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Master of Science in Mechanical Engineering
Department of Mechanical and Aerospace Engineering

Master Thesis

Assessment of the Indoor Environmental Quality in a typical K-12 school in the Lisbon area

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Academic Year 2019/2020

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Acknowledgements

I would first like to thank my Portuguese supervisor Dr. Rui Pedro da Costa Neto for his patience and support demonstrated from the beginning to the very end. His constant trust in my work gave me a stronger motivation to carry out this project providing my best effort.

I sincerely acknowledge Prof. Paolo Tronville for his expertise and precious advice.

I should also remark my gratitude to Dr. Ricardo Gomes for his extremely helpful suggestions which allowed me to clarify doubts and uncertainties.

A special mention goes to Prof. Carlos Santos Silva that introduced me to the subject with interest and curiosity.

I would also express a sincere thanks to all *Escola Conde de Oeiras staff*, in particular to Prof. Inês Carvalho and Prof. Carlos Figuera who were always available and courteous during the various visits.

Finally, this accomplishment could not possible without the encouragement of my parents and the people who shared with me the toughest moments.

Abstract

Public buildings represent an important opportunity to depict suitably how energy efficiency may impact on the two most crucial aspects: management costs and indoor environmental quality. In this regard, many of the secondary schools in Portugal are facing the structural decay of their facilities. Among all, *EB23 Escola Conde de Oeiras,* built in 1982 in Lisbon district, must enhance its current energy performance in order to guarantee acceptable environmental conditions to students and employees. To accomplish that, it needs to define a number of measures that could provide immediate and permanent effects.

With this premises, the present study aims to identify a systematic approach to assess indoor environmental quality before and after the implementation of adequate energy efficiency measures for *Escola Conde de Oeiras*. To pursue this purpose, it was carried out the detailed study of its principal facilities in three main phases, namely: *creation of the geometrical model* with *Google SketchUp* and *OpenStudio*, *dynamical thermal simulation* of buildings with *Energy+*, *results analysis and discussion*.

Outcomes proved that thermal discomfort is mainly induced by excess of solar gains and poor insulation degree caused by glass surfaces. As a consequence, it is shown that all the thermal zones do not comply with comfortable acceptability limits provided by ISO 16798 standards.

Therefore, once assessed the performance of three new types of double-glazing systems, it was identified as the best option the installation of *selective low emissivity* glass with a *thermal break aluminium frame.* With this new type of windows, it was estimated an average of 30% less time of discomfort in four of the six buildings examined. In addition to this first measure, it was study, for various thicknesses of expanded polystyrene (EPS), whether the realisation of thermal coat could provide benefits or not. What emerged was that only for one type of building, namely pavilion with classrooms, it was advantageous to install 12cm of EPS insulating layer.

Successively, the study examines how the measures above could affect other aspect of environment quality, namely: indoor air quality, visual and acoustic comfort. It was first evaluated the design of a mechanical ventilation systems that has to meet an increased need of air changes caused by the improved sealing of new windows. Then, it was analysed the glass trade-off between natural daylight requirements and solar gains reduction. Subsequently, acoustic insulation standards provided by ISO 12354 are discussed.

Finally, it is proposed the project evaluation of the investment alternatives available for the school.

1 Introduction and aim of the study

Escola Conde de Oeiras, a lower secondary school (5th and 6th grade) in Lisbon district, has some critical inefficiencies which affect significantly indoor environmental comfort of students, employees, staff members and electricity and gas consumption.

As a prevailing aspect, many constructive elements have never been replaced since 1982, year in which the school complex was built, and they are now facing their natural decay. The most practical example is represented by doors and windows: poor sealing, low degree of insulation and sometimes their complete inoperability are the most are the most frequent cause of uneasiness. Besides, glass surfaces are obsolete and therefore the excess of solar gains may be unbearable during the hottest months.

All these factors converge towards the main issue that is, essentially, thermal discomfort. According to the period of the year, occupants have to deal with three major types of discomfort:

- thermal discomfort due exceedingly warm environment mainly caused by the abundance of solar gains.
- thermal discomfort due to exceedingly cold environment, mainly caused by absence of space heating systems and poor air tightness.
- discomfort due to poor air quality, mainly caused by the absence of mechanical ventilation systems especially needed in highly occupied spaces with large CO_2 concentration.

Given these premises, the focus of the study was addressed on the alternatives that the school may take into account to evaluate eventual structural interventions scenarios.

Aiming to provide reasonable options, it was planned a systematic path which consisted in three phases:

i. Development of the virtual geometric model of the buildings which are part of the school complex through the collection of all the most useful pieces of information regarding: materials of the constructive elements, people activity in the facilities, presence of electric equipment etc.
ii. Exportation of the created geometry into a thermal simulation software environment.
iii. Outcomes analysis and comparisons.

Thus, all the possible options were evaluated according to two fundamental criteria: indoor environmental quality enhancement and economic convenience.

The prevailing intent of the present work was to demonstrate, with the use of tools of the thermal analysis, that pursuing energy efficiency measures is not only a way to meet regulations standards, but also a project for future energy independence and resources optimization.

2 Energy consumption in schools

Among all type of buildings, schools have a ‘major social responsibility as they can be used as communication means towards pupils and their families, and can thus reach many different society groups’ [1]. Besides, educational-purpose buildings contribute to a considerable part of the total amount of energy consumption of a country due to their numerosity. It is also to take into account that, after salaries of teachers and staff, energy costs are the second most significant expense in the overall schools’ running costs [2].

In this chapter it is intended to provide the reader with key information about schools’ consumption which may ease him to make comparison with the case study.

2.1 Worldwide average energy use

If on one hand data concerning energy consumption in public school is often available and relatively easy to access, on the other hand these are mostly not disaggregated. Consequently, the difficulty in categorizing the consumptions by end-use technology greatly increases.

According to the records of U.S. Department of Energy the average energy use profile of schools can be illustrated in the pie-chart of Fig. 1.

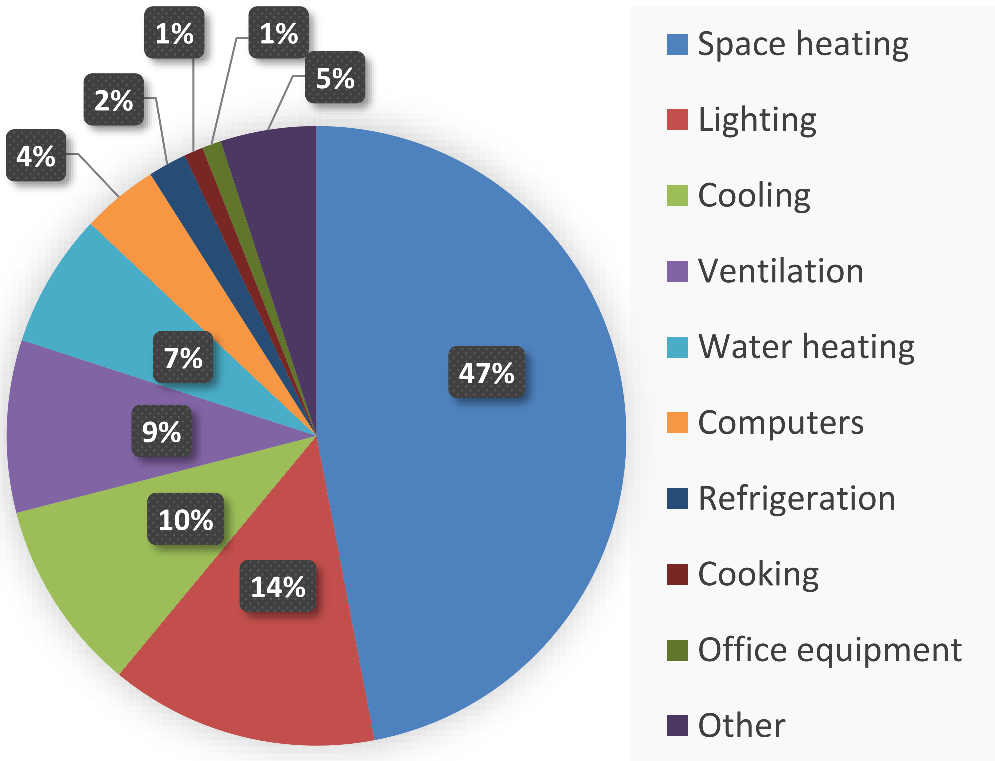


Figure 1 - Average energy use profile for U.S. schools [22].

Hence, lighting, ventilation, heating and cooling account for 80% of energy consumption. However, it may be inaccurate to assume the same percentages for European schools, and in particular for the case study, for two main reasons:

a) Schools are not classified according to the climate zone they belong to.
b) Schools are not categorized by type: primary, secondary, nursery etc.

These aspects rise the need to include additional parameters in the analysis that can make the comparison between two buildings as fair as possible. In this regard, specific energy consumption (SEC) represents a useful indicator that allows to compare similar facilities. It is usually expressed in kWh/m^2 per year.

Thus, as reported in [3], a good way to deal with issue (a) is to normalise energy intensity through a climate adjustment based on Heating Degree Days (HDD) or Cooling Degree Days (CDD). An example is reported in table 1:

Table 1 - Reference values for school specific consumption [3].

Country	HDD[1] 2015	kWh/m^2/year	Wh/m^2/year/HDD
Denmark	3133	95	30.3
Italy	1809	86	47.5

According to these values, it can be stated that Denmark schools in 2015 were, on average, more efficiently since having almost twice the HDD of Italy they need just 9% more energy.

As far as point (b) is concerned, various authors [3] share the idea that consumptions tend to increase with the level of education. Indeed, it is quite intuitive to acknowledge that high school students have access to numerous energy demanding services, like computer lab, libraries, study rooms, whereas children from primary do not.

In conclusion, to assess whether a school is less or more efficient than another, these should be located in the same climate area and have similar educational levels. Once acknowledged these considerations, it was expected to outline the benchmark of energy consumption of Portuguese secondary schools.

[1] Source: Eurostat

2.2 Energy consumption benchmark of Portuguese schools

In 2007 Portuguese government launched *Modernization of Public Secondary Schools Program* aiming to contrast the structural obsolescence that characterized an increasing number of buildings. To reach this scope, a state-owned company named *Parque Escolar* (PE) was found and after a few months it tried to schedule the retrofit 332 schools by 2015. After six years (in 2013) R&D unit of Coimbra University was commissioned to assess the performance improvements registered in those schools that were completely refurbished.

Thus, professors da Silva, Bernardo, Antunes and Jorge drew up a paper [4] in which was analysed and discussed energy consumption data from 57 schools. This information proved to be particularly interesting due to their affinity with the topics covered in the present study.

In this passage, are shown some extracts of [4] that could provide some reference values of SEC to compare with the case study of *Escola Conde de Oeiras*.

