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THERMAL AND ACOUSTIC COMFORT IN BUILDINGS

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Abstract
To achieve an adequate quality of buildings it is necessary to consider a set of aspects that are interconnected and influence each other, not always in a favourable way. The selection of the most suitable construction solution for the building elements must consider its contribution to the thermal and acoustic comfort inside the buildings, the daylight conditions, its energy efficiency and sustainability, and also the weight of the solution and its effect on the structural project of the building.
In this work, the use of a multi-criteria analysis, to balance all these aspects on the design phase, in order to assist the designer in the selection of construction solutions and materials, will be presented. The selection of the most adequate construction solutions will increase the buildings thermal and acoustic behaviour and also its energy performance and sustainability.

Keywords: Thermal behaviour, Acoustic performance, Energy efficiency, Sustainability, Multi criteria analysis.

1 Introduction

Energy efficiency and sustainability of buildings are nowadays major concerns. Buildings must guarantee a healthy and comfortable indoor climate as Men spend about 90% of their time inside closed spaces. Thus, it is mandatory to control the energy consumption in the building sector, while maintaining, or even improving, the indoor comfort conditions.
But, as buildings are complex systems, where all aspects are interconnected and influence each other, an integrated and comprehensive approach to the buildings design that enhance indoor health and comfort besides the energy savings and environmental sustainability, should be followed. 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 simultaneously.
Therefore, heating, cooling, daylight availability, Indoor Air Quality, acoustic behaviour, sustainability and energy reduction strategies should be meshed at an early stage 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, on the design phase, 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.

Multi-criteria analysis is, in this way, an important tool in such problems, since it employs mathematical models that evaluate alternative scenarios, in this case, materials and construction solutions, fenestration strategies, etc., taking into account both their objective characteristics (U-Value, acoustic insulation, embodied energy) and the preferences of the decision makers regarding the objectives and constraints of each project.

The aim of this study was to investigate the viability of the use of multi-criteria analysis to assist the designer in the selection of construction solutions and materials. A simple case study was studied to demonstrate the feasibility of the approach using the multi-criteria analysis method Electre III [1].

2 Methodology

To achieve an adequate behaviour of the buildings it is necessary to consider either the overall comfort conditions (thermal, acoustic, visual and Indoor Air Quality) as well as sustainability. 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 embodied energy. 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 lighting 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 IAQ.

The design phase is the ideal moment to mesh and implement all these principals as it is still possible to implement modifications on the project. So, it is during the design phase that the sustainable, energy efficient and comfortable building concepts should be applied, by a judicious selection of materials, technologies and construction methods to be used.

To test this integrated approach, two floors and four rooms, were studied, estimating the thermal quality of the envelope (calculating the U-value), the acoustic behaviour of the envelope (estimating the weighted normalized airborne sound insulation index of the façade and walls and the weighted normalized airborne sound insulation index and the weighted normalized impact insulation index of the floor), the weight, the embodied energy and the thickness of the construction solution were also calculated.

The analysis considered the factors that have influence on the behaviour of the buildings, such as glazing type, construction solutions and materials, weight (associated with thermal inertia, acoustic insulation and to the building structure) and embodied energy.

2.1 Prediction Tools

The prediction of the building thermal behaviour was done using the U-value, determined using the publication ITE50 – U-Values of Building Envelope Elements [2]. All the solutions selected respect the minimum requirements defined in the Portuguese Thermal Regulation [3]. The acoustic behaviour was considered estimating the weighted normalized airborne sound insulation index of the façade, measured at 2m from them ($D_{2m, nT, W}$), the weighted normalized airborne sound insulation index ($D_{nT,\,w}$) for the walls and floors and the weighted normalized impact sound insulation index ($L'_{nT,\,w}$) for the floors, according the to the EN 12354 standard, using the Acoubat Sound Program [4, 5, 6]. The embodied energy was assessed using Cumulative Energy Demand 1.04 [7].

