminium frame	5.14
Partition walls	Hollow brick	-

2.2 Multi-criteria analysis

The multi-criteria decision analysis defines flexible approach models to help the decision maker, and/or the design team, to perform a multi-objective optimization to select the most adequate solutions to optimize the building's IEQ and energy efficiency among a large number of options and possibilities. The problem of the decision makers is a multi-objective optimization problem characterized by the existence of multiple, and in several cases competitive, objectives that should be optimized, taking into account a set of parameters (criteria) and constraints (Ehrgott & Wiecek 2005). The MCDA methods can be applied when there are several decision agents, each one with different objectives and criteria, sometimes with opposite visions.

This kind of analysis is able to reflect the objectives and limitations of each one of the alternatives to be studied, but it is necessary to be thorough on selecting the criteria that should be exhaustive but not redundant (it is recommended to use no more than 12, which represents an acceptable compromise between feasibility and detailed description) and must be coherent (which are the criteria to be maximized and to be minimized) (Roy & Bouyssou 1993, Roulet et al. 2002).

The MCDA method selected in this work to help the decision maker selecting the most adequate solutions to optimize the building indoor environmental quality and energy efficiency, was the ELECTRE III (ELimination Et Choix Traduisant la REalité - ELimination and Choice Expressing the REality) model as it may be considered as a decision-aid technique suited to the appraisal of complex civil engineering projects (Roy 1978, Papadopoulos & Karagiannidis 2008).

2.2.1 The ELECTRE III method

ELECTRE III is a multi-criteria decision analysis method that takes into account the uncertainty and imprecision, which are usually inherent in data produced by predictions and estimations (Roy 1978). 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.

The ELECTRE III 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) have been introduced, 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).

The ELECTRE III 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, with quantitative and qualitative information and with aspects that must be maximized and others must be minimized.

This method allows, in an easy and quick way, to outrank construction solutions options 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 (thermal and acoustic insulation, embodied energy, weight, heating and cooling needs, etc.). This methodology is not specific to a country and can be used in an early stage of the design phase of a new building or of a refurbishment project, when not all the characteristics are defined.

2.3 Prediction Tools

The prediction of the building thermal behaviour, related to thermal comfort and energy efficiency, was done using the thermal insulation through the calculation of the U-value, determined using the publication ITE50 – U-Values of Building Envelope Elements (Pina dos Santos & Matias 2006). All the solutions selected respect the minimum requirements defined in the Portuguese Thermal Regulation (RCCTE 2006).

The acoustic performance of the building elements was characterized using the weighted standardized level difference of the façade ($D_{2m, nT, w}$), defined in the Portuguese Acoustic Regulation, estimated using the Acoubat Sound Program (RRAE 2008, EN 12354-3 2000). All the solutions selected respect the requirements defined in the Portuguese Acoustic Regulation (RRAE 2008).

The embodied energy was assessed using the Cumulative Energy Demand 1.04 method from the Life Cycle Assessment (LCA) software, SimaPro 7.1.8 (Asif et al 2001, Frischknecht et al. 2003, Pre Consultants BV 2008).

3 RESULTS

3.1 Criteria, Criteria Weights and Thresholds

In the study performed, the ELECTRE III method was applied to the evaluation of several alternative solutions for the façade walls on the basis of five criteria: thermal and acoustic insulation, embodied energy, superficial mass and thickness. Table 2 lists the different criteria, thresholds and criteria weights that were selected, by the design team, for this case-study.

The criteria selected to outrank the construction solutions options are related to the most important characteristics of the IEQ, the thermal and acoustic comfort and influence the energy efficiency of the building. These criteria were also selected because it is possible to define them in

a non subjective way, it is possible to predict them in an early stage of the design phase, they are under the designer scope and they are the issues that are also the most valued by the users of the buildings. The minimum thermal and acoustic insulation values are also defined in the Portuguese thermal and acoustic regulations and are mandatory (RCCTE 2006, RRAE 2008).

Table 2. Criteria, criteria weighting and thresholds (criteria to: ↓ - minimize; ↑ - maximize).

Criteria	Units	Criteria Weight	Threshold		
			Preference	Indifference	Veto
Thermal Insulation (U-Value)	W/(m ² °C)	↓ 25	0.30	0.10	0.60
Acoustic Insulation (D _{2m, nT, w})	dB	↑ 25	5	2	10
Embodied Energy (EE)	MJ/m ²	↓ 20	200	40	400
Superficial Mass (Msi)	kg/m ²	↑ 20	50	10	100
Thickness	cm	↓ 10	15	3	30

The embodied energy, the superficial mass and the thickness of the construction solution were also selected. The embodied energy is considered to account the environmental impact of the construction solution, as this is nowadays a concern of the building sector. The superficial mass is considered to account the impact of the construction solution in the thermal inertia of the building, as this is essential to the correct behaviour of the building. The thickness of the solutions was selected as it influences the useful area and is an important factor, valued by the designer.