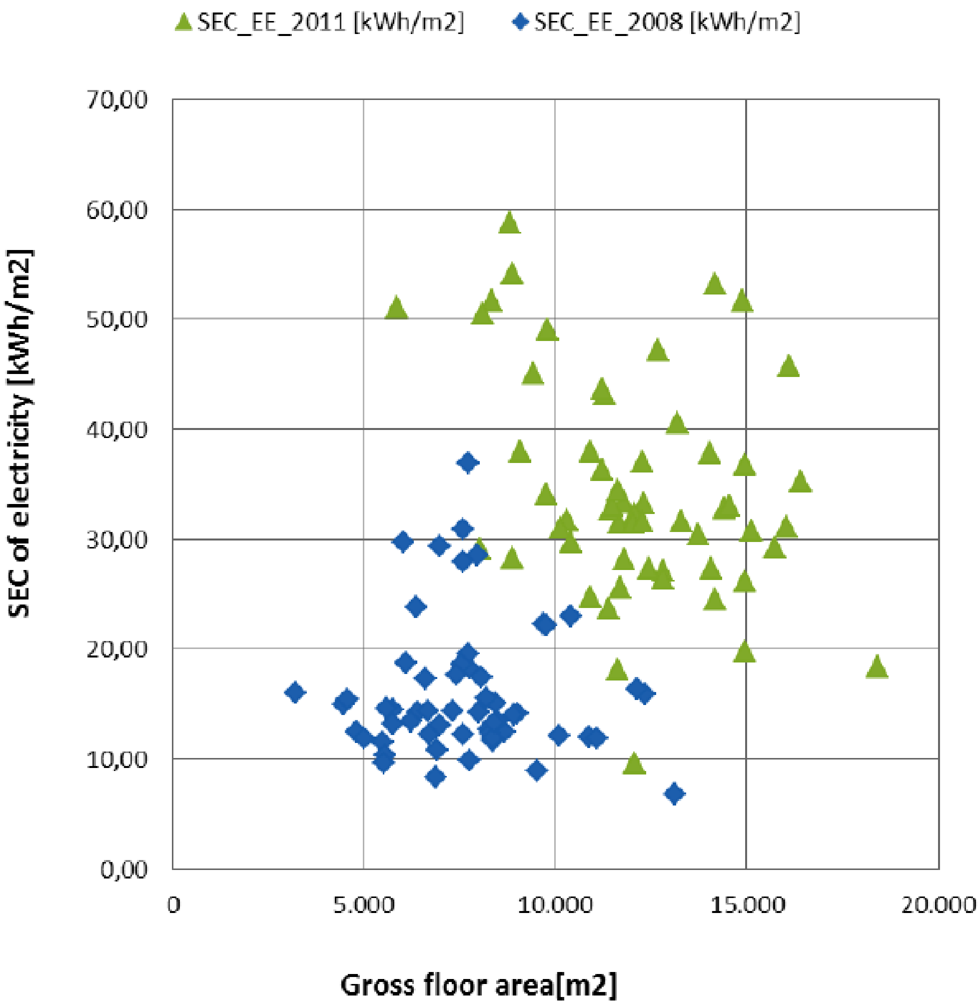


Figure 2 - Specific energy consumption of schools before (2008) and after (2011) the complete refurbishment [4].

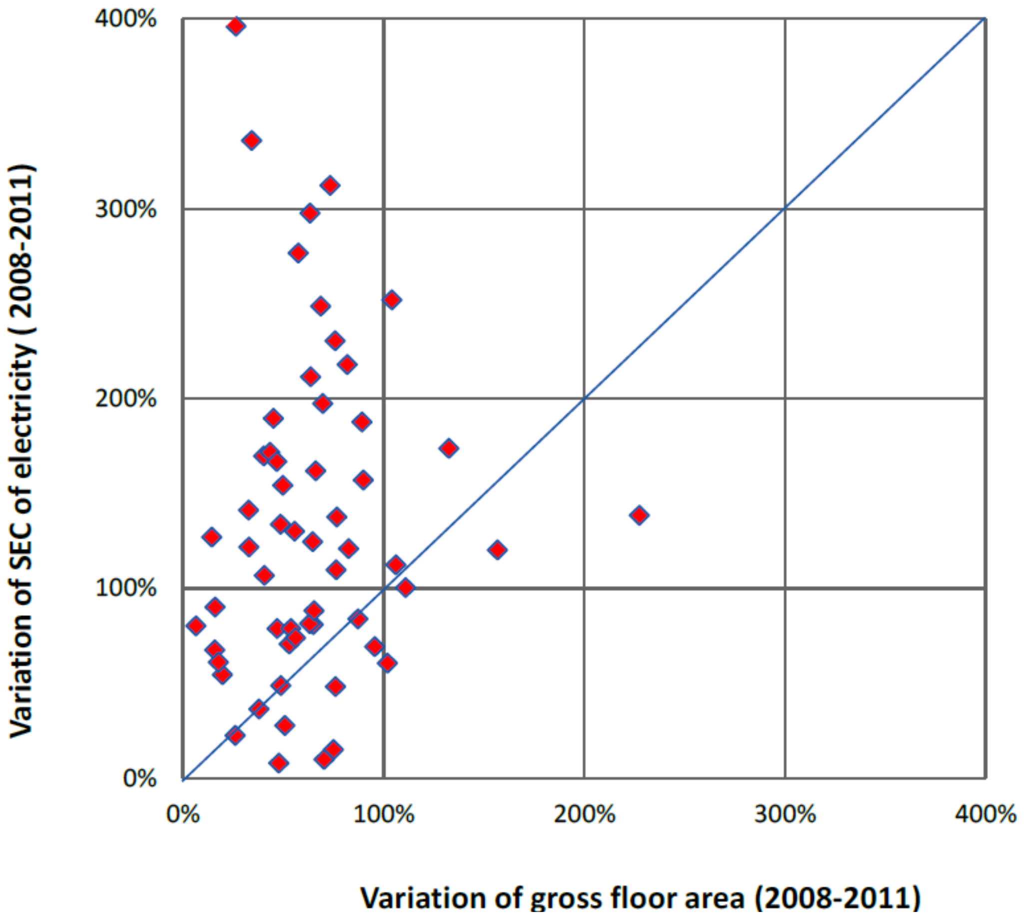


Figure 3 - Variation of Specific energy consumption vs. variation of gross floor area [4]

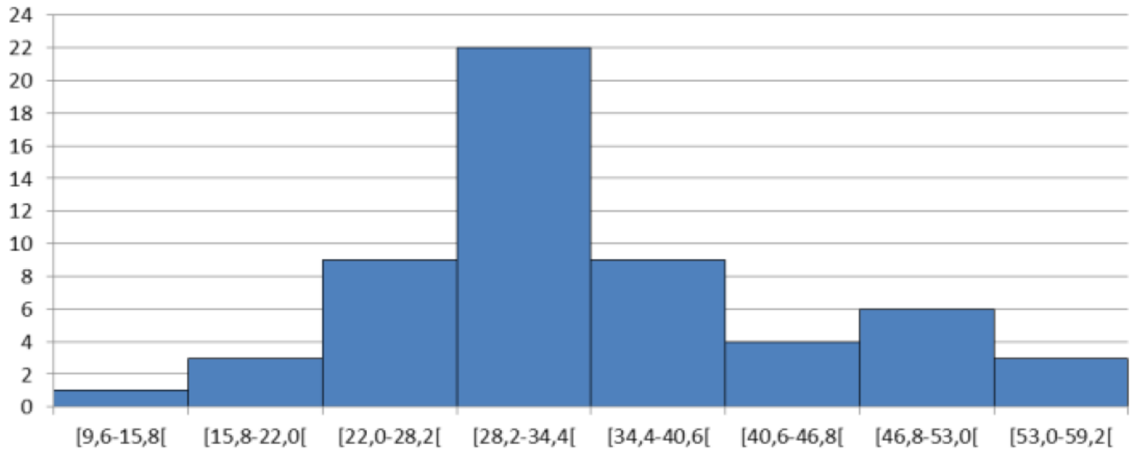


Figure 4 – Frequency distribution of the Specific energy consumption in all the 57 school, expressed in kWh/m2/year [4]

Outcomes of this preliminary assessment identified four important facts:

- In 2008, all the 57 schools granted just very basic services to the students and were not able to guarantee an adequate indoor environmental quality. The average SEC of the 57 schools was equal to 16,18 kWh/m^2 per year [4];
- The complete refurbishment implied the enlargement of the gross floor area assessed around 165%, but the SEC growth was not directly proportional (see Fig. 3).
- In 2011, the average SEC of the 57 schools raised up to 35,53 kWh/m^2 per year with percentual increment of 231%.
- 22 out of 57 schools (Fig. 4) were in the range of specific consumption of 28,2-34,4 kWh/m^2/year.

From these essential pieces of information many observations could be done. Above all, modernising the school facilities would lead to an increment of their consumptions and this is mainly due to: the upgraded services, the expansion of the infrastructures and their technological development. This may be proved by a simple numerical example:

According to [4]*, an average primary school in Portugal in 2008 had a SEC of electricity of 16,18 kWh/m^2/year, not guarantying space heating/cooling services.*

According to U.S. Department of Energy, space heating and cooling services share together the 57% (Fig. 2) of the total energy consumption of U.S. schools. Adopting, as a first approximation, the same percentage for the Portuguese schools, it is obtained:

$$\left.\frac{Avg.\ SEC_{2008}}{(1-0{,}57)}\right|_{No\ HVAC} = 37{,}63\,\frac{kWh}{m^2} \tag{1}$$

$$Avg.\ SEC_{2011}|_{With\ HVAC} = 35{,}53\,\frac{kWh}{m^2} \tag{2}$$

Even admitting the extremely simplified approach of these calculation, it is to be noted how the result (1) differs only by 5% from the actual data of Portuguese schools. This could mean that during the refurbishment of the 57 schools also involved the installation of HVAC systems. As a matter of fact, this statement is confirmed in [4].

What can be concluded after this short discussion, is that developing an eventual modernisation intervention leads in most cases to an increase in energy consumption equal to about twice the current ones, especially if the building in question is not equipped with essential services such as space heating and cooling.

One of the objectives of the present study is to understand and evaluate the weight of energy efficiency measures (EEM's) in school's refurbishment processes.

3 Comfort in school environment – Legislative framework

In this chapter is introduced the legislative framework that regulates the various aspects of indoor environmental comfort, in particular for K-12 school buildings. Seeking conciseness, in Table 2 are listed the standards for thermal comfort, indoor air quality, visual and acoustic comfort that are taken as references for the present study.

Table 2 - Regulations framework.

	Standards
Thermal comfort	EN ISO 16798:2019, ISO 7730;
Indoor Air Quality	EN ISO 16798:2019
Visual comfort	ISO 12464, UNI ISO 10840, UNI ISO 10380
Acoustic comfort	EN ISO 12354

EN ISO 16798 is a set of European standards which aims to uniform the energy performances assessment of buildings. In particular, it specifies parameters that have to be evaluated in order to meet *thermal comfort*, *ventilation* and *indoor air quality* requirements. Each of these fields contributes directly to Indoor Environmental Quality (IEQ) that is classified in categories as follows:

Table 3 – Categories of Indoor Environmental Quality.

Category	**Expectation**
IEQ_{I}	High
IEQ_{II}	Medium
IEQ_{III}	Moderate
IEQ_{IV}	Low

The categories are related to the level of expectations the occupants may have. A normal level would be “Medium”. A ‘high’ level may be selected for occupants with special needs (children, elderly, persons with disabilities, etc.). A lower level will not provide any health risk but may decrease comfort. As it will be described in 3.2, 3.3 and 3.4, each category corresponds to certain parameter or variable. To mention some example: CO_2 concentration is the reference parameter for Indoor Air Quality; Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) are the ones for thermal comfort. According to the building type (offices, restaurants, schools, hospitals etc.) the requirements may be more restrictive and as far as the case study is concerned, categories III and IV should be avoided because of the presence of children. It has to be specified that ISO 16798 does not suggest a design methodology for indoor spaces, but it aims to be a guide for engineers, architects or legislators who have to guarantee satisfactory comfort conditions for occupants.

ISO 12464 absorbs the previous 10840 and 10380 and provides an analytic procedure for visual comfort assessment as it will be exposed in 3.3.

ISO 12354 will be followed for the estimation acoustic performances of windows, which will be the object of section 7.1.3.

3.1 Thermal comfort assessment

The famous Vitruvius, writer, engineer and architect of the Roman age, argued that the pursuit of thermal comfort had given birth to the science of architecture [5]. In the ANSI/ASHRAE standards thermal comfort is defined as '*the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation'*.

In any case, regardless of the historical period we live in, the achievement of thermal comfort has always been a priority especially due to his influence on human health.

