Selection of refurbishment construction solutions to improve the Indoor Environmental Quality and Sustainability of buildings

Sandra Monteiro da Silva
Assistant Professor
University of Minho
Portugal
sms@civil.uminho.pt

Manuela Guedes de Almeida
Associate Professor
University of Minho
Portugal
malmeida@civil.uminho.pt

Dr. Manuela Almeida, University of Minho, Portugal, malmeida@civil.uminho.pt

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. Besides the energy efficiency the Indoor Environmental Quality of Buildings (IEQ) and environmental impact must also be considered when planning a refurbishment 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, indoor air quality and environmental impact 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. Throughout the multi-criteria analysis performed, it was possible to verify that the rehabilitation solutions with lower embodied energy were the best refurbishment options.

Keywords: Refurbishment; Thermal behaviour; Acoustic performance; Energy efficiency; Multi-criteria decision analysis

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 the population spend about 90% of their time inside closed spaces [1]. 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 pre-scribed in the Energy Efficiency in Buildings Directive (EPBD) and reinforced with the "EPBD recast" [1, 2].

The rehabilitation of the building stock is an opportunity to achieve these goals. In Portugal, 80% 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 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 [3].

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, 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. 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). 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 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 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 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 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. The MCDA method ELECTRE III was chosen to assist the design team in the selection of the most adequate refurbishment solutions [4].

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 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. 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 1980s. The building is a single residential unit with two bedrooms, north 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 (Polyvinyl chloride) roller shutters. The window to wall ratio is approximately 20%. Table 1 lists the main characteristics of the building envelope.

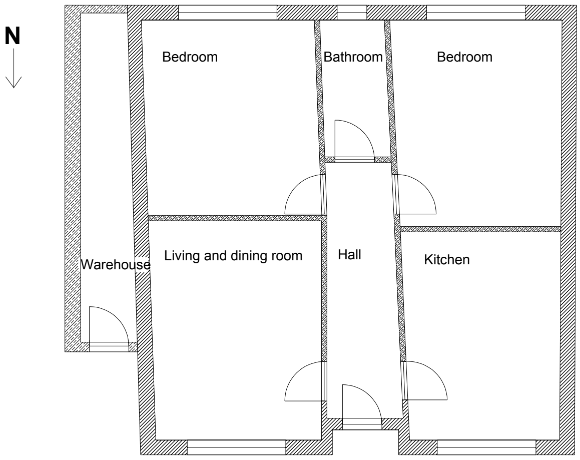

Fig. 1: Floor plan of the building

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

2.2 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 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 [5].

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) [6, 7].

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 (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 [4, 8].

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 [4]. 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 [4].

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 [9].

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 [10]. 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 [11]. 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 must be maximized and others 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 (U-value, 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 U-value, determined using the publication ITE50 – U-Values of Building Envelope Elements [12]. All the solutions selected respect the minimum requirements defined in the Portuguese Thermal Regulation [13].

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 [14, 15]. All the solutions selected respect the requirements defined in the Portuguese Acoustic Regulation [14].

The embodied energy was assessed using the Cumulative Energy Demand 1.04 method from the Life Cycle Assessment (LCA) software, SimaPro 7.1.8 [16, 17, 18].

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 selected, by the design team, for this case-study.

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}ºC)	↓	25	0.25	0.10	0.50
Acoustic Insulation ($D_{2m,\,nT,\,W}$)	dB	↑	25	5	2	10
Embodied Energy (EE)	MJ/m^2	↓	20	200	50	400
Superficial Mass (Msi)	kg/m^2	↑	20	50	10	100
Thickness	cm	↓	15	10	2	30

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 [13, 14].

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 [19, 20, 21]. 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 [22].

3.2 Construction Solutions

The first step of the refurbishment 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 (U_w = 2.50 W/(m^{2}ºC)) 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_{wdn} = 2.00 W/(m^{2}ºC)). The air inlets were introduced to improve the air change rate and the indoor air quality. Additionally 20 cm of mineral wool were placed in the roof (0.21 W/(m^2°C)) to improve its thermal performance.

The rehabilitation construction solutions selected (shown in Figure 1 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 four insulation materials (expanded polystyrene, EPS, expanded extruded polystyrene, XPS, mineral wool, MW and cork, ICB).