The U-Value, the embodied energy and the thickness of the construction solution are criteria to be minimized to improve the thermal comfort conditions, energy efficiency and environmental impact and to increase the useful area available. The Façade acoustic insulation, D_{2m, nT, w}, and the superficial mass are criteria that should be maximized, to improve the acoustic comfort and the thermal inertia of the building.

As 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, 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 thermal and acoustic insulation criteria, associated to the thermal and acoustic comfort, were defined according to the relative importance of each one to the occupants based on studies performed in Portugal and according to literature (Monteiro Silva 2009, Rohles et al. 1987, Kim et al. 2005). These studies showed that the thermal and acoustic comfort are the most valued criteria. The embodied energy, superficial mass and thickness of the solutions are essentially a concern of the designer.

The thresholds were defined according to the criteria characteristics, for example a 2 dB difference is the threshold at which human beings can perceive differences in noise levels and 5 dB is the noise difference at which clear preference can be expressed for one option over another (Rogers & Bruen 1998).

3.2 Refurbishment's Construction Solutions

The first step of the refurbishment process was the replacement of the existing windows and roller shutters by windows with double pane glass with aluminium frame with thermal break ($U_w = 2.50 \text{ W/(m}^2\text{°C)}$) and insulated roller shutters (considering the thermal resistance of the window, during daytime and the thermal resistance of the window and of the roller shutter during the night-time, $U_{\text{wdn}} = 2.00 \text{ W/(m}^2\text{°C)}$). The window frame selected has adjustable air inlets to ensure an adequate air change rate and improve the indoor air quality. Additionally 20 cm of mineral wool were placed in the roof ($U = 0.21 \text{ W/(m}^2\text{°C)}$) to improve its thermal performance.

The refurbishment construction solutions selected (shown in Figure 2 and listed in Table 3) cover the solutions most used in Portugal (External Thermal Insulation Composite Systems, ETICS, ventilated wall, insulation and plasterboard or hollow brick panes). The study was done considering three insulation materials (expanded polystyrene, EPS, expanded extruded polystyrene, XPS, and mineral wool, MW).

In Table 3 are also listed the cost of the refurbishment solutions for the façade wall. The costs include the materials, execution and 10 years of maintenance.

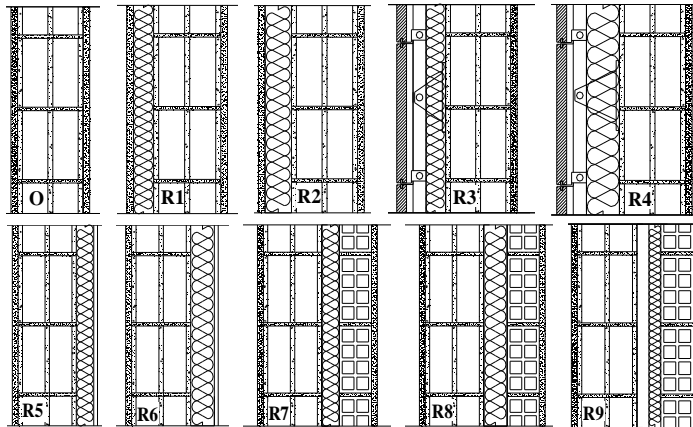


Figure 2. Vertical cross-section of the existing (O) and rehabilitation construction solutions of the façade walls (Ri)

Table 3. Construction solutions studied for the façade (as represented in Figure 2).

Option	Wall	U-Value [W/(m ² °C)]	Cost [€/m ²]
O	Hollow concrete block (20 cm)	1.90	-
R1	Hollow concrete block wall (20 cm) and ETICS system with 6 cm of EPS	0.49	58
R2	Hollow concrete block wall (20 cm) and ETICS system with 8 cm of EPS	0.40	71
R3	Hollow concrete block wall (20 cm) and ventilated wall with stone (1 cm) and 6 cm of XPS	0.53	160
R4	Hollow concrete block wall (20 cm) and ventilated wall with stone (1 cm) and 8 cm of XPS	0.44	200
R5	Hollow concrete block wall (20 cm), MW (6 cm) and plasterboard (1.3 cm)	0.73	34
R6	Hollow concrete block wall (20 cm), MW (8 cm) and plasterboard (1.3 cm)	0.64	38
R7	Hollow concrete block wall (20 cm), MW (6 cm) and hollow brick (11 cm)	0.45	15
R8	Hollow concrete block wall (20 cm), MW (8 cm) and hollow brick (11 cm)	0.36	20
R9	Hollow concrete block wall (20 cm), air gap (2 cm), MW (6 cm) and hollow brick (11 cm)	0.42	22

* EPS – expanded polystyrene; XPS – expanded extruded polystyrene; MW – mineral wool.

