THE OPTIMIZATION OF THE OVERALL COMFORT IN BUILDINGS

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Abstract. *Building plan and shape are the result of a complex process. Functional, technical and aesthetic considerations all contribute to the building design. Wind, solar availability, shelter, exposure, air quality and noise conditions will affect the relationship between the building and its external environment and influence the shape and the design of the envelope. Heating, cooling, daylighting, indoor air quality (IAQ), acoustic behaviour and energy strategies should be meshed at an early stage with the other requirements to ensure the buildings overall comfort conditions.*

To accomplish this goal is necessary to predict the thermal, acoustic, lighting 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, fenestration strategies, construction solutions and materials, to improve the occupants overall comfort and, simultaneously, to reduce the energy costs. So is necessary to have an integrated approach to ensure the best overall behaviour taking into account all of the, sometimes incompatible, comfort requirements.

The aim of this study is to select a range of optimized solutions (envelope construction solutions, materials, fenestration and ventilation strategies, etc.) throughout a multi-criteria analysis, in order to improve the overall performance of buildings.

Keywords: *Overall comfort, Indoor air quality, Acoustic behaviour, Thermal behaviour, Daylighting*

1. INTRODUCTION

A healthy and comfortable indoor climate is a basic premise in all buildings. As the buildings are complex systems, were all aspects are interconnected and influence one another is necessary an integrated and comprehensive approach to the building that should enhance indoor health and comfort besides the energy savings and environmental sustainability.

To achieve this goal is necessary the use of environmentally friendly products (to minimize the Volatile Organic Compounds - VOC - and other emissions), methods and techniques for buildings, re-use of components or use of recycled materials, minimize the use of materials or components that rely on scarce materials resources, select materials that balance durability and low embodied energy and design and plan the building for demolition and re-use.

To guarantee an adequate thermal, acoustic and daylight behaviour and the internal air quality (IAQ) of the buildings is necessary to consider thermal storage (thermal inertia) using the building structure, selecting exterior walls systems and insulation according to the climate zone, implement passive heating and cooling solar systems (using solar and photovoltaic panels).

It is also necessary to select the correct fenestration for each orientation, according to the latitude, lighting and natural ventilation, considering also the solar gains, the outdoor obstructions and choosing the shading devices to optimize the energy and comfort needs to ensure the acoustic and thermal exigencies, the indoor visual comfort related to the visual task to be performed, as well as psychological and physiological requirements.

It is necessary to optimize the building envelope, by improving insulation, glazing, optimizing natural ventilation and daylighting techniques through appropriate design in order to reduce the thermal losses of the building.

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 on the indoor air quality.

The solutions adopted on the conventional buildings are only compatible with one or two of the necessary requirements, and don't fulfil the others (for example the windows' frame air tightness is good for the thermal and acoustic behaviour, but not to natural ventilation and doesn't interfere with the natural lightning). Therefore, is necessary an integrated analysis to ensure the best overall behaviour (for instance, the definition of the area, shape, shading device, way of opening, type of glazing of a window, considering its orientation, the external environment, etc.).

In some cases as, for example, the use of heavy construction elements, leads to good airborne sound insulation behaviour and, if well located, may also contribute to a good thermal performance, due to their thermal mass, some solutions don't have influence on the others (for example, the surface colours are important to the lighting conditions of a room, but don't interfere with the acoustic behaviour of the element). But, in most cases, the best solutions to accomplish the different comfort requirements are not compatible, specially the natural ventilation and daylighting strategies with the acoustic behaviour, and even in what concerns the thermal performance, because daylight not only replaces artificial lighting, reducing energy use, but also influences both heating and cooling loads and acoustic insulation façade performance, for example, the north façade glazing area, that for natural lighting and for cross ventilation considerations should be larger than the necessary to acoustic and thermal exigencies. Another example is the need to ensure a minimum number of air changes per hour that will reduce the thermal comfort conditions and increase the energy consumptions, since it will remove indoors warmer air, in winter, and cooler air in summer and also will increase the sound levels inside the rooms.

Daylight strategies and architectural design strategies are inseparable. Daylighting planning must take in account the building shape proportions and apertures, as well as about the integration and building systems (including artificial lighting), the design of the façade and interior finishing and the selection of materials and products.

