# OPERATIVE CONDITIONS EVALUATION FOR EFFICIENT BUILDING RETROFIT – CASE STUDY

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**Abstract**:
The implementation of energy efficiency measures into the existing building stock is essential to meet the 2020 targets set by the EU Energy Performance of Buildings Directive (EPBD) and reinforced with the "EPBD-recast". Thus, energy refurbishment of existing buildings is fundamental to achieve these goals. However, energy issues should not be the only concerns since the indoor environmental quality (IEQ) is also as important. When planning a building retrofit it is then necessary to consider the energy efficiency requirements as well as the IEQ. To do so, the main problems of the existing buildings should be identified. This work presents a study carried out in a large office building to identify the main pathologies related to the energy efficiency and to the IEQ. The main objective of this study was to characterize the actual situation of a building that represents a great number of the Portuguese office buildings in order to identify the principal problems that occurs in this type of buildings, to support the development of a refurbishment project of the building that can optimize both the energy efficiency and the relevant parameters to the IEQ and that are also solutions with potential to be used in other buildings.

**Keywords**: buildings' refurbishment, energy efficiency, indoor air quality, indoor environmental quality, operative conditions, thermal comfort

## 1. Introduction

One of the biggest challenges that the construction sector has nowadays to face is the improvement of the energy performance of the building stock, as the European building stock is responsible for 33% of raw materials consumption, 50% of electricity use and 25% of final energy consumption, of which 27% are due to office buildings [1, 2, 3].

Non residential buildings, and mainly office buildings, are among the buildings presenting the highest energy consumption [4]. Thus, the office buildings have a high energy savings potential [5].

According to Santamouris and Dascalaki [6] the total annual energy use in office buildings varies in the range 100-1000 kWh/m$^2$ depending on the geographic location, use and type of office equipment, operational schedules, type of envelope, use of HVAC systems, type of lighting, etc.. Thus, the improvement of the energy performance of the buildings is being tackled by an extensive public awareness to reduce the energy consumption, but mainly due to the implementation of more restrictive energy regulations [7, 8].

Considering only the energy performance perspective, the tendencies of the most recent regulations are to increase the insulation thickness and reduce the air change rates.

The option for the retrofit solutions that increase the thermal insulation of the envelope (thermal insulation placed inside or thermal insulation placed outside the existing walls and roofs) must take into consideration not only the constraints of the project but also its effect on the useful area available in the building.

The air change rate has also to be thought carefully, since the reduction of the air change rates can decrease the intake of fresh outside air and thus increasing the consequent build-up of internally generated pollutants including carbon dioxide, volatile organic compounds, fungi, etc.. However, only in the last decades indoor air quality (IAQ) has become an important occupational health and safety concern and a public and governmental awareness issue.

In 2006 Portugal implemented the National Building Energy and Indoor Air Quality Certification System, corresponding to the transposition of the Energy Performance of Building Directive, EPBD [7], which imposes minimum energy efficiency for all buildings and periodic IAQ and energy audits for office buildings.

As 90% of the population spends about 90% of their time in enclosed spaces exposed to consistently higher concentrations of air pollutants than outdoors, which led to the increase of the allergies and asthma incidence rate, thus a good indoor air quality has a vital impact in human health.

Asthma affects of about 150 million people worldwide and approximately 1 million in Portugal (10% of the population) and its incidence continues increasing, both in young as in elderly people [9].

Several factors are thought to contribute to that, namely the atmospheric pollution by ozone and suspended particles, and the indoor pollution by the volatile organic compounds and carbon dioxide.

Indoor air pollution may have many sources in an office building, and indoor air quality can vary widely. Suspended particles are seen by many as one of the most critical air pollutants and some estimates suggest that particles are responsible for up to 10,000 premature deaths in the United Kingdom each year [10]. Thus, when planning a building refurbishment, energy efficiency issues should be merged with the indoor air quality exigencies.

Besides the IAQ the thermal and acoustic, as well as the visual comfort, have also a significant effect, not only on the health and well-being, but also in productivity.

Studies show that increasing indoor temperatures in buildings may be associated with increased intensity of symptoms of fatigue, headache and difficulty in thinking clearly and on the prevalence of sick building syndrome (SBS) symptoms, even within the temperature comfort zone [11, 12]. Therefore elevated intensity of SBS symptoms may be expected to negatively affect the performance of occupants' mental work [13].

According to Kolarik et al. [14] the speed of repetitive tasks that require mental efforts (addition and text typing) slightly decrease with increasing operative temperatures. It has been also shown that expenses incurred in employee salaries exceed building energy costs by a factor of 100 and maintenance costs by a factor of 10 [15].

Lighting is also an important issue in minimizing overall energy consumption [16]. Electric lighting is one area where energy savings are possible at reasonable cost in new buildings as well as in retrofit projects [4].

The investments in energy-efficient lighting is considered as one of the most cost-effective ways of reducing $CO_2$ emissions and studies show that electricity use for lighting could be reduced by 50% using existing technology [17, 18, 19].

The study of the combined effect of the different comfort stressors in the global comfort perceived by building's occupants is thus very important to ensure a suitable IEQ.

Therefore reduced energy consumption should not be achieved at the expense of occupants' comfort, productivity or health. It is then essential to take measures to achieve energy efficiency through buildings' refurbishment and, at the same time, ensure the indoor environmental quality and the overall comfort of the occupants. To do so, the main problems of the existent building should be identified.

This work presents a study carried out in a large office building to identify the main pathologies, related to the energy efficiency and also to the indoor environmental quality.

The study encompasses an "in-situ" evaluation of the operating conditions, thermal, acoustic and visual conditions, indoor air quality, and air change rate. Besides these measurements, a survey to the occupants was also performed to assess their main complaints, to obtain a subjective appraisal of the IEQ and help identifying the most important IEQ related problems present in the building.

The main objective of this study was to characterize the actual situation of a building in order to identify its major problems. This study also intended to support the development of a

refurbishment project that can optimize both the energy efficiency and the relevant parameters to the building IEQ.
The results gathered were also used to point out some potential rehabilitation solutions for this building and, as it is representative of a great number of the Portuguese office buildings, the results of this study might also be used in other buildings' refurbishment projects as well as helping to develop guidelines to improve the rehabilitation process of the Portuguese building stock.

## 2. Methods

In this paper a study carried out to characterize the actual situation of a building and to support the development of the refurbishment project of a building is presented. The project aimed at optimizing the energy efficiency of the building and the relevant parameters to the IEQ.
The building, located in the centre of Porto, Portugal, was chosen as it is representative of a great share of the Portuguese office buildings built before the implementation of the first Portuguese Thermal Regulation, though without any thermal concerns.
To identify the main problems of a building, related to the energy efficiency and also to the indoor environmental quality, it is necessary not only to perform a thorough analysis of the building and an "in-situ" evaluation of the operating conditions but also an evaluation of the thermal, acoustic and visual conditions, indoor air quality and air change rates.
Thus, a measurement campaign was performed to identify the main problems of the building and to assess its operative conditions. This campaign was divided into three major areas:

- Comfort conditions – Thermal comfort (air temperature and relative humidity, operative temperature), Acoustic comfort (A-weighted sound pressure level, $L_{Aeq}$) and daylight conditions (illuminance level);
- IAQ conditions – measurement of the concentration of suspended particles, carbon dioxide ($CO_2$), carbon monoxide (CO), ozone ($O_3$), formaldehyde (HCHO) and total volatile organic compounds (VOCs).
- Characterization of the operating conditions of the buildings – Building air tightness (air change rate, ACH), occupation patterns, equipment and appliances existing in the rooms and their use pattern.

A standard questionnaire was also delivered to the occupants to obtain a subjective assessment of the IEQ and to assess the occupants' main complaints.

The energy performance of the building was also assessed through simulation to characterize the actual situation and to allow the definition of the refurbishment proposals.

### *2.1. Building Characteristics*

The building under analysis is located in an urban area, in the city centre of Porto in the North-West of Portugal. The building, represented in Figures 1, 2 and 3, has 5 floors (the ground floor is partially underground), 3.3 m of floor to ceiling height and 2713 $m^2$ of useful area. The building was built in the 1970's and suffered some minor changes in the 1990's.

Figure 1. Views of the building (general perspective, SW and SE perspective)

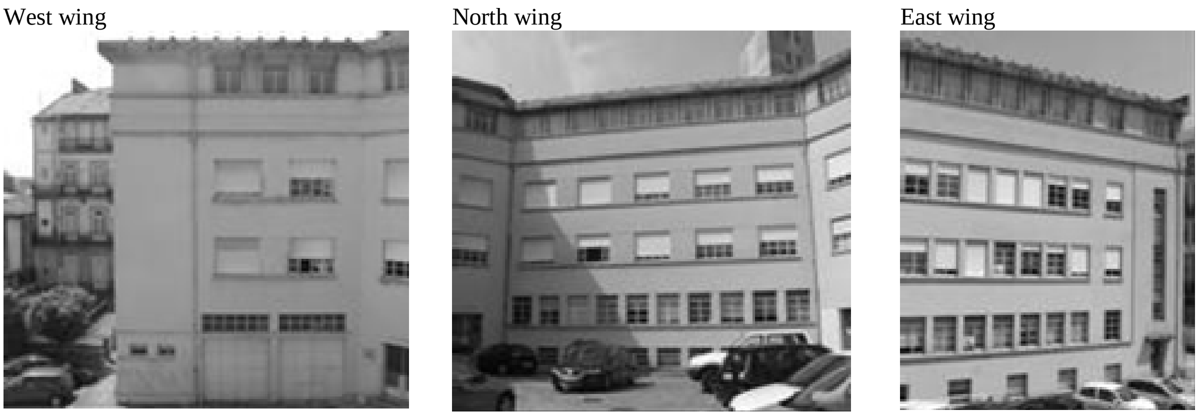


Figure 2. General view of the building

The ground floor's north wing is a storage area and a Laboratory is located in the east wing. The offices and meeting rooms are located in the first, second and third floors. The last floor is a cafeteria.

In Figure 3 the different types of occupation of the building area are represented. The storage areas are represented in dark grey and the offices and meeting rooms are represented in light grey. The remaining areas are technical areas, circulation zones and WCs.

The walls are concrete masonry units (CMU) with 27 cm thick with plaster finishing and the roof is a concrete slab.

All the windows are single glazed with metallic frame. The ground floor windows do not have any shading devices and the first floor windows have venetian blinds placed inside. The windows in the second and third floor have roller shutters and the windows in the fourth floor have curtains.

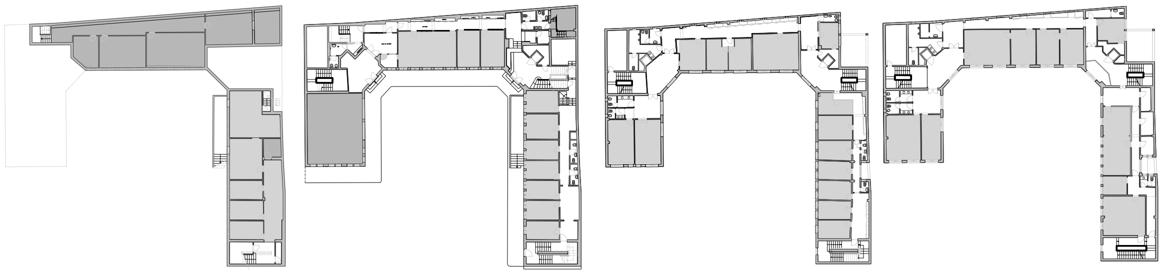

Figure 3. Floor plans of the building (storage areas are represented in dark grey and offices and meeting rooms are represented in light grey)

The building is naturally ventilated and has a diesel boiler associated with water heaters radiators in the offices and meeting rooms. Some rooms have additionally electric oil radiators. There is no centralized cooling system and most part of the offices did not have any active cooling systems, some had fans and others had split type systems for cooling that were only turned on when the occupants were in the rooms.

### *2.2. Measurement procedures*

The measurement campaign was performed during the months of June and July. The “in situ” measurement of the parameters associated to the IEQ and energy efficiency followed the procedures defined in national and international standards [20, 21, 22, 23, 24, 25, 26].

#### *2.2.1. Thermal Comfort*

The quantification of the thermal comfort was carried out applying the ISO EN standards [21, 22] and ASHRAE standards [27], both recommending the measurement of the PPD – percentage of people dissatisfied – and the PMV – predicted mean value. According to EN 7730 [22], comfort conditions are reached whenever no more than 5% of people are dissatisfied and when the PMV value is zero and according to ASHRAE 55 [27] when the operative temperature, To, ranges from 20ºC to 25ºC and the relative humidity varies from 20% to 60%.

In order to obtain the required parameters for the calculation of PPD and PMV the measuring equipment Delta Ohm HD32.1 - Thermal Microclimate Data Logger was used. This equipment monitors in parallel the following parameters: black bulb temperature, to calculate the mean radiant temperature (-10 to 100 °C); air speed and direction (0 to 5 m/s,); air temperature and relative humidity (-10 to 80 °C and 5 to 98%); dry and wet bulb temperature (4 °C to 80 °C).

*2.2.2. Acoustic Comfort*

The assessment of the acoustic comfort was performed using the A-weighted sound pressure level, $L_{Aeq}$, according to the NP 1370 and the EN 15251 standards, measured using a CEL 573.C1 sound level meter type 1 (5 to 140 dB in 7 ranges, 10 Hz to 25 kHz) [20, 23]. The typical range of the A weighted sound pressure level in office buildings should be between 30 to 40 dB(A) [20].

*2.2.3. Visual Comfort*

The energy spent on lighting in buildings has an important influence on the global energy balance. Thus, it is also important the effective and efficient use of natural lighting to minimize the use of artificial lighting and increase the visual comfort.

According to the EN 15251 standard [20], the light quality is based on illuminance measurements on the task area, that are conform the recommended values in EN 12464-1 [28]. The recommended illuminance level for office buildings on the task area is 500 lux [20, 28].

The illuminance levels were measured with portable luxmeters HD2302.0 (0 to 200000 lux) placed outside the analyzed space and placed on the desk inside the room for three situations: with artificial light turned on, windows with shading devices not activated; and windows with shading devices partially (70%) activated [25].

The two positions of the shading devices were defined to consider use of the shading devices to control the incidence of direct sunlight in the work place.

*2.2.4. Indoor Air Quality (IAQ)*

According to the thermal regulations in Portugal, it is mandatory to carry out IAQ audits in office buildings. Table 1 lists the maximum reference concentrations of each pollutant according to the Portuguese regulation [24, 25].

Table 1. Maximum reference concentration of pollutants inside buildings [24, 25]

| **Type of pollutants** | **Parameter** | Maximum reference concentration | |
|---|---|---|---|
| | | $mg/m^3$ | ppm |
| Physical and Chemical | Suspended particles ($PM_{10}$) | 0.15 | - |
| | Carbon Dioxide ($CO_2$) | 1800 | 984 |
| | Carbon Monoxide (CO) | 12.5 | 10,7 |
| | Ozone ($O_3$) | 0.2 | 0,10 |
| | Formaldehyde (HCHO) | 0.1 | 0,08 |
| | Volatile Organic Compounds (VOCs) | 0.6 | 0.26 (isobutylene)<br>0.16 (toluene) |

In this study, a complete IAQ audit was not performed. The presence of radon and microbiological contaminants was not assessed since they require significantly higher measurement times, and thus were scheduled for a 2nd measurement campaign.

The measurements were performed in operating conditions – with all elements (shading, lighting, and HVAC systems) defined by the occupants.

The physical and chemical pollutants were measured in several offices with portable measuring equipments: Testo 435 ($CO_2$ and CO; 0 to 10000 ppm); TSI DustTrack II (PM10; 0.001 to 400 $mg/m^3$); ZDL-300 (HCHO; of 0 to 30 ppm); ZDL-1200 ($O_3$; 0 to 2 ppm); Photovac 2020ppb (VOCs; 10 ppb to 10 ppm).

#### *2.2.5. Air tightness*

The air tightness of the building is also an important indicator of its IAQ and energy performance and it can be obtained by the building Air Changes Rate (ACH). If the building is naturally ventilated, this parameter can be estimated using the methodology presented on the Portuguese building thermal regulation [25]. However, in existing buildings, a more accurate ACH value can be measured.

Using equipments such as a blower-door, which pressurize/depressurize the building, the air flow that enters/exits the building is measured while the pressure stabilizes, thus allowing the measurement of the air leak.

In this survey a Minneapolis Blower Door (+/- 3%) was used to measure the air change rate of an office room.

### ***2.3. Occupants'' Survey***

A standard questionnaire was also delivered to the occupants to obtain a subjective assessment of the IEQ and to assess the occupants' main complaints.

The questionnaire was done according to the methodology defined in EN 15251 standard [20].

In the survey, besides questions related to age, gender, metabolic activity, clothes and characteristics of the offices, number of occupants, position related to the windows, identification of appliances and systems and patterns of use, the occupants were asked to identify the three most relevant aspects for their comfort conditions (thermal, acoustic and visual comfort, ventilation conditions and IAQ).

Additionally, the occupants were asked to indicate their opinion about the: thermal conditions (very uncomfortable, uncomfortable, comfortable and very comfortable), for the four seasons;

acoustic conditions (5 levels from noisy to noiseless); visual conditions (5 levels from insufficient to excessive illuminance levels); IAQ (5 levels from very bad to very good); ventilation conditions (5 levels from insufficient to excessive ACH); global comfort conditions (very uncomfortable, uncomfortable, comfortable and very comfortable), for the four seasons.

### *2.4. Simulation Code*

The prediction of the building energy needs and energy consumption was done using the EnergyPlus simulation code, estimating the heating and cooling needs of the building [29, 30]. As the building is only acclimatized during occupied periods, the HVAC system was set up to maintain the indoor temperatures above 20ºC in winter and under 25ºC, in summer, according to the Portuguese thermal legislation [24, 25], only during this period, that is between 9 am and 6 pm.

## 3. Results

### *3.1. Characterization of the Actual Situation*

The characterization of the actual conditions of the building was done in four phases. The first step was to identify the building mains deficiencies through a thorough analysis of the building during several visits. During these visits the occupants were asked to identify the main problems of the building.

The second step was the definition and delivery of the standard questionnaire to the occupants and the analysis of the survey results.

The third step was the "in-situ" evaluation of the existing conditions related to the IEQ ($T_a$, RH, $L_{Aeq}$, CO, $CO_2$, $O_3$, HCHO, VOCs and ACH).

The last step was the evaluation of the operating conditions through the simulation of the building energy consumption.

#### *3.1.1. Occupants' Survey*

A total of 46 questionnaires were analysed, corresponding to the responses of 43% males and 57% females. The major part of the occupants are under 34 years old (43%) and 35% are between 35 and 54 years old.

Most of the occupants work in the first (25%) and second floor (46%). Only 9% work in the partially underground floor and 20% work in the third floor. The top floor is the cafeteria and it is not occupied in permanence.

Each office is in general occupied by two (41%) or three (35%) persons.

The most common appliances in the offices are the personal computers and printers. In general the offices have tubular fluorescent lamps and sometimes compact fluorescent lamps in the ceiling and a table lamp.

Most of the rooms have a water heating radiator associated to a centralized diesel boiler (61%) and several rooms have, additionally, an electric radiator (7%) and a fan (63%). Some of the spaces have portable split type systems for cooling (30%).

According to the survey, 33% of the occupants have the lights turned on most part of the day, 4% when they are performing specific tasks and 63% only turn on the lights when the daylight level is insufficient.

The survey also allowed verifying that the thermal comfort conditions are the most valued, followed by the daylight availability and acoustic conditions. The natural ventilation conditions are the less valued aspect.

The main complaints were due to the inexistence of thermal comfort conditions due to the high temperatures.

The occupants had also complaints about the noise, due to outside noise (intense traffic) and from inside (mainly due to the printers), classifying the spaces as noisy.

The lack of quality of the windows (with single glass) is the main problem that leads to the thermal and acoustic discomfort.

The occupants considered the air quality just acceptable and reported the existence of a weak odour. The main complaints were from the occupants of the Laboratory.

There were also complaints related to the visual comfort, specially related to glare and in some cases insufficient light levels, even when the lights were on.

*3.1.2. Assessment of the Indoor Environmental Quality*

The results obtained through the measurement campaigns performed on this case study are presented below according to the type of analysis performed.

The offices where the measurement campaign was performed were selected to characterize and represent the different situations existing in the building.

The selection was done also taking into account the orientation, number of occupants of the spaces, occupation period and existing systems.

Additionally, some measurements were also performed outdoors (temperature, relative humidity, pollutants, $L_{Aeq}$).

Figure 4 shows the rooms where the measurement campaign was performed.


Figure 4. Measured rooms (first number represents the number of the floor, the letter represents the orientation of the room and the last two numbers represent the room number)

### 3.1.2.1. Thermal Comfort

The air temperature and relative humidity (RH) of several office rooms were measured during two weeks (24th of June to 8th of July) to assess the thermal condition of the offices.

During the measurement period, the outdoor temperature varied between 21 ºC and 42 ºC, as Figure 5 shows.

The air temperature in the office rooms were in general over 23ºC, and reached 33ºC in periods when the outdoor temperature reached 41ºC (Figure 5). The lower temperatures measured were in the partially underground floor and in the rooms with split type systems for cooling.

During most of the occupied period, the temperatures were above the comfort temperature (25ºC) according to the Portuguese thermal regulation [24, 25].

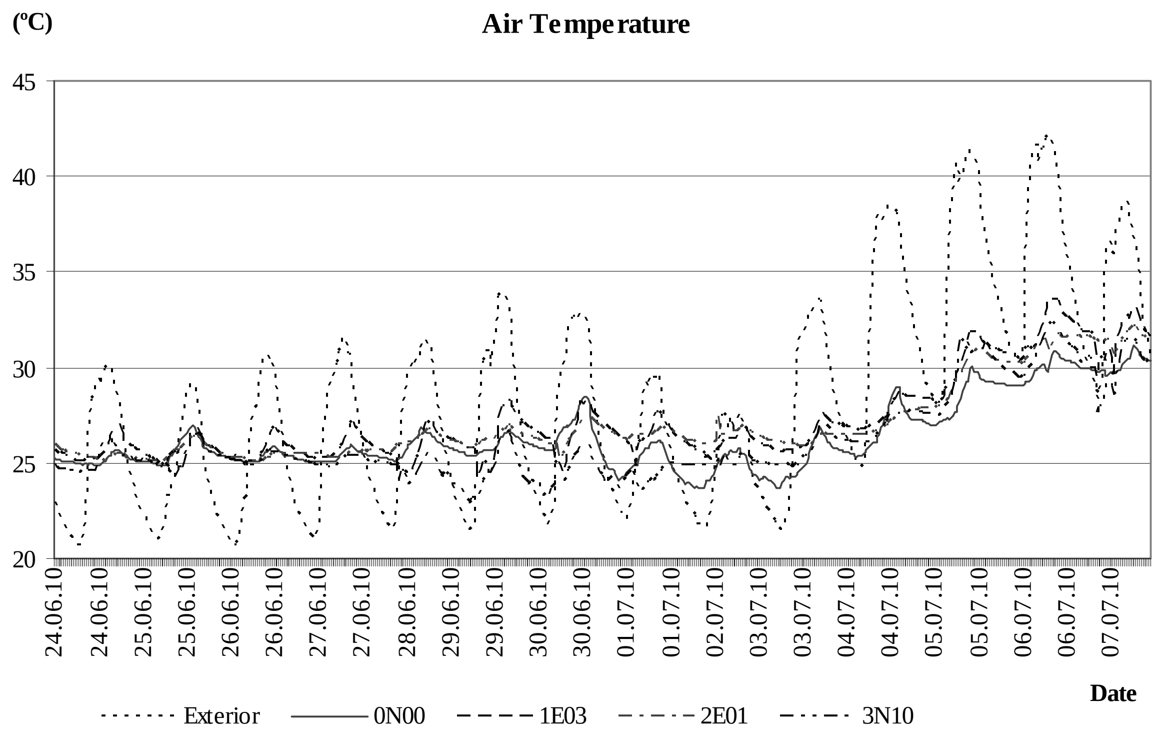


Figure 5. Air temperature ($T_a$) of some of the office rooms monitored (from 0 am of 24th of June to 0 am of 8th of July)

The relative humidity measured was between 30% and 60% (Figure 6). According to the current standards, indoor relative humidity should be within the range 30-50% [20, 22].

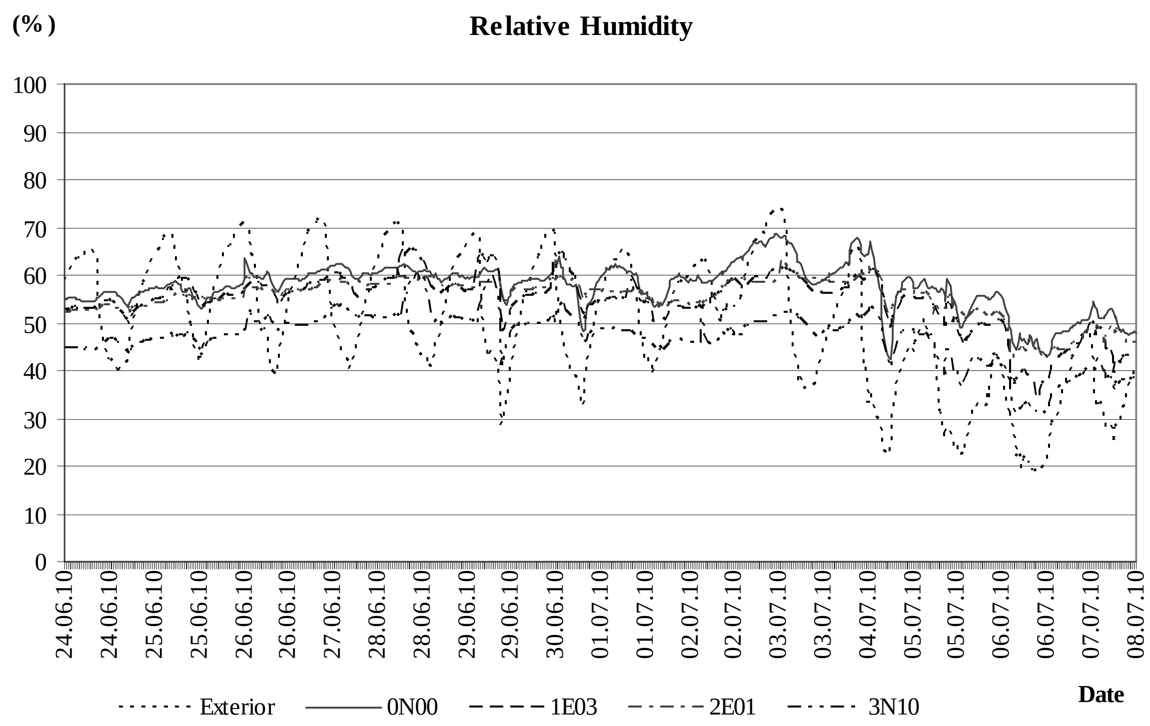


Figure 6. Relative humidity (RH) of some office rooms (from 0 am of 24th of June to 0 am of 8th of July)

Although the relative humidity does not have a strong impact on thermal comfort in the comfortable range of temperatures, it is known that it may negatively affect the perceived air quality [11]. Moreover, high relative humidity indoors means an increasing risk of mould growth, which can be associated with serious health problems [31].

From the results obtained in the measurement campaign, the comfort conditions defined in EN 15251 standard for naturally ventilated buildings are exceeded in what concerns the air temperature and relative humidity (22ºC to 27ºC and 50% RH) [20].

It was also observed that the occupants do not leave the windows open during the night (when outdoor air temperature is approximately 20ºC) and the warmer air temperature could be used to cool the heavy thermal inertia of the building.

The thermal comfort conditions were also assessed through the calculation of the PPD – percentage of people dissatisfied – and the PMV – predicted mean value. The measurements were performed in the 8th of July and it was verified that in these circumstances, comfort conditions were not reached for the most part of the office rooms (Figure 7).

According to EN 7730 [22] and EN 15251 [20] standards, the desired thermal environment in a space of an existing building (category C or III buildings, respectively) are: PPD less than 15%; and PMV from +/- 0.7. These conditions were only met in office 3N12, as Figure 7 shows. In the other assessed offices, PPD is over 30% and PMV varies from 0.9 to 1.1.

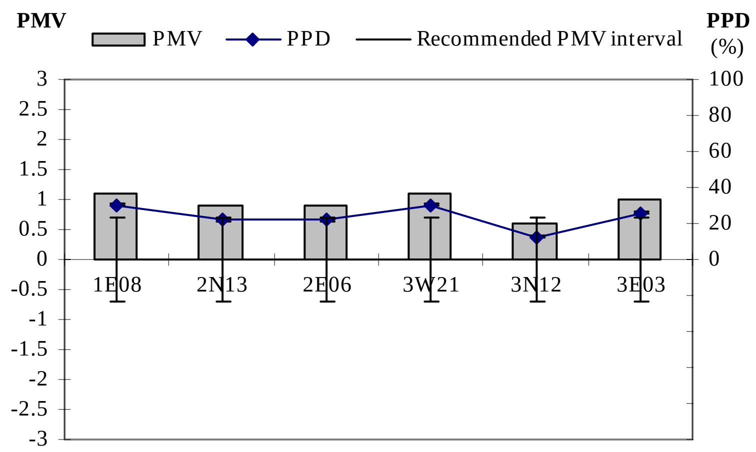


Figure 7. PMV and PPD in some of the office rooms

#### 3.1.2.2. Acoustic Comfort

The assessment of the acoustic comfort was performed using the A-weighted sound pressure level, $L_{Aeq}$. The main source of noise is the traffic, as the building is located near a heavy traffic road, and also due to computers and printers. Due to that, the measured values are higher than the recommended ones (30 to 40 dB(A)) [20]. The measured values range from 47 dB(A) to 58 dB(A) and 61 dB(A) in the outside (Figure 8).

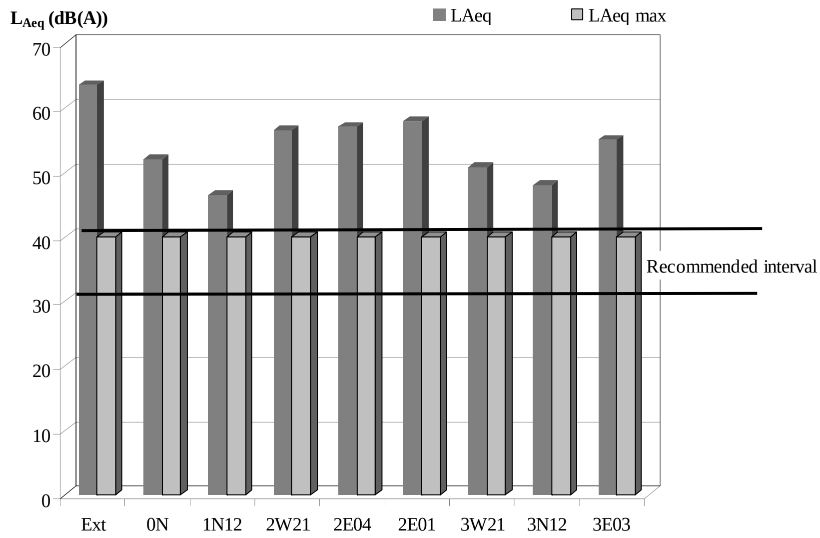


Figure 8. A-weighted sound pressure level, $L_{Aeq}$, measured in some office rooms

### 3.1.2.3. Visual comfort

The evaluation of the natural lighting potential of the buildings was done, as mentioned, measuring the illuminance levels on the task area. The illuminance levels obtained for the several offices are shown in Figure 9. According to EN 15251 [20] and to EN 12464-1 [28] the recommended illuminance level in offices is 500 lux.

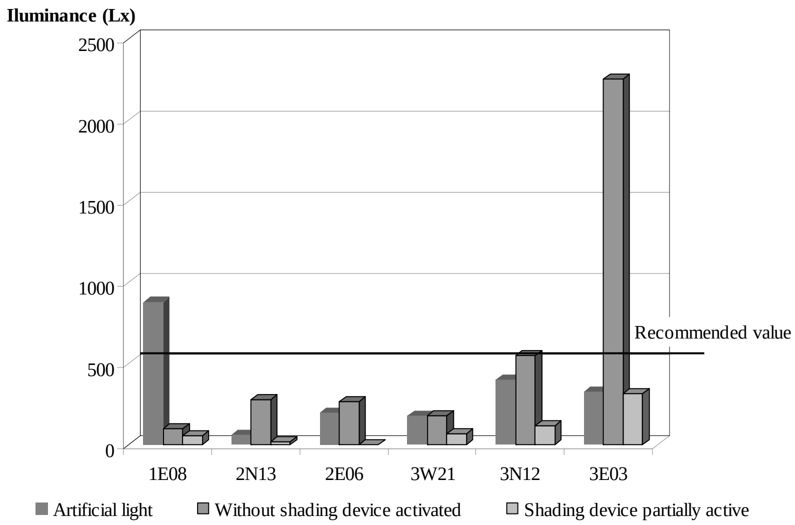


Figure 9. Illuminance levels on the task area for the different office rooms studied

The visual comfort measurement campaign showed that, except for office 3E03, even when using artificial light, the recommended illuminance level is not reached. In office 3E03, the recommended value for the illuminance levels was largely exceeded during the measurement without the shading device activated due to direct sunlight incidence.

As the first floor windows have venetian blinds placed inside, it is possible to prevent the direct sunlight to enter the space and also reducing the light levels inside the rooms.

The windows in the second and third floor have roller shutters that when used to avoid the entrance of direct sun light in the room reduce the light levels inside the offices.
These results showed that even with artificial light the illuminance levels are not reached. It is then necessary to intervene not only at the daylight and shading devices level but also at the artificial light level.

### 3.1.2.4. Indoor Air Quality Assessment

The Indoor Air Quality (IAQ) was assessed through the measurement of the concentration of physical pollutants (CO, $CO_2$, HCHO, VOCs, $O_3$, $PM_{10}$).
Figure 10 shows the results of the carbon dioxide and monoxide ($CO_2$ and CO) measurements for the different studied office rooms of the building.

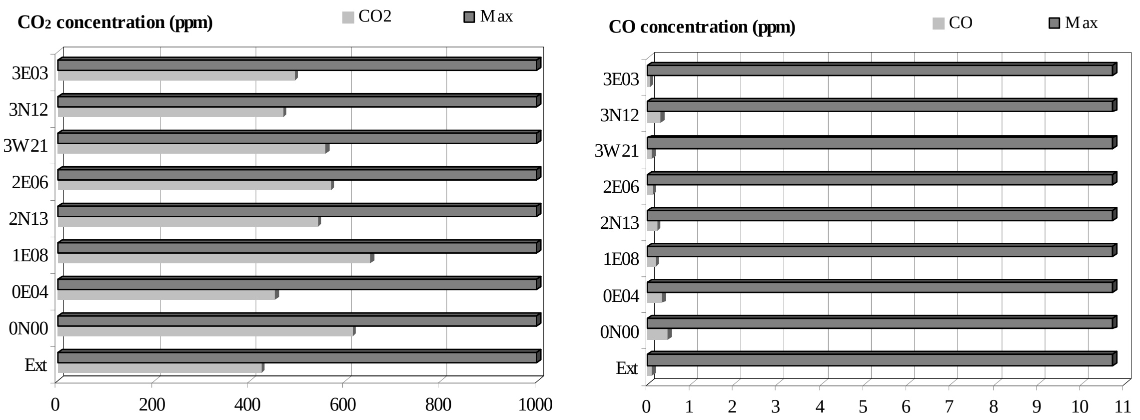


Figure 10. $CO_2$ and CO concentration and maximum reference values

The measurements show that the concentrations of $CO_2$ and CO are considerably lower than the limits due to the fact that the occupants open the windows and the outdoor concentration is also low.
Figure 11 shows the results of the volatile organic compounds (VOCs) and formaldehyde (HCHO) measurements for the different office rooms of the building that were studied.

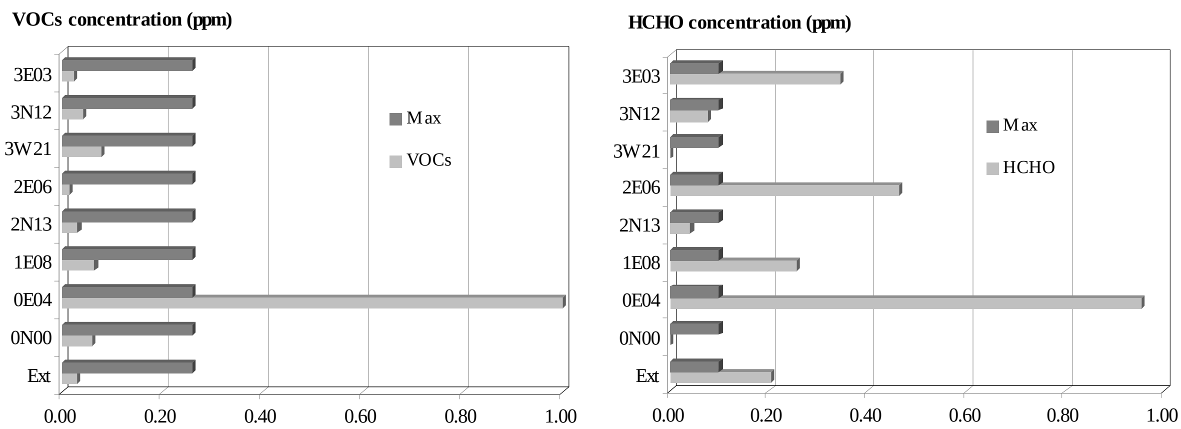


Figure 11. VOCs and HCHO concentration and maximum reference values

Regarding VOCs, the measurements showed a high concentration (almost 5 times higher) in the room 0E04 – the laboratory – where several reagents are used. A high concentration of HCHO (about 8 times higher than the maximum value allowed) was also measured in the exterior and in this same room 0E04 - the laboratory. A high concentration of HCHO was also measured in the offices located above the laboratory, offices 1E08, 2E06 and 3E03.

Figure 12 shows the results of the ozone ($O_3$) and suspended particles ($PM_{10}$) measurements for the different office rooms of the building that were studied.

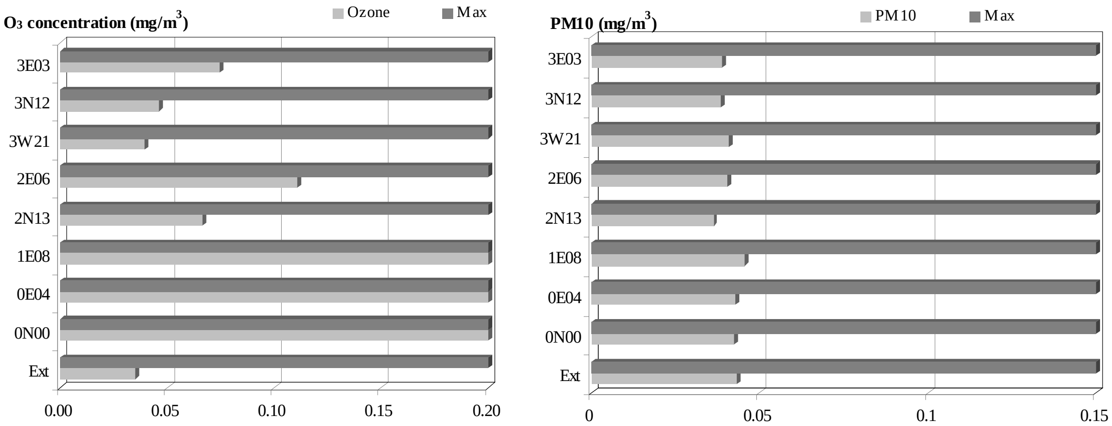


Figure 12. $O_3$ and PM10 concentration and maximum reference values

The high ozone concentrations are probably due to the outdoor concentration (intense traffic) and the presence of laser photocopiers in some offices and then the air movement between spaces transfer the contaminant between rooms.

The suspended particles concentration does not present a problem and is mainly due to the outdoor concentration as the building is located near a heavy traffic circulation road.

#### 3.1.2.5. Air tightness

Figure 13 shows the measured values of the air flow rate, depending on the building pressure, of the room 1E08. The minimum air change rate according to the Portuguese thermal code is of $0.6h^{-1}$. The air change rate of the room, obtained from Equation (1) [32] and according to Figure 13, was of 1.03 $h^{-1}$.

$$Q = C \times P^n \quad (1)$$

with:

Q – Air flow rate ($m^3/s$);

C – Flow coefficient ($m^3/s/Pa^n$);

P – Pressure difference from indoors and outdoors (Pa);

n – Flow exponent (-).

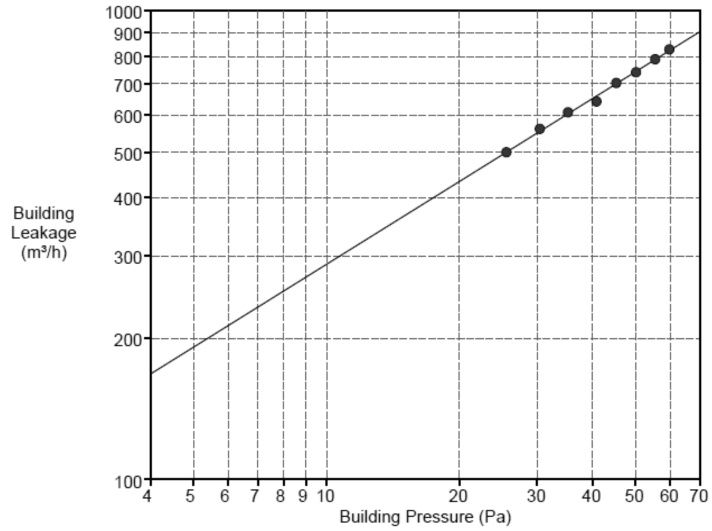


Figure 13. Air flow rate of the room 1E08

The measured air change rate is quite high and will result in substantial heat losses in winter and heat gains in summer.

### *3.1.3. Characterization of the operating conditions of the buildings*

Taking into consideration the results of the IEQ and air tightness assessment, an estimation of the building thermal behaviour was performed using Energy Plus simulation code [29, 30].

The building characteristics, envelope construction solutions, shading systems (venetian blinds on the first floor and roller shutters on the second and third floors on the outside, sometimes complemented by sliding shutters and venetian blinds in the interior), lighting systems (tubular fluorescent lamps and compact fluorescent lamps), appliances, air-conditioning systems were also assessed and the occupation and systems use schedules were defined in accordance with the Portuguese thermal code [24, 25].

Most of the rooms had a water heating radiator associated to a 20 years old centralized diesel boiler; several rooms have an electric radiator (1500 W) and a fan (45 W). Some of the spaces have portable split systems for cooling.

Table 2 presents the main building envelope characteristics and the maximum U-value and shading factor according to the Portuguese regulation [24, 25].

Table 2. Main building envelope characteristics

| | **Walls** | **Roof** | **Windows** | |
|---|---|---|---|---|
| | U-Value [W/m$^2$.ºC] | U-Value [W/m$^2$.ºC] | U-Value [W/m$^2$.ºC] | Shading Factor (including glazing and shading device) |
| Building | 1.90 | 1.40 | 6.20 | 0.45 |
| Maximum allowed value | 1.60 | 1.00 | - | 0.56 |

Applying the dynamic simulation code, it was possible to obtain the energy needs (Table 3). As the existing heating system of the building did not fulfil their energy needs (as the existence of several electric radiators showed) and the building had no cooling system, the equipment capacity needed was also calculated. For the same reason, the final energy consumption was calculated considering the reference systems defined in the Portuguese thermal regulation (an electric resistance with 100% efficiency and a chiller with a COP of 3) [24, 25].

The energy needs are the thermal energy necessary to maintain a given space at the comfort temperature – 20ºC in winter and 25ºC with 50% RH in summer. The Energy consumption or Final Energy –is the energy necessary to maintain a given space at a comfort temperature considering the efficiency of the equipments used (in this case the reference systems). The equipment's capacity – power of the heating and cooling equipments – the equipment's sizing was based on the maximum hourly heating demands obtained from the simulation tool.

Table 3. Energy needs, final energy for the office building

| | | | |
|---|---|---|---|
| **Energy needs** | Heating | kWh/m$^2$.year | 68.5 |
| | Cooling | kWh/m$^2$.year | 11.2 |
| | Total | kWh/m$^2$.year | 79.7 |
| **Final energy** | Heating | kWh/m$^2$.year | 95.1 |
| | Cooling | kWh/m$^2$.year | 11.2 |
| | Appliances | kWh/m$^2$.year | 40.5 |
| | lighting | kWh/m$^2$.year | 16.0 |
| **Equipment Capacity** | Heating | kW | 168.6 |
| | Cooling | kW | 32.4 |
| | Total | kW | 201.0 |

The measurement campaign confirmed the necessity of reducing the envelope U-values, using higher insulation levels and replacing the windows, since the original building values are always higher than the recommended ones by the actual Portuguese legislation (0.6 and 0.45 W/m$^2$.ºC for walls and roofs, respectively), and in some cases even higher than the maximum allowed values (1.6 and 1.0 W/m$^2$.ºC for walls and roofs, respectively). The air change rate must also be controlled, replacing the windows.

### 3.2. Refurbishment Proposal

With the operating conditions assessment carried out, it was possible to identify some of the most critical problems of the building, the ones that need particular attention during the rehabilitation interventions.

The assessment of the existing conditions showed an inadequate behaviour of the building at all IEQ levels.

The IEQ measurement campaign showed that the temperature in the offices was higher than the comfort zone leading to the thermal discomfort of the occupants. The offices were also noisy and uncomfortable at the acoustic level.

In what concerns the visual comfort, both with natural and artificial light the iluminance level did not met the recommended values. If the occupants were not able to adjust the shading system to control the sunlight that enters the room, glare problem occurred.

Even with a high air change rate, the building also presented some problems related to the IAQ, namely high concentrations of VOCs, formaldehyde and ozone.

Thus, as the thermal and acoustic insulation of the façade is insufficient, the daylight and artificial light levels are inadequate, the ACH is high and the IAQ is inadequate, interventions at these levels are essential to increase the energy performance and IEQ.

It is then necessary to improve the thermal and acoustic quality of the envelope, mainly through the replacement of the windows, optimization of the shading systems and improvement of the thermal quality of the walls. As the windows should be more air thigh the installation of ventilation system is also necessary to ensure the IAQ.

The artificial light system should also be studied in order to effectively complement the daylight levels, when necessary, and ensure an adequate illuminance level on the task area.

### *3.2.1. Refurbishment Options*

Building envelope improvements for reduced energy use are typically measures that improve the thermal characteristics of the envelope and/or that increase solar gains through the transparent parts of the envelope. The building envelope refurbishment options investigated in the case study primarily aim at improving the thermal characteristics of the envelope by reducing transmission, infiltration, and ventilation losses (as it is not possible to change the windows dimensions to increase the solar gains, and the existing glass has a high solar factor).

Maintaining the original wall construction, two retrofit options were studied to refurbish the building. These two solutions were selected as they are the most widely used in Portugal.

The first option was to install a thermal insulation layer on the outside (8 cm of expanded polystyrene – ETICs system). The second option was to apply thermal insulation placed inside (6 cm of cork and 1.3 cm plasterboard). When placing the insulation inside the existing wall it is necessary to consider the impact on the useful area of the room that will be reduced. Thus, a thinner layer of thermal insulation was used in this refurbishment option.

In both options, a suspended ceiling with a 10 cm thick layer of cork and 1.3 cm plasterboard was added to the roof. Cork was selected for these insulation solutions because it is an abundant material in Portugal with good thermal properties and sustainable characteristics.

The existing windows were replaced, in both refurbishment options, by aluminium frames with thermal break and double clear glazing with venetian blinds placed on the outside.

Also, for both retrofit options, more energy efficient appliances (the substitution of CRT computer monitors for TFT monitors) and light bulbs were applied.

The heating system was also replaced and a cooling system was installed. The heating system selected was a pellets boiler (efficiency of 60%). The cooling system chosen was a chiller (COP of 3).

Additionally an extractor must be installed in the Laboratory to ensure the removal of the polluted air. The polluted air should be released above the building in order to prevent the polluted air to enter in the office rooms adjacent to the Laboratory.

Table 4 presents the main building envelope characteristics considering the original building and the two refurbishment options.

Table 4. Main building envelope characteristics

| | **Walls** | **Roof** | **Windows** | |
|---|---|---|---|---|
| | U-Value [W/m$^2$.ºC] | U-Value [W/m$^2$.ºC] | U-Value [W/m$^2$.ºC] | Shading Factor (inc. glazing and shading device) |
| Original | 1.90 | 1.40 | 6.20 | 0.45 |
| Refurbishment - outside insulation | 0.40 | 0.30 | 3.30 | 0.11 |
| Refurbishment - inside insulation | 0.48 | 0.30 | 3.30 | 0.11 |
| Maximum allowed value | 1.60 | 1.00 | - | 0.56 |
| Recommended value | 0.60 | 0.45 | - | 0.20 |

Additionally, as the existing heating system is not able to fulfil the heating needs and the building has no cooling system, it is necessary to select a HVAC system that fulfils the building’s needs.

### *3.2.2. Energy Analysis*

For the original solution, the final energy consumption was calculated considering the reference system defined in the Portuguese thermal regulation (an electric resistance with 100% efficiency and a chiller with a COP of 3) [24, 25]. Afterwards, a pellets boiler (efficiency of 60%) was selected to replace the existing diesel boiler (efficiency of 72%). The cooling needs will be assured by a chiller (COP of 3).

Applying the dynamic simulation code, it was possible to obtain the energy needs, final energy for the original office building and for both retrofit options, as shown in Figures 14, 15 and 16.

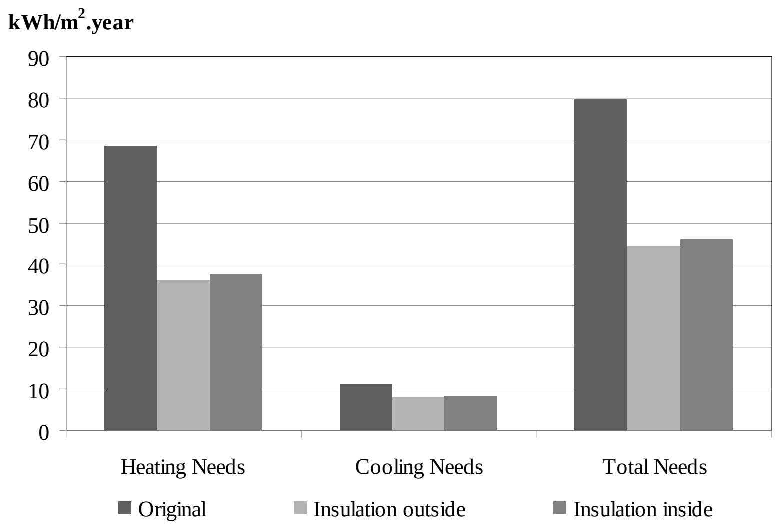


Figure 14. Heating and cooling needs for the original building and retrofit alternatives

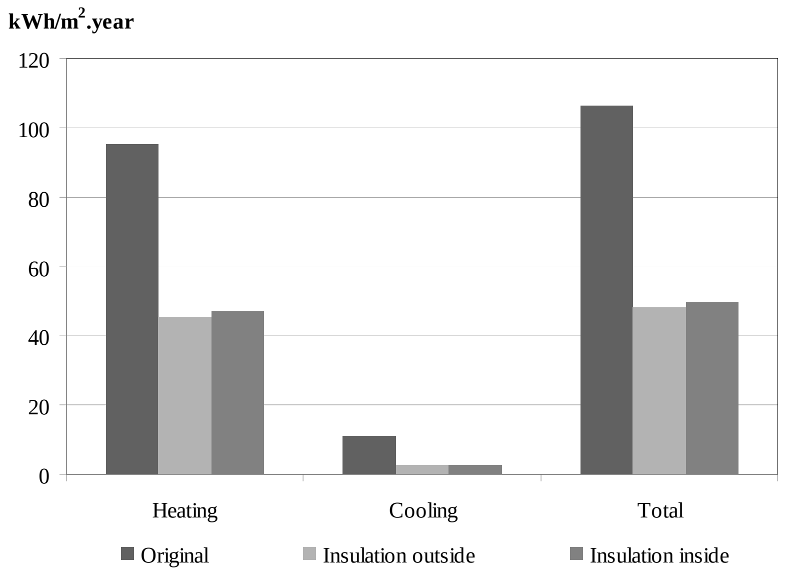


Figure 15. Heating and cooling consumption for the original building and retrofit alternatives

With the retrofit of the building envelope the heating needs will be reduced in 45% and the cooling needs in more than 25%. The annual energy needs reduction is more than 40%.

With the installation of a pellets boiler (efficiency of 60%) and of a chiller (COP of 3) in addition to the improvement of the envelope, the required heating and cooling final energy consumption is reduced in more than 20%.

With the retrofit of the building envelope, the heating system, appliances, and light bulbs replacement and the installation of a cooling system, the final energy consumption can be reduced in about 47%.

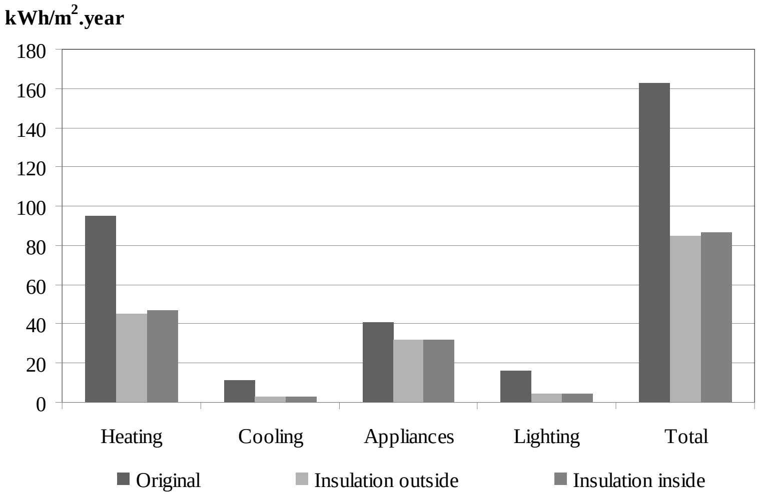


Figure 16. Total final energy for the original building and retrofit alternatives

The annual energy bill of the building (Figure 17) was also calculated for the three situations. The energy bill is the price of energy necessary for heating, cooling, appliances and lighting. The lighting systems and appliances characteristics were identified during the visits to the building. The occupation, lighting systems, appliances and HVAC systems schedules were defined in accordance with the Portuguese thermal code [24].

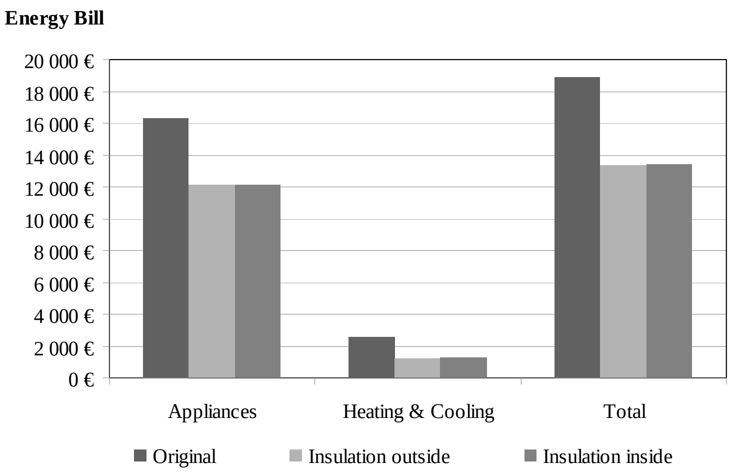


Figure 17. Anual energy bill for the original building and retrofit alternatives

The reduction of the energy bill with the retrofit of the building envelope and with the replacement of the heating system, appliances and light bulbs and with the installation of a chiller is of about 37%.

Since the results obtained applying exterior or interior insulation are similar (differences less than 4%), both the use of insulation placed outside or inside the existing wall was an alternative.

The use of a mechanical ventilation system with heat recovery, would allow an even higher energy saving, ensuring the achievement of the optimum values for the air change rates (0.6 $h^{-1}$), with minimum waste of energy in winter.

**4. Discussion**

The building was built before the implementation of the Portuguese thermal codes, thus the envelope, especially the windows, has a low thermal resistance, leading to high heat losses, during winter, and heat gains, during summer. Additionally the poor thermal quality of the envelope leads to low indoor temperatures in winter and high indoor temperatures in summer and high heat exchanges due to radiation with the surfaces, thus, the thermal comfort conditions are not met  (even with the use of HVAC systems).

Also due to the inadequate airborne sound insulation of the facades the offices were uncomfortable due to outdoor noise. The indoor noise, mainly due to occupancy and printers and copiers, also contribute to the existence of noisy spaces.

To ensure the visual comfort is necessary to select the glass type and adjustable shading systems balancing the control of daylight (preventing glare) and the energy needs.

The artificial light systems must also be thought carefully as even with the light turned on the lighting levels did not fulfil the recommendations.

Thus, in general improving the thermal and acoustic quality of the envelope will have a positive effect on the thermal, acoustic and visual comfort indoors. Additionally to ensure the thermal comfort conditions it is necessary to install an adequate heating and cooling system with high efficiency.

These measures would not have a direct impact in the IAQ, or will have a negative impact, as improving the thermal and acoustic quality of the windows will reduce the air change rate. And, in this case study, even with a high ACH and the use of natural ventilation in the offices the concentration of some pollutants was high (manly $O_3$, VOCs and HCHO).

As the printers and copiers are the potential cause of noise and high $O_3$ concentration the placement of these equipments in specific areas, with an adequate ACH and envelope, will be beneficial both for acoustic comfort and for IAQ.

Besides the installation of more airtight window frames and doors it is necessary to install mechanical ventilation systems with heat recovery units to ensure an adequate air change rate of the building to reduce the uncontrolled infiltrations through the envelope that lead to high energy losses through ventilation and to guarantee the indoor air quality.

To mitigate the VOCs and HCHO concentrations in the Laboratory and, by extension, in the adjacent office rooms additional measures are required. It is necessary to install an extractor in the Laboratory to remove the polluted air and release it above the building in order to prevent the polluted air to enter in the office rooms adjacent to it.

The above referred measures are adequate for a vast set of buildings that might be represented by this case study building and can be adapted to their specific situation and would ensure the IEQ gaols in an energy retrofit project.

**5. Conclusions**

This paper presents the “in situ” assessment of the operating conditions and of the Indoor Environmental Quality (IEQ) of a Portuguese office building located in the center of a big city. The measurement campaign was divided into three major areas: characterization of the buildings operating conditions, comfort conditions (thermal, acoustic, visual) and Indoor Air Quality (IAQ).

With the operating conditions assessment carried out, it was possible to identify some of the most critical problems of the building, the ones that need particular attention during the rehabilitation interventions.

The study of the building actual situation revealed problems related both to the indoor environmental quality and energy efficiency.

The IEQ assessment showed an inadequate behaviour of the building in what concerns the thermal, acoustic and visual comfort conditions.

The indoor temperature was above the comfort interval and the offices were uncomfortable due to both indoor and outdoor noise.

With the daylight availability analysis, it was possible to conclude that if the shading devices are not activated, the illuminance values are too high and glare problems occur, when direct sunlight enters the offices. The daylight conditions were also not adequate when the shading systems were partially activated to prevent the solar radiation to enter the building. The artificial lighting system of the office rooms was also unable to ensure the necessary illuminance levels to the tasks that are usually performed in those spaces.

The study also showed some problems related to the indoor air quality as were detected high concentrations of some pollutants, like volatile organic compounds and formaldehyde, and also small concentrations of ozone, even in the presence of a high air change rate that characterizes this building.

The envelope had a poor thermal insulation. The envelope U-values were, in general, higher than the maximum allowed values by the Portuguese legislation and significantly higher than the recommended ones.

The poor thermal resistance of the envelope and high air chance rate leads to high energy consumptions that the existing heating system was not able to fulfil (electric radiators in some offices were a way to overcome this problem). Additionally, as there is no cooling system installed in the building, the occupants used fans to minimize their thermal discomfort.

The measurement campaign confirmed the necessity of reducing the envelope U-value, using higher thermal insulation levels.

It is also important to reduce the uncontrolled infiltrations through the envelope, using more airtight window frames and doors and using mechanical ventilation systems with heat recovery units to ensure an adequate air change rate of the building to reduce the energy losses through ventilation and to guarantee the indoor air quality.

Improving the quality of the window frames and doors and increasing the insulation level of the façades, will also have a favourable effect on the acoustic and thermal comfort. However, to achieve comfort conditions it is necessary to install heating and cooling systems, carefully selected to ensure energy efficiency.

The refurbishment options were defined to tackle the most relevant deficiencies presented by the building, at three levels: envelope quality, appliances and lighting and HVAC systems.

Two retrofit options were studied to refurbish the building: thermal insulation placed inside (6 cm of cork and 1.3 cm plasterboard) and thermal insulation placed outside (8cm of expanded polystyrene). A suspended ceiling with a 10 cm thick layer of cork and a 1.3 cm plasterboard was added to the roof and the existing windows were replaced by aluminium frames with thermal break and double clear glazing with venetian blinds placed on the outside. Also, more energy efficient appliances (the substitution of CRT computer monitors for TFT monitors) and light bulbs were applied.

The dynamic energy simulation study of the existing office building and of the two retrofit options showed important reduction in the energy consumptions of the building.

Retrofitting the building envelope, replacing the systems, appliances and light bulbs by more efficient ones, will lead to a reduction of about 47% in the final energy consumption and to a reduction of the energy bill of about 37%.

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