To avoid hypo/hyperthermia and all the related symptoms, human body must keep its temperature between 36 °C and 37 °C. In this range, if the surrounding environment temperature is not below 20 °C or above 50 °C, all the heat exchange mechanisms are performed in an efficient and self-regulated way.

In other words, thermal discomfort sources may be found in:

- Human body related factors, such us metabolic disease.
- Environmental factors.

Obviously, designers can only deal with the latter. In this regard, the main environmental factors that can influence thermal comfort are presented here:

- *Air temperature*, as it influences heat exchange through conduction; *air speed*, since it is most important variable for the calculation convection coefficient.
- *Radiant temperature* affects heat exchange through radiation, even though this effect is usually negligible compared to the others.
- *Relative humidity* that plays an important role on the perspiration mechanism.
- *Clothing insulation* which depends on occupant's perception.

At this point, it remains to define the models that engineers, or architect could adopt to assess thermal comfort.

In the next sections, the reader will be provided with a brief description of:

- ISO standard that regulates thermal comfort in school buildings.
- the two most widely used thermal comfort assessment models: Predicted Mean Vote and Adaptive.

3.1.1 Predicted Mean Vote (PMV) model

Professor Fanger studies, carried out in Technical University of Denmark, have been fundamental in the determination of correlations between the poor quality of the air in closed environment and the pulmonary diseases in young age individuals. Besides, one of his main achievements was the development of an empirical model which allows to assess whether conditions of thermal comfort are satisfied or not. This was called *Predicted Mean Vote* (PMV) model and nowadays is referenced as ISO 7730 standard.

PMV is an index whose calculation is based on several empirical equations that take into account: metabolic rates, mean radiant temperature, relative humidity, air speed and clothing insulation.

To produce a sufficiently solid database, experimental work focused on probing individuals who had shared a climate chamber with different conditions for a certain period of time. They were asked for their perception on a scale from -3 to +3 where:

+3=Hot   +2=Warm   +1=SlightlyWarm   0=Neutral   -1=SlightlyCool   -2=Cool   -3=Cold

The results of study were that the PMV index computed though Fanger's equations could represent the mean vote that a group of people would give to their thermal comfort perception under certain conditions. Thus, even assuming an average vote of 0 (the optimum) it has to be considered the presence of small percentage of people who are uncomfortable. For this reason, the *Predicted Percentage Dissatisfied* (PPD) index is always coupled with PMV. A visual example of that is shown in Fig. 5.

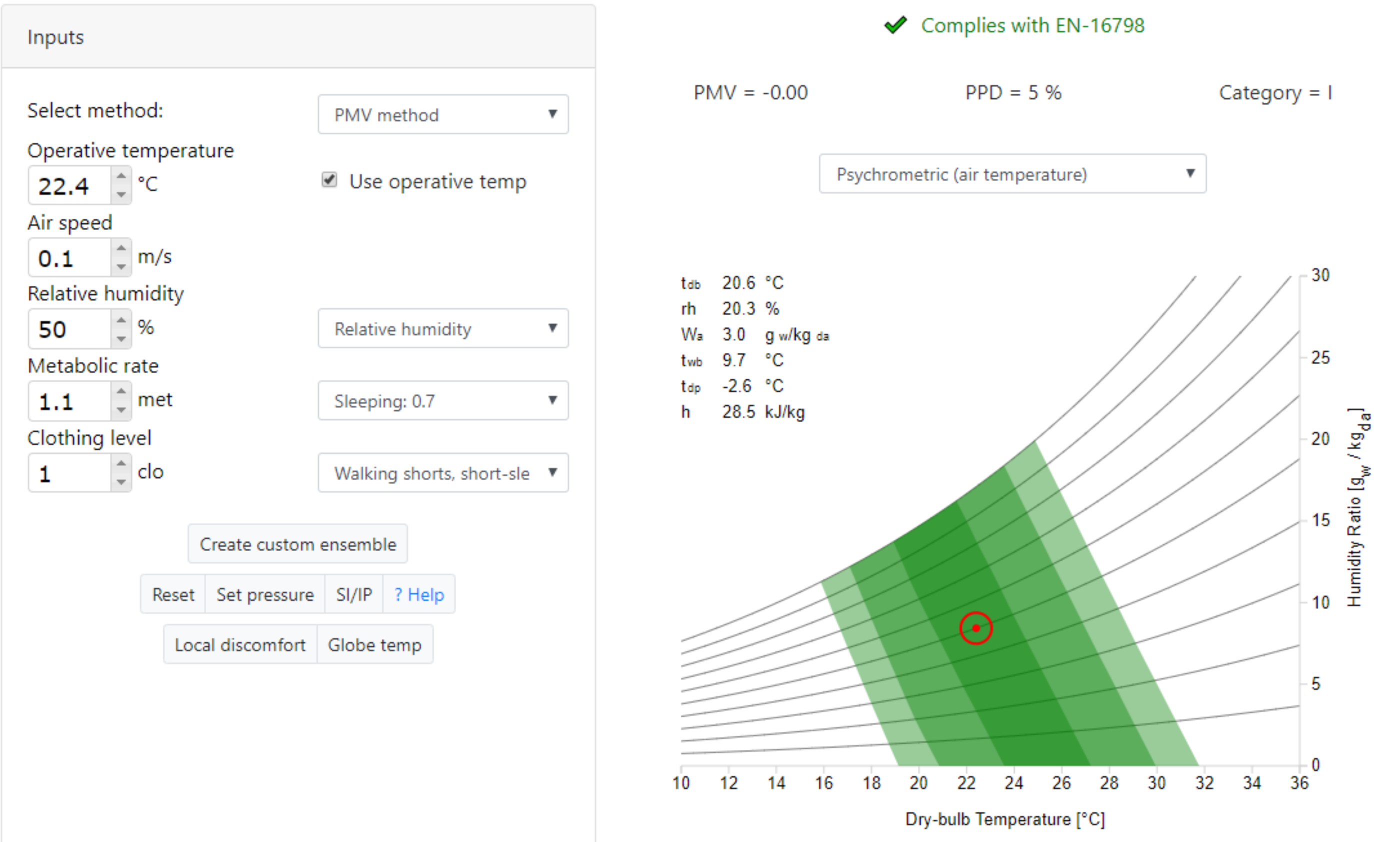


Figure 5 - CBE thermal comfort tool displaying *PMV* model [20].

ISO 16798 correlates the indices previously mentioned by ISO 7730 with IEQ categories as follows:

Table 4 – Thermal Comfort indices defined by ISO 7730 and relative categories.

Category	PPD [%]	PMV
IEQ_I	<6	-0.2<PMV<0.2
IEQ_{II}	<10	-0.5<PMV<0.5
IEQ_{III}	<15	-0.7<PMV<0.7
IEQ_{IV}	<25	-1<PMV<1

It is important to remark that ISO 16798 states that values in Table 4 can be used as design reference only for building in which heating/cooling services are provided. This is the primary reason why, for the case study, a different thermal comfort assessment model was chosen.

In addition, since various authors [6] asses the overall accuracy of PMV model around 34% it would be appropriate to highlight the limits of this methodology. Firstly, it does not involve the seasons variability and climate location, which means that the results shown in Fig. 5 are valid for every day of the year in every place on earth. Also, it is not considered the ability of the human body to adapt to the environmental conditions to which it is subjected.

In order to overcome these limits, scientists Richard de Dear and Gail Brager developed in 1998 the Adaptive Model of Thermal Comfort and Preference [7]

3.1.2 Adaptive model

Adapting to the most variable, yet extreme, situations has always been a distinctive trait of the human being. In terms of thermal comfort, three different kind of adaptation have been identified:

- Psychological: perception of heat/cold is affected by personal experiences. Since, by definition, thermal comfort is a 'condition of mind', psychological factors play a crucial role.
- Physiological: individuals that spend long period of time in tough conditions develop a higher tolerance than the people who do not. This also happens due to the natural self-thermoregulation ability of the human body which tends to enhance over time.
- Behavioural: people adapt themselves to periodicity of seasons and weather changing their daily habits. Another example of behavioural adaptation is when several occupants have to share a space whose conditions approaches to thermal discomfort. To deal with that, their first response is to adopt one or more strategies. In naturally ventilated buildings is common to adjust the windows [8] and 'those occupants who take these sorts of actions tend to feel cooler at warmer temperatures than those who do not' [9]

Adaptive model takes into account thermal comfort dependency on the individual's adaptation to outdoor conditions.

In their major work, de Dear and Brager conclude that 'occupants of naturally ventilated buildings accept and even prefer a wider range of temperatures than their counterparts in sealed, air-conditioned buildings because their preferred temperature depends on outdoor conditions' [7]. A visual example of thermal comfort tool [11] set to adaptive method is provided in Fig. 6 which is the graphical representation of the reference ranges of temperatures provided by ISO 16798 and shown in Table 5 below.

Table 5 - Examples of recommended design values of indoor operative temperatures.

Type of building/space	Category	Operative temperature, °C	
Single office (cellular office) Sedentary approximately 1,2 met	I	21,0	25,5
	II	20,0	26,0
	III	19,0	27,0
	IV	17	28

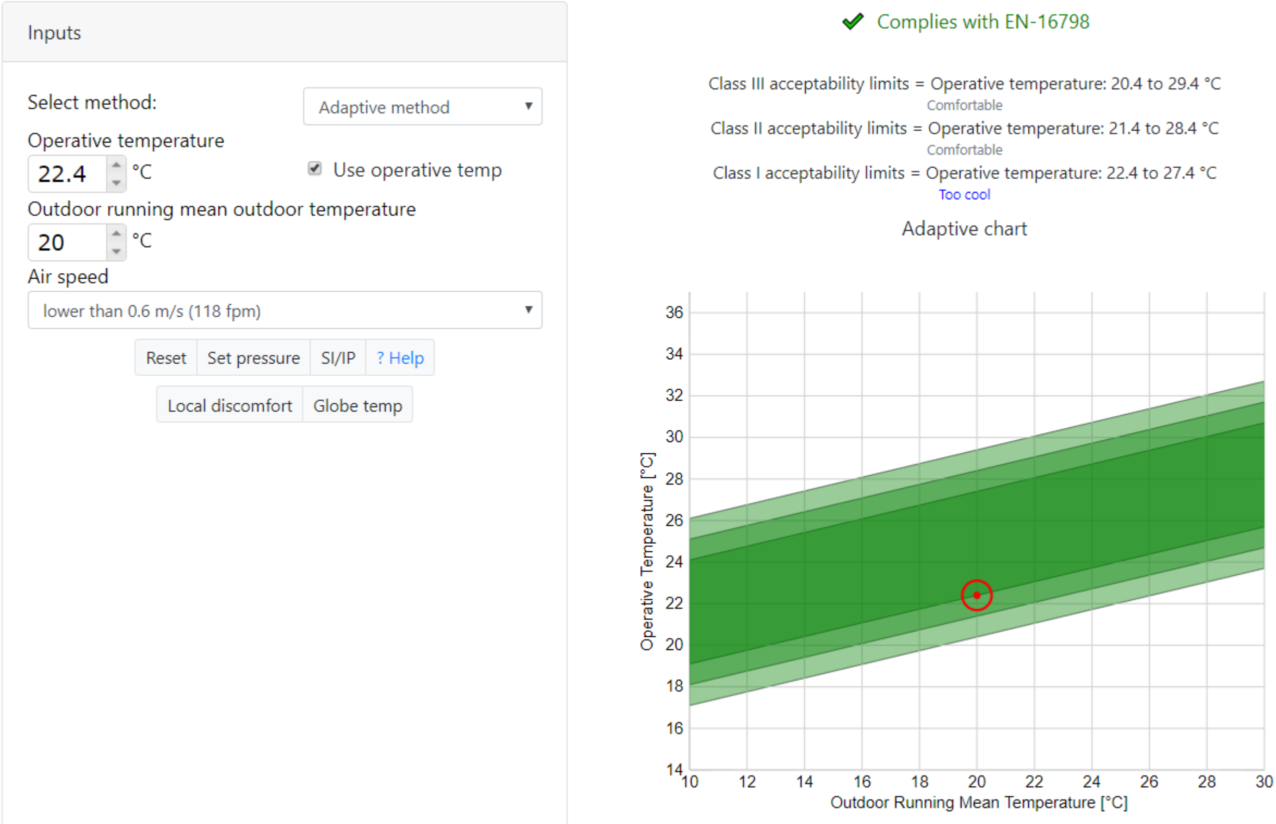


Figure 6 – CBE thermal comfort tool displaying *Adaptive* model [20].