Therefore, it is necessary to have an integrated approach to ensure the best overall behaviour taking into account all of the, sometimes incompatible, comfort requirements.

The aim of this study is, then, to select a range of optimized solutions (envelope construction solutions, materials used, fenestration and ventilation strategies, etc.) throughout a multi-criteria analysis, in order to improve the overall performance of buildings accomplishing all the comfort requirements, because a well designed building has the potential to reduce energy costs and also to improve occupant comfort.

This study will consist on the optimization of the overall comfort conditions through the analysis and control of four major parameters related to the thermal insulation level, the acoustic insulation level, the illuminance levels (taking into account the indoor daylight requirements) and the number of air changes per hour (related to the indoor air quality), considering the factors that have influence on the buildings behaviour.

To achieve this goal of a three South oriented bedroom dwelling (that represents the conventional Portuguese buildings) will be studied, predicting the heating and cooling needs to maintain the indoor temperatures between 20 and 25ºC (comfort zone) (RCCTE, 2006), the acoustic behaviour of the envelope elements, estimating the weighted normalized airborne sound insulation indexes and the weighted normalized impact sound pressure level index, the indoor daylighting conditions, and the IAQ, for several construction solutions for its envelope and partition elements.

2. BUILDING AND CONSTRUCTIVE SOLUTIONS CHARACTERISTICS

The building under analysis is a three-bedroom dwelling, representing typical Portuguese buildings.

2.1. Building geometry

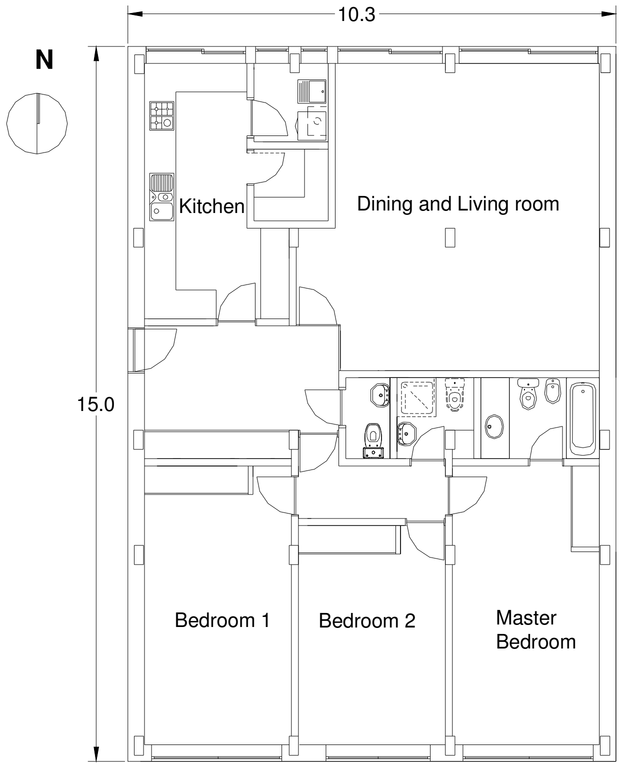

Figure 1 - Schematic plan of the studied building.

This building, with 129.3m^2, has three south oriented bedrooms, the kitchen and the dining and living room are north oriented (Fig. 1). The kitchen area is of 18.20 m^2, the area of the dining and living room is of 37.32 m^2, the bedrooms have 18.13, 14.29 and18.04 m^2.

The windows dimensions were defined to maximise the use of the solar gains and the daylight use, on the initial stage the glazing area was of 15% of the floor area (windows with 1m,

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corresponding to 3.36m^2 on the kitchen, 5.15m^2 on the dinning and living room, 2.75, 2.20 and 2.75 m^2 for the bedrooms), on a second stage the glazing area was doubled to 30% of the floor area (window doors with 2m).

2.2. Construction characteristics

The factors studied are the ones that need to be considered when designing the building envelope including amongst others: the building shape and its orientation; the area of windows, their orientation, type, and shading device; the insulation levels used in the building; the air-tightness of the building construction; the colour of the building, and its surface properties; the potential for natural ventilation; and the amount of exposed internal thermal mass.

