TITLE: Retrofit strategies towards Net Zero Energy Educational Buildings: a case study at the University of the Basque Country.

1. Introduction

Educational buildings in Europe account for around 20% of the entire non-residential floor space [1]. Good indoor comfort and air quality are essential for correct educational development considering the long hours that students spend in buildings of this type.

Moreover, the achievement of adequate comfort levels is essential in order to reduce energy consumption. A study conducted at the Polytechnic University of Timisoara (Rumania), revealed that the classroom temperature affects the ability of students to grasp instruction [2]. Furthermore, a favourable learning environment correlates significantly to student involvement, teacher support, and classroom order and organization [3] [4] [5] [6] [7].

Acting on existing educational buildings is essential, not only to achieve the EU 2020 targets but also in order to improve the educational performance and academic outcomes of future generations. However, it is not easy to modify the existing heritage; given the fact that many energy solutions in the field of renovation are not compatible with historical buildings, which need to preserve authenticity and integrity [8].

The school sector consumes high amounts of energy for heating and electricity, and therefore energy-saving measures are necessary. An average of 13% of total energy in USA, 4% in Spain and 10% in the UK is consumed by schools [9]. Moreover, energy consumption patterns in educational buildings, especially in electricity demand, have changed considerably in the last decades. An intensive use of computers to support lessons has changed user behavior, with a 71% increase in the number of computers per square meter between 1999 and 2012 [10]. The internal gain increase due to electric appliances in poorly ventilated buildings might emphasize overheating problems not only during the summer period but in the shoulder seasons. Understanding the interaction of users and buildings is therefore relevant to promoting better design strategies to enhance the sustainability of buildings [11]. However, behavioral issues are still among the areas least covered in scientific literature [12].

Some reports focus on the building "envelope and system" features in order to propose adequate strategies for energy efficiency and indoor air quality in schools [13] [14] [15] [16]. Several studies also examined the typical yearly use of heating in school buildings [17][18][19]. [15] also mentioned that information on the energy consumption of school buildings is still very limited. Most reports in this field focus on primary and secondary school buildings, with numerous projects conducted in the Mediterranean Zone [20] [21] [22] [23] [24] [25]. Among them MED - TEENERGY (high-energy efficiency of Mediterranean school buildings) and ZEMeds (Zero Energy MEDiterranean Schools) play a significant roll. MED - TEENERGY pointed out the lack of energy saving benchmarks targeted to south Europe climatic conditions and the low energy efficiency of existing school buildings taking into account not only heating but also cooling needs. In addition, the main goal of ZEMedS is to increase the knowledge and know-how on the nZEB renovation of schools in Mediterranean climates and give support to several new initiatives on the nZEB refurbishment of schools.

However, little has been done in the context of university buildings, where the typological features and use patterns seem to be closer to office buildings. Thus, this paper wants to highlight the need to act on the particular typology, which merits an individual analysis and tailored approach.

Some studies conducted in Universities in Italy and Rumania [26] [27] [18] [29] [2] focus on the hygrothermal comfort analysis via experimental and subjective measurements thanks to the use of questionnaires and monitoring campaigns. In [8] monitoring campaigns made it possible to analyze comfort and to define retrofit actions: use of thermostatic valves on radiators, replacement of the current old boilers with condensation gas heaters, replacement of single glazed windows.

In this context, this paper discusses the critical issue of dealing with energy and comfort in a particular building, the Faculty of Architecture in San Sebastian, in order to present the best retrofit strategies where user preferences haven been considered as an energy saving opportunity.

2. The Net Zero University project of the Basque Country

The research Project “Towards a Net Zero Energy University of the Basque Country” is financed by the University of the Basque Country and started in September 2014. The main aim is to study the existing building stock and propose retrofit strategies in order to become the first University in Spain to achieve the NZEB target.

The University of The Basque Country is a public university, with 32 Faculties spread across four Campuses (Bilbao, San Sebastian, Vitoria and Eibar), with more than 40,000 students and around 7,500 workers. Most of the buildings were constructed in the eighties and nineties whilst only a few have been refurbished up till now. Given the NZEB target and the need to act on these buildings in the short term, this research is necessary and urgent in order to evaluate energy saving strategies and to provide general retrofit guidelines.

The energy consumption of the academic building stock varies significantly. Looking at the heating consumption (provided by radiators and fuel gas in most cases) this value ranges from 36.8 to 76 kWh/m^2 year. In the case of electricity consumption the value ranges from 18 to 107 kWh/ m^{2}year (the highest values are recorded in the Computing Faculty and are directly linked to the intensive use of computers by students). Most of the buildings are not provided with an air conditioning system due to a mild climate (the average daily maximum is below 22ºC) and little academic activity during the summer period (from June to August). However, some overheating problems have been reported in the shoulder seasons, mainly due to poorly insulated envelopes, inefficient ventilation and air renewal, and the increase in internal gains (mainly due to the use of computers in classrooms). Overheated classrooms directly affect student performance, therefore, improving comfort is a central target of any University. The achievement of this aim, whilst avoiding the installation of an air-conditioning system with all the inconveniences that have been widely reported [30] [31] [32] [33] [8], is one of the main goals and the first step in retrofitting towards a NZEB. This article analyses in detail the case of the Faculty of Architecture.

2.1. The faculty of Architecture in San Sebastian

The Faculty of Architecture is located in San Sebastian (Spain), characterized by a mild climate (mean annual temperature of 15ºC) and high relative humidity, 70-80%. Most of the lecturing period develops in months with temperate climate. Due to this fact, this paper prioritizes attention towards shoulder seasons.

The building was constructed in 1992 by Miguel Garai and Santos Barea and the design style is based on “Tendenza”, a postmodern architectural movement. The 6-storey building is rectangular in shape and has a total heated surface area of 13,722m^2 where the main façade is oriented towards the southeast. Considering the layout of the classrooms on the main floors, the building has a large open workshop area facing the southeast façade and 3 small seminar rooms facing the northwest façade. The building envelope is made of double brick walls with a 40cm total thickness, a 5cm air gap and a 5cm polystyrene insulation layer in between. The U-value is: 0,630W/m^{2}K. Windows account for around 25% of the total vertical surface area. Windows (2,5x2m) were replaced in 2006 and comprise double glazing with an aluminum frame. The U-value of the glass is 2.80 W/m^{2}K and 4.0 W/m^{2}K of the aluminum frame. The solar factor is 0.7.

The heating plant system comprises 3 gas boilers for heating located in the basement, for a total of 1358 installed kW, and radiators are located throughout the building. The energy consumption in 2014 was 639,803 kWh, 46.62 kWh/ m^{2}year.

The climate control system controls the supply of hot water as a function of the outdoor air temperature. In general, the heating operates from October to the end of April during the week and starts up at 06:00 a.m. and shuts down at 20:00 p.m.. The control system allows for 24 h adjustment at two different set-point temperatures (day-night and weekdays/holidays). Thermal control units for single spaces or thermal zones are not yet present.

The electricity consumption was 313,808 kWh in 2014, 22.86 kWh/ m^{2}year. 50% of which corresponds to classrooms and 30% to common zones. General lighting is composed of fluorescent lamps with a total of 1151 units.

The building is provided with a roof-mounted PV system with an estimated annual production of 46,000 kWh.

There is no ventilation system, the air renewal is through the windows and the building is not provided with an air-conditioning system.

2.2. Method

The proposed method consists of a study and definition of best energy retrofit strategies based on student comfort preference analysis under real conditions. Thus, user preferences have been considered as an energy saving opportunity.

With this purpose, the structure of the paper is the following:

- Comfort analysis:
    - Monitoring campaign.
    - Subjective comfort analysis: questionnaire campaign.
    - Objective comfort analysis: ISO 7730 [34], ASHRAE 55:2010[35] and Fanger Method [36].
    - Comparison between subjective and objective comfort analysis.
    - Definition of comfort ranges adapted to real users preferences.
- Energy efficiency analysis based on the optimum comfort ranges:
    - Simulations for the summer period with different ventilation scenarios.
    - Simulations for the winter period: separate analysis of different retrofit scenarios (thermal bridge improvement, heat recovery simulation, glazing improvement, insulation improvement).
- Retrofitted building scenario: a combined analysis of strategies with the highest impact: improvement of thermal bridges, natural ventilation in summer and heat recovery ventilation in winter.