On the ordinate of the graph in Fig. 6 it is shown the *Operative Temperature* in °C. It is defined by ISO 7730:2005 as a "uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment". In design, operative temperature can be defined as the average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients. On the abscissa there is the outdoor temperature, which is the independent variable of the problem.

Hence, for a specific building type, metabolic rate, wind speed and outdoor temperature it is possible to found out whether a certain space complies with ISO 16798.

Since for the case study it is necessary to assess comfort conditions during a long period of time (week, months, year) and not just in a defined instant, it was made use of simulation software called *Energy+* that enables the user to perform a detailed analysis varying a large number of inputs such as: metabolic rate, wind speed, number of people, internal gains etc.

3.2 Indoor Air Quality (IAQ) assessment

Indoor air quality is affected by the following three parameters: *Pollutants concentration*, *Ventilation*, *Air filtration*.

In enclosed spaces occupied by people, Oxygen availability decreases due to respiration and transpiration processes of human body. These also generate various forms of products, such as water vapour, Volatile Organic Components (VOC) and CO_2. With the constant increment of the concentration of these substances the sensation of discomfort tends to rise quickly. Serious health risks may be encountered if people are frequently exposed to bad air quality environment, most of them are represented by *building related illnesses* which include Pontiac fever, legionellosis, alveolitis etc. In order to exclude any potential risk European and national standards have been updating IAQ requirements throughout the years.

For EN ISO 16798, the most recent standard, IAQ has to be expressed as the required level of ventilation or CO_2 concentrations based on health and comfort criteria. Comfort is more related to the perceived air quality (odour, irritation). In these cases, different sources of emission can have an odour component that adds to the odour level. In any case, there is no general agreement on how different sources of emission should be added together.

The standard provides three possible criteria to assess IAQ:

- method 1, based on perceived air quality.
- method 2, based on limit values of gas concentration.
- method 3, based on predefined ventilation rates.

3.2.1 Method 1

Method 1 it is the least restrictive method since it just takes to into account the subjective perception of the occupants instead of their actual body needs. It prescribes ventilation rates for occupants either for adapted or non-adapted building occupants. It can be a reasonable approach the design of a specific room types for adapted persons for auditoriums, cinemas, classrooms.

Table 6 is an extract from EN ISO 16798 which defines minimum requirements of ventilation in terms of mass flow rate according to the following equation:

$$q_{tot} = n \cdot q_p + A_r \cdot q_b \qquad (3)$$

Where:

q_{tot} is total ventilation rate requirement of the indoor space, in [l/s].

n is the number of people.

q_p is the ventilation rate per person, in [l/s per person].

A_r is gross floor area, in [m^2].

q_b is the ventilation rate for buildings emissions, in [l/s.m^2].

Standard recommends keeping ventilation rate above the minimum value of $q_{tot,\ min}$ = 4 l/s.

Table 6 - Adapted persons. Examples of recommended ventilation rates for classrooms with default occupant density for three categories of pollution from building itself.

Type of building or space	Category	Floor area m²/per-son	q_p Adapted q_p according to Table B.1		q_B	q_{tot}		q_B	q_{tot}		q_B	q_{tot}	
			l/s, m²	l/s, person	l/s,m²	l/s,m²	l/s, person	l/s,m²	l/s,m²	l/s, person	l/s,m²	l/s,m²	l/s, person
			for occupancy		for very low-polluted building			for low-polluted building			for non-low polluted building		
Class room	I	2	1,75	3,5	0,5	2,25	4,5	1	2,75	5,5	2	3,75	7,5
	II	2	1,25	2,5	0,35	*1,60*	*(3,2)4*	0,7	*1,95*	*(3,9)4*	1,4	2,65	5,3
	III	2	0,75	1,5	0,3	*1,05*	*(2,1)4*	0,4	*1,15*	*(2,3)4*	0,8	*1,55*	*(3,1)4*
	IV	2	0,50	1	0,25	*0,75*	*(1,5)4*	0,3	*0,80*	*(1,6)4*	0,6	*1,10*	*(2,2)4*

NOTE Values in italics indicate situations where the calculated ventilation rate is lower than the minimum value of 4l/s per person required for health. The values are expressed per m² floor area even if the emitting surfaces can be floor, wall, etc.

A building is by default a low-polluting building unless prior activity has contaminated the building (e.g. smoking). In this case, the building is defined non-low polluting. The category 'very low-polluting' requires that the majority of building materials used for finishing the interior surfaces meet the national or international criteria of very low-polluting materials.

Using the values of Table 6, EN ISO 16798 estimates the corresponding ΔCO_2 [2] concentration in ppm as exposed in Table 7.

Table 7 - Example of equivalent increase in CO2 levels indoor above outdoor for the total ventilation rates specified in Table 6.

Type of building or space	Category	Occupancy	ΔCO_2 [ppm]		
		person/m²	Very low-polluting	Low-polluting	Not low-polluting
Classroom	I	0,5	505	463	397
	II	0,5	722	661	567
	III	0,5	1 263	1 157	992
	IV	0,5	1 543	*1 389*	1 502

[2] $\Delta CO_2 = CO_{2,indoor} - CO_{2,\ background}$. $CO_{2,background} \approx 400$ppm.

3.2.2 Method 2

Method 2 defines ventilation rates required to dilute a substance according to the following equation:

$$Q_h = \frac{G_h}{C_{h,i} - C_{h,o}} \cdot \frac{1}{\varepsilon_v} \quad (4)$$

Where

Q_h is the required ventilation rate for dilution, in [m^3/s].

G_h is the pollutant production rate, in [mg/s].

$C_{h,I}$ is the indoor pollutant concentration, in [ppm].

$C_{h,o}$ is the background concentration level of the pollutant, in [ppm].

ε_v is the ventilation efficiency.

Equation (4) should be applied for all the possible pollutants. However, the standard makes it mandatory only for CO_2.

In Table 8 are shown maximum levels of ΔCO_2 concentrations and the corresponding categories of IEQ, only for non-adapted persons[3]. This means that ventilation rates must be designed to not exceed ΔCO_2 limits in a certain environment. It is a more restrictive method since it does not take into account the type of building, metabolic rate, number of people etc.; but it just prescribes not-to-exceed thresholds.

Table 8 - Default design CO2 concentrations above outdoor concentration assuming a standard CO2 emission of 20 L/h per person

Category	Corresponding CO_2 concentration above outdoors in PPM for non-adapted persons
I	550 (10)
II	800 (7)
III	1 350 (4)
IV	1 350 (4)
NOTE The above values correspond to the equilibrium concentration when the air flow rate is 10, 7 and 4 l/s per person for cat. I, II, and III, IV, respectively, and the CO_2 emission is 20 l /h per person.	

[3] Method 2 does not distinguish between adapted and non-adapted persons.

3.2.3 Method 3

Method 3 defines default ventilation rates expressed for a certain space, just considering the number of people or the gross floor area. These values are reported in Table 9.

Table 9 – ISO 16798 default ventilation rates for school buildings.

Category	**[l/s·pers]**	**[l/s·m²]**
IEQ_{I}	20	2
IEQ_{II}	14	1.4
IEQ_{III}	8	0.8
IEQ_{IV}	5.5	0.55

These numbers were obtained through a series of calculations and assumption that can be found in annex B of EN ISO 16798-II.

3.3 Visual comfort assessment

Visual comfort is addressed by various[4] standards but none of them provides a concise definition of it. Therefore, it seems reasonable to appropriate the definition of thermal comfort: ‘visual comfort is that condition of mind that expresses satisfaction with visual environment’ [10]. It is determined by two factors:

- Visual performance, which depends on how quickly and accurately a specific *visual task* is completed as safely as possible.
- Environmental agreeableness, which mainly depends on light type (natural or artificial), space characteristics and individual attitude related to the experience and psychology of the subject.

To assess visual comfort condition for the case study, ISO 12464-1 will be adopted. In order to understand its requirements, it is necessary to introduce the following parameters:

E_m medium illuminance, [lux = lm/m^2];

UGR_L Unified Glare Rating, which has to be calculated according to CIE[5] method.

R_a Colour rendering, which varies from 0 (no distinction between colours) to 100 (max rendering). It represents how faithfully a lamp can render colours.

Firstly, the standard prescribes in quantitative terms the lighting conditions to be met according to the indoor activity or space type, as shown in Table 10.

Then, it defines some recommendations regarding qualitative aspects of lighting: a certain amount of natural light (also called daylight) has to be guaranteed throughout the day.

[4] ISO 12464-1:2011; ISO 16798; UNI 10840 and UNI 10380.
[5] Described in UNI 10380.

Table 10 - ISO 12464: example of lighting requirements for two types of classrooms.

Type of space	**E_m [lx]**	**UGR_L [-]**	**R_a [-]**
Standard classroom	300	19	80
Technical drawing classroom	750	19	80

The amount of natural light is quantified through the *medium daylight factor* η_m that has to be calculated according to the following equation:

$$\eta_m = \frac{A_f \cdot t \cdot \varepsilon}{A_{tot} \cdot (1 - r_m)} \cdot \Psi \qquad (5)$$

Where

A_f is the glass-area of a certain enclosed environment, in [m^2].

t is the visible transmittance of the glass.

ε is the window factor, see Fig. 7 (ε=0,5 for vertical window).

A_{tot} is the total gross area of the surfaces surrounding the environment, in [m^2].

r_m is the medium reflective factor of the surfaces surrounding the environment.

Ψ is the window reduction factor, see Fig. 8.

To comply with standard ISO 12464 $\eta_m \geq 3\%$ has to be always verified for school buildings.

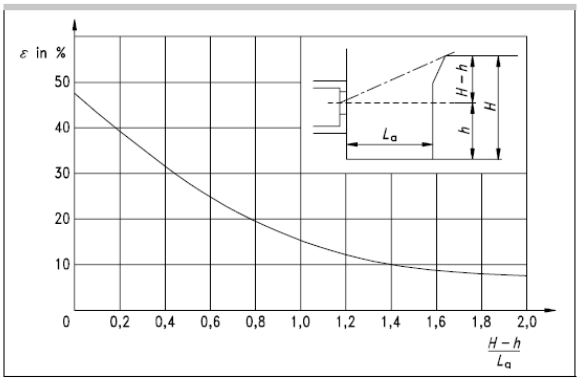


Figure 7 - Window factor.

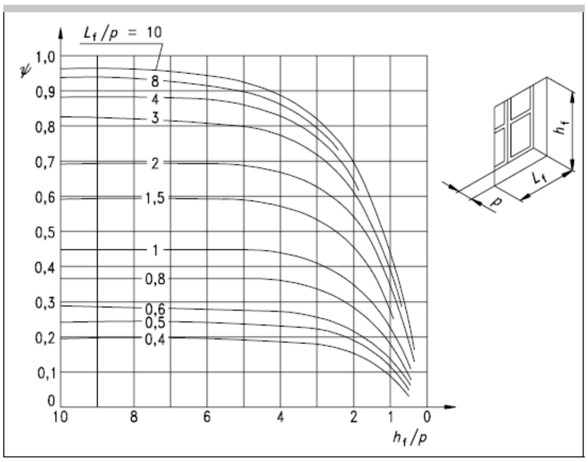


Figure 8 - Window reduction factor.

