Achieving Sustainability through Energy Efficiency while Assuring Indoor Environmental Quality

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ABSTRACT: Sustainability in the Building sector is nowadays a major concern. Taking in consideration that in the EU buildings account for about 40% of the total energy consumption (35% in Portugal), the EU Directive 2002/91/EU on Energy Efficiency in Buildings (EPBD), recently reinforced with the "EPBD-recast", imposes an increasingly stronger control of the energy consumption in this sector while maintaining, or even improving, their indoor environmental quality (IEQ). But, as buildings are complex systems, where all aspects are interconnected and influence each other, not always in a favourable way, an integrated and comprehensive approach to the buildings design, that enhance indoor health and comfort besides the energy savings, should be followed. In this work it is presented a multi-criteria analysis, suitable for the design phase that balances all these aspects, with the potential of becoming a valuable tool to assist the designer in the most appropriate selection of design alternatives, construction solutions and materials.

1 INTRODUCTION

As EU buildings account for 40% of the total energy consumption, it is important to take measures to reduce these needs and, consequently, reduce the EU energy dependency as well as reducing the greenhouse gas emissions, in accordance with what is prescribed in the EU Directive 2002/91/EU on Energy Efficiency in Buildings (EPBD), recently reinforced with the "EPBD-recast" (EPBD, 1991; EPBD-recast, 2009).

Besides the energy efficiency, 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 environmental quality. 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. This aim leads to the analysis of several alternative solutions, which differ geometrically, technologically, environmentally and economically, and also in terms of comfort and Indoor Air Quality (IAQ). 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 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 predict the thermal, acoustic and daylight conditions and also the IAQ behaviour of the buildings, on the design phase, in order to be able to do the right choices, regarding, for instance the geometry, space organization, fenestration strategies, construction solutions and materials, to improve the occupants overall comfort and, at the same time, reduce the energy costs.

Furthermore, to make a conscious selection of the possible design 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, design alternatives, that include geometry, construction solutions, fenestration strategies, etc., taking into account both their objective characteristics (like thermal behaviour, daylight factor, energy consumption of the building) 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 improve the energy efficiency and IEQ in buildings. A simple case study was studied to demonstrate the feasibility of the approach using the multi-criteria analysis method Electre III.

2 METHODOLOGY

To achieve an adequate IEQ it is necessary to consider either the overall comfort conditions (thermal, acoustic, visual and Indoor Air Quality) as well as energy efficiency in buildings. It is then essential to optimize the building envelope, by improving construction solutions and insulation levels, glazing type and shading devices, optimizing the thermal and acoustic behaviour, the natural ventilation and daylighting techniques through an appropriate design. 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 building concepts should be applied, by a judicious selection of materials, technologies and construction methods to be used.

To test this integrated approach, two dwellings with three bedrooms, representative of the conventional Portuguese buildings, were studied, estimating the heating and cooling needs, the acoustic behaviour of the envelope (estimating the weighted normalized airborne sound insulation index), the daylight factor, the percentage of time considered comfortable by the buildings occupants and the index PPD which means the percentage of people dissatisfied with the IAQ.
The analysis considered all the factors that have influence on the behaviour of the buildings, such as glazing type, area and orientation, shading devices, construction solutions, thermal inertia, number of air changes per hour (ach), etc..

To predict the energy consumption and the thermal comfort conditions of the selected dwellings, it was used dynamic simulation. As in Portugal, in general, residential buildings are only acclimatized during occupied periods, the HVAC system was set up to maintain an indoor temperature of 20ºC in winter and 25ºC in summer (in accordance with the Portuguese legislation - RCCTE, 2006) only during this period that is between 7 pm and 8 am.

2.1 *Simulation Tools*

The prediction of the building thermal behaviour was done using the EnergyPlus simulation code, estimating the heating and cooling needs, for different construction solutions for the envelope and for the partition elements. The buildings had mixed ventilation, with air inlets on the windows frames of the main rooms and with mechanical ventilation in the kitchen and in the WCs. In summer, during night periods, the buildings were ventilated to use the cooler outside air to reduce indoor temperature.
The thermal comfort conditions of the occupants were determined according to EN ISO 7730 and EN 15251. The comfort period (number of hours during the occupied period where the occupants were comfortable) was ascertain by EnergyPlus according to ASHRAE 55 - 2004 graph (Section 5.2.1.1) (ASHRAE 55, 2004; EN ISO 7730, 1994; EN 1521; 2007).

