# Using a Multi-Criteria Analysis to Select Design Alternatives Aiming Energy Efficiency and IEQ

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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 for the thermal comfort, the Indoor Air Quality, the daylight conditions inside the buildings, its energy efficiency and the acoustic behaviour. In this work the use of a multi-criteria decision analysis method, to balance all these aspects on the design phase, in order to assist the designer in the selection of design alternatives, construction solutions and materials regarding the different aspects that affect the Indoor Environmental Quality and the energy performance of the buildings is presented. The selection of the most suitable design alternative will increase the buildings thermal behaviour and also its energy performance. The proposed multi-criteria method allows buildings to be rated according to their energy use and comfort conditions, or by using a set of parameters involving environmental factors. 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.

## 1. Introduction

Taking into consideration that in the EU, buildings account for about 40% of the total energy use, it is mandatory to control the energy consumption in the building sector and, therefore, reduce the EU energy dependency as well as decreasing the greenhouse gas emissions [1, 2]. Thus, it is essential to control the energy consumption in the building sector and at the same time it is necessary to maintain or even improve the Indoor Environmental Quality (IEQ), because as Men spend about 90% of their time inside closed spaces, a healthy and comfortable indoor climate is a basic premise in all buildings.

However, these aims are often in conflict. To achieve an adequate IEQ it is necessary to consider either the overall comfort conditions (thermal, acoustic, visual and IAQ) as well as the 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 availability techniques through an appropriate design. But the solutions adopted in buildings, usually, only optimize no more than one of the necessary comfort requirements and, 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.

To accomplish this goal, it is necessary to predict the thermal, acoustic, daylight conditions and 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, to 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 an important tool in such problems, since it employs mathematical models that evaluate alternative scenarios, taking into account both their objective characteristics (like acoustic behaviour and energy needs of the building) and the preferences of the decision makers regarding the objectives and constraints of each project.

In this work, it was verified the viability of the use of a multi-criteria decision analysis method (MCDA), suitable for the design phase that balances all these aspects, with the potential of becoming a valuable tool to assist the designer in the selection of the most appropriate design alternatives, construction solutions and materials to improve the IEQ and the energy efficiency in buildings. A simple case study was studied to demonstrate the feasibility of the approach using the MCDA method Electre III [3].

## 2. Methodology

Some of the aspects that influence the IEQ and the energy efficiency of the buildings are interrelated and influence each other but not always in a positive way. Therefore, there is not a unique criterion that describes the consequences of each alternative solution adequately, and there is no single solution that optimizes simultaneously all the criteria. Thus, the thermal and acoustic behaviour, daylight availability, Indoor Air Quality (IAQ) and energy reduction strategies should be meshed at an early stage with the other requirements to ensure the buildings overall comfort conditions, energy efficiency and sustainability. 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 and efficient building concepts should be applied, by a judicious selection of materials, technologies and construction methods to be used.

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

### 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 [4]. 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) only during this period that is between 7 pm and 8 am [5].

The thermal comfort conditions of the occupants were determined according to EN ISO 7730 and EN 15251 [6, 7]. The comfort period (number of hours during the occupied period where the occupants were comfortable) was calculated by EnergyPlus according to ASHRAE 55 - 2004 graph [8].

The acoustic behaviour was considered estimating the weighted normalized airborne sound insulation index of the façade, measured at 2 m from them ($D_{2m,\, nT,\, W}$), according the to the Portuguese acoustic regulation (RRAE) and EN 12354-3 standard, using the Acoubat Sound Program [9, 10].

The visual comfort was accessed through the daylight factor, using the Desktop Radiance Tool, for the 21st of December considering the existence of a light-colour curtain in every window [11].

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, the percentage of smokers among the occupants and the type of materials used (low-polluting or non low-polluting) [12, 13, 14].

## 2.2 Building Characteristics

The buildings used to test the methodology, have similar areas, but the glazings have different orientations. The three bedrooms are south oriented but the kitchen and the dining and living room are north oriented, in building 1 and South oriented in building 2 (Figure 1). The area of the windows was defined in order 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, WWR, (percentage obtained by dividing the glazed area of the wall by the total wall area) of about 30% [15].

The buildings had mixed ventilation, the WCs are mechanically ventilated and two situations were analyzed: windows with and without adjustable air inlets in the frame of the main rooms to guarantee the natural ventilation of the dwelling. In summer, during night periods, the buildings were ventilated using the cooler outside air to reduce indoor temperature. The ventilation rate was 0.98 ach.