3.4 Acoustic comfort assessment

Acoustic comfort is the psycho-physical condition where a person, in a certain environment, experiences a sense of well-being in relation to the specific task he/she is performing. As far as the present study is concerned, acoustic comfort analysis will be addressed to quantify the improved noise insulation provided by windows replacement, which will be the principal energy efficiency measure to be implemented.

ISO 12354 classifies buildings and defines the related minimum value of *Façade Standardised Level Difference* ($D_{2m\,nT,w}$). These are reported in Table 11.

Table 11 – Buildings classification with related $D_{2m,nT,w}$ minimum values.

Category	**$D_{2m,\,nT,w}$ (dB)**
D	45
A, C	40
E	48
B, F	42

A: residential buildings
B: Offices and similar
C: Hotels and similar
D: Hospitals and similar
E: Schools and similar
F: Commercial activities

To understand the significance of equations (7) an (8), it is necessary to introduce the *apparent sound reduction index R'.* It essentially depends on the thermo-physical properties and internal structure of a given material; it is expressed in dB and it is defined as:

$$R' = 10\log\left[\frac{W_i}{W_1 + W_2}\right] \tag{6}$$

Where

W_i is the sound power impacting the partition.

W_1 is the sound power transmitted through the partition.

W_2 is the sound power transmitted through the lateral structures.

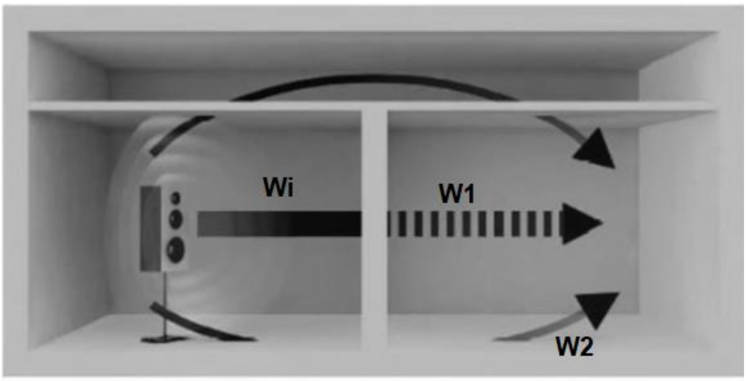


Figure 9 – Propagation of sound powers through an internal partition.

$D_{2m,\,nT,w}$ is a more crucial parameter since it gives an estimation of the noise insulation performance of one of the facades which surrounds an enclosed space. According to EN ISO 12354 it has to be calculated as follows:

$$D_{2m,nT,w} = R'_w + \Delta L_{fs} + 10\log\left[\frac{V}{6T_0S}\right] \tag{7}$$

Where

R'_w is the *Apparent Sound Reduction Index* of the partitions surrounding the space. Subscript ‘w’ indicates that R’ was determined adopting ISO 12354 equation:

$$R'_w = -10\log\left[\sum_{i=1}^{n}\frac{S_i}{S}\cdot 10^{\frac{-R_{wi}}{10}} + \frac{A_0}{S}\cdot\sum_{i=1}^{n} 10^{\frac{-D_{n,e,wi}}{10}}\right] - K \qquad (8)$$

having

- S_i as the surface of the element-i (i.e. windows glass area), in m^2.
- S as the total[6] surface surrounding the enclosed space, in m^2.
- R_{wi} as the apparent sound reduction index of the element-i, in dB.
- A_0 as a reference area, $A_0 = 10\ m^2$.
- $D_{n,e,wi}$ as the standardised level difference of element-i; defines noise insulation performance of small elements (i.e. ventilation grids).
- K as the correction factor related to transmissions through lateral structures. Usually, this contribution can be neglected except for facades having rigid and heavy elements[7]. In that case $K = 2\ dB$.

ΔL_{fs} is the Sound Pressure Level (SPL) difference given by

$$\Delta L_{fs} = L_{1,2m} - L_2 \qquad (9)$$

having

- $L_{1,2m}$ as the SPL measured 2m from the façade, in dB.
- L_2 as the SPL measured inside the receiving enclosed space, in dB.

V is the volume of the receiving enclosed space, in m^3.

T_0 is the reference reverberation time, $T_0 = 0,5s$.

Hence, knowing values of apparent sound reduction indices (R_w) of walls, windows and all other elements characterising a specific façade it is possible to estimate its acoustic performance through the equations above. Indeed, this is what will be exposed in section 7.1.3 where performances of different type of windows will be compared.

[6] Including windows, walls doors and other constructive elements.

[7] Made with concrete, bricks, steel etc.

4 Methodology

Once discussed the legislative framework, it seemed appropriate to describe which path was followed to reach the final objective. Thus, in this chapter are discussed tools and models which characterized the study methodology.

4.1 Selection of space heating and cooling model

One of the purposes of energy analysis is to estimate the building demand for space heating and cooling. To achieve this scope, the designer can rely on three types of models:

A. Model based on physical principles, such as thermodynamics laws and heat transfer equation.
B. Statistical models, which involve the use of a large number of data, like weather or energy consumption data.
C. Artificial Intelligence models, that rely on more complex approaches based on neural networks and fuzzy logic.

It is possible to distinguish two categories of physical models:

A.1. Simplified models, which can be referenced in the ISO 52016.

A.2. Detailed simulation software.

What energy simulation software does is essentially to apply physical principle to a geometry which may be complex (large buildings with numerous spaces) or very simple (a small room).

In any case, for an accurate study, it is first necessary to draw a geometry and then characterize it through ‘its constructive solutions, the list of the equipment and its schedules and the climate information’ [11].

Due to its availability and reliability, *Energy+* is one of the most used detailed simulation software for buildings and it is the mean through which the present study will be developed on.

In the following paragraphs the reader will be provided with the description of the software used for the construction of the geometry and for the thermal simulation.

4.1.1 Google Sketchup and OpenStudio

As said, the first step consists in the creation of geometry. To do that, it has been chosen the software '*Google SketchUp*' that is also available open source.

The intuitive interface (Fig. 10) allows the user to build very complex geometry faster than in other more advanced software like AutoCAD.

However, the main reason that led to the choice of this software was certainly its ability to interact with *OpenStudio* and *Energy+* which will be the most important tools used in the study.

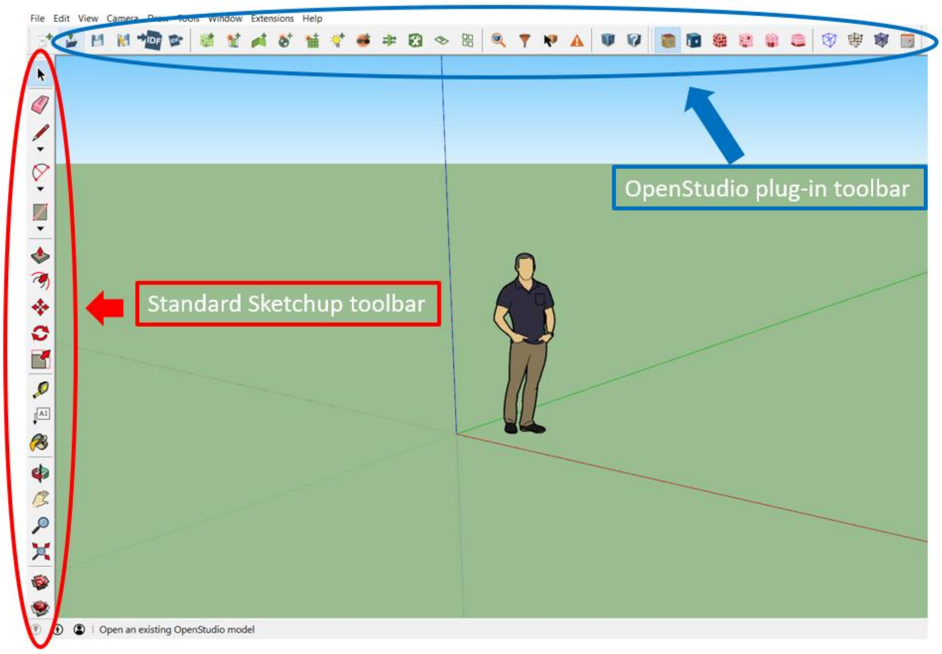


Figure 10 - Google SketchUp interface with its OpenStudio plug-in

OpenStudio works as a *SketchUp* plug-in through which it is possible to attribute important features to the model that will be later processed in Energy+. To give a more practical explanation of the workflow:

1) Geometry is created within *SketchUp* environment (walls, windows, roof and all the constructive elements).
2) All the spaces become <u>thermal zones</u>. This action is done with the proper function available in *OpenStudio* plug-in toolbar present in *SketchUp* environment.
3) Assign <u>construction names</u> to the surfaces. All the thermal zones have at least 3 types of surfaces (ground, walls and roof). To do thermal simulation is fundamental to assign to every surface his construction name. A construction is an ordered set of layers each representing a material[8].
4) Once the thermal zones and the related surfaces are defined, it is possible to export the model as a file with .idf extension. This is the final file that will be processed with *Energy+* software.

[8] Materials and constructions can be created also in the Energy+ environment and imported in the *SketchUp* environment using the option 'Import construction' of OpenStudio toolbar.

4.1.2 Heat transfer equations in *Energy+*

Heat transfer is thermal energy in transit due to a temperature difference. There are three different types of heat transfer: **conduction**, which is heat transfer across a medium; **convection**, which is heat transfer between a surface and a moving fluid with a different temperature and **radiation**, which is heat transfer through the form of electromagnetic waves between two surfaces at a different temperature.

For conduction, the rate equation, also known as *Fourier´s law* is of the form:

$$q'' = -k\nabla T \tag{10}$$

Were q'' (w.m^{-2}) is the local heat transfer rate per unit area, k (W.m^{-1}. k^{-1}) is the thermal conductivity of the medium and ∇T is the temperature gradient.

For convection, the rate equation is of the form:

$$q'' = h(T_s - T_\infty) \tag{11}$$

Were T_s is the temperature of a surface, T_∞ is the temperature of a fluid and h (W.m^{-2}.k^{-1}) is the convection heat transfer coefficient which depends on many factors.

For radiation, the net rate of heat transfer from a surface is of the form (assuming grey surface):

$$q'' = \epsilon\sigma(T_s^4 - T_{sur}^4) \tag{12}$$

Were ϵ is a radiative property of a material that ranges between 0 and 1 and measures how efficiently a surface emits energy relative to a black body, σ is the Stephan Boltzmann constant ($\sigma = 5{,}67 \times 10^{-8}$ W.m^{-2}.k^{-4}) and T_{sur} is the temperature of the surroundings.

In *Energy+,* heat transfer is analysed layer by layer in just one dimension. The conduction transfer function (CTF) solution algorithm is the default method to solve heat transfer problems due to its simplicity that allows to solve problems quickly. However, CTF cannot simulate materials with variable properties (such as PCMs), therefore this algorithm cannot be used in this study.

The conduction finite difference (CondFD) solution algorithm has the ability to simulate materials with variable properties due to its iterative nature. This algorithm uses an implicit finite difference model in which the user can chose between the fully implicit scheme and Crank-Nicolson, which is semi-implicit.

In this work, the Crank-Nicolson scheme was selected because it has a significantly smaller error of truncation when compare to the other scheme, this gives it an advantage when dealing with time-accurate solutions, making this scheme the one that offers higher accuracy for this work.