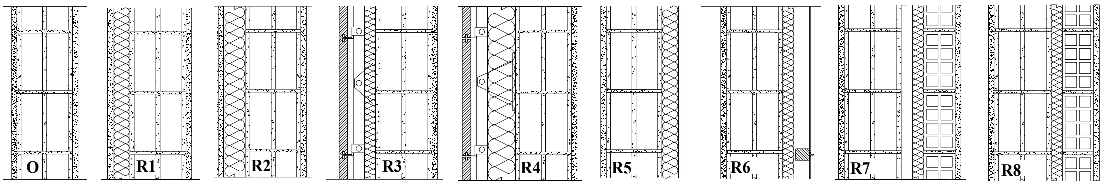

Fig. 2: Vertical cross-section of the existing and rehabilitation construction solutions of the façade walls

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

Option	Wall	U-Value [W/(m^2°C)]
O	Hollow concrete block with 20 cm	1.90
R1	Hollow concrete block wall, 20 cm and ETICS system with 4 cm of EPS	0.65
R2	Hollow concrete block wall, 20 cm and ETICS system with 8 cm of EPS	0.40
R3	Hollow concrete block wall, 20 cm and ventilated wall with stone with 5 cm with 4 cm of XPS	0.67
R4	Hollow concrete block wall, 20 cm and ventilated wall with stone with 5 cm with 10 cm of XPS	0.34
R5	Hollow concrete block wall, 20 cm and plasterboard wall (1.3 cm) with 4 cm of MW	0.57
R6	Hollow concrete block wall, 20 cm and plasterboard wall (1.3 cm) with 6 cm of MW	0.48
R7	Hollow concrete block wall, 20 cm, air gap and hollow brick (11 cm) with 4 cm of MW	0.48
R8	Hollow concrete block wall, 20 cm and hollow brick (11 cm) with 6 cm of ICB	0.42

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

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 opaque, the glazing part of the façade and the roller shutter box.

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	2.23	30	0	150	24.0
R1	1.09	35	61	150	30.0
R2	0.90	35	145	150	34.0
R3	1.10	37	2018	150	35.0
R4	0.86	38	2184	150	41.0
R5	1.04	35	161	75	29.3
R6	0.97	37	205	75	32.2
R7	0.97	38	261	150	41.5
R8	0.93	39	262	150	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 Options
										A	m(A)	
O	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	O	0.09	R2
R1	0.91	-	0.85	1.00	0.70	1.00	0.97	0.88	0.73	R1	0.93	R1
R2	0.72	0.92	-	1.00	0.92	0.95	1.00	0.92	0.83	R2	0.99	R8
R3	0.00	0.00	0.00	-	0.77	0.00	0.00	0.00	0.00	R3	0.00	R5
R4	0.00	0.00	0.00	0.77	-	0.00	0.00	0.00	0.00	R4	0.00	R7
R5	0.64	0.78	0.78	0.85	0.63	-	1.00	0.77	0.67	R5	0.78	R6
R6	0.53	0.72	0.84	0.85	0.83	0.98	-	0.85	0.85	R6	0.75	O
R7	0.65	0.65	0.81	0.92	0.98	0.78	0.86	-	1.00	R7	0.77	R3, R4
R8	0.65	0.66	0.85	0.95	1.00	0.78	0.89	1.00	-	R8	0.93	

Table 5 shows that option R2 (refurbishment with the ETICS system with 8 cm of EPS) is ranked as the best action and is “at least as good as” options R3 and R5 in all criteria, as the number 1 in columns 4 and 7 indicates. This refurbishment solution has one of the lower U-Value, the second lower embodied energy and is one of the solutions with the higher superficial mass and is also one of the thinner solutions.

Solutions R1 (4 cm of EPS ETICS), with the lower embodied energy, acoustic insulation and thickness and one of the higher U-values and superficial mass, was ranked second. Option R8 (6 cm of ICB and hollow brick pane with 11cm) was ranked third. This option has the third best thermal performance and the best acoustic behaviour, has a high superficial mass but is also the third thicker solutions and has the third higher embodied energy.

The existing solution (O) with the worst thermal and acoustic performance and the ventilated walls, option R3 and R4 (with the lowest U-value), with high thermal mass, with the second and third best acoustic insulation, but with the higher embodied energy were ranked last.

4. Conclusion

Throughout the multi-criteria analysis performed, it was possible to verify that the refurbishment solutions with ETICS system, with low U-value and embodied energy and higher superficial mass were ranked the best rehabilitation options.

The solution with ICB and a second hollow brick pane, that presents the second lower U-value, the higher acoustic insulation and a high thermal mass, was ranked third.

The existing solution with the worst thermal and acoustic performance and the ventilated walls, with the lowest U-value, high thermal mass, with the second and third best acoustic insulation, but with the higher embodied energy were ranked last.