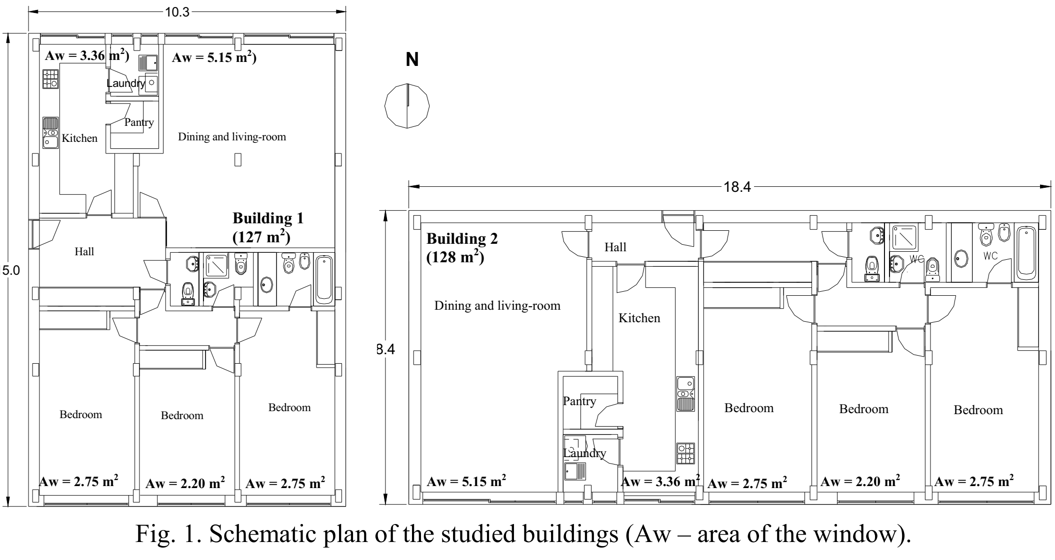

Fig. 1. Schematic plan of the studied buildings (Aw – area of the window).

## 2.3 Construction Characteristics

The construction solutions analyzed are shown in Figure 2, for the different types of elements of the building envelope. Two solutions were studied for the façade walls, single pane concrete wall (15 cm), with 4 cm of expanded extruded polystyrene (XPS), finished with plaster on both sides and double pane wall, hollow brick wall (15cm + 11cm), with 6 cm of mineral wool (MW) in plates placed in the air cavity and finished with plaster on both sides. The partition walls selected were single pane hollow brick walls with 11cm, finished with plaster on both sides. The windows have double clear glazing (8+10+6) mm or double low-e glazing (6+10+4) mm, metallic window frames with adjustable air inlets, venetian blinds on the outside and overhangs on south windows. The floors have pre-stressed concrete "T" beams and hollow brick pots, with 25 cm, 5 cm regularization layer, 0.5 cm of polyethylene foam, 0.8 cm of wood on the top surface and finished with plaster underneath.

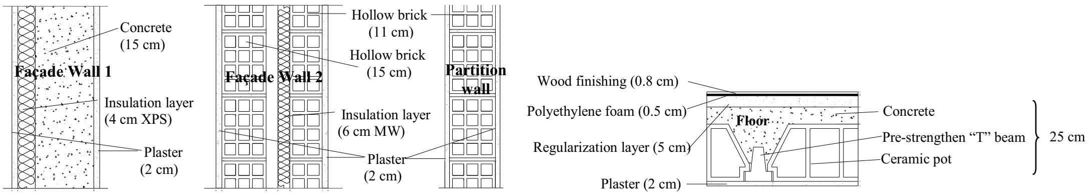

Fig. 2. Vertical cross-section of the construction solutions of the walls and floors of the buildings (façade walls and partition elements)

## 2.4 Multi-criteria analysis

The multi-criteria decision analysis (MCDA) defines flexible approach models to help the decision maker selecting the most adequate solutions between a large number of options and possibilities 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. 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 [16].

### 2.4.1 The Electre III method

The Electre III model is a highly developed multi-criteria analysis model, which takes into account the uncertainty and imprecision, which are usually inherent in data produced by predictions and estimations [3]. The Electre III is an outranking method that requires the definition of weights, which allows the decision maker to provide his preferences, according to the objective of the study. 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 [3]. Due to the use of the veto threshold the Electre III method does not allow for compensation, which may occur when using methodologies based on performance indexes. Using this method, a building which shows too poor results in one criterion cannot be ranked in a higher position [17, 18].