Equation (13) shows the formulation for the Crank-Nicolson scheme:

$$C_p\rho\Delta x\frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{1}{2}\left[\left(k_W\frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E\frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x}\right) + \left(k_W\frac{T_{i+1}^{j} - T_i^{j}}{\Delta x} + k_E\frac{T_{i-1}^{j} - T_i^{j}}{\Delta x}\right)\right] \tag{13}$$

Were C_p and ρ are the specific heat and density of the material; Δx is the finite difference layer thickness, Δt is the time step; T is the temperature of a node i; $i + 1$ and $i - 1$ are the adjacent nodes to interior and exterior, respectively, of a material layer; j and $j + 1$ are the previous and new time steps, respectively; k_W and k_E represent the thermal conductivities, $k_W = \frac{k_{i+1}^{j+1}+k_i^{j+1}}{2}$ and $k_E = \frac{k_{i-1}^{j+1}+k_i^{j+1}}{2}$.

In the CondFD algorithm, all elements are discretized as shown in equation 14.

$$\Delta x = \sqrt{c\alpha\Delta t} \tag{14}$$

Were α is the thermal diffusivity of the material and c is the space discretization constant that can be defined by the user (3 is the default value).

In this study, a PCM will be used, therefore the CondFD algorithm needs to be coupled with an enthalpy-temperature function $h = h(T)$, this function is presented in appendix 1. The algorithm uses this function to update an equivalent specific heat (C_p^*) at each time step as shown in equation 15.

$$C_p^*(T) = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \tag{15}$$

4.1.3 Thermal balance inputs in *Energy+*

Once the geometry is completely defined, the model created on SketchUp is exported as an .idf file. Hence, it is possible to open it in the Energy+ environment and enter all the parameters needed. This software will compute the thermal balance for each room of each building in a certain period, set by the user. To give accurate results, the simulation requires several inputs which must be consistent with each other. In this regard, it is here described the logic adopted for the definition of the parameters required by Energy+.

First, one must imagine computing a thermal balance on very simple control volume, like an isolated room. Hence, four mechanisms have to be studied [11]:

I. Heat gains/losses through the envelope.
II. Air mass balance.
III. Solar gains.
IV. Internal gains.

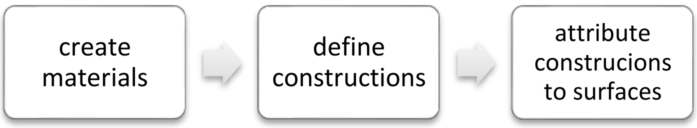
The model built adopting this simplified approach could be considered validated according to the results provided in Appendix C.

4.1.3.1 Heat gains/losses through the envelope

This type of gains/ losses is related to conduction, convection and radiation mechanisms.

Conduction

To evaluate conduction heat flow through surfaces, the user must follow the path summarised below:



Materials, constructions and surfaces are the objects that user will find in the Energy+ environment.

'*Material*' object (Fig. 11) presents field that needs to be filled knowing the actual thermophysical properties.

'*Constructions*' (Fig. 12) are ordered sets of materials and represents indeed the constructive elements.

In the geometrical model, spaces (also called thermal zones) are surrounded by surfaces (walls, roof and ground) and sub-surfaces (windows and doors). Since the case study represents an entire school, the

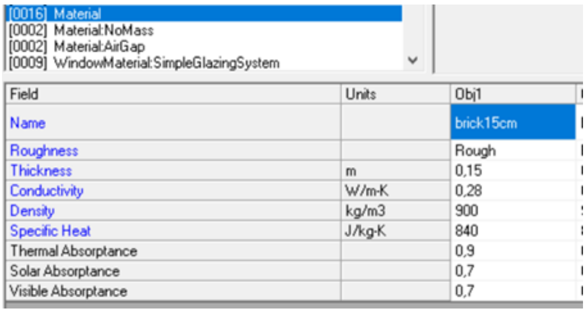


Figure 11 - *material* object in *Energy+* environment

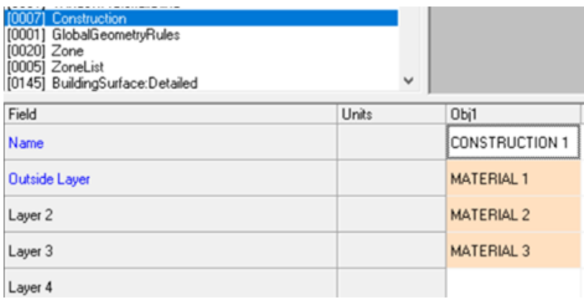


Figure 12 - *construction* object in *Energy+*

geometry is complex and presents several surfaces. Constructions must be assigned to each of them.

Once having this input set, Energy+ will compute the thermal conduction coefficient for each surface in the model.

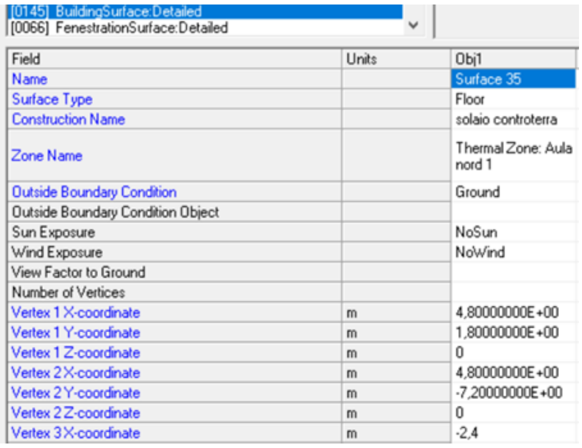


Figure 13 - *Surface* object in *Energy+*

Convection

Energy+ has some default pre-set options that provide the algorithm for convection calculation. However, user may choose a different algorithm if needed, even though this will cause longer simulation times.

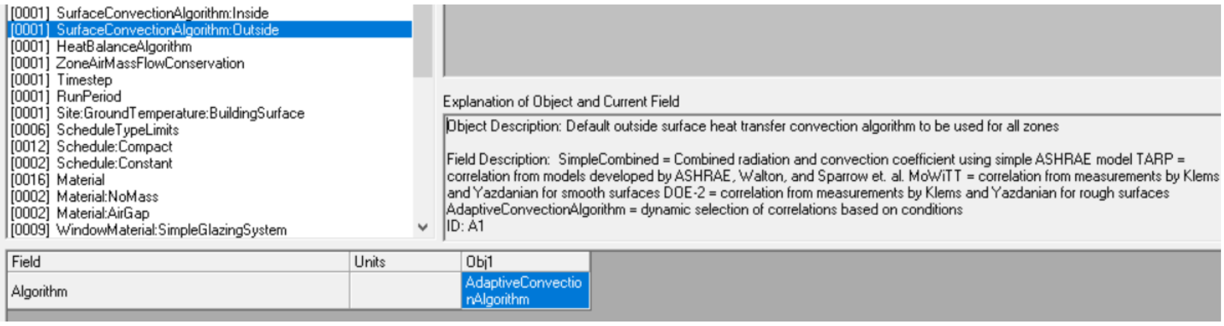


Figure 14 – *Surface convection algorithm* settings in *Energy+* environment

In any case, it is crucial to set the proper boundary condition to the surfaces. As an example, an internal surface cannot be wind exposed or sun exposed.

Radiation

It is as well calculated by default, but it is influenced by the thermophysical properties of the materials which must be set by the user.

4.1.3.2 Air mass balance

The air mass flow rates are due to ventilation and infiltration.

Air Infiltration rate

Infiltration rate is intended as the amount of air entering the room regardless of the conditions imposed by the occupants. Basically, they are due to micro-cracks and the imperfect airtightness of the building envelope. To estimate the average infiltration, rate the benchmark values of 0,3 Air Changes per Hours (ACH) for rooms on the perimeter and 0,15 ACH (internal rooms) provided by the DOE[9] were used (Table 12).

Table 12 - Infiltration flow rate input for all zones assuming air changes are distributed equally in all zones of the buildings

Model Id	Model Name	Building infiltration rate basis
BM	Constant Infiltration (DOE Benchmark)	0.3 ACH perimeter, 0.15 ACH core
90.1-1989	Constant Infiltration (90.1-1989)	0.038 cfm/sf of exterior wall area
DOE-2	DOE-2 Methodology	1.8 cfm/sf of above grade envelope area @ 0.3 in. w.c. (75 Pa)

To verify whether assuming 0,3 ACH is appropriate or not, it was done a simple calculation taking as reference 'Aula Nord 2' classroom in *pavilion C* (described chapter 4) with the following conditions:

- Gap for each side of all the window frames = 1cm[10];
- Sum of the gaps on the perimeters of all the openings (doors and windows) = 14m.
- Wind speed=0,1m/s
- Total volume of the classroom = 249 m^3.

$$flow\ rate\ through\ the\ openings = 0{,}01m \cdot 14m \cdot 0{,}1\frac{m}{s} = 0{,}014\ {m^3}/{s} \quad (16)$$

$$Air\ Changes\ per\ Hour = 0{,}014\,{m^3}/{s} \cdot 3600s \cdot \frac{1}{249} = 0{,}202 \quad (17)$$

Hence, considering that in this very simple calculation were not considered factors like leakages through walls and roof, eventual damages in the window frames, etc; the value of 0,3 ACH provided by the DOE could be considered a good approximation. Indeed, the input values for air infiltration rate will be:

- 0,3 ACH for rooms on the external perimeter.
- 0,15 ACH for all other rooms.
- 0,05 ACH for new doble glass windows[11];

These air flows are always present regardless of room occupancy.

---

[9] Department of Energy of the United States. DOE has given the major contribution in the development of *Energy+* software.
[10] Directly measured *in situ*.
[11] Windows replacement will be treated in 7.1. Various glass manufacturer (i.e. Pilkington) provide 0,05 ACH as a reference value for infiltration rate for new windows.

Ventilation and Schedules

Unlike infiltration, air flow rates due to ventilation are much more complex to evaluate since they depend on occupants' behaviour, that varies according to several factors like:

- Number of people sharing the same space. A high number of occupants increases need of air renovation.
- Seasonality: more window openings are expected in summer than in winter.
- Precipitation and other meteorological events.

Hence, the designer must consider all these aspects if he wants to obtain accurate results. To do that, he makes use of *schedules*.

'*Schedule*' object in *Energy+* allows the user to quantify a certain activity during the day. For example, it is possible to set in which time of the day a certain equipment will be switched on.

In Fig. 15 an example of occupancy schedule can be observed. Various fields are present, namely:

- '<u>Name</u>': the name of the schedule. This will be recalled by other objects.
- '<u>Schedule Type Limits Name</u>': is the type of values entered in the next fields. It can be set to 'Temperature' (if it is a thermostat schedule), to Watt, Ampere and so on. In the example the values indicate 'dimensionless' quantities.
- '<u>Through</u>…' indicates the period in which the next values are related to.
- '<u>For</u>…' defines the day type. It can be set to weekdays, weekends, all-days holidays etc.
- '<u>Until</u>…'' defines the time of the day which the next values refer to.
- <u>Input value</u> defined by user.

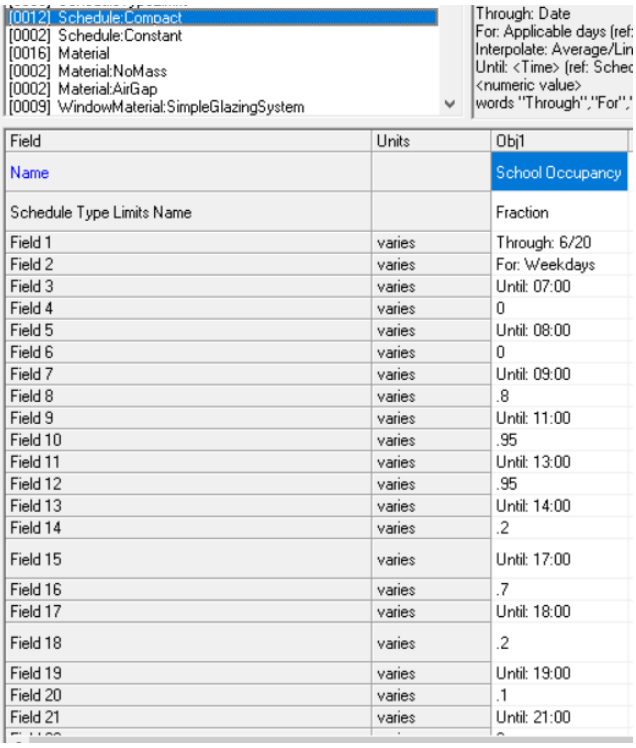


Figure 15 – *Schedule* object in *Energy+* environment

In the present study, it will be assumed that natural ventilation rates vary according to people occupancy. To explain how this is implemented in the model, it is here provided a numerical example:

"The maximum natural ventilation rate of a certain room A is equal to 1 ACH. Assuming that ventilation rates vary during the year according to people occupancy schedule displayed in Fig. 15, the following values are obtained:

> *in weekdays from January 1st to June 20th, occupancy rate of room A is equal to 0% before 8am → ventilation rate of room A is equal to 0% * 1 ACH = 0 ACH before 8am".*

Thus, knowing the maximum value of ventilation rate (ACH_{max}) of a specific room and its average occupancy it is possible to include the effect of natural ventilation in the thermal simulation.