3. Comfort Analysis

3.1. Monitoring campaign

Since September 2015 a significant area of the second floor has been monitored by a wireless (SMD SHT 11) and internet-connected technology where thermo-hygrometric parameters (temperature and relative humidity) are recorded every 15 min. The temperature sensors and humidity are stated respectively with an accuracy of ±1.5◦C and 3% of the measured value. The sensor position and height is shown in the following figure (Fig.1). The monitoring campaign is to last 3 years and for security reasons, it was decided to locate Sensors 2-6 at a higher position than that recommended by the various standards ISO 7726:1998 [37] and ASHRAE 55:2004 [35]. Sensor 1 is the only one positioned on the ceiling. The position of the sensors is strategically decided in order to analyze the temperature and humidity variation along the cross section of the building, making it possible to study the impact of the orientation and classroom type.

In order to analyze overheating problems, widely reported by students and professors during the shoulder seasons, a detailed study was conducted in a typical spring week: from 25th April to 1st May 2016. The results of the comfort analysis of Seminar room 2.2 are described in the following section. The heating system was off during the week studied. The following graphs (Fig. 2) show that, despite the low exterior temperature, under 14ºC around midday and around 11ºC at night, the indoor temperature was quite high. This is over 23ºC most of the time and close to 25ºC as reported by Sensor 4. During the weekend, when there is no academic activity, the indoor temperature drops slowly and stays between 21-23ºC.

In the case of exterior relative humidity, this value ranges from 55 to 95 % but the interior relative humidity moves from 30-45% and is sometimes close to 55% (Fig.3). The highest values coincide with breaks when the windows are open for air renewal and exterior air comes in.

3.2. Subjective and objective comfort analysis

A detailed evaluation of the thermal comfort in Seminar Room 2.2 was conducted through an objective approach and a subjective analysis, directed at comparing the results. The objective assessment, which consisted of field measurements of variables, was made by elaborating data recorded in order to evaluate the Fanger's thermal comfort indices [36], while the adaptive method was applied mainly as proposed by ASHRAE 55:2010 [35]. The subjective data were collected by interviews with occupants in a typical shoulder season week. Objective and subjective data were then compared by comparing the Predicted Percentage of Dissatisfied - PPD and Neutral Temperature - Tn.

The results reveal that there is a low correlation between the subjective and objective analysis, in general, students need a cooler indoor environment than stated by theoretical methods. The user´s comfort perception study suggested that the temperature range with greatest comfort corresponds to temperatures between 20°C and 22.5°C in accordance to [29]. However, the proposed temperature range contraries the one stated by [2] where in the absence of a cooling system and natural ventilated university classroom, the maximum comfort limit is 27ºC. This diversity of results evidences that user preferences are dependent on cultural, climatic characteristic of every location and as suggested by [27], as a function of the season. All this approaches indicate that a detailed study is required in every study case and further research is necessary in this direction.

-Subjective comfort analysis: questionnaire campaign

A questionnaire campaign was implemented from 25th April to 1st May 2016 in Seminar room 2.2 on the second floor in order to conduct a subjective comfort analysis. One of the main parts for evaluating comfort in existing buildings is the collection of data provided by users under real conditions.

The Seminar room has a fully windowed façade facing northwest composed of 9 windows, only the smaller ones are openable (Fig. 4, 5). The windows are provided with blinds and curtains to control natural lighting.

The lighting is provided by 5 rows of 6 fluorescents lamps and a projector connected to a PC is installed in the ceiling. The average occupancy is 20 students, usually seated in the last rows. As shown in the following picture students usually work with their laptops (Fig.6).

As with the rest of the building, the room is heated by radiators, positioned under the windows, with no thermostatic valves,. Ventilation and air renewal is through the windows and usually takes place at break time (around 14:30) and at the end of daily classes (around 20:00). On Friday morning, classes finish at 15h and there is no academic activity in the afternoon. Air renewal and the internal gains patterns are shown in the following figures (Fig. 7, 8) and were obtained from monitored data. It is also noteworthy that the highest occupancy occurs in the first class (over 100 W/m^2) and then remains constant (around 55 W/m^2).

Students and professors of the Seminar 2.2 were asked to complete a comfort questionnaire at the beginning and end of each lesson. This took place 12 times and a total of 202 questionnaires were collected.

The EN ISO 10551 [38] defines the requirements of the questionnaire to assess the results using the PMV and PPD indices. Furthermore, the ASHRAE 55:2010 [35] standard defines the necessary comfort issues to be evaluated using the adaptive model. Taking these topics into account, the questionnaires covered the following questions:

- Personal data: age, sex, weight and height.
- Classroom layout.
- Information about clothing.
- Thermal sensation vote (TSV), defined in a 7-point scale: cold, cool, slightly cool, neutral, slightly warm, warm, and hot, from -3 (Cold) to +3: (Hot).
- Thermal preference vote (TPV), defined in a 7-point scale: -3: much cooler; -2: cooler; -1: a little cooler; 0: no change; +1: a little warmer; +2: warmer; +3: much warmer.
- Thermal environment acceptability.
- Possibility of control over microclimate conditions.
- Satisfaction with the possibilities of action.
- Reactions to the lack of comfort (opening windows and doors, changing clothes, etc.)

The average TSV calculated in each class was used to obtain the neutral temperature Tn and the range of comfort by linear regression. The neutrality was derived by solving the regression equations for a mean sensation vote of zero, choosing the larger correlations between all data. The comfort zone is defined by adding ±2.5 ºC to the Tn calculated, covering the thermal conditions in which a larger number of people are comfortable, thus $PPD < 10\%$ corresponding to $0.5 < PMV < 0.5$, in accordance with the ISO 7730, category B. [34]. In order to improve the linear regressions, the analysis was made by considering 4 student groups, the morning classes -

Group 1 males and Group 1 females, and the afternoon classes – Group 2 males and Group 2 females, with data for the three sensors.

Best regressions were calculated for sensor 6 with Group 1 – males, with a $R^2 = 0.9642$, and for sensor 6 with Group 2 – males with $R^2 = 0.7756$. Results are reported in Table 1.

In addition, from the average TSV, the correspondent PPD was calculated. Table 2.

As shown in the table, the TSV ranges from -0.38 (between neutral and slightly cool) to +1.66 (between slightly warm and warm). This latter value indicates a high percentage of dissatisfaction: 59.6%.

The average TSV is over +0.5 in 8 out of 12 questionnaires which implies a PPD value of over 10%. This result means that the 2.2. Seminar room is not comfortable 65% of the time and is therefore out of the B category according to ISO 7730.

Despite the average TSV (slightly warm) and PPD reported in most of the questionnaires, it must be highlighted that 60% of the respondents considered the room temperature to be acceptable.

A 100% acceptability was reported on the 26th at 16:30, with an average TSV of -0.37 (between slightly cool and neutral). Thus, the highest acceptability occurs when TSV is below neutral.

According to a gender perspective, in most cases the TSV reported by women is 0.7 points higher than that reported by men. Women feel comfortable at a higher temperature but show a higher acceptability.

According to the position in classroom (Table 3), people seated in the back rows reported in 30% of the questionnaires an average TSV of +2 (warm) and neutral in the remaining cases.

In a central position, people reported TSV close to +1 (slightly warm) and +2(warm) when the questionnaires were conducted in the afternoon. In addition, students located close to the exterior façade reported a higher variability that ranges from negative values in the morning and values close to +2 in the afternoon.

83.56% of the students said that the microclimate element that they most control when feeling discomfort are windows. The second element is clothing with 54.79%. 41.09% of the people usually control these elements and 38.35% sometimes.

-Objective comfort analysis: the ISO 7730, ASHRAE 55:2010 and Fanger Method

The Fanger method [36] is based on a formula that relates variables of ambient temperature, radiant temperature, air speed, relative humidity, metabolic rates due to activity level (met) and thermal resistance of clothing (clo). Sensors used in field measurement recorded ambient temperature and relative humidity; the data are reported in (Table 4). The metabolic rate was assumed to be 1.2 met units according to ASHRAE Standard 55 – 2010 for seated activity [35]. According to some indoor climate studies [39] [40] [41] [42], the mean radiant temperature can be assumed to be equal to the air temperature based on the hypothesis that surrounding indoor surfaces have uniform temperatures and radiation fluxes in case of low air speed.

Finally, clo values were obtained through the questionnaires used for the subjective comfort analysis.

Under these hypotheses and using the field data, the PMV and PPD were calculated by the objective approach (Table 5).

The Adaptive Comfort Model according to the ASHRAE-55 2010 Standard [35], is used in occupant-controlled natural-conditioned spaces, defined as those spaces where the thermal conditions of the space are regulated primarily by the occupants through the opening and closing of windows.

The study of adaptive comfort requires the measurement of indoor dry bulb temperature and the outdoor ambient temperature. For this purpose the data used were collected from the weather station of the Basque Government, located in the Avenida Tolosa, in San Sebastián, close to the faculty building [43].