The best ranked options were not the ones that had the best performance in the criteria with highest weights. This example shows that applying this methodology, due to the use of weights and thresholds, the best action is not the one associated to the highest weight, even if it is the one that has the best performance in that criterion.

5. References

[1] DIRECTIVE 2002/91/EC, “Directive of the European Parliament and of the Council on the Energy Performance of Buildings (EPBD)”, from 16 of December, 2002.

[2] DIRECTIVE 2010/31/EU, “Directive of the European Parliament and of the Council, on the Energy Performance of Buildings (recast)”, from 10 of May, 2010.

[3] CENSUS 2011, “XV Recenseamento Geral da População, V Recenseamento Geral da Habitação”. INE - Instituto Nacional de Estatística, 2012.

[4] ROY, B., "ELECTRE III - Algorithme de classement base sur une représentation floue des préférences en présence de critères multiples“. *Cahiers de CERO*, 1978.

[5] EHRGOTT, M. and WIECEK, M.M., “Multiobjective programming“, in: J. Figueira, S. Greco, M. Ehrgott (Eds.), *Multiple Criteria Decision Analysis: State of the Art Surveys*, Springer. New York.

[6] ROY, B. and BOUYSSON, D., “Aid multiple a la decision: methods et cas“. *Económica*. Paris, 1993.

[7] ROULET, C.-A., FLOURENTZOU, F., et al., “ORME: A multicriteria rating methodology for buildings“. *Building and Environment*, Vol. 37, 2002, pp 579-586.

[8] PAPADOPOULOS, A. and KARAGIANNIDIS, A., “Application of the multi-criteria analysis method ELECTRE III for the optimisation of decentralised energy systems“. *Omega - The International Journal of Management Science*, Vol. 36, 2008, pp 766-776.

[9] MAYSTRE, M., PICTET, J. and SIMOS, J., “Methodes multicriteres ELECTRE“. *EPFL Presses Polytechniques et Universitaires Romandes*. Lausanne,1994

[10] ROULET, C.-A., et al., “ORME: Office Building Rating Methodology for Europe“. *Office Project Report*, University of Athens, Athens. 1999.

[11] ROGERS, M., “Using ELECTRE III to aid the choice of housing construction process within structural engineering“. *Construction Management and Economics*, Vol 18 No. 3, 2000, pp. 333-342

[12] PINA DOS SANTOS, C. and MATIAS, L., “U-Values of Building Envelope Elements“, *LNEC*. Lisbon, 2006.

[13] DECREE-LAW Nº 80/2006 2006. “Portuguese Building Thermal Legislation“ (In Portuguese), RCCTE 2006, April 4th, Lisbon.

[14] DECREE-LAW Nº 96/2008 2008. “Portuguese Building Acoustics Legislation“ (In Portuguese), RRAE 2008, July 9th, Lisbon.

[15] EUROPEAN STANDARD EN 12354-3, “Building acoustics - Estimation of acoustic performance of buildings from the performance of elements - Airborne sound insulation against outdoor sound“, CEN, Belgium. 2000.

[16] ASIF, M., DAVIDSON, A. and MUNEER, T., “Embodied energy analysis of aluminium-clad windows”. *Building Services Engineering Research and Technology*, Vol 22 No 3, 2001, pp. 195-199.

[17] FRISCHKNECHT R., et al., “Implementation of Life Cycle Impact Assessment Methods”. *Final report ecoinvent 2000*. Duebendorf. Swiss Centre for LCI, 2003.

[18] PRE CONSULTANTS BV, “SimaPro 7 User's Manual”, Netherlands, 2008.

[19] MONTEIRO SILVA, S., “Building sustainability and Comfort“ (in Portuguese). PhD Thesis. *Universidade do Minho*, Guimarães. 2009

[20] ROHLES, F. H. WOODS, J. E. and MOREY, P. E., “Occupant Perception of the Work Environment“. *Human Factors and Ergonomics Society Annual Meeting Proceedings*, Vol. 31, No. 10, 1987, pp 1105-1108(4).

[21] KIM, SUN-SOOK; et al., “Development of a housing performance evaluation model for multi-family residential buildings in Korea“. *Building and Environment.* Vol 40, 2005, pp 1103-1116.

[22] ROGERS, M. and BRUEN M., “Choosing realistic values of indifference, preference and veto thresholds for use with environmental criteria within ELECTRE“. *European Journal of Operational Research*. 107, 1998, pp. 542-551.