Table 4 lists the results of the prediction of the façade walls behaviour according to the five criteria selected to outrank the design alternatives. The U-Values are weighted averaged values taking into account the roller shutter box, the opaque and the glazing part of the façade.

Table 4. Criteria for the different design alternatives studied for the façade.

Options	U-Value (weighted averaged values) [W/(m ² °C)]	D _{2m, nT, w} [dB]	EE [Mj/m ²]	Msi [kg/m ²]	Thickness [cm]
O	2.64	30	0	150	24.0
R1	0.81	33	190	150	32.0
R2	0.74	33	231	150	34.0
R3	0.84	35	1715	150	37.0
R4	0.77	36	1770	150	39.0
R5	0.98	35	195	15	32.3
R6	0.90	36	237	15	34.3
R7	0.77	37	232	140	43.0
R8	0.70	38	275	140	45.0
R9	0.75	39	276	140	45.0

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 shows that the best refurbishment options are the ones with the creation of double pane wall with the construction of an 11 cm brick pane, options R7, R8 and R9. The worst ranked solutions are the ventilated walls and double walls with plasterboards, options R3, R5, R4 and R6.

Option R7 (construction of a 11cm brick pane with 6 cm of MW) is ranked as the best action and is “at least as good as” options R8 and R9 in all criteria, as the number 1 in columns 10 and 11 indicates. This refurbishment solution has one of the lower U-Value, the highest acoustic insulation, has the fourth lower embodied energy and is one of the solutions with the higher superficial mass but is also one of the thicker solutions.

Solutions R8 (construction of an 11cm brick pane with 8 cm of MW), with the lower U-Value, the second highest acoustic insulation and superficial mass and one of the lower embodied energy was ranked second.

These solutions (R7, R8 and R9) are widely used in Portugal and their execution costs (Table 2), are also the lowest.

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

Options	O	R1	R2	R3	R4	R5	R6	R7	R8	R9	Non-Dom A m(A)	Ranking Options	
O	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O	0.23	R7
R1	0.77	-	1.00	1.00	0.92	1.00	0.92	0.83	0.74	0.75	R1	0.88	R8
R2	0.74	1.00	-	1.00	0.92	1.00	0.92	0.83	0.75	0.75	R2	0.82	R9
R3	0.00	0.00	0.00	-	1.00	0.00	0.00	0.00	0.00	0.00	R3	0.00	R1
R4	0.00	0.00	0.00	0.98	-	0.00	0.00	0.00	0.00	0.00	R4	0.01	R2
R5	0.00	0.00	0.00	0.00	0.00	-	1.00	0.00	0.00	0.00	R5	0.00	O
R6	0.00	0.00	0.00	0.00	0.00	1.00	-	0.00	0.00	0.00	R6	0.05	R6
R7	0.70	0.93	0.95	0.97	0.99	0.94	0.95	-	1.00	1.00	R7	1.00	R4
R8	0.70	0.86	0.93	0.96	0.97	0.87	0.94	1.00	-	1.00	R8	1.00	R5, R3
R9	0.70	0.86	0.93	0.96	0.97	0.87	0.94	0.99	1.00	-	R9	1.00	

The ventilated wall with 6cm of XPS, option R3 (with the lowest U-value but with the higher embodied energy), and the double wall with 6 cm of MW and a plaster board, option R5 (with the lower thermal mass and one of the thinner solutions), both with the same acoustic insulation, were the last ranked options.

Due to their high embodied energy (R3 and R4) and low superficial mass (R5 and R6) are ranked after the existing wall.

The ventilated walls are also the most expensive refurbishment solutions (more than 10 times the cost of the construction of a second brick pane) making them unattractive options for the refurbishment of buildings.

4 CONCLUSION

Throughout the multi-criteria analysis performed, it was possible to verify that the construction of a second hollow brick pane (with insulation), with lower U-value and embodied energy and higher acoustic insulation and superficial mass were ranked the best rehabilitation options. These solutions are the thicker ones and, as the ones with plasterboards, will reduce the building's useful area and it will be necessary to redo the installations that might exist in the wall.

The last ranked options are the ventilated wall with 6cm of XPS (with the lowest U-value but with the higher embodied energy), and the double wall with 6 cm of MW and a plasterboard (with the lower thermal mass and one of the thinner solutions), both with the same acoustic insulation.

The placement of the insulation inside the existing wall, R5 to R9 refurbishment options, leads to the necessity of redoing the coupling with windows and door frames and lead to more inconvenient during the refurbishment works.

The placement of the insulation outside the existing walls is not always possible, in multifamily buildings and when the buildings are in contact with the streets or public spaces and it's not possible to expand the wall outwards.

The case study here presented allows a robust analysis of the refurbishment options for the building's façade as it comprises a broad study of each alternative through a detailed analysis of the main factors that affect the IEQ, based on the thermal and acoustic insulation levels and the embodied energy of the construction solutions.

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