As an initial stage and in order to compare results, the neutral temperature Tn, which corresponds to a neutral thermal sensation in the environment, i.e. a sensation neither of warmth nor of chill, was calculated using different adaptive comfort models. The ASHRAE 55:2010 [35] recommends the Brager-De Dear model.

Results are summarized in Table 6.

The ASHRAE-55 2010 [35] adaptive standard sets out two thermal comfort zones – one for 80% acceptability, and another for 90% acceptability. Acceptable ranges of 10% and 20%

predicted percentage dissatisfaction (PPD) with ±2.5 ºC and ±3.5 ºC as ranges of acceptance respectively, and are equivalent to ±0.5 and ±0.8 predicted mean vote (PMV).

In ISO 7730 [34] comfort category B corresponds to an allowable predicted mean vote $-0.5 < \text{PMV} < 0.5$, and to an allowable predicted percentage dissatisfied PPD < 10%.

By calculating the average April outdoor temperature, and considering an acceptability of 90% (PPD < 10%), the comfort range of the classroom is between 19.3 ºC and 24.3 ºC.

With a PPD < 20%, the calculated comfort range should be between 18.3 ºC and 25.3 ºC.

3.3. Comparisons between questionnaires, the ISO 7730 and the ASHRAE 55:2010 comfort range

Table 7 reports the comparison between the comfort range calculated from the questionnaires for Groups 1 and 2, the comfort range recommended by ISO 7730 [34] and ASHRAE 55:2010 [35].

Comparing these data with temperature ranges recorded by sensors (Table 4), the temperature of the seminar room is considered to be acceptable and is always within the limits calculated by using the adaptive comfort model proposed by ASHRAE Standard 55: 2010 [35]. In the case of ISO 7730 [34] standard, the temperature is rarely above or below the recommended limits.

Focusing the analysis on a gender perspective, the temperature of the room is consistently within the comfort ranges for women and men in Group 1 (except for one case where the temperature measured by sensor 2fell sharply, probably due to opening doors and windows).

However, due to the large difference between the comfort range of females and males in Group 2, the temperature of the room is sometimes above the comfort range for males but never below, while for females the temperature is almost constantly within the comfort limit (except for the temperature recorded by sensor 2 located between two windows).

However, in Group 2, there is a significant difference between the comfort range of females and males. The room temperature is sometimes above the comfort range for males but never below, while for females the temperature is almost constantly within the comfort limit (except for the temperature recorded by sensor 2 located between two windows).

3.4. Comparisons between questionnaires and Fanger's PMV-PPD

The tables below report the results of the questionnaires with the calculated PMV and PPD according to seating position in the Seminar room. Table 8, corresponds to students seated in a central position, Table 9 corresponds to students seated close to the exterior façade and (Table 10) in the back rows.

The feeling of warmth is quite magnified in most of the questionnaire responses compared to the objective results where students reported a higher thermal sensation than that indicated by the objective data. The difference between subjective and objective results ranges from -1.06 to +2.96, although most of the time the subjective results are significantly higher than the objective results. As is reported in the table, the subjective analysis reveals that students need a cooler indoor environment.

Therefore, in general there is a low correlation between the PMV calculated from the results of the questionnaires and the PMV obtained from the experimental data which disagrees with [28].

4. Energy saving strategy

Retrofit operations in existing buildings imply acting on the envelope and on the conditioning systems. The former is extremely limited due to the fact that the interventions must preserve external aspects in iconic and historical buildings [8] as is the case of the Faculty of Architecture. The latter should consider effective and easy-to-implement strategies that do not entail drastic interventions.

In addition "a detailed envelope knowledge (opaque and transparent) is fundamental to identify thermal heat flow, thermal inertia, insulation level and proper retrofit actions" [45] [46] [47], since it allows the proper realization of simulations with reliable results.

4.1. Retrofitting options for the summer period

According to the occupants perception analyzed in the previous section, indoor temperatures are slightly high in this period (from June to September) which could imply the need to install an air conditioning system in the future. Counteracting the environmental and energy impact of air conditioning is one of the main objectives in the near future. Main retrofitting options to reduce or avoid the use of a cooling system are: Ventilative cooling [48] [46], increasing thermal mass [49], solar protection [50] and implementation of ventilated walls and roofs (Boeri, Antonini, Gaspari, & Longo, n.d.). These techniques can operate together or isolated and depend on exterior conditions, building design, and interior operational settings, some of them can be low effective or inapplicable for a particular building. For the case of Architecture Faculty, the implementation of ventilated walls and roofs, is almost impossible since the external aspect of the building has to be preserve as stated before; the increase of solar protection should cause a reduction on light available in the interior so, this technique is discarded. The increase of the internal mass is possible but it could be expensive and it probably will require works in combination with ventilation to be effective. Ventilative cooling can be applicable to this building and it is presented as an effective strategy in order to achieve the Kyoto Agreement, reducing the energy demand of buildings and providing adequate thermal comfort [52]. Many studies evaluate the benefits of natural ventilation and night ventilation [53] [54] [55], Some research works state that the peak temperature inside office buildings can be reduced between 0ºC and 2.6ºC for cross-ventilated buildings and between 0.2ºC and 3.5ºC in single-sided ventilation buildings [56]. Other studies show that for day and night ventilation of 4 ACH, the internal temperature is reduced by around 1ºC to 1.5ºC in the UK [57].

Consequently, the first and only strategy explored in this document for the summer season retrofitting of the building is the ventilative cooling since, as results demonstrated, it is enough to achieve comfort conditions.

4.2. Retrofitting options for the winter period

In order to reduce the energy consumption during this period, there are many possible strategies that can be divided in two main groups:

- Increasing the energy efficiency of the heating system.
- Reducing the energy requirements of the building.

In this work the focus is centered on the second group that also can be divided in three main categories:

- Losses reduction.
- Solar gain increasing.
- Energy recovery.

For each one of the precedent categories different techniques can be applied, but the simplest should have priority, since they could be easier to implement. Under this point of view, the alternatives considered in this paper are:

- Insulation (losses reduction).
- Thermal bridges (losses reduction).
- Windows (losses reduction and potential solar gain increment).
- Hear recovery ventilation (energy recovery).

5. Energy simulations

Selected strategies towards a NZEB are proposed in this paper and their impact quantified thanks to energy simulations which are divided into two main groups:

- **Simulations for the summer period:** as the building has no cooling equipment and temperatures can vary, a free floating simulation was performed considering different natural ventilation scenarios.
- **Simulations for the winter period** when the indoor temperature is controlled by a heating system. The aim of these simulations is to perform a diagnosis of the current building and to use this to suggest improvements to reduce the heating demand. Simulations were performed by separately analyzing different retrofit strategies (thermal bridges improvement, heat recovery, window replacement, insulation improvement) in order to determinate those actions with the highest impact. The main results were then analyzed. Finally, the scenario of a retrofitted building is proposed which complies with the target to either eliminate the use of the heating system or to reduce it

The simulation program used is LIDER, the official software used for regulation purposes in Spain [58]. LIDER uses a dynamic and multi-zone detailed simulation model to perform simulation in free floating mode and calculations of the heating and cooling requirements of buildings. The calculation engine of LIDER, is the evolution of the simulation software “S3PAS” which was developed in the University of Seville. S3PAS was validated with the

Building Energy Simulation Test (BESTest), [59] performed an experimental validation of several dynamic thermal simulation programs proving an excellent agreement between the results predicted by S3PAS and the measured data.

5.1. Simulations for the summer period

This set of simulations consider that in the absence of cooling equipment, indoor temperature varies as a result of heat gains, heat losses and heat stored. According to this, the first set of simulations analyses the impact of natural ventilation compared to the results of the "current state" and are classified into groups. (Table 11)

The current state considers that the users control the ventilation by manually opening and closing the windows. In order to estimate the current flow rates for the "normal" operation of the classroom, several simulations with different ventilation flow rates were performed until a good level of agreement between measured and simulated temperatures was achieved. The ventilation profile deduced by this technique is shown in Fig. 7.

5.1 Simulations for the winter period

The heating period in the building is between October and May (both inclusive) and from 06:00 to 20:00 on weekdays. Simulations performed for this period follow a real operating schedule, with the set point temperature at 20ºC. When the heating equipment is off, the temperature fluctuates freely.

6. Results

The results of the simulations are summarized in this section.

6.1 Results for the summer period

To evaluate the results of the free-floating summer simulations, a number of temperature ranges were established in order to calculate the percentage of hours in each range.

This procedure was performed only for the classroom studied, considering only the hours of occupancy. The results are shown in Table 12.

As the user´s comfort perception study suggested, the temperature range with greatest comfort corresponds to temperatures between 20°C and 22.5°C. The highest percentage of hours in this temperature range occurs in simulations 1.4, 1.5, 2.1, 3.1 and 3.2.

However, in all these simulations, with the exception of 1.4, there are temperatures below 17.5ºC. On the other hand, considering that in the group of simulations “2.x”, daytime ventilation is controlled by the manual opening of windows, it is reasonable to assume that in those days when the indoor temperature is low, the windows will remain closed.

Among the possible options, 2.1 is probably the best. This option has 4ach for nighttime ventilation whilst, during the daytime, the ventilation is controlled by the manual opening of windows. Strategy 2.1 reduces the percentage of hours in which the temperature exceeds 25 ° C from 13% to only 1%, and the temperatures between 22.5 ° C and 25 ° C drop from 51% to 23% .The temperature range with a greater degree of satisfaction (20 to 22.5 ° C) increases significantly, from 35% to 42%. However, according to the simulation, there are considerable periods in which the temperature would be below 20 ° C.

Nevertheless, as users would be responsible for daytime ventilation, it is expected that in the days with low temperatures, the ventilation would not be used, thus avoiding low temperatures inside the classroom.

6.2 Results for the winter period

As mentioned above, several simulations were performed in order to establish the current state of the building and to define possible improvements.

6.2.1. Current state of the building

The first simulation for the winter period was for the building in its current state. The result of the heating demand was 38.4 kWh/m^2 for the whole building, and 26.6 kWh/m^2 for the classroom studied.

According to the recorded data, the building energy consumption for heating in 2014 was 46.6 kWh/m^2. The difference with the simulation result is due to three factors: a) the Efficiency of the heating system, b) the differences between the actual user behavior and the assumed behavior for simulation purpose and c) the differences between actual climate conditions and climate data for simulations, since the latter are based on an average year.

For these reason the values obtained in the simulation can be considered consistent and useful for the analysis, in order to propose improvements in the building.

In the classroom studied, Seminar room 2.2, the heat losses broken down into the main components are shown in Figure 9. The three main components are: thermal bridges, ventilation and windows. Nevertheless, the loss distribution in the whole building and in the classroom studied is quite different, mainly due to the lack of an exterior roof.

For the whole building, the most important losses are due to thermal bridges, followed by ventilation losses. Heat losses through opaque elements (walls, roof and floor) are the lowest of all, suggesting an adequate insulation level for this building.

6.2.2. Thermal bridge improvement

Thermal bridges are the main cause of heat losses. The improvement suggested is to apply the recommendations set out in the official document proposed by the building energy regulations in Spain: document "DA DB-HE / 3 Puentes térmicos" (DA DB-HE / 3 Thermal bridges) "[60]. This document can be applied as a best practice guide.

Appling recommendations for thermal bridges, the heating demand of the building is reduced by 37%, obtaining a value of 24.3 kWh/m^2. For the studied classroom, the heating demand reduction is 39% with a value of 16.2 kWh/m$^{2.}$.

6.2.3. Heat recovery ventilation

Heat losses due to ventilation and infiltration are the second highest component in the heating demand of the building. To reduce these losses, a heat recovery system could be implemented by using an air-to-air heat exchanger. The overall efficiency of this kind of system can be close to 65% according to [61].

By using this strategy, the heating demand of the entire building is reduced to 31.4kWh/m^2 (18% reduction) and in the classroom studied to 19.4 kWh/m^2 (27% reduction).

6.2.4. Glazing improvement

To evaluate the effect of changing the glazing system, two alternatives available in the Spanish market were considered. Table 13 shows the main thermal characteristic of the glazing system.

The calculation takes into account the balance between gains (solar radiation entering the building) and losses.

Replacing all the windows of the building by the glazing system “Windows 1”, produces an increase in the heating demand of 4% (39.9 kWh/m^2)) in comparison with the current state of the building. Increasing the energy demand is a result of the lower solar factor “g” of the new glazing system. However, the heating demand for the classroom studied shows a reduction of 11% (23.5 kWh/m^2). The difference in the performance of the entire building and the classroom studied is mainly due to the fact that the classroom is north-facing, being this the main cause of a lower direct solar radiation gain, while for the south-facing areas of the whole building, the solar gains are significant. With “Windows 2”, the heating demand of the whole building is almost equal to the current state. But, as for “Windows 1” and for the same reason, in the classroom studied the heating demand drops 22% (20.7 kWh/m2). For these reasons, the improvement suggested should be to replace the glazing system of the north-facing windows.

6.2.5. Insulation improvement of exterior walls and roof

By adding exterior insulation (10cm polystyrene) to walls and roofs, the heating demand for the entire building drops 4% (37.0 kWh / m2), and in the classroom 2% (25.9 kWh / m2).

A greater insulation thickness would not be realistic and neither would it increase savings considerably. It can be assumed that the current insulation is suitable for the climate and operating conditions of this building.

7. Retrofitted building scenario

The results show that those interventions with the highest impacts relate to the improvement of thermal bridges, natural ventilation in summer and heat recovery ventilation in winter. Whilst the improved thermal insulation of walls and roofs does not significantly reduce the heating demand. In summer, comfort is improved thanks to natural ventilation. The glazing system should be modified in north-facing facades to “Windows 2” but no changes should be made to the south-facing facade.

With the previous considerations, the proposed retrofitted building should consider the following improvements. In this scenario, the heating demand of the whole building is 16.1 kWh / m^2 instead of the initial 38.4 kWh / m^2. In the case of the seminar room, the heating demand is 6.2 kWh / m^2 instead of the initial 16.2 kWh / m^2.

The results show a potential energy saving of up to 58% in the whole building and up to 62% in the classroom studied.

- Improved thermal bridges following recommendations of document DA DB-HE / 3 Puentes térmicos (Thermal bridges)" [60].
- Daytime natural ventilation (4 ach) where users open and close the windows in order to control ventilation. At nighttime, ventilation is performed from 23:00 to 08:00 during the summer season.
- Heat recovery ventilation by means of air-to-air heat exchangers
- Replace glazing system in north-facing façades with option "Windows 2"

The result of the heating demand for each individual improvement and for the proposed retrofitted building is showed in (Fig. 10). The heat losses by component of the retrofitted building are shown in (Fig. 11). The heat losses are more balanced than in the current building due to a reduction of the heat losses for those components with the greatest impact. Nevertheless, for the classroom studied, the proportion of the contribution of the windows has been increased as the reduction of thermal bridges and ventilation is proportionally greater.

7.1. Reduction of the heating period in the retrofitted scenario

The analysis of the monthly heating demand makes it possible to determine the operating period of the heating equipment and a potential operating time reduction.

Figure 12 shows the comparison of the monthly heating demand of the building for both current state and retrofitted. The heating demand of the retrofitted building is lower than current building, and above all, the heating period required is shorter: from November to April, two months less.

7.2. Analysis of the free-floating mode in the winter period

The last analysis was performed under the assumption that the building operates without heating equipment during the winter season. The results of this simulation were limited to the classroom studied, since the results show that in general, heating would be only necessary in several areas of the building. Table 14 shows the percentage of hours at different temperature ranges in the occupancy period during the winter season.

Comparing the current state with the retrofitted scenario, the hours with a temperature below 15°C are reduced from 61% to just 5%. Moreover, the percentage of hours with a temperature within the 20°C - 25°C range, increases from 29% to 42%. This indicates a clear increase in comfort conditions inside the building as a result of the refurbishment.

However, in the retrofitted condition, the percentage of hours between 17.5ºC and 20ºC is 53%, this means that there is a considerable amount of time in which conditions may be outside the comfort limits. It is therefore necessary to use a heating system in order to increase the temperature to at least 20C.

8. Conclusions

Good indoor comfort and air quality are essential for correct educational development considering the long hours that students spend in buildings of this type.

Most reports in this field focus on primary and secondary school buildings, with numerous projects conducted in the Mediterranean Zone. However, little has been done in the context of university buildings, where the typological features and use patterns seem to be closer to office buildings. Thus, this research wants to highlight the need to act on the particular typology, which merits an individual analysis and tailored approach.

In this context, this paper discusses the critical issue of dealing with energy and comfort in a particular building, the Faculty of Architecture in San Sebastian.

This article proposes a method to define and assess energy saving strategies based on the comfort analysis made by real users. The proposed method consists of a study and definition of best energy retrofit strategies based on student comfort preferences under real conditions. User preferences have been considered as an energy saving opportunity.

- **Results of the subjective and objective comfort analysis:** The comparison of results obtained by an objective approach applying Fanger and Adaptive Models and results obtained by a subjective approach conducted by a questionnaire campaign showed unexpected results: The comfort range for university students, during their activity in the classroom, is quite different from that stated by a conventional comfort analysis.

Users achieve comfort conditions at lower temperatures, with noteworthy differences between men and women, and the seating position in the classroom.

- **Retrofitting strategies for the summer period:** It has been demonstrated that, using natural ventilation, it is possible to achieve comfort conditions without an air conditioning system in the summer and shoulder seasons. The optimal ventilation mode for the case study is 4ACH ventilation during the daytime and nighttime, controlled by the manual opening of windows. Thanks to this strategy the percentage of hours in which the temperature exceeds 25 ° C is reduced from 13% to just 1%, whilst the temperatures between 22.5 ° C and 25 ° C are reduced from 51% to 23% . The temperature range with the greatest degree of satisfaction (20 to 22.5 °C) increases significantly, from 35% to 42%. However, according to the simulation, there are considerable periods in which the temperature would be below 20 ° C. Nevertheless, as users would be responsible for daytime ventilation, it is expected that in the days with low temperatures, ventilation would not be used, thus avoiding low temperatures inside the classroom. The need for lower temperatures (20-22.5ºC) combined with high internal gains mainly due to computers and lighting, comprise the first strategy to reduce the heating needs.
- **Retrofitting strategies for the winter period:** the key measures that make it possible to achieve comfort conditions, work together with energy saving strategies, that can be achieved through effective interventions in the buildings:
    - eliminating thermal bridges
    - using an air-to-air heat recovery system
    - improving the windows in the north façade of the building.

In this scenario, the heating demand of the entire building is 16.1 kWh / m^2 instead of the initial 38.4 kWh / m^2. In the case of the seminar room, the heating demand is 6.2 kWh / m^2 instead of the initial 16.2 kWh / m^2. The results show a potential energy saving of up to 58% in the whole building and up to 62% in the classroom studied.

Furthermore, the new heating period for the Faculty of Architecture is from November to April, a reduction of two months.

Any intervention in existing buildings is frequently complicated due to the limitation imposed by its historical and architectural importance; moreover the budget for the intervention is often limited. Therefore, in these cases the achievement of NZEB should be considered as a path where interventions, changes and improvements must be prioritized, as demonstrated in this study, must be based on actual climate conditions and user-dependent.

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Figure 1. Architecture Faculty floor plan. Location of sensors.

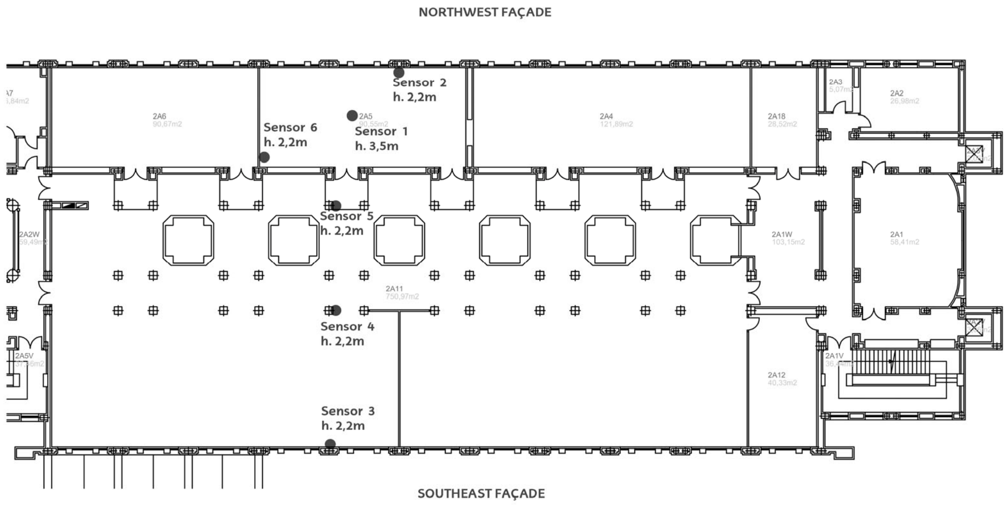

Figure 2. Temperature variation in a typical spring week: from 25th April to 1st May 2016.

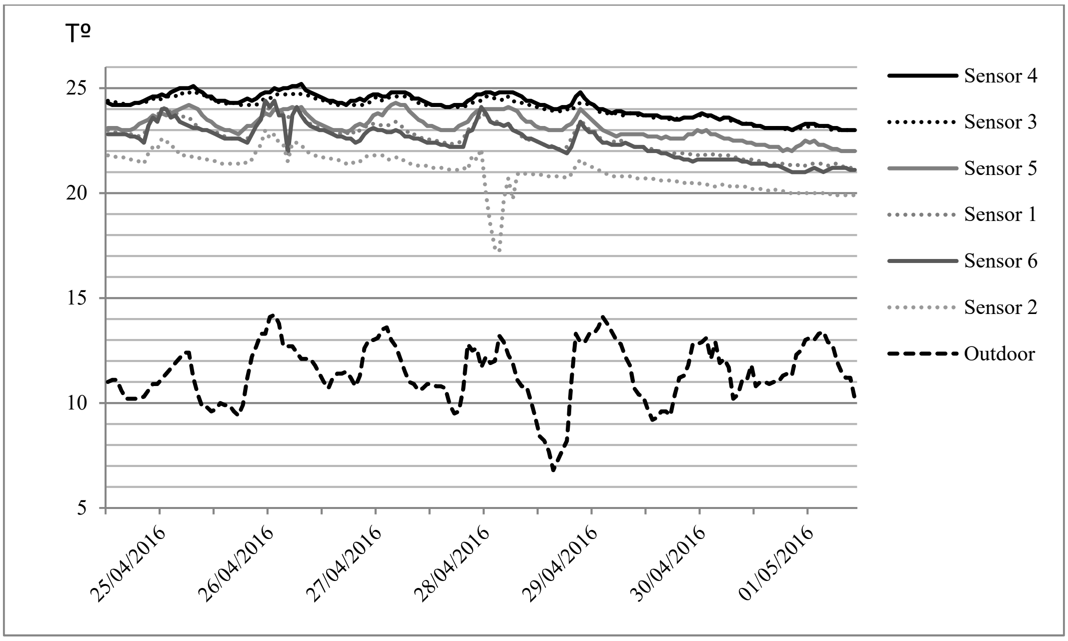

Figure 3. Relative Humidity variation in a typical spring week: from 25th April to 1st May 2016.

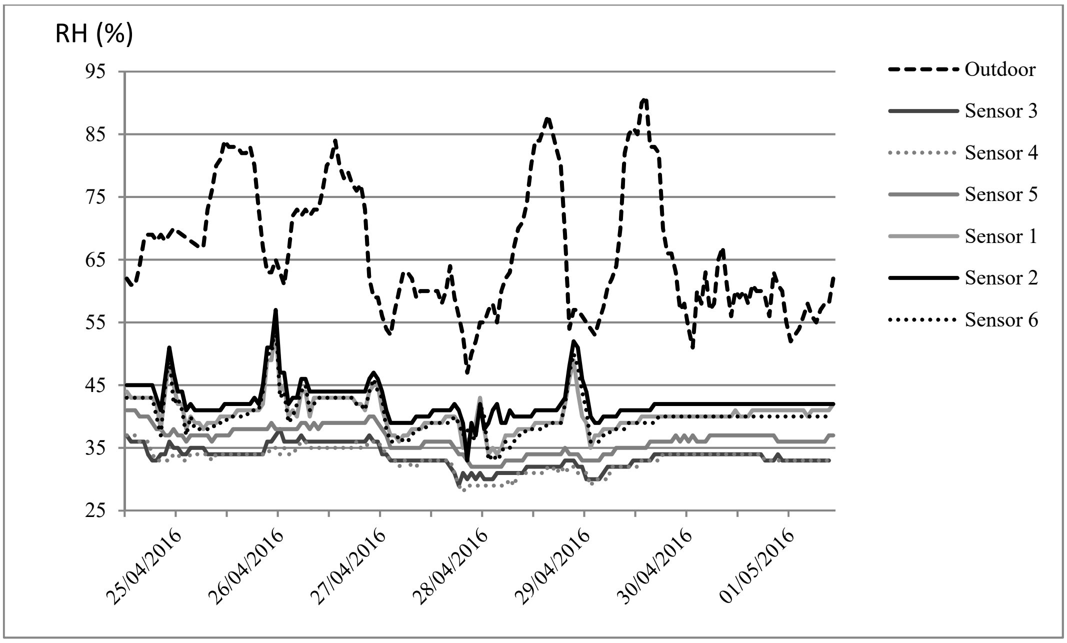

Figure 4. View of the exterior façade. Architecture Faculty.