The construction elements studied are listed below on Table 1. The study is done for different insulation materials (polystyrene expanded extruded and mineral wool), placed in the exterior, interior of the single pane walls or in the exterior, interior or on the air gap of the double pane walls, and thickness (0, 2, 4, 6, 8, 10cm).

Table 1. Construction solutions characteristics

Element	Construction Solutions
External walls	Single pane concrete wall (15cm) Single pane hollow brick wall (22cm) Single pane hollow concrete wall (20cm) Double pane wall, hollow brick (15cm) and hollow brick (11cm) Double pane wall, brick (11cm) and hollow brick (11cm) Double pane wall, concrete wall (20cm) and pane plasterboard wall (1.3cm) Double pane wall, stone (5cm) and concrete wall (15cm)
Glazing	Double pane clear glazing (8+10+6)mm Double pane LowE glazing (6+10+4)mm
Internal walls	Double pane wall, hollow brick (11cm) and hollow brick (11cm)
Partition walls	Single pane hollow brick wall (11cm) Double pane plasterboard wall (1.3cm) with mineral wool (10cm)

The floor and ceiling are of pre-stressed concrete "T" beams and hollow pots with 26 cm plus a 4 cm regularization layer a 0.5 cm thick layer of polyethylene foam and 0.8 cm of wood as surface finishing, with plaster as inferior surface finishing.

The internal walls have 4 cm of mineral wool in plates placed in the air cavity and finished with plaster or gypsum on both sides. The characteristics of the floor, walls and windows are presented in Fig. 2.

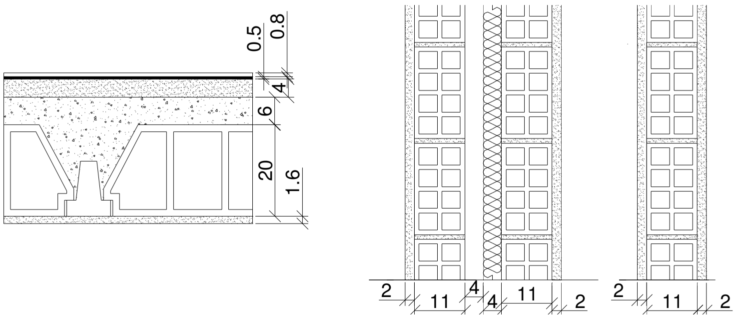

Figure 2 - Vertical cross-section of the construction solution of the building floor and walls (internal and partition).

The south windows are shaded by overhangs and all the windows have an adjustable shading system (venetian blinds) on the outside to minimize the unwanted solar gains and at the same time not darkening the living space, thus, avoiding the use of artificial lighting. The window frames are metallic and have adjustable air inlets that guarantee the ventilation of the space. The WCs are mechanically ventilated.

3. METHODOLOGY

The Prediction of the building thermal behaviour will be done using computer modelling, with EnergyPlus, estimating the heating and cooling needs to maintain the indoor temperatures between 20 and 25ºC (comfort zone) for different construction solutions for the envelope and for the partition elements. The IAQ will be assured by the number of air changes per hour (ach) ensured by the air inlets on the windows frame and by the mechanical ventilation of the WCs, according to the Portuguese legislation (RCCTE, 2006). In summer, during night periods the building is ventilated to use the warmer outside air to reduce the temperature inside the building. The number of hours were the occupants were uncomfortable in the zone were determined by EnergyPlus based on ASHRAE 55-2004 graph (Section 5.2.1.1) (ASHRAE 55, 2004).

The acoustic behaviour will be considered estimating the weighted normalized airborne sound insulation indexes and the weighted normalized impact sound pressure level index ($D_{n,w}$ and $D_{2m,\, n,\, W}$, $L'_{n,w}$), using the Acoubat sound.

The lighting behaviour will be verified using the Desktop Radiance, for the 21st of December and for the 21st of July, calculating the illuminance levels and the daylight factor which 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 daylight a space.

4. RESULTS

4.1. Thermal behaviour

The typical Portuguese dwelling has double pane hollow brick walls (15+11)cm with 4cm of polystyrene expanded extruded place on the air gap and double glazing, usually doesn't have HVAC systems, in general are heated only in short periods, in this situation the inside temperatures are under 20ºC, as Fig. 3 shows for the coolest day.