2.2 Room Characteristics

To estimate the acoustic behaviour of the building, using Acoubat Sound Program, a geometry with two floors and two rooms (3m x 4m x 2.5m) was defined. The window area, 1.2m x 1.2m, was maintained constant. The area of the windows was defined to optimize the solar gains during winter and the daylight availability and minimize the unwanted solar gains during summer, according to the Illuminating Engineering Society of North America (IESNA) recommendations, corresponding to a Window - Wall Ratio of about 20% (percentage that results from dividing the glazed area of the wall by the total wall area) [8, 9].

2.3 Construction Solutions Characteristics

The construction solutions analyzed are shown in Figure 1, for the different types of elements of the building. The construction solutions selected, single and double pane walls (hollow concrete blocks, brick and hollow brick), concrete, hollow core concrete and beam and pot slabs and materials (concrete, brick), cover a wide range of situations. The study was done for two insulation materials (expanded extruded polystyrene, XPS, and mineral wool, MW). The insulation could be placed in the exterior or in the interior of the single pane walls and in the air cavity of the double pane walls (Figure 1).

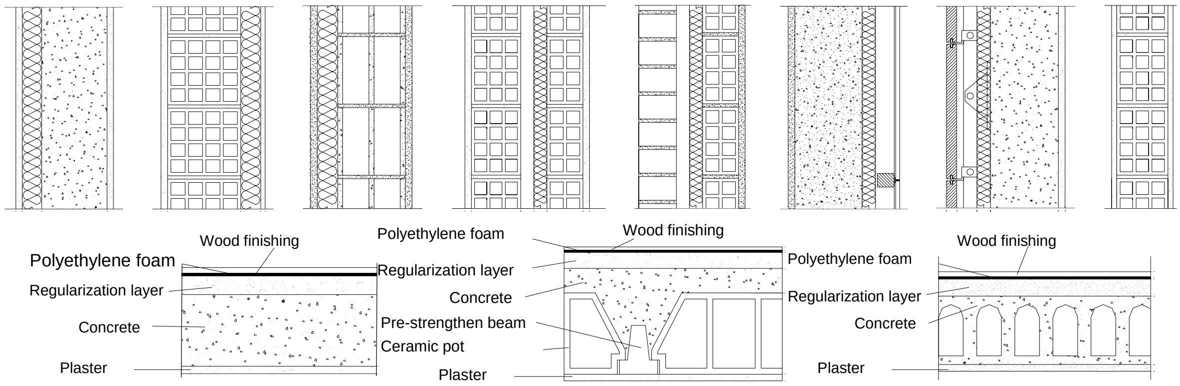

Figure 1 – Vertical cross-section of the construction solutions of the walls and floors (external and partition elements)

Different glazing types and frames were selected for the windows considering the existence of PVC roller shutters or air inlets in the windows frames.

The air inlets were introduced to improve the air change rate and the indoor air quality. The roller shutters were selected as they are the most used shading devices in Portugal and they also allow controlling daylight. Roller shutters are also the most penalizing systems in what concerns thermal and acoustic behaviour of the façade (when comparing with the venetian blinds and shutters, for example) due to the existence of the roller shutters boxes.

2.4 Multi-criteria analysis

The multi-criteria decision analysis (MCDA) defines flexible approach models to help the decision maker, and/or the design team, selecting the most adequate solutions among a large number of options and possibilities. The problem of the decision maker is a multi-objective optimization problem [10] 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 (no more than 12) and must be coherent (which are the criteria to be maximized and to be minimized) [11, 12].

The selection of the best options to optimize the sustainability and the comfort conditions of buildings is a type of problem that fits the purposes of a multi-criteria analysis.

The multi-criteria methodology selected in this work to help the decision maker selecting the most adequate solutions to optimize the building comfort and sustainability was the Electre III model as it may be considered as a decision-aid technique suited to the appraisal of complex civil engineering projects [13]. This method requires the definition of weights and thresholds, which allows the decision maker to provide his scale of values, according to the objectives.