The model permits a general ordering of alternatives and is capable of dealing with the use of different units, the mix of both quantitative and qualitative information and when some aspect are "the higher the better” and others are “the lower the better”, as occurs within an engineering project appraisal and the rank of a building in a series does not change much when the weights given to the various criteria or the threshold levels are changed within a realistic range [17, 18].

## 3. Results

In the study performed, the Electre III method was applied to the evaluation of different alternatives, based on two types of buildings, with one and two façades with glazing, on the basis of five criteria related to the sustainability of the buildings (energy consumption) and to the most important characteristics of the IEQ (thermal, acoustic and visual comfort and IAQ). These criteria were selected also because it is possible to define them in a non subjective way, they are also ones of the few that are possible to predict in the design phase and are under the designer scope. Table 1 lists the different criteria, thresholds and weights that are needed to use the Electre III method.

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

| **Category (Criteria)** | **Units** | | **Weight** | **Threshold** | | |
|---|---|---|---|---|---|---|
| | | | | **Preference** | **Indifference** | **Veto** |
| Thermal Comfort:<br>Percentage of Comfortable Time | (%) | ↑ | 25 | 20 | 10 | 50 |
| Acoustic comfort (acoustic insulation):<br>$D_{2m, nT, W}$, $D_{nT, W}$ and/or $L'_{nT, W}$ | (dB) | ↑ | 22 | 5 | 2 | 10 |
| Indoor Air Quality:<br>Percentage of People Dissatisfied, PPD | (%) | ↓ | 18 | 5 | 2 | 15 |
| Visual Comfort:<br>Daylight Factor, DF | (%) | ↑ | 15 | 0.5 | 0.2 | 2 |
| Energy Needs | kW/($m^2$.year) | ↓ | 20 | 50 | 10 | 100 |

The weights were defined taking into account the relative importance of each criterion. The weight of the energy consumption was established based on the targets defined by the "EPBD-recast" [2]. 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 [19, 20, 21]. 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.

The weights and thresholds are presented here just as an example. These values must be defined by the project team according to the objectives and constraints of the project.

Five design alternatives were selected, based on two different buildings, shown in Figure 1, Building 1 and Building 2. The construction solutions analyzed, defined in Figure 2, 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.

Table 2 lists the results of the prediction of the building behaviour according to the five criteria selected to outrank the design alternatives. The acoustic insulation of the façade and the daylight factor shown in Table 2 are from the dining and living-room that is the most unfavourable room of the building. The other criteria are from the whole building.

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.

Table 2 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 |

The results of the outranking using Electre III method are presented in Table 3. The dwelling with 2 façades, option 1C, was ranked as the best action, however this option was not the one that had the best performance in the criterion with highest weight, the thermal comfort. It was only in the third position. This option had the best behaviour in two of the criteria (the acoustic and visual comfort), but option 1A, that was ranked in last position, had the same acoustic performance and option 1B, ranked in third position, had the same daylight factor.

Table 3 Credibility degrees matrix

| **Options** | **1A** | **2A** | **1B** | **1C** | **2B** | **Non-Dom** | | **Ranking Options** |
|---|---|---|---|---|---|---|---|---|
| | | | | | | **A** | **μ(A)** | |
| **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 |

As Tables 2 and 3 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..

Once the solutions are outranked the design team or the decision maker can select the option taking into account other factors like the cost associated to the solution or subjective aspects like the aesthetic quality of the design, for example.

## 5. Conclusion

The use of a multi-criteria decision analysis method is a way to help the decision maker to select the most suitable design alternative regarding the different aspects that affect the IEQ and the energy performance of the buildings. The proposed multi-criteria method, which can easily be applied using building simulation software, allows, in an easy and quick way, to outrank design options according to a set of criteria pre-defined (energy use and comfort conditions, or by using a more complete set of parameters involving environmental factors) and based on the weight and thresholds assigned to each one.

The Electre III method, may be used in the design phase or to evaluate rehabilitation or retrofitting scenarios buildings, allowing design alternatives or retrofit scenarios to be ranked according to several criteria and weights representing the preferences and objectives of the decision maker.

The possibility of the design team to change the criteria, weights and thresholds according to the aims and constraints of the project enable the use of this methodology to a vast set of possibilities.

Using this methodology, the design team can optimized each one of the different components of the building, selecting and comparing materials and construction solutions, considering, for example the U-value, acoustic insulation level, thickness, weight, embodied energy, just to name a few and then compare different design alternatives based on different criteria (using the same criteria, weight and thresholds as the study presented or select other that best adjusts to the study under analysis, for example, the useful area, space organization, glazing area, etc.), compare locations (considering 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.

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.

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