Evaluation of ACH_{max} through experimental data, for indoor air quality assessment

Level of [CO_2][12] were experimentally measured in one of *pavilion*[13] C classrooms namely *Aula Nord 3* (further details in Appendix C). Seeking reasonable input values to be included in the *ventilation schedule*, it has been made use of those metered [CO_2] values to estimate ACH_{max}.

To quantify the air flow entering the classroom properly, the measurement was carried out under the following conditions:

- Classroom with maximum number of occupants.
- Window with constant opening: air flow section is kept constant during the measurement.
- Door closed.

Since these conditions were only met from 15:30pm (metered hour 63.5 in Fig. 16) to 17:30pm (metered hour 65.5) on 10/10/19, in the graph in Fig. 16 only the concentrations measured in this interval are shown.

As it can be seen, linear regression showed an appreciable fitting with experimental data (R^2=0,97). This implies that dilution effect of the inlet flow of outdoor air causes a decrement of [CO_2] that can be considered linear during the monitored period. For outdoor air it was considered $[CO_2]_{outdoor}$ = 500ppm.

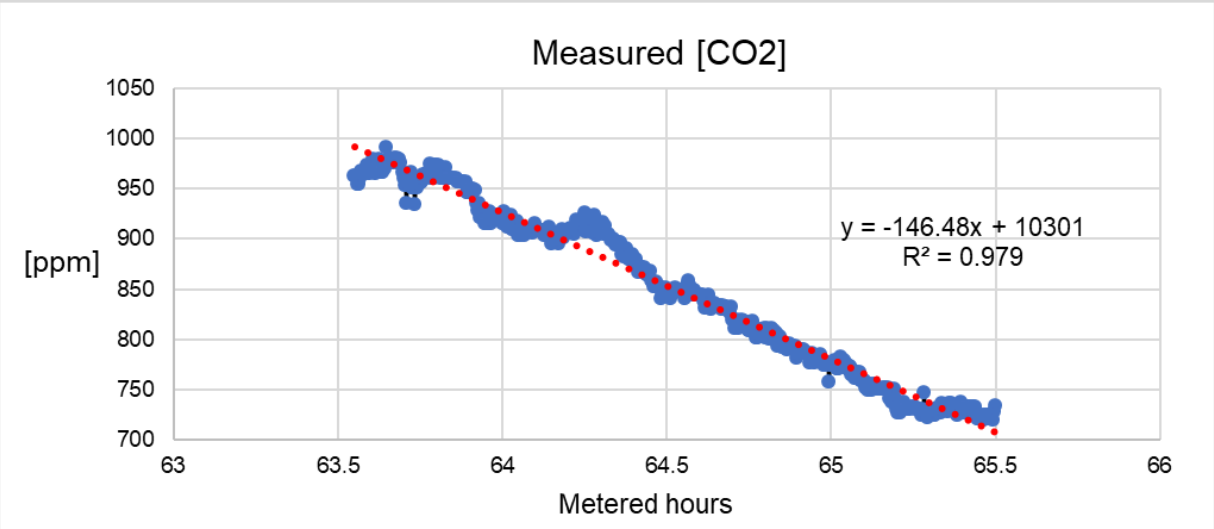


Figure 16 - Extract from [CO_2] measurements. Metered hour '63' corresponds to 3pm of 10/10/2019.

Having the following linear regression

$$y = -146{,}48x + 10301 \qquad (18)$$

which describes, with fairly good approximation, the decrease of [CO_2] levels in the classrooms, *Energy+* software was used to find the ACH_{max} value which could respect as much as possible the (18). This iterative procedure consisted in:

1. selection of *first attempt* value of ACH_{max} to be used as input in ventilation schedule (see Fig. 17).

[12] Term in brackets indicates volume concentration.
[13] Described in section 5.2.

[0004] ZoneVentilation:DesignFlowRate | ID: N10

Field	Units	Obj1
Name		Ventilation_aule
Zone or ZoneList Name		AULE
Schedule Name		School Occupancy
Design Flow Rate Calculation Method		AirChanges/Hour
Design Flow Rate	m3/s	
Flow Rate per Zone Floor Area	m3/s-m2	
Flow Rate per Person	m3/s-person	
Air Changes per Hour	1/hr	0,9
Ventilation Type		Natural

Figure 17- Inputs of *ventilation schedule object* in *Energy+*.

2. simulation launch and analysis of [CO_2] level predicted by the model.
3. check whether linear regression [CO_2] level matches eq. (18). For this step, output of *Energy+* was exported in excel and plotted.
4. iterate 1. to 3. until match was found.

Finally, the value of $\boldsymbol{ACH_{max}=0,9}$ was found.

However, it is important to specify that this value may not be accurate enough for different classrooms, offices or other types of spaces in the school. Moreover, it could be subjected to large variation due to various of factors[14].

According to these considerations, this value was used only to predict CO_2 concentration for indoor air quality assessment[15] of *Aula Nord 3*, which was the classroom where the measurements were taken.

Evaluation of ACH_{for} thermal simulations

Since experimental data available is not sufficient to estimate accurately the ventilation rates for all the buildings characterising *Escola Conde de Oeiras* case study, the ventilation values suggested by EN ISO 16798 have been adopted for thermal simulations.

To guarantee PPD lower than 15% in each space, the standard prescribes an inlet air flow rate equal to 10 l/s per person. Thus, knowing the number of people and the volume of each room is possible to quantify the related *ACH* value. Calculations are displayed in sections 5.2.2, 5.3.2 and 5.4.2.

[14] Mentioned in Appendix C.
[15] Exposed in chapter 8.

4.1.3.3 Solar gains

Solar gains depend on two main factors:

- Climate location of the buildings.
- Properties of surfaces.

Climate information is contained in the 'weather file' that the user has to enter in 'Launch menu' (Fig. 18). It can be downloaded from *Energy+* website for free. Every surface absorbs solar radiation, but the major contribution comes from non-opaque surfaces. Therefore, it is very important to set correctly the thermophysical properties of glass materials. This can be done adopting a simplified or detailed approach, both are discussed in Appendix A.

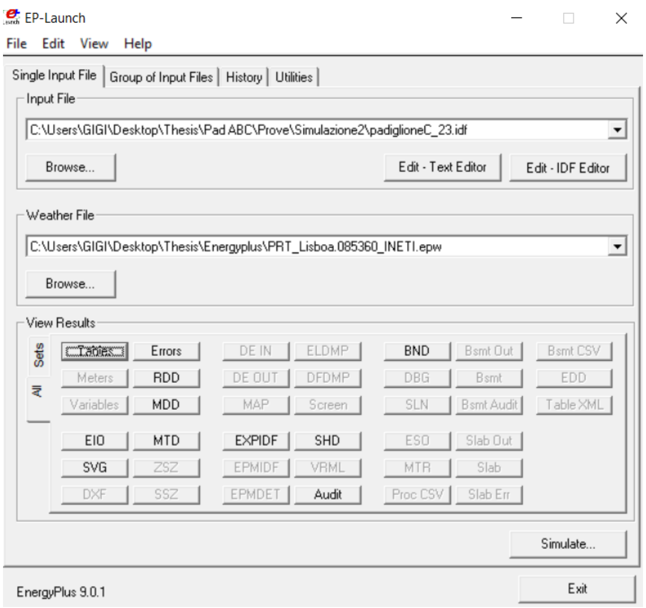


Figure 18 – *Energy+ launch menu*

4.1.3.4 Internal gains

Internal gains treated for the case study will be due to: People, electric and gas equipment.

People

The definition of *people object* in *Energy+* is one of the most crucial steps of the analysis for two reasons:

- quantification of internal gains and CO_2 emissions.
- thermal comfort assessment.

In the *Energy+* environment is possible to define the amount of heat and CO_2 that each person produces and release to the surrounding environment. These quantities depend on several factors such as: metabolic rate and type of activity. Average values are given in Table 13.

Table 13 – Reference values for people activity level [17].

Activity	Activity w/Person EnergyPlus Value	Level Energy Schedule	Activity W/m2	Level	met*
Seated, quiet	108		60		1
Standing, relaxed	126		70		1.2
Walking (on level surface)					
3.2 km/h (0.9 m/s)	207		115		2
4.3 km/h (1.2 m/s)	270		150		2.6
6.4 km/h (1.8 m/s)	396		220		3.8
Office Activities					
Reading, seated	99		55		1
Writing	108		60		1
Typing	117		65		1.1
Filing, seated	126		70		1.2
Filing, standing	144		80		1.4
Walking about	180		100		1.7
Lifting/packing	216		120		2.1

The value of dissipated heat is defined in *Activity level schedule name* in *People* object (Fig. 19).

[0003] People — Select from list of choices

Field	Units	Obj1
Name		Internal gains people aule
Zone or ZoneList Name		AULE
Number of People Schedule Name		School Occupancy
Number of People Calculation Method		People
Number of People		25
People per Zone Floor Area	person/m2	
Zone Floor Area per Person	m2/person	
Fraction Radiant		0,3
Sensible Heat Fraction		autocalculate
Activity Level Schedule Name		internalgainspeople
Carbon Dioxide Generation Rate	m3/s-W	0,00000005
Enable ASHRAE 55 Comfort Warnings		No
Mean Radiant Temperature Calculation Type		ZoneAveraged
Surface Name/Angle Factor List Name		
Work Efficiency Schedule Name		
Clothing Insulation Calculation Method		CalculationMethodSchedule
Clothing Insulation Calculation Method Schedule Name		
Clothing Insulation Schedule Name		
Air Velocity Schedule Name		
Thermal Comfort Model 1 Type		Adaptive

Figure 19 – *People* object in *Energy+* environment

As mentioned, with *people* object is possible to assess thermal comfort conditions choosing among different models[16]. *Energy+* computes the hours in which the environment does not comply with the certain standard requirements, in this case ISO 16798.

Electric and gas equipment

Electric and gas equipment contribute to increase the heat gains. This is happening because a fraction of the power with which they are feed is converted into heat. User can quantify this contribution setting a proper value for 'Fraction Lost' field in the *electric equipment* object in the *Energy+* editor.

[0002] ElectricEquipment
[0003] ZoneInfiltration:DesignFlowRate
ID: N6
Default: 0

Field	Units	Obj1
Name		elec_equip_salaPC
Zone or ZoneList Name		Thermal Zone: Sala pc
Schedule Name		School Occupancy
Design Level Calculation Method		EquipmentLevel
Design Level	W	3500
Watts per Zone Floor Area	W/m2	
Watts per Person	W/person	350
Fraction Latent		
Fraction Radiant		
Fraction Lost		0,3
End-Use Subcategory		electrical appliances

Figure 20 - *Electric equipment* object in *Energy+* environment.

[16] The two major thermal comfort assessment models were discussed in 3.1.1 and 3.1.2.