2.4.1 The Electre III method

Electre III is a multi-criteria decision analysis method [1] 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 [1].

The model permits a general ordering of alternatives, even when individual pairs of options remain incomparable where there is insufficient information to distinguish between them. 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”, as occurs within an engineering project appraisal.

The rank of a building in a series does not change much when the weights given to the various criteria or the threshold levels for veto, preference or indifference are changed within a realistic range [12, 14].

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. Compensation occurs when a criterion with poor rating according to one parameter is compensated by fair results on several other parameters. Using this method, a building which shows too poor results in one criterion cannot be ranked in a higher position [12, 14].

3 Results

In the study performed, the Electre III method was applied to the evaluation of several alternative solutions for the façade walls, for the walls separating dwellings and separating dwellings from common circulation zones and for the floors, on the basis of five criteria: thermal and acoustic insulation, embodied energy, weight and thickness. Table 1 lists the different criteria, thresholds and weights that are needed to use the Electre III method. The weights and thresholds presented here are just an example. These values must be defined by the design team according to the objectives and constraints of the project.

The criteria selected are related to the sustainability of the buildings and to the most important characteristics of the IEQ, the thermal and acoustic comfort. These criteria were also selected because it is possible to define them in a non subjective way, they are possible to predict in the design phase and are under the designer scope. The minimum thermal and acoustic insulation values are also defined in the Portuguese thermal and acoustic regulation and are mandatory. The weight and the thickness of the solutions are also relevant as they affect the structural design of the building and their useful area.

Table 1 – Criteria, weights and thresholds (criteria to: ↓ - minimize; ↑ - maximize).

Category (Criteria)	Units		Weight	Threshold		
				Preference	Indifference	Veto
Thermal Insulation (U-Value)	$W/(m^2 {}^oC)$	↓	25	0.25	0.10	0.50
Acoustic Insulation ($D_{2m,\,nT,\,W}$, $D_{nT,\,W}$, $L'_{nT,\,W}$)	dB	↑ / ↓	25	5	2	10
Embodied Energy (EE)	MJ/m^2	↓	20	220	80	460
Weight	kg/m^2	↓	15	80	30	160
Thickness	cm	↓	15	7	3	15

The weight and the thickness are criteria to be minimized to reduce the weight of the building and to increase the useful area available. The U-Value and the $L'_{nT,W}$ are criteria that should be minimized and the $D_{2m,\,nT,\,W}$ and the $D_{nT,\,W}$ are criteria that should be maximized.

The weights were defined taking into account the relative importance of each criteria. The weights 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 [15, 16, 17]. These studies showed that the thermal comfort is the most valued criterion, followed by the acoustic comfort. The thresholds were defined according to the criteria characteristics, for example a 2 dB difference is not perceptible to the human ear, but 5 dB is a significant difference. Differences in the embodied energy and in the weight of about 10% are not significant, differences of about 25% are relevant and if the difference is higher than 50% the options are not comparable.

Several alternatives were selected for the walls and for the floors, based on different construction solutions (single and double pane walls) and materials (concrete, brick, mineral wool, MW and expanded extruded polystyrene, XPS). All the options fulfil the Portuguese Thermal and Acoustic regulation.

3.1 Façade Wall

The construction solutions analyzed for the façade walls are listed in Table 2, where F stands for façade wall, S for single wall with insulation on the outside and D for double pane wall with insulation placed in the air cavity. Several options were defined for the opaque part of the façades walls and for the windows (frame and glazing type) and the existence, or not, of roller shutter box and air inlets. Table 3 lists the results of the prediction of the façade walls behaviour according to the five criteria selected to outrank the design alternatives. The acoustic requirements of façade walls are $D_{2m,\,nT,\,W} \geq 28$dB for sensitive zones (residential areas, areas with schools, hospitals and leisure areas), and $D_{2m,\,nT,\,W} \geq 33$dB for the other zones (named as mixed zones) [4].

The U-Value, embodied energy and the weight of the solution are weighted averaged values taking into account the opaque, the glazing part of the façade and the roller shutter box.

The results of the outranking using Electre III method are presented in Table 4. The single pane hollow concrete block wall, option FS2, was ranked as the best action, this solution has the second higher acoustic insulation. The double wall with hollow brick with 11cm and hollow concrete block with 12cm was ranked second. The best ranked options are the one with lower embodied energy.

Table 2 – Construction solutions studied for the façade.

Option	Wall	Frame	Glazing	Roller box	Air inlets
FS1	Single pane concrete wall with 20cm with 4cm of XPS	Aluminium	6+12+4	No	Yes
FS2	Single pane hollow concrete block wall, 20cm, with 4cm of XPS	wood	4+12+4	No	No
FS3	Single pane hollow brick wall with 22cm with 4cm of XPS	Aluminium	4+12+6	Yes	Yes
FD4	Double pane wall, concrete wall with 20cm and plasterboard wall with 1.3cm with 6cm of MW	PVC	4+12+6	No	Yes
FD5	Double pane wall, hollow brick with 11cm and hollow concrete block with 12cm with 5cm of MW	Wood	6+8+6	No	Yes
FD6	Double pane wall, hollow brick with 15cm and hollow brick with 11cm with 6cm of MW	PVC	4+8+6	Yes	Yes
FD7	Double pane wall, hollow brick with 11cm and hollow brick with 11cm with 6cm of MW	Wood	6+12+6	Yes	No
FD8	Double pane wall, brick with 15cm and hollow brick with 15cm with 6cm of MW	Aluminium	4+12+4	Yes	No
FD9	Double pane wall, brick with 11cm and hollow brick with 15cm with 6cm of MW	PVC	4+12+4	No	No
FD10	Ventilated wall, stone with 5cm and concrete wall with 22cm with 6cm of MW	Aluminium	4+12+6	No	Yes

Table 3 – Criteria for the different design alternatives studied for the façade.

Options	Thermal insulation U-Value [W/(m2ºC)]	Acoustic insulation $D_{2m,\,nT,\,W}$, [dB]	Embodied Energy EE [MJ/m^2]	Weight [kg/m^2]	Thickness [cm]
FS1	1.21	39	1768	464	27.5
FS2	1.02	42	699	265	27.5
FS3	1.11	34	1864	208	29.5
FD4	1.07	34	1378	395	29.3
FD5	0.96	34	907	355	32.5
FD6	0.78	34	1534	227	35.5
FD7	0.82	40	1004	226	31.5
FD8	0.84	44	2850	268	33.5
FD9	0.86	42	2162	296	37.5
FD10	1.24	41	3360	489	38.5

Table 4 – Credibility degrees matrix for the alternative solutions selected for the façade walls.

										Non-Dom		Ranking
Options	FS1	FS2	FS3	FD4	FD5	FD6	FD7	FD8	FD9	FD10	A	μ(A)	Options
FS1	-	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	1.00	FS1	0.02	FS2
FS2	0.77	-	0.67	0.75	0.75	0.73	0.97	1.00	1.00	0.8	FS2	1.16	FD5
FS3	0.98	0.00	-	0.00	0.00	0.80	1.00	1.00	1.00	0.95	FS3	0.33	FS3
FD4	0.93	0.00	0.00	-	0.00	0.00	0.00	0.85	0.85	0.88	FD4	0.02	FD6
FD5	0.68	0.59	0.53	0.98	-	0.85	0.85	0.85	0.91	0.75	FD5	0.84	FD4
FD6	0.42	0.00	0.64	0.52	0.00	-	0.96	1.00	1.00	0.48	FD6	0.15	FS1
FD7	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	FD7	0	FD10, FD9, FD8, FD7
FD8	0.00	0.00	0.00	0.00	0.00	0.00	0.80	-	0.00	0.67	FD8	0	
FD9	0.13	0.00	0.00	0.00	0.00	0.00	0.77	0.96	-	0.75	FD9	0	
FD10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	FD10	0	