The acoustic behaviour was considered estimating the weighted normalized airborne sound insulation index of the façade ($D_{2m,\,nT,\,W}$), using the Acoubat Sound Program, as this is the only requirement that the building elements of single detached family houses have to fulfil (RRAE, 2008).

The visual comfort was accessed through the daylight factor, for the most unfavourable situation, using the Desktop Radiance Tool, for the 21st of December and for the 21st of July considering the existence of a light-colour curtain in every window. The daylight factor is the International Commission on Illumination (CIE from its French title) recommended method to determine the performance of a daylighting system, and is independent on the window design and location, outdoor obstructions, optical characteristics of inner surfaces and windows. It is useful for estimating the amount of glazing needed to illuminate a space.

To assess the Indoor Air Quality it was applied the Fanger method to predict the number of persons dissatisfied with the IAQ, taking into account the number of ach, predicted using Comis studio program, the number of occupants and the materials used (low-polluting or non low-polluting) (Fanger, 1988; CEN CR 1752, 1998).

2.2 *Building Characteristics*

The buildings under analysis, used to test the methodology, have three south oriented bedrooms. The kitchen and the dining and living room are north oriented, in building 1 and South oriented in building 2 (Figure 1).

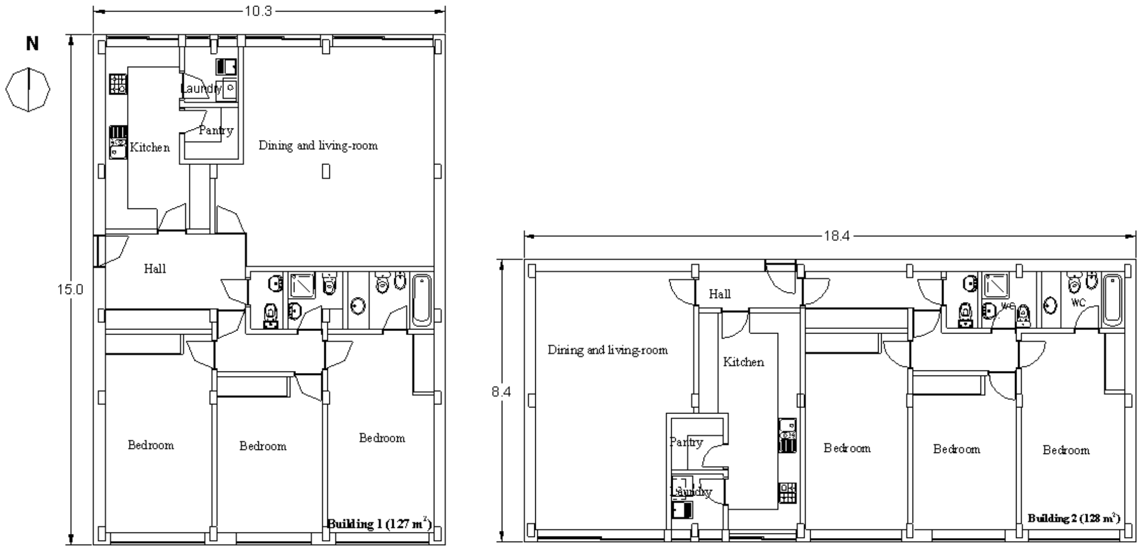

Figure 1 Schematic plan of the studied buildings

The WCs are mechanically ventilated and the windows have adjustable air inlets in the frame to guarantee the ventilation of the dwelling. The glazing area corresponds to 15% of the floor area (30% of the walls area), to optimize the use of solar gains in winter and the daylight availability (3.36 m^2 on the kitchen, 5.15 m^2 on the dining and living room, 2.75 m^2, 2.20 m^2 and 2.75 m^2 for the bedrooms).

2.3 *Construction Characteristics*

The construction solutions analyzed are shown in Figure 2 and listed on Table 1, for the different types of elements of the building envelope. The windows have an adjustable shading system (venetian blinds) on the outside to maximize the solar gains during winter and minimize the unwanted solar gains during summer and at the same time allowing the control of daylight, thus, avoiding the use of artificial lighting.