5 Case study: Escola Conde de Oeiras

Built in 1982, Conde de Oeiras is a K-12 school complex of 6 buildings located in Oeiras municipality, consisting in:

- *Administrative pavilion* (P.A.), that hosts the offices and the main library, it is second most energy demanding building.
- *Canteen*, which also hosts some free time activities carried out in the afternoon, it is first most energy demanding building.
- *Gym* (not treated in this study).
- *Pavilions A, B, C* in which the classes are held.

Figure 21 - *Escola Conde de Oeiras* view 1. Source: Google Earth Pro; year: 2018.

The 11-a side football pitch and playground in front of the gym are also part of the school's infrastructures.

The complex is 2 km far from the main station of Oeiras, which can be reached from Lisbon with the regular urban transport service.

With the numbers provided in Table 14, *Escola Conde* can be considered medium-size school if referred to the Portuguese average [4].

Table 14 - People attending Escola Conde de Oeiras from 2014 to 2018.

School period	Students	Staff
2014-2015	772	102
2015-2016	810	104
2016-2017	808	102
2017-2018	765	103

5.1 Location and climate

Oeiras is a Portuguese municipality sited in Lisbon district on the northern margin of Tagus River. His position on the Estoril coast makes the temperature quite moderate throughout the year. Köppen's climate classification collocates Oeiras is in the transition between *temperate dry and hot summer* (*Csa*) and *temperate dry and temperate summer* (*Csb*).

Nevertheless, the '*Relatório de Caracterização e Diagnóstico do Concelho de Oeiras*' of 2013 sustained that, due to the its topography and distance from the ocean, the area may suffer the influence of microclimates which may affects negatively thermal comfort in buildings and concentration of pollutants in certain time of the year.

Rainfall regime presents marked annual irregularities with drought periods of variable length, but usually coinciding with the months between July and September, in which the average monthly precipitation rarely exceeds 6 mm [12].

Relative humidity range of variation is between 55% (August) and 73% (January).

The wind is generally moderate, yet enough to ensure a good dispersion of air pollution locally produced by traffic and other human activities [12].

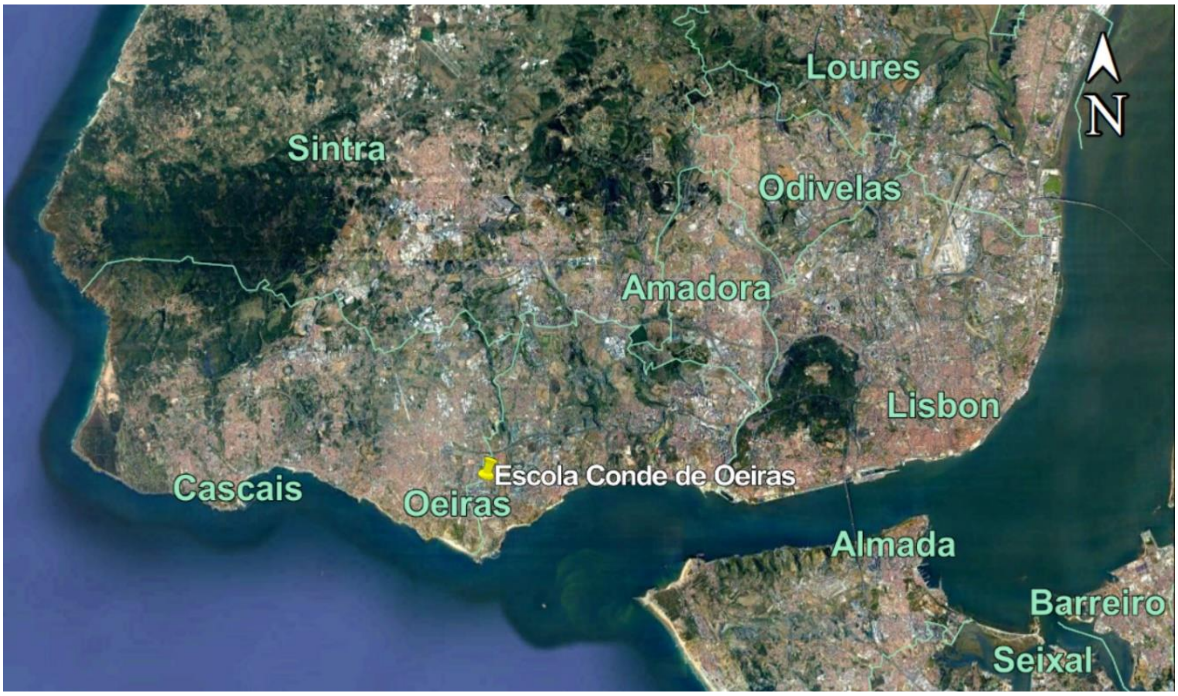


Figure 22 - *Escola Conde de Oeiras* view 2. Source: Google Earth Pro; year: 2018.

5.2 Pavilions with classrooms

Pavilions A, B and C have the same constructions and shape and for this reason they are presented together in this paragraph. The only difference between the pavilions is their orientation. Taken pav. C as reference:

- Pav. A plant is rotated by 180° on plane parallel to the ground.
- Pav. B plant is rotated by 180° on a plane perpendicular to the ground.

Figure 23 – *Pavilion C* view. Source: Google Earth Pro; year: 2018.

As can be noted in the *SketchUp* model of Fig. 25 and in the real view of the north façade of Fig. 24, the main feature of these buildings is a large window/wall ratio (44,5 %).

Figure 24 – *Pavilion C*, north façade. Source: Google Earth Pro; year: 2018.

This feature has a considerable impact in different aspects: while on the one hand this makes the rooms bright and potentially well ventilated, on the other hand it makes them extremely hot in summer and cold in winter. Moreover, it must be considered that windows and glass surface installed in 1982 were never replaced. Thus, air leakages, thermal bridges, structural decay of the materials are crucial aspects to be taken into account.

However, some fairly important changes have been made recently:

- Replacement of the old and dangerous fibrocement roof covers (visible in Fig. 23) with a new one in expanded polystyrene (EPS) with a 6 cm thickness.
- Application of a cork insulating layer (2 cm) in the indoor part of the roof.

Thermal zones arrangement

The building has a total area of 825 m^2 and presents eight classrooms, five on the north side ('*Aula nord 1,2,3,4,5*) and three on the south side ('*Aula sud 1,2,3*). All of them can be entered both from the entrance or from the external perimeter. Computer lab hosts also lectures. Bathrooms are located next to the entrance and are used by children only. This arrangement is also valid for pavilion A and B.

In Fig. 25 it is provided a view of pavilion C in which are indicated and named all the thermal zones.

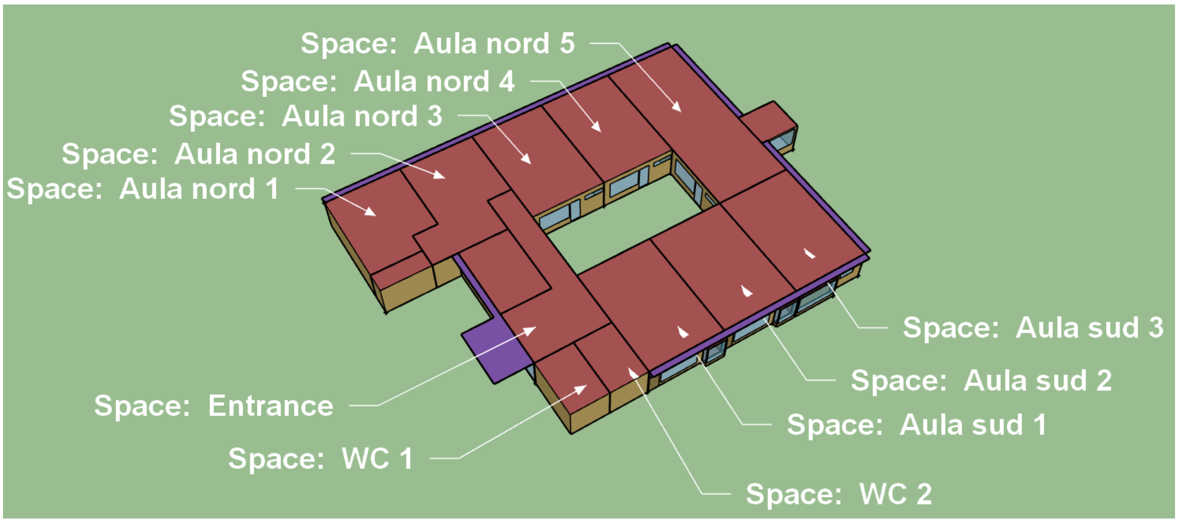


Figure 25 – Virtual view of *pavilion C.*

As already mentioned, pavilions A, B and C are geometrically identical, and they present the same type of electrical equipment and people occupancy. Hence, <u>only pavilion C will be part of the thermal analysis discussed later.</u>

5.2.1 People occupancy

People occupancy in Pavilions A, B, C varies according to school timetable[17]. Despite not having classes, in the noon some children spend time in the classrooms doing homework or various extracurricular activities. Fig. 26 represents daily occupancy profile of a standard weekday. This building is not used during July, August and holidays. Max number of occupants per classroom is estimated in 25[18] people. Considering an average of 11 hours per day (from 7am to 8pm), the presence of people in this building is estimated in 2043 hours per year.

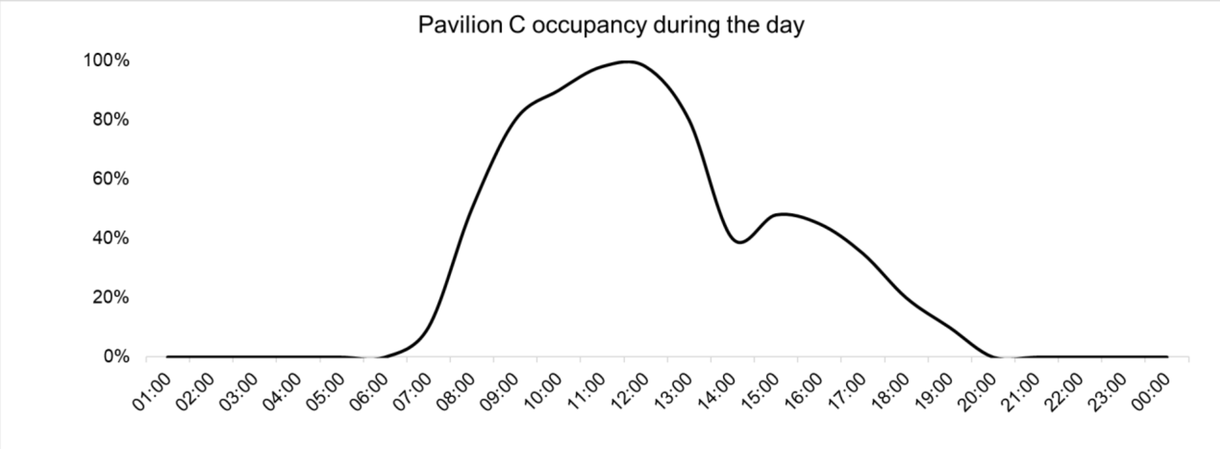


Figure 26 - *pavilion C* daily occupancy. Source*: Escola Conde de Oeiras*.

5.2.2 Ventilation schedules

To compute Air Changes per Hour (ACH_{ref}) to be guaranteed in each classrooms of the pavilion C, standard values from ISO EN 16798 were adopted.

For adapted persons with a 1.1 met of activity level, the suggested air flow rate for a classroom is 10 l/s per person which corresponds to a PPD ≤ 15%. Hence, the following values were calculated for pavilion C.

Table 15 – Minimum values of *Air Changes per Hour* to be guaranteed in *pavilion C* classrooms.

	Aula Nord 1	Aula Nord 2	Aula Nord 3	Aula Nord 4	Aula Nord 5	Aