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Selection of rehabilitation construction solutions using ELECTRE III method

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ABSTRACT: 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. Besides the energy efficiency the Indoor Environmental Quality of Buildings (IEQ) must also be considered when planning a rehabilitation project. Thus to propose an effective building rehabilitation is necessary select the adequate construction solutions taking into account their impact on the energy performance, thermal and acoustic comfort and indoor air quality of the building. In this work a multi-criteria decision analysis method, ELECTRE III, is applied to balance all these aspect, during the design phase of a refurbishment project, in order to assist the design team on the selection of construction solutions.

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 about 90% 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).

The rehabilitation of the building stock is an opportunity to achieve these goals. In Portugal, 77% of the building stock was built before 1990, year of the publication of the first Portuguese thermal regulation, leading to high levels of thermal discomfort and the 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 (CENSUS 2001).

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, but also their contribution to the thermal inertia of the building, the weight of the solution and its effect on the structural project 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.

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 trough 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 MCDA method ELECTRE III was chosen to assist the design team in the selection of the most adequate rehabilitation solutions (Roy 1978).

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 (U-value, acoustic insulation, 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 rehabilitation project, when not all the characteristics are defined.

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 (U-value and acoustic insulation) and the designer must conciliate. The superficial mass, weight and thickness of the construction solutions were also considered as they are a designer concern, affecting the thermal behaviour of the building, the structural design and the useful area.

2 METHODOLOGY

To achieve an adequate behaviour of the buildings it is necessary to consider either the indoor environmental quality as well as 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 rehabilitation. But the solutions adopted in buildings, usually, only optimize no more than one of the necessary comfort requirements. In many cases, the best solutions to accomplish different comfort requirements are not compatible, especially in what concerns natural ventilation and daylighting strategies and the acoustic and thermal performance. 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).

In the selection of the rehabilitation materials and construction solutions it is important to implement all these principals. In this study several construction solutions for the façade walls were studied.

2.1 *Retrofit Building Characteristics*

The case-study building to be refurbished is a detached single family house (Figure 1), from the 1980's. The building is a single residential unit with two bedrooms, East oriented, with 54.42 m^2 and 2.44 m of floor to ceiling height.

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 (CMU) and clear single glass with aluminium frame windows with PVC roller shutters. The window to wall ratio is of about 20%.

Table 1 lists the main characteristics of the building envelope.

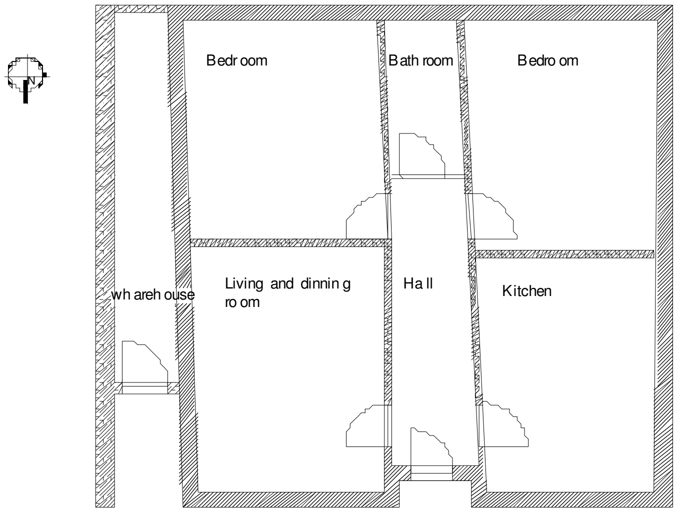

Figure 1. Floor plan of the building.

Table 1. building characteristics

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 area of 20%)	Single clear glass with aluminium frame	5.14
Partition walls	Hollow brick	-

2.2 *Construction Solutions Characteristics*

The construction solutions analyzed for the rehabilitation of the façade walls are shown in Figure 2. The rehabilitation construction solutions selected: ETICs system, ventilated wall, insulation and plasterboard or hollow brick panes, cover the solutions most used in Portugal.

A pre-fabricated rehabilitation module, MRP, with, from the outside to inside: aluminium composite exterior finishing (0.6 cm); insulation corkboard (6.0 cm); extruded polystyrene insulation (XPS – 12.0 cm); and air vapour barrier, was also studied.

The study was done considering four insulation materials (expanded polystyrene, EPS, expanded extruded polystyrene, XPS, mineral wool, MW and cork, ICB).

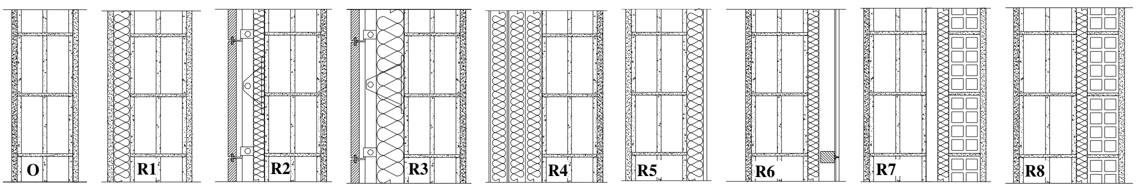

Figure 2. Vertical cross-section of the existing and rehabilitation construction solutions of the façade walls

During the rehabilitation process 20 cm of mineral wool were placed in the roof and the existing single glass windows and PVC roller shutters were replaced by windows with double pane glass with air inlets in the aluminium frame (with thermal break) and insulated roller shutters. The air inlets were introduced to improve the air change rate and the indoor air quality.

2.3 *Multi-criteria analysis*

The multi-criteria decision analysis (MCDA) defines flexible approach models to help the decision maker, and/or the design team, 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 MCDA methods can be applied when there are several decision agents, each one with different objectives and criteria, sometimes with opposite visions. The problem of the decision makers is a multi-objective optimization problem (Ehrgott & Wiecek 2005) 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.

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 & Bouysson 1993, Roulet et al. 2002).

The multi-criteria methodology selected in this work to help the decision maker selecting the most adequate solutions to optimize the building indoor environmental quality, was the ELECTRE III model as it may be considered as a decision-aid technique suited to the appraisal of complex civil engineering projects (Papadopoulos & Karagiannidis 2008).

2.3.1 *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.

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, the mix of both quantitative and qualitative information and when some aspects are “the higher the better” and others are “the lower the better”.

2.4 *Prediction Tools*

The prediction of the building thermal behaviour, related to thermal comfort and energy efficiency, was done using 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 the weighted standardized level difference of the façade ($D_{2m,\ nT,\ W}$) was 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).

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, superficial mass, weight and thickness. Table 2 lists the different criteria, thresholds and criteria weights that were considered in the use of ELECTRE III method for this case-study. The criteria weights and thresholds presented here are just an example and should be defined by the design team according to the objectives and constraints of the project.

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

Criteria	Units		Criteria Weight	Threshold		
				Preference	Indifference	Veto
Thermal Insulation (U-Value)	$W/(m^{2o}C)$	↓	25	0.25	0.10	0.50
Acoustic Insulation ($D_{2m,\ nT,\ W}$)	dB	↑	25	5	2	10
Superficial Mass (Msi)	kg/m^2	↓	20	50	10	100
Weight	kg/m^2	↓	15	150	50	300
Thickness	cm	↓	15	10	5	30

The U-Value is a criterion that should be minimized. The façade acoustic insulation, $D_{2m,\ nT,\ W}$, and the superficial mass are criteria that should be maximized. The weight and the thickness of the construction solution are criteria to be minimized to reduce the weight of the building and to increase the useful area available.

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).

The superficial mass, the weight and the thickness of the construction solution were also selected. 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 behavior of the building and is not accounted neither by the U-value nor by the weight of the construction solution.

The weight and thickness of the solutions were selected as they are also relevant to the building design. These criteria influence the structural design of the building and its useful area and are important factors, valued by the designer.

Reduce the rehabilitation solution weight is a request of the structure design (to reduce the impact in the existing structure). The thickness of the solution is also important as the thinner they are more useful area is available. This criterion cannot be considered on the weight as several solutions with the same thickness have different weights.

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 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 1987, Kim 2005). These studies showed that the thermal and acoustic comfort are the most valued criteria, as they are linked to thermal and acoustic comfort inside the buildings. The superficial mass, the weight 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 *Façade Walls*

The construction solutions analyzed for the façade walls are shown in Figure 1 and listed in Table 3.

Table 3. Construction solutions studied for the façade (as represented in Figure 1).

Option	Wall	Insulation material*	Insulation thickness
O	Hollow concrete block with 20cm	-	-
R1	Hollow concrete block wall, 20cm and ETICS system	EPS	4
R2	Hollow concrete block wall, 20cm and ventilated wall with stone with 5cm	XPS	4
R3	Hollow concrete block wall, 20cm and ventilated wall with stone with 5cm	XPS	10
R4	Hollow concrete block wall, 20cm and prefabricated rehabilitation module	ICB + XPS	6 + 12
R5	Hollow concrete block wall, 20cm and plasterboard wall (1.3 cm)	MW	6
R6	Hollow concrete block wall, 20cm and plasterboard wall (1.3 cm)	MW	4
R7	Hollow concrete block wall, 20cm, air gap and hollow brick (11 cm)	MW	4
R8	Hollow concrete block wall, 20cm and hollow brick (11 cm)	ICB	6

* EPS - expanded polystyrene; XPS - expanded extruded polystyrene; ICB - Insulation corkboard; 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 first step of the rehabilitation process was the replacement of the existing single glass windows and PVC roller shutters by windows with double pane glass with air inlets in the aluminium frame with thermal break and insulated roller shutters. Additionally 20 cm of mineral wool were placed in the roof.

The rehabilitation construction solutions selected: ETICs system; ventilated walls; with plasterboard and hollow brick panes placed inside cover the solutions most used in Portugal. The pre-fabricated rehabilitation module, MRP, was also selected.

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

Options	U-Value [W/(m^2°C)]	$D_{2m, nT, W}$ [dB]	Msi [kg/m^2]	Weight [kg/m^2]	Thickness [cm]
O	1.90	30	150	307	24.0
R1	0.65	35	150	348	30.0
R2	0.67	37	150	439	35.0
R3	0.34	40	150	441	41.0
R4	0.20	41	150	319	42.8
R5	0.48	35	75	336	29.3
R6	0.57	37	75	334	32.2
R7	0.48	38	150	421	41.5
R8	0.42	39	150	451	39.4

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	O	R1	R2	R3	R4	R5	R6	R7	R8	Non-Dom		Ranking
										A	μ(A)	Options
O	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O	0.03	R4
R1	0.97	-	1.00	0.50	0.20	0.88	1.00	0.80	0.62	R1	0.35	R3
R2	0.73	0.94	-	0.67	0.11	0.75	0.92	0.85	0.75	R2	0.19	R8
R3	0.72	0.79	0.97	-	0.83	0.77	0.80	1.00	1.00	R3	0.83	R7
R4	0.85	0.85	0.92	1.00	-	0.85	0.85	1.00	1.00	R4	1.17	R6
R5	0.79	0.80	0.80	0.47	0.21	-	1.00	0.72	0.63	R5	0.36	R5
R6	0.70	0.80	0.80	0.50	0.31	1.00	-	0.80	0.72	R6	0.46	R1
R7	0.75	0.82	0.95	0.93	0.59	0.80	0.82	-	1.00	R7	0.59	R2
R8	0.71	0.79	1.00	1.00	0.68	0.75	0.83	1.00	-	R8	0.68	O

Table 5 shows that option R4 (with the prefabricated rehabilitation module) is ranked as the best action and is “at least as good as” options R3, R7 and R9 in all criteria, as the number 1 in columns 5, 9 and 10 indicates. This rehabilitation solution has the lower U-Value and the higher acoustic insulation and is the lighter one, but is the thicker one.

The ventilated wall with 10 cm of XPS (R3) was ranked second. This is the rehabilitation option with second best thermal and acoustic performance, but is one of the heaviest and thicker ones.

The 6 cm of ICB and hollow brick pane with 11cm was ranked third. This option has the third best thermal and acoustic performance, but is the heaviest one.

The rehabilitation solutions with ETICs system and the ventilated wall with 4 cm of XPS were the worst ranked rehabilitation options. As expected the existent solution is the worst ranked option.

4 CONCLUSION

This methodology 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 design team has the possibility to change the criteria, criteria weights and thresholds according to the objectives and constraints of the 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, acoustic insulation, useful area, glazing area, 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, when not all the building characteristics are defined.

Throughout the multi-criteria analysis performed, it was possible to verify that the rehabilitation solutions with lower U-values and higher airborne acoustic insulation and superficial mass, the prefabricated rehabilitation module, the ventilated wall with 10 cm of XPS and the 6 cm of ICB and hollow brick pane with 11 cm were the best rehabilitation options.

The rehabilitation solutions with ETICs system and the ventilated wall with 4 cm of XPS were the worst ranked options.

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