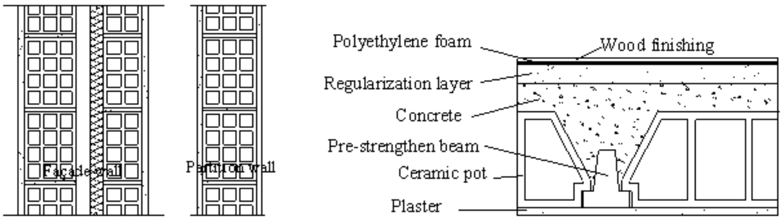

Figure 2 Vertical cross-section of the construction solutions of the walls and floors of the buildings (external and partition elements)

Table 1 Construction solutions characteristics

Element	Construction Solutions (see Figure 2)	
Façade	Double pane wall, hollow brick wall (15cm + 11cm), with 6 cm of mineral wool in plates placed in the air cavity and finished with plaster on both sides Single concrete wall (15 cm), with 4 cm of expanded extruded polystyrene, finished with plaster on both sides	
Partition walls	Single pane hollow brick wall with 11cm, finished with plaster on both sides	
Windows	Metallic window frames with adjustable air inlets, venetian blinds on the outside and overhangs on south windows	Double pane clear glazing (8+10+6) mm Double pane Low-e glazing (6+10+4) mm

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 between a large number of options and possibilities. The problem of the decision maker 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 (no more than 12) and must be coherent (which are the criteria to be maximized and to be minimized) (Roy & Bouysson, 1993; Roulet et al, 2002).

The selection of the best options to optimize the sustainability through energy performance, and the IEQ 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 IEQ and energy efficiency 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). This method requires the definition of weights, which allows the decision maker to provide his scale of values, according to the objective.

2.4.1 *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 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 (Roulet et al., 1999, Roulet et al., 2002).

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 (Roulet et al., 1999, Roulet et al., 2002).

3 RESULTS

In the study performed, the Electre III method was applied to the evaluation of five alternatives, based on two types of buildings, with one and two façades with glazing, on the basis of five criteria covering energy needs, comfort period, acoustic insulation, Percentage of People Dissatisfied with the IAQ and Daylight Factor (DF).

Table 2 lists the different criteria, thresholds and weights that are needed to use the Electre III method. The weights and thresholds are presented here just an example. These values must be defined by the project team according to the objectives and constraints of the project.

Table 2 Criteria, weights and thresholds

Category (Criteria)	Units	Weight	Threshold		
			Preference	Indifference	Veto
Thermal Comfort (Percentage of Comfortable Time)	(%)	25	20	10	50
Acoustic Insulation ($D_{2m,\,nT,\,W}$, $D_{nT,\,W}$ and/or $L'_{nT,\,W}$)	(dB)	22	5	2	10
Indoor Air Quality (Percentage of People Dissatisfied, PPD)	(%)	18	5	2	15
Visual Comfort (Daylight Factor, DF)	(%)	15	0.5	0.2	2
Energy Consumption	kW/(m^2.year)	20	50	10	100

The criteria that were selected are the ones that are related to the sustainability of the buildings, the energy consumption, and the most important characteristics of the IEQ, and also because it is possible to define them in a non subjective way. These criteria are also ones of the few that are possible to predict in the design phase and are under the designer scope.

The weights were defined taking into account the relative importance of each of the criteria. The weight of the energy consumption was established based on the targets defined by the "EPBD-recast" (EPBD-recast, 2009). The weights established for the IEQ criteria 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 comfort is the most valued criterion, followed by the acoustic comfort and IAQ. The visual comfort is the less valued criterion.

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.

Five design alternatives were selected, based on two different buildings, shown in Figure 1, Building 1 and Building 2. The buildings have similar areas, but the glazings have different orientations, conducting to different solar gains and energy needs.

The study was performed considering that there are four households and the HVAC system was set up to maintain an indoor temperature of 20ºC in winter and 25ºC in summer, working between 7 pm and 8 am. The ventilation rate was of 0.98 ach. All the options fulfil the regulations.

The construction solutions analyzed, defined in Table 1, were the same for the two buildings. Option A corresponds to a façade with a double brick wall and option B to a single concrete wall. Option C has the same walls as option A, but the painting used is low polluting. In option 1A the occupants are non-smokers, and in option 1B and 1C 20% of the occupants smoke inside the building. In option 2A 20% of the occupants are smokers and in option 2B the occupants are non-smokers.

The acoustic insulation of the façade and the daylight factor shown in Table 3 are from the dining and living-room that is the most unfavourable room of the building. The other criteria are from the whole building.

Table 3 lists the results of the prediction of the building behaviour according to the five criteria selected to outrank the design alternatives.