3.2 Walls Separating Dwellings and Separating Dwellings and Common Circulation Zones

The solutions studied for the walls separating dwellings and separating dwellings from common circulation zones are listed on Table 5, where I stands for internal wall, S for single and D for double pane wall, MW for mineral wool (placed in the air cavity) and EPS for expanded polystyrene. All the walls are finished with 1.5cm of plaster on both sides except the concrete walls that have plaster only in one side.

The values obtained for the different criteria are also listed on Table 5. Some of the solutions do not fulfil the requirements established on the Portuguese Acoustic Regulation for elements separating dwellings, but all can be used as walls separating the dwellings and the common circulation zones (elevator shaft, staircase and the common hall) ($D_{nT,\,w} \geq 48$dB, $D_{nT,\,w} \geq 40$dB if the source room is the staircase and the building have an elevator or $D_{nT,\,w} \geq 50$dB if the source room is a garage) [4].

Table 5 – Criteria for the different design alternatives for the walls separating dwellings and common circulation zones.

Options	U-Value [W/(m^{2}ºC)]	$D_{nT,\,w}$ [dB]	EE [MJ/m^2]	Weight [kg/m^2]	Thickness [cm]
Single concrete wall with 20cm with 2cm of EPS (IS1)	1.16	52	710	470	20
Single concrete wall with 25cm with 2cm of EPS (IS2)	1.13	55	865	595	25
Single pane hollow concrete block wall with 20cm (IS3)	1.71	48	625	275	23
Single pane hollow brick wall with 20cm (IS4)	1.25	43	830	210	23
Double pane wall, hollow brick with 7cm and hollow brick with 11cm with 5cm of MW (ID5)	0.50	45	969	220	26
Double pane wall, hollow brick with 7cm and hollow brick with 15cm with 5cm of MW (ID6)	0.47	46	1052	250	30
Double pane wall, hollow brick with 11cm and hollow concrete block with 12cm with 5cm of MW (ID7)	0.50	50	885	440	31
Double pane wall, hollow brick with 11cm and hollow brick with 11cm with 5cm of MW (ID8)	0.48	45	1006	240	30
Double pane wall, hollow brick with 11cm and hollow brick with 15cm with 5cm of MW (ID9)	0.46	46	1183	280	34
Double pane wall, hollow brick with 15cm and hollow brick with 15cm with 5cm of MW (ID10)	0.43	47	1172	310	38

The results of the outranking using Electre III method are presented in Table 6 and in Table 7.

Table 6 – Credibility degrees matrix for the different design alternatives for walls separating dwellings and common circulation zones.

											Non-Dom		Ranking
Options	(IS1)	(IS2)	(IS3)	(IS4)	(ID5)	(ID6)	(ID7)	(ID8)	(ID9)	(ID10)	A	μ(A)	Options
(IS1)	-	0.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(IS1)	0.29	ID5
(IS2)	0.67	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(IS2)	0.36	ID8
(IS3)	0.00	0.00	-	0.29	0.00	0.00	0.00	0.00	0.00	0.00	(IS3)	0.28	ID6
(IS4)	0.45	0.00	0.57	-	0.00	0.00	0.00	0.00	0.00	0.00	(IS4)	0.08	ID9
(ID5)	0.44	0.00	0.72	0.92	-	1.00	0.74	1.00	1.00	1.00	(IS5)	1.00	ID10
(ID6)	0.33	0.22	0.26	0.62	0.96	-	0.71	1.00	1.00	1.00	(IS6)	0.96	IS2
(ID7)	0.71	0.64	0.00	0.00	0.00	0.00	-	0.00	0.00	0.85	(IS7)	0.26	IS1
(ID8)	0.40	0.00	0.43	0.71	0.96	1.00	0.69	-	1.00	1.00	(IS8)	0.96	IS3
(ID9)	0.00	0.13	0.00	0.50	0.57	0.89	0.63	0.79	-	1.00	(ID9)	0.57	ID7
(ID10)	0.00	0.22	0.00	0.11	0.49	0.70	0.57	0.61	0.96	-	(ID10)	0.49	IS4

The Double pane wall, brick with 7cm and hollow brick with 11cm with 5cm of mineral wool in plates placed in the air cavity, option ID5, was ranked as the best option for walls separating dwellings and common circulation zones, according to the weights and thresholds defined. This option was not the one that had the best performance on the different criteria, the best behaviour was when considering the weight and the thickness, that are the less valued criteria.

The double pane wall, with brick with 11cm and hollow concrete block with 12cm and with 5cm of mineral wool in plates placed in the air cavity (ID7) was the wall separating dwellings that was best ranked, as Table 7 shows. This option was one of the worst ranked for the walls separating dwellings and common circulation zones. So it is important to rank the options according to the requirements.

Table 7 – Credibility degrees matrix for the design alternatives for walls separating dwellings.

				Non-Dom		Ranking
Options	(IS1)	(IS2)	(ID7)	A	μ(A)	Options
(IS1)	-	0.32	0.00	(IS1)	0.29	(ID7)
(IS2)	0.67	-	0.00	(IS2)	0.36	(IS2)
(ID7)	0.71	0.64	-	(ID7)	1.64	(IS1)

3.3 Floors

The solutions studied for the floors and other data obtained for the different criteria are listed on Table 8, where F stands for floor. The floors between dwellings do not have thermal requirements and have acoustic requirements regarding airborne and impact insulation ($D_{nT,W} \geq$ 50dB and $L'_{nT,W} \geq$ 60dB) [4]. As, in general, the floors have the worst performance related to the impact insulation this index was selected to represent the acoustic insulation. All the floors have 0.8cm of wood as top surface finishing, and 1.5cm of plaster as inferior surface finishing, except floor F2 that have a suspended ceiling with a plasterboard.

Table 8 – Criteria for the different design alternatives for the floors.

Options	U-Value [W/m^2°C]	$D_{nT,W}$ / $L'_{nT,W}$ [dB]	EE [MJ/m^2]	Weight [kg/m^2]	Thickness [cm]
Concrete with 15cm, 0.5cm of polyethylene foam (F1)	2.10	50 / 60	1325	390	17.8
Concrete with 15cm, 0.5cm of polyethylene foam and a suspended ceiling with 5cm of mineral wool, 1.3cm plasterboard (F2)	0.64	55 / 51	1430	410	34.1
Concrete with 15cm, 2.5cm of cork, 4cm concrete (F3)	1.00	53 / 58	1526	470	23.8
Concrete with 20cm, 0.5cm of polyethylene foam (F4)	1.90	55 / 55	1480	555	22.8
Concrete with 20cm, 2.5cm of cork, 4cm concrete (F5)	0.94	57 / 56	1680	596	28.8
Pre-stressed concrete “T” beams, 25cm hollow brick pots, 5cm regularization layer, 0.5cm of polyethylene foam (F6)	1.43	50 / 60	1089	320	32.8
Pre-stressed concrete “T” beams, 25cm hollow brick pots, 5cm regularization layer, 2.5cm of cork (F7)	0.62	53 / 56	1290	415	38.8
Pre-stressed concrete “T” beams, 25cm hollow concrete pots, 5cm regularization layer, 0.5cm of polyethylene foam (F8)	1.52	53 / 58	1505	346	32.8
Pre-stressed concrete “T” beams, 25cm hollow concrete pots, 5cm regularization layer, 2.5cm of cork (F9)	0.65	54 / 57	1706	440	38.8
Hollow core concrete slab with 20 cm, 4cm regularization layer, 0.5cm of polyethylene foam (F10)	1.46	53 / 55	1182	430	25.3

The results of the outranking of the floor solutions using Electre III method are presented in Table 9. The concrete floor with 15cm and with polyethylene foam as resilient layer, option F1, was the solution best ranked. This option is the lighter and thinner and also one of the solutions with less embodied energy, but has the worst performance according to the thermal and acoustic insulation. The hollow core concrete slab (F10) that is one of the floors with best acoustic performance was ranked second. The slabs with floating layer of concrete, F3, F5, F7 and F9, that are the thicker and have the higher embodied energy are the worst ranked.

Table 9 – Credibility degrees matrix for the different design alternatives for the floors.

											Non-Dom		Ranking
Options	(F1)	(F2)	(F3)	(F4)	(F5)	(F6)	(F7)	(F8)	(F9)	(F10)	A	µ)A(	Options
(F1)	-	0.60	1.00	0.75	0.83	0.68	0.83	0.96	0.92	0.66	(F1)	1.60	F1
(F2)	0.00	-	0.60	0.00	0.66	0.00	0.91	0.00	1.00	0.00	(F2)	0.17	F10
(F3)	0.00	0.64	-	0.00	1.00	0.06	0.72	0.00	1.00	0.12	(F3)	0.00	F6
(F4)	0.00	0.40	0.85	-	1.00	0.00	0.56	0.00	0.85	0.65	(F4)	0.25	F4
(F5)	0.00	0.00	0.67	0.00	-	0.00	0.00	0.00	0.28	0.00	(F5)	0.00	F2
(F6)	0.00	0.60	0.85	0.06	0.80	-	0.83	1.00	0.92	0.60	(F6)	0.32	F8
(F7)	0.00	0.69	0.00	0.00	0.60	0.00	-	0.00	1.00	0.00	(F7)	0.00	F9, F7,F5,F3
(F8)	0.00	0.75	0.85	0.51	0.96	0.73	0.81	-	1.00	0.57	(F8)	0.04	
(F9)	0.00	0.49	0.00	0.00	0.60	0.00	0.73	0.00	-	0.00	(F9)	0.00	
(F10)	0.00	0.83	1.00	0.72	1.00	0.83	1.00	0.85	1.00	-	(F10)	0.34	

The best ranked options for the floors 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.

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 weights and thresholds assigned to each one. The design team has the possibility to change the 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 design alternatives, etc.).

Using this methodology, the design team can compare materials, construction solutions or design alternatives based on different criteria, for example, the U-value, acoustic insulation, thickness, weight, embodied energy, just to name a few, select and compare design alternatives, considering, for example the useful area, glazing area, etc..

The disadvantages of the methodology are the need to compare a large set of alternatives, to be able to select the best one, the necessity to determine the different solutions characteristics (thermal and acoustic insulation, embodied energy, etc.) and also the time needed to perform such detailed analysis.

The example here presented allows a robust analysis of the building elements as it comprise a broad study of each alternative through a detailed analysis of the main factors that affect the IEQ and also the sustainability, based on the thermal and acoustic insulation levels and the embodied energy of the construction solutions.

Throughout the multi-criteria analysis performed, it was possible to verify that there are a large number of construction solutions that, when adequately used, will assure the all the needs, being only necessary to integrate the exigencies of all the different requirements.

The proposed multi-criteria method, which can easily be applied, allows construction solutions to be rated according to their performance and may be used in the design phase or to evaluate rehabilitation or retrofitting scenarios. Using the Electre III method, buildings, design alternatives, construction solutions and materials or retrofit scenarios can be ranked according to several criteria and weights representing the preferences of the decision maker.

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