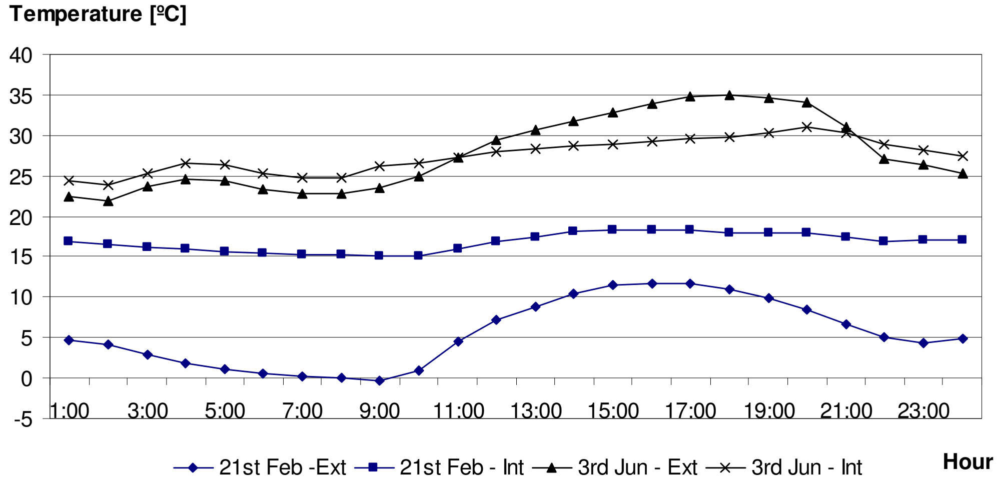

Figure 3 – External and internal temperatures for the coolest and the hottest day – without HVAC.

From the study that was carried out was possible to verify that there are no significant differences (less than 1%), on the thermal behaviour, due to the finishing material of the walls, plaster or gypsum.

In this case, according to ASHRAE 55 - 2004, during the occupation period 3448.5 hours were uncomfortable (60% of the occupied period). So, is necessary a mechanical system to maintain the indoor temperature in 20ºC in winter and 25ºC during occupation period (and above 15ºC and under 35ºC on non occupation periods) which will mean consume 3016.6kW/year (75% in winter). The number of uncomfortable hours will be reduced to 40% of time.

On Table 2 are listed the heating and cooling needs and the number of uncomfortable hours during occupation period for two different constructive solutions, for single walls, under analysis.

Table 2. Thermal behaviour of the dwelling for single external walls and windows with 1m, with different thickness of polystyrene expanded extruded placed on the outside (CW - Single pane concrete wall, BW - Single pane hollow brick wall)

Constructive solution	Heating needs [kW/year]	Cooling needs [kW/year]	Heating + Cooling needs [kW/year]	Number of uncomfortable hours [Hours]
CW15cm	3258.039	849.118	4107.157	2771.8
CW 15cm, 2cm PEE, o	2546.399	748.446	3294.845	2512.3
CW 15cm, 4cm PEE, o	2287.623	731.978	3019.601	2293.3
CW 15cm, 6cm PEE, o	2161.125	726.753	2887.877	2170.0
CW 15cm, 8cm PEE, o	2086.527	724.088	2810.615	2091.5
CW 15cm, 10cm PEE, o	2037.235	722.504	2759.739	2035.3
BW 22cm	3100.965	848.540	3949.505	2722.0
BW 22cm, 2cm PEE, o	2481.702	745.231	3226.934	2469.8
BW 22cm, 4cm PEE, o	2260.049	732.300	2992.349	2271.3
BW 22cm, 6cm PEE, o	2146.622	728.195	2874.818	2159.5
BW 22cm, 8cm PEE, o	2078.001	726.137	2804.138	2084.0
BW 22cm, 10cm PEE, o	2032.017	724.500	2756.517	2080.0

As Table 2 shows a concrete wall has a worst thermal behaviour in the winter, than a single pane hollow brick wall with 22cm due to is higher conductivity, but during the summer has a better behaviour due to his higher thermal mass. As can be seen on Table 2, if the external walls don't have insulation, according to ASHRAE 55 - 2004, during the occupation period in more than 2700 hours the occupants were uncomfortable (more than 55% of the occupied period) due to the lower surface temperatures. Increasing the insulation level the number of uncomfortable hours is reduced in 10%.

The same occurs when the windows are replaced for equivalent window doors, duplicating the winter solar gains. In this case both walls have a similar thermal behaviour, better during heating season, than the one with windows with 1m, but worst during summer due to higher solar gains, for example for the brick wall with 4cm of expanded extruded the heating needs are reduced in almost 30%, but the cooling needs are increased by 43%, resulting only in 3% reduction on the global needs.

The same kind of study was done considering the placement of the insulation material (on the outside or in the inside) and was verified that the heating and cooling needs are similar and are more significative for higher mass and insulation levels and in the cooling period (5%), due to the effect on the thermal inertia. The same type of analysis, but with windows with 2m and Low E, maximizing the solar gains and minimizing the heat losses was carried out and shows that a concrete wall with 15cm and 6cm of polystyrene expanded extruded on the external face has a better thermal behaviour than a single pane hollow brick wall with 22cm and 10cm of polystyrene expanded extruded, and uses less space. In this case the reduction on the heating needs is of 24% and an increase of 37% on the cooling needs meaning a reduction of 4% in the global needs each year. The increase on the cooling needs due to the higher glazing area could be minimized with a better shading device or with the use of reflective glazing which will reduce also the solar gains during winter.

If the external walls don't have insulation, according to ASHRAE 55 - 2004, during the occupation period in more than 2000 hours the occupants were uncomfortable (about 50% of the occupied period) due to the lower surface temperatures. Increasing the insulation level the number of uncomfortable hours is reduced to 35%.

This study shows that is necessary to pay attention to the glazing area and to the shading device, because even with a good glazing and shading systems, is required to control the solar gains during summer.

The same kind of analysis was done for double pane walls. In this case it was verified that there are no significant differences (2%) in the thermal behaviour due to the type of insulation material. The differences on the energy needs, due to the different types of constructive solution are of about 3%, being smaller for the higher insulation thickness.

The increase on the insulation thickness can reduce the energy needs in more than 33%, for example when comparing a concrete wall without insulation and with 10cm of polystyrene expanded extruded, and a minimum of 4.6% when replacing 4cm by 6cm of the same insulation material.

The number of uncomfortable hours, during occupation period, according to ASHRAE 55 - 2004, will be reduced to 1568.5 hours (27%).

Reducing the number of air changes per hour (from 1.0 to 0.6 ach) will decrease the energy needs to almost 1/4, considering an optimized solution with 10cm of insulation and LoE glazing. In this situation the occupants will be comfortable in more than 80% of the time.

Another possible approach is to reduce the north façade windows' area (kitchen and dining and living room), from the 30% of the façade area, avoiding unnecessary heat losses.

4.2. Acoustic behaviour

According to the Portuguese Building Acoustics Legislation [(Decree-Law nº 129/2002), partition elements must meet some acoustic requirements. In this context, the airborne sound insulation index for partitions between dwellings and for partitions between dwellings and garages must be greater than 50dB, and for partitions separating dwellings from commercial areas must be greater than 58dB. The impact sound insulation index for floors separating two dwellings must be less than 60dB and for floors separating dwellings from commercial areas must be less than 50dB.

According to the Portuguese Building Acoustics Requirements Regulation (Decree-Law nº 129/2002), the weighted normalized airborne sound insulation index of façades, measured at 2m from them ($D_{2m,\ n,\ w}$), must be greater than 28dB for sensitive zones (exposed to $L_{Aeq} \leq 55$dB(A) between 7h and 22h and $L_{Aeq} \leq 45$dB(A) between 22h and 7h) and greater than 33dB for the other zones (usually named as mixed zones).

The airborne sound insulation index for partitions between bed or living rooms and common circulation zones of the building must be greater than 48dB and the impact sound insulation index for the same element must be less than 60dB. The partitions elements between bedrooms or living rooms and vertical circulation paths (stairs), when the building has elevators, must have an airborne sound insulation index greater than 40dB. The Portuguese Building Legislation (Decree-Law nº 129/2002) does not have any requirements for partitions between parts of the same residential unit.

The conventional pavement studied has a weighted normalized airborne sound insulation index, $D_{n,w}$, of 49dB and a weighted normalized impact sound pressure level index ($L'_{n,w}$) of 72dB, not fulfilling the minimum requirements of the Portuguese legislation (Decree-Law nº 129/2002). The internal wall has a weighted normalized airborne sound insulation index, $D_{n,w}$, of 50dB, fulfilling the exigencies of the Portuguese regulations. For the partition wall the $D_{n,w}$, is of 38dB.

On Table 3 are shown the estimated values for the weighted normalized airborne sound insulation index of the façade ($D_{2m,\ n,\ w}$). For situation under analysis almost all the cases fulfil the Portuguese regulation, the exceptions are the kitchen and the dining and living room with 2m high windows.

Table 3. Acoustic behaviour (D2m,n,W) of the dwelling for single external walls with 4cm of polystyrene expanded extruded on the outside of the single walls and on the air gap of the double walls, double glazed windows (6+10+8)mm, with 1m and 2m (CW – Single pane concrete wall, BW - Single pane hollow brick wall, dHBW – double pane hollow brick wall and dM+HBW - double pane massive and hollow brick wall)

Room	Constructive solution			
	CW 15cm	BW 22cm	dHBW (15+11)cm	dM+HBW (11+11)cm
		Windows with 1m		
Kitchen	34	34	34	34
Dinning and living room	33	33	33	33
Bedroom 1	34	34	34	34
Bedroom 2	35	35	35	35
		Windows with 2m		
Kitchen	32	32	32	32
Dinning and living room	31	31	31	31
Bedroom 1	33	33	33	33
Bedroom 2	33	33	33	33

As Table 3 shows, for external walls with 4cm of polystyrene expanded extruded and windows with 1m and 2m there are no differences considering the different constructive solutions, as they are all heavy, but there are differences of 2dB with windows with 2m. So to improve the quality of the façade walls is essential to balance the window area and the acoustic quality of the glazing.

The reduction on the north windows area, as previously suggested, will also have a favourable effect on the acoustic behaviour.

Traditionally Portuguese buildings are heavy ones, and the study performed show that in general the façade fulfil the requirements, for the case were the glazing area is of about 15% of the pavement area (corresponding in the present situation to 30% of the wall area), if the windows area is doubled the legislation is not verified, so in these case is necessary to increase the quality of the windows.

The acoustic behaviour of the floors, especially in what concerns the impact insulation, must be improved, using better resilient elements and floating pavements.

4.3. Daylighting behaviour

The illuminance levels and the daylight factor, for the 21st of December and for the 21st of July, for the bedroom 2 are shown on Fig. 4, for windows with 1m.

The recommended illuminance levels for study zones (300 – 500lux) in winter are respected only on the area near the window, and in almost space during summer, but for the luminous climate in Portugal the recommended external minimum illuminance considered for an overcast sky is exceeded in more than 90% of the time during the year (Silva, 2002). According to the CIE recommendations a daylight factor of 2% - 5% is usually the optimum rage of daylighting for overall energy use, and considering the recommended daylight factors for bedrooms (0.5% at 3/4 of room depth) these values are fulfilled during winter, but are largely overcome in summer or even in winter when the windows have 2m (CIE, 1975).

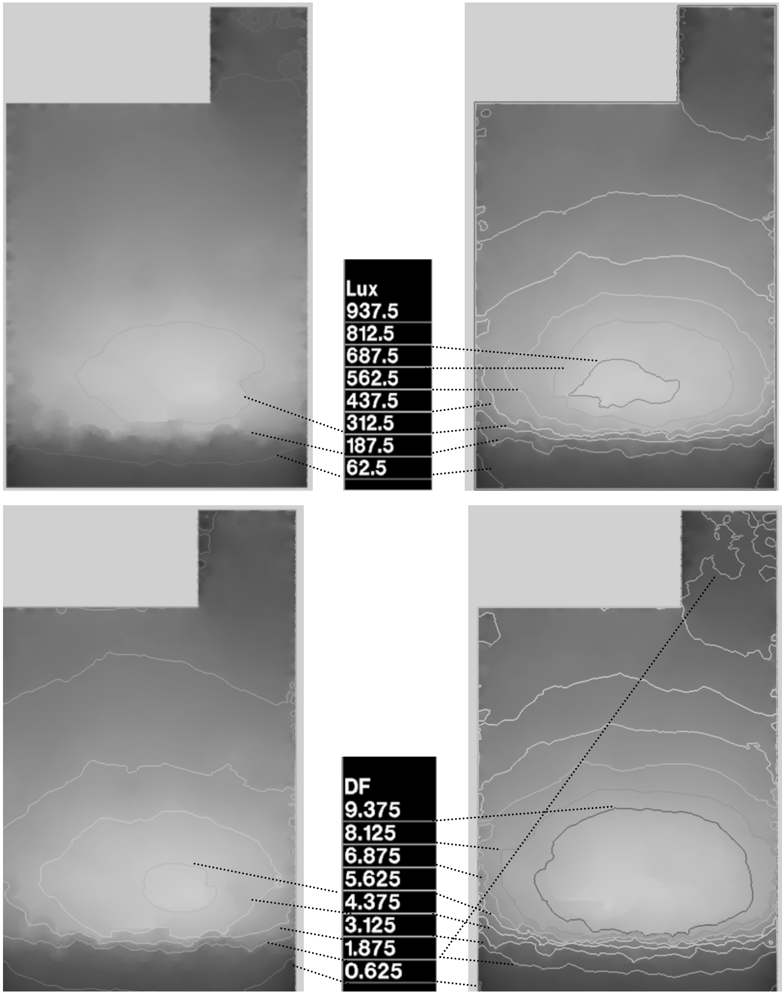

Figure 4 – Illuminance and Daylight factor for the bedroom 2 on the 21st of June and 21st of December, for an overcast sky

The reduction on the north windows area will also have a favourable effect on the daylight behaviour, minimizing the glare, as, even in winter, in the zones nearest to the windows, the daylight factor and the illuminance levels will be high.

4.4. Global behaviour

Analysing the results of the study was possible to verify that, even with conventional solutions used in Portugal, is possible to achieve a good global behaviour, considering the buildings' thermal, acoustic and daylight behaviour, but is necessary to increase the insulation level of the external walls, and the acoustic quality of the glazing. It is also necessary to improve the acoustic behaviour of the pavements, increasing the quality of the resilient layer and using floating pavements.

5. CONCLUSION

From the analysis performed it was possible to conclude that there are a great number of constructive solutions, that when adequately used will fulfil the comfort exigencies.

In Portugal is necessary to improve the thermal insulation levels of the façades and the acoustic quality of the glazing parts of the façade. It is also necessary to use windows with improved frames, with low permeability, to guarantee that the number of air changes per hour is of 0.6.

The selection of the shading devices must also be done carefully, to reduce the heat losses during the heating season and the heat gains during the cooling season, and at the same time allowing the penetration of natural light and not reducing the acoustic behaviour of the façade.

The improvement of the night cooling of the buildings with high thermal inertia, during the summer, and with the control of the radiation that penetrates into the building will also improve the thermal behaviour of the building.

The shading devices must be movable allowing the control of the radiation but, at the same time admit the entrance of the daylight, control the glare and adjust for variations on daylight availability.

The acoustic behaviour of the conventional floors and of the windows must be improved.

It is necessary to select the correct fenestration for each orientation, according to the latitude, lighting and natural ventilation, considering the solar gains, the outdoor obstructions and choosing the shading devices to optimize the energy and comfort needs to ensure the acoustic and thermal exigencies, the internal air quality and the indoor visual comfort.

But through the integrated approach to the building behaviour was possible to conclude that the overall comfort exigencies are not restrictive, because there are a large number of constructive solutions that will assure all the requirements being only necessary to integrate the exigencies of the different requirements.

The windows area and the quality of the frame, the glazing and the shading device are the most important factors to take in account to fulfil the overall comfort requirements. The solution adopted for the fenestration must be selected carefully and may be different for each orientation.

The optimization of the building envelope, by improving insulation, glazing, and optimizing natural ventilation and daylighting techniques through appropriate design in order to improve the overall comfort does not limit the creative process of the designer.

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