Table 3 Criteria for the different design alternatives

Options	Energy needs [kW/m^2.year]	Comfort period [%]	Acoustic insulation [dB]	PPD with the IAQ [%]	Daylight Factor [%]
(↓ - lower is better; ↑ - higher is better)	↓	↑	↑	↓	↑
2 façades, with double brick wall, non smokers (1A)	53.3	40	35	20	1.2
1 façade, with double brick wall, 20% smokers, painting used are low polluting (2A)	41.2	35	31	15	1.5
2 façades, with double brick wall, 20% smokers (1B)	23.5	48	33	22	2.0
2 façades, with double brick wall, 20% smokers, painting used are low polluting (1C)	32.3	45	35	15	2.0
1 façade, with single concrete wall, non smokers low polluting painting (2B)	55.6	60	33	13	1.5

Option 1C and 1A are the ones with best behaviour according to acoustic insulation and option 1C and 1B are the ones with best performance according to the daylight factor.

The results of the outranking using Electre III method are presented in Table 4. The dwelling with 2 façades, with optimized construction solutions, option 1C, was ranked as the best action.

Table 4 Credibility degrees matrix

						Non-Dom		Ranking
Options	1A	2A	1B	1C	2B	A	μ(A)	Options
1A	-	0.76	0.75	0.61	0.52	1A	0.52	1C
2A	0.85	-	0.74	0.70	0.75	2A	0.70	2B
1B	1	0.82	-	0.82	0.77	1B	0.82	1B
1C	1	1	1	-	0.88	1C	1.09	2A
2B	1	0.98	0.74	0.78	-	2B	0.91	1A

The best ranked option was not the one that had the best performance in the criteria with highest weights, was in the third position in the highest weighted criterion. This option had the best performance in two of the criteria, but other option had the same performance.

As Tables 3 and 4 show, the option 2B, that has the higher comfort period (which is the criterion that has the highest weight), is not the one best ranked.

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. The methodology is sensitive to small changes, associated to the area of the building, the energy needs, etc..

4 CONCLUSION

This methodology allows, in an easy and quick way, to outrank design options according to a set of criteria pre-established and based on the weight and thresholds assigned to each one.

The possibility to change the criteria, weight and thresholds according to the objectives and constraints of the project enable the use of this methodology to a vast set of possibilities (different areas, selection of construction solutions, materials, etc.).

Using this methodology, the design team can compare design alternatives based on different criteria, for example, the useful area, space organization, glazing area, etc., select and compare materials and construction solutions, considering, for example the U-value, acoustic insulation level, thickness, weight, embodied energy, just to name a few. The criteria, weight and thresholds should be selected by the design team according to the aims of the project.

The design team, once optimized each one of the different components of the building, can compare different design alternatives (using the same criteria, weight and thresholds as the study presented or select other that best adjusts to the study under analysis), compare locations (orientation, shading due to other buildings, amenities, accessibility to public transportation, and so on).

As it is necessary to compare a large set of alternatives, to be able to select the best one, the number of areas under analysis (thermal, acoustic, IAQ, natural lighting behaviour of buildings), the use of detailed simulation methods to increase the rigor of the study, that not all the design teams are acquainted with and also due to the time needed to perform such detailed analysis, are some of the disadvantages of the methodology.

This handicap may be overcome by using simplified methods to estimate the energy needs, for example the national energy codes based on the EPBD. The study may also be carried out in phases, in a first phase, with many alternatives, are used simplified analysis to select the most suitable ones and afterwards the best ranked solutions are object of a detailed analysis.

Thus, the use of a multi-criteria decision analysis is a way to help the decision maker to select the most suitable design alternative regarding different aspects that affect Indoor Environmental Quality (IEQ) and energy performance of the buildings.

The example here presented allows a robust analysis of the buildings as it comprise a detailed study of each alternative through a detailed simulation and analysis of the main factors that affect the IEQ and also the sustainability, based on the energy needs of the buildings.

Throughout the multi-criteria analysis performed, it was possible to verify that the overall comfort exigencies are not restrictive, because there are a large number of constructive solutions that, when adequately used, will assure 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 using building simulation software, allows buildings to be rated according to their energy use and comfort conditions, or by using a more complete set of parameters involving environmental factors. This methodology may be used in the design phase or to evaluate rehabilitation or retrofitting scenarios.

Using the Electre III, buildings, design alternatives or retrofit scenarios can be ranked according to several criteria and weights representing the preferences of the decision maker.

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