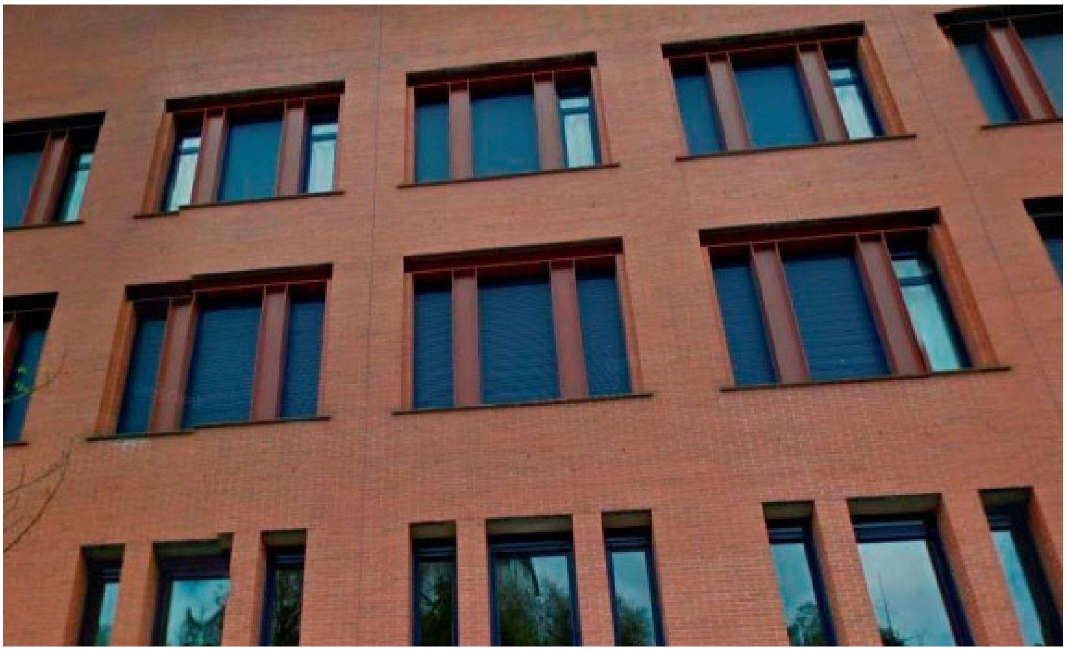

Table 1. Neutral temperature – Tn and comfort range for the 4 student´s groups.

		Tn (ºC)	**Comfort zone (ºC)**
GROUP 1	TOTAL	20.5	18-23
	FEMALES	22.3	19.8-24.8
	MALES	22.2	19.7-24.7
GROUP 2	TOTAL	21	18.5-23.5
	FEMALES	25	22.5-27.5
	MALES	21	18.5-23.5

Table 2. Results of the questioning campaign and calculated PPD, subjective approach.

DAY	**TIME**	**Students**	**Male**	**Female**	**TSV**	**TPV**	**Acceptability(%)**	**PPD(%)**
April 25	9:15	19	13	6	0.94	-0.8	36.8	*23.7*
April 25	15:15	11	7	4	1.18	-1.1	54.5	*34.3*
April 26	10:00	19	8	11	0.84	-0.3	68.4	*19.9*
April 26	16:30	8	1	8	-0.4	0.25	100	*7.8*
April 26	18:45	11	5	6	1.27	-1	81.8	*38.7*
April 27	10:00	9	6	3	0.66	-0.6	66.7	*14.2*
April 27	12:30	6	4	2	1	-0.8	83.3	*26.1*
April 28	9:15	29	17	12	0.44	-0.4	68.9	*9.0*
April 28	13:30	38	27	11	0.15	-0.1	57.9	*5.5*
April 28	15:15	12	7	5	1.66	-1	50	*59.6*
April 29	9:00	21	10	11	0.38	-0.3	52.4	*8*
April 29	11:00	20	9	11	1.35	-0.9	55	*42.9*

Table 3. Results of the questioning campaign according to student´s position in classroom

		Central position	**Close to exterior facade**	**Back rows**
Day	**Time**	**TSV**	**TSV**	**TSV**
April 25	9:15	+0.83	+0.7	+2
April 25	15:15	+0.75	+1.5	-
April 26	10:00	+0.83	+0.91	0
April 26	16:30	-1	0	0
April 26	18:45	0	+1.44	+0.5
April 27	10:00	+0.75	+0.25	+2
April 27	12:30	+1	+0.75	+2
April 28	9:15	-0.33	+0.65	0
April 28	13:30	0	+0.07	+0.6
April 28	15:15	+2	+1.75	0
April 29	9:00	-0.16	+0.38	+2
April 29	11:00	+1.66	+1.25	+1.4

Table 4. Results of the field measurements, Tº and Relative Humidity

DAY	**TIME**	**TEMPERATURE (ºC)**			**RELATIVE HUMIDITY (%)**		
		Sensor 1	**Sensor 2**	**Sensor 6**	**Sensor 1**	**Sensor 2**	**Sensor 6**
April 25	9:15	22.8	21.4	22.5	39	41	39
April 25	15:15	23.7	22.2	23.5	39	40	38
April 26	10:00	23.2	22	23.2	51	51	50
April 26	16:30	23.8	22.3	23.6	41	43	40
April 26	18:45	24	22.6	24.1	44	47	45
April 27	10:00	23.1	21.7	22.8	44	46	44
April 27	12:30	23.3	21.8	23.2	45	46	45
April 28	9:15	22.6	21.3	22.2	35	38	36
April 28	13:30	23.9	22.2	24.2	43	43	42
April 28	15:15	23.4	17.7	23.3	34	41	33
April 29	9:00	22.6	20.9	22.2	42	43	42
April 29	11:00	23.4	21.6	23.4	49	52	50

Table 5. PMV and PPD calculated by objective approach

		Sensor 1		**Sensor 2**		**Sensor 6**	
DAY	**TIME**	**PMV**	**PPD (%)**	**PMV**	**PPD (%)**	**PMV**	**PPD (%)**
April 25	9:15	0.2	5.93	-0.2	5.43	0.08	5.13
April 25	15:15	0.4	8.45	0.02	5.01	0.29	6.81
April 26	10:00	0.4	7.92	0.04	5.03	0.3	6.92
April 26	16:30	0.4	9.07	0.06	5.07	0.33	7.27
April 26	18:45	0.5	10.33	0.15	5.47	0.48	9.72
April 27	10:00	0.3	7.03	-0.1	5.07	0.18	5.65
April 27	12:30	0.4	7.67	-0	5.03	0.27	6.54
April 28	9:15	0.1	5.43	-0.2	5.76	-0	5
April 28	13:30	0.5	9.74	0.04	5.03	0.48	9.77
April 28	15:15	0.3	6.99	-1	24.49	0.22	5.99
April 29	9:00	0.2	5.73	-0.3	6.32	0.03	5.02
April 29	11:00	0.4	8.43	-0.1	5.04	0.35	7.54

Table 6. Neutral temperature according to different adaptative comfort models

COMFORT MODELS	**Tn (ºC)**	Formula [$T_{a,out}$ = average monthly outdoor temperature]
Humphreys [44] (1976)	18.74	$Tn=11.9+0.534\cdot T_{a,out}$
Auliciems [45] (1981)	21.57	$Tn=17.6+0.31\cdot T_{a,out}$
Griffiths [46] (1990)	18.94	$Tn=12.1+0.534\cdot T_{a,out}$
Nicol et al [47] (1993)	21.86	$Tn=17+0.38\cdot T_{a,out}$
Brager-De Dear [48] (1998)	21.77	$Tn=17.8+0.31\cdot T_{a,out}$
Humphreys-Nicol [49] (2002)	20.41	$Tn=13.5+0.54\cdot T_{a,out}$

Table 7. Subjective and objective comfort range comparisson

	GROUP 1	**GROUP 2**	**ISO 7730**	**ASHRAE 55:2010**	
	PPD<10%			PPD<10%	PPD<20%
Comfort range [ºC]	18-23	18.5-23.5	20-24	19.3-24.3	18.3-25.3

Table 8. Results comparison of the subjective and objective approach in student´s seated in a central position in classroom.

DAY	TIME	PMV			PPD	
		Subjective	**Objective**	**Difference**	**Subjective**	**Objective**
25-April	9:15	0.7	0.21	0.49	15.3	5.93
25-April	15:15	1.5	0.41	1.09	50.9	8.45
26-April	10:00	0.91	0.37	0.54	22.48	7.92
26-April	16:30	0	0.44	-0.44	5	9.07
26-April	18:45	1.44	0.51	0.93	47.65	10.33
27-April	10:00	0.25	0.31	-0.06	6.29	7.03
27-April	12:30	0.75	0.36	0.39	16.84	7.67
28-April	9:15	0.65	0.14	0.51	13.87	5.43
28-April	13:30	0.07	0.48	-0.41	5.1	9.74
28-April	15:15	1.75	0.31	1.44	64.4	6.99
29-April	9:00	0.38	0.19	0.19	8	5.73
29-April	11:00	1.25	0.41	0.84	37.72	8.43

Table 9 Results comparison of the subjective and objective approach in student´s seated close to the exterior façade in classroom.

DAY	TIME	PMV			PPD	
		Subjective	**Objective**	**Difference**	**Subjective**	**Objective**
25-April	9:15	0.83	-0.15	0.98	19.53	5.43
25-April	15:15	0.75	0.02	0.73	16.84	5.01
26-April	10:00	0.83	0.04	0.79	19.53	5.03
26-April	16:30	-1	0.06	-1.06	26.11	5.07
26-April	18:45	0	0.15	-0.15	5	5.47
27-April	10:00	0.75	-0.06	0.81	16.84	5.07
27-April	12:30	1	-0.04	1.04	26.11	5.03
28-April	9:15	-0.33	-0.19	0.14	7.26	5.76
28-April	13:30	0	0.04	-0.04	5	5.03
28-April	15:15	2	-0.96	2.96	76.76	24.49
29-April	9:00	-0.16	-0.25	0.09	5.53	6.32
29-April	11:00	1.66	-0.05	1.71	59.6	5.04

Table 10 Results comparison of the subjective and objective approach in student´s seated in the back rows in classroom.

DAY	**TIME**	**PMV**			**PPD**	
		Subjective	**Objective**	**Difference**	**Subjective**	**Objective**
25-April	9:15	2	0.08	1.92	76.76	5.13
25-April	15:15	-	0.29	-	-	6.81
26-April	10:00	0	0.3	-0.3	5	6.92
26-April	16:30	0	0.33	-0.33	5	7.27
26-April	18:45	0.5	0.48	0.02	10.22	9.72
27-April	10:00	2	0.18	1.82	76.76	5.65
27-April	12:30	2	0.27	1.73	76.76	6.54
28-April	9:15	0	-0.01	0.01	5	5
28-April	13:30	0.6	0.48	0.12	12.54	9.77
28-April	15:15	0	0.22	-0.22	5	5.99
29-April	9:00	2	0.03	1.97	76.76	5.02
29-April	11:00	1.4	0.35	1.05	45.51	7.54

Table 11. Simulation description

Simulation Group 1 (*)	Simulation 1.2	1 ach
	Simulation 1.3	2 ach
	Simulation 1.4	5 ach
	Simulation 1.5	10 ach
Simulation Group 2 (**)	Simulation 2.1	4 ach
	Simulation 2.2	8 ach
	Simulation 2.3	12 ach
	Simulation 2.4	16 ach
	Simulation 2.5	24 ach
Simulation Group 3 (***)	Simulation 3.1	1 ach(day), 4 ach (night)
	Simulation 3.2	2 ach(day), 4 ach (night)
	Simulation 3.3	5 ach(day), 8 ach (night)
	Simulation 3.4	10 ach(day), 12 ach (night)
	Simulation 3.5	10 ach(day), 24 ach (night)

(*)Diurnal ventilation coinciding with the classroom occupation and with the following flow rates
(**)At daytime, the current ventilation is maintained, namely, the users opens and closes the windows in order to control ventilation. At night, ventilation is performed from 23:00 to 08:00 during summer season.
(***)A combination of daytime and night ventilation.

Table 12. Percentage of hours at each temperature range

Temperature ranges	Current	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	3.5
27.5ºC<= T < 30ºC	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
25ºC<= T < 27.5ºC	13%	15%	9%	5%	3%	1%	0%	0%	0%	0%	2%	1%	1%	1%	1%
22.5ºC<= T < 25ºC	51%	53%	48%	32%	22%	23%	14%	9%	7%	5%	23%	21%	11%	11%	9%
20ºC<= T < 22.5ºC	35%	32%	38%	41%	41%	42%	34%	28%	25%	22%	42%	41%	30%	25%	22%
17.5ºC<= T < 20ºC	1%	0%	5%	22%	28%	31%	36%	39%	37%	35%	31%	32%	37%	37%	35%
15ºC<= T < 17.5ºC	0%	0%	0%	0%	6%	3%	15%	22%	25%	29%	3%	5%	19%	21%	25%
10ºC<= T < 15ºC	0%	0%	0%	0%	0%	0%	1%	3%	6%	10%	0%	0%	2%	5%	9%
T < 10ºC	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 13. Glazing systems considered for the improvement of the building

	Glasses		**Frame**	
	g	**U [W/m^{2}K]**	**Description**	**U [W/m^{2}K]**
Current glazing system	0.7	2.80	Aluminium	4.0
Windows 1	0.62	1.8	Aluminium, with thermal break	2.0
Windows 2	0.62	1.4	Aluminium, with thermal break	2.0

Table 14. Percentage of hours at different temperature ranges in winter period

Temperature	**Current state**	**Retrofitted**
25ºC<= T < 27.5ºC	0%	0%
22.5ºC<= T < 25ºC	10%	22%
20ºC<= T < 22.5ºC	19%	20%
17.5ºC<= T < 20ºC	10%	53%
15ºC<= T < 17.5ºC	33%	5%
10ºC<= T < 15ºC	28%	0%
T < 10ºC	0%	0%

Figure 5. Seminar room 2.2 plan and location of sensors 1, 2 and 6.

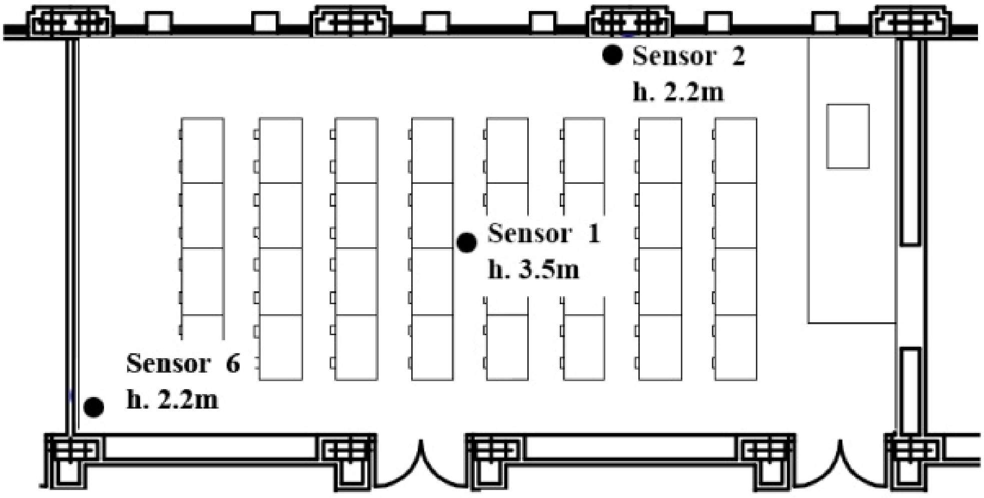

Figure 6. Interior view of Seminar room 2.2. Students working with their computers.

Figure 7. Ventilation rate pattern in seminar room 2.2

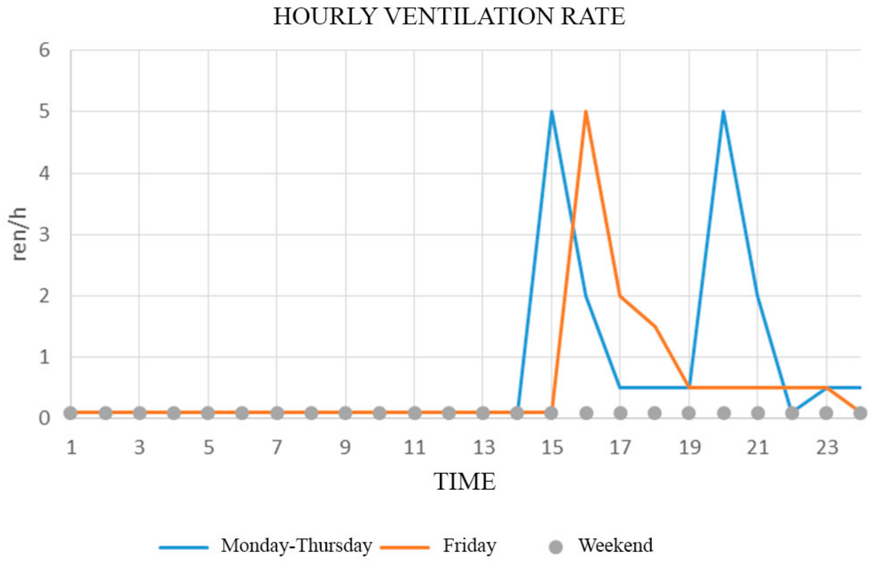

Figure 8. Internal gains pattern in seminar room 2.2.

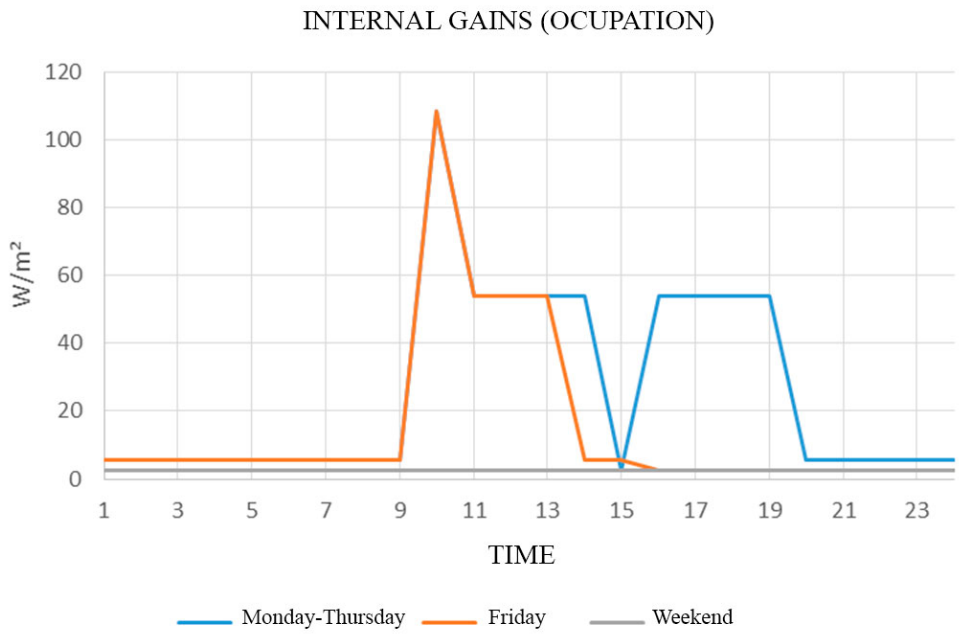

Figure 9. Heat losses distribution in the current building. (For the windows, the information showed is the difference between net heat losses and net solar gains).

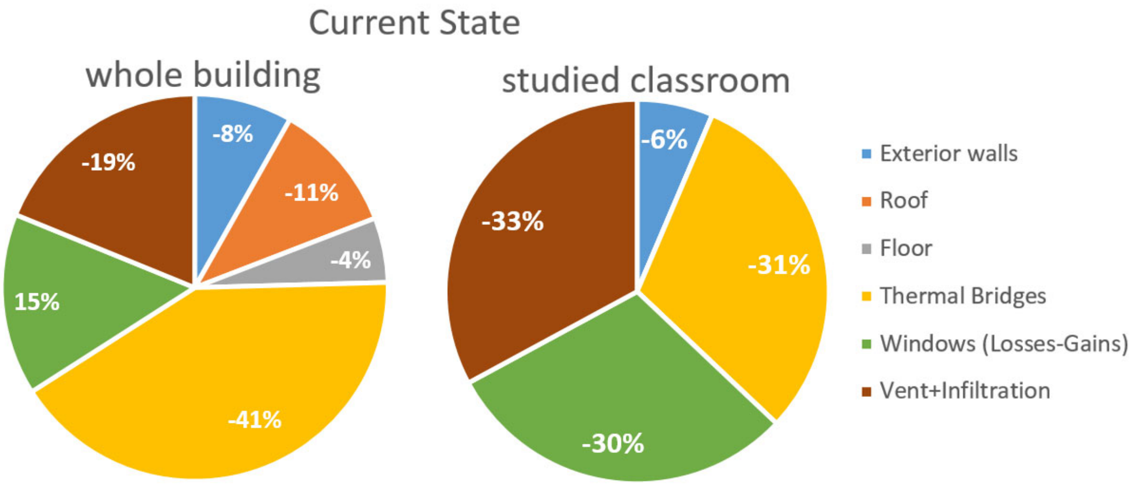

Figure 10. Summary of the heating demand under the different scenarios

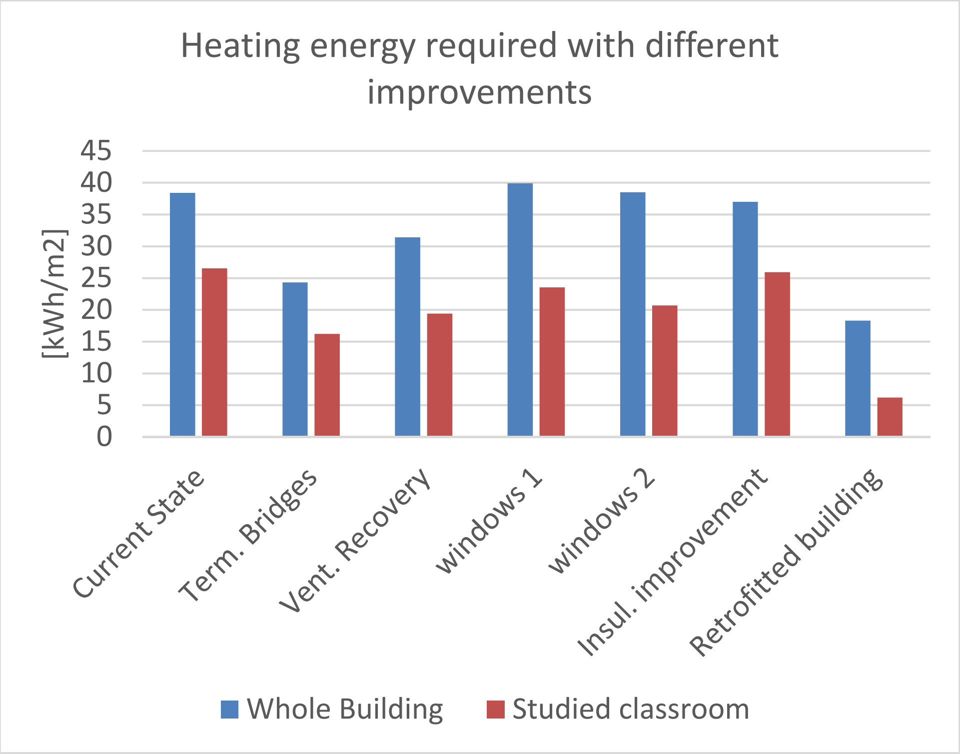

Figure 11. Heat losses distribution in the building improving thermal bridges, windows and energy recovery from expulsion air. (For windows, the information showed, is the difference between net heat losses and net solar gains.).

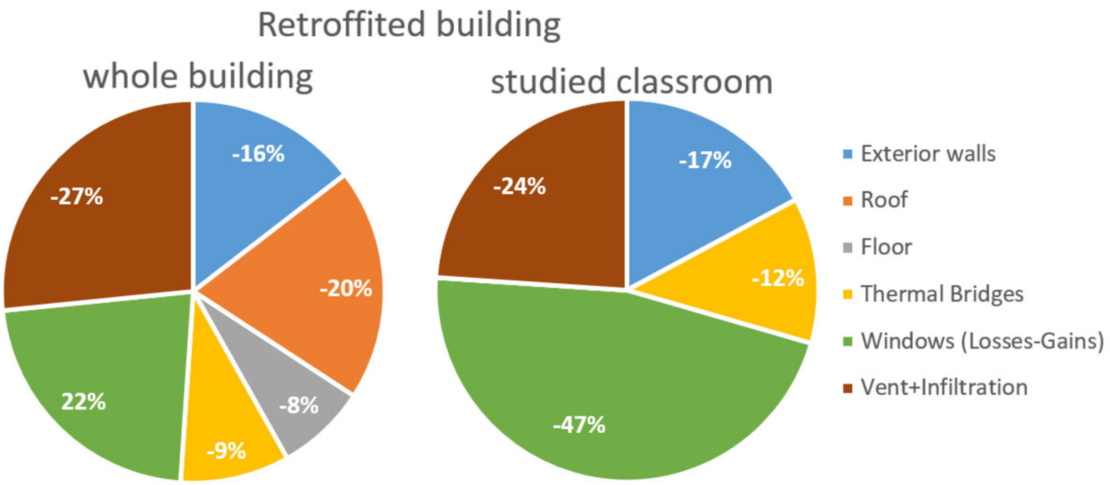

Figure 12. Comparison between monthly heating demand of the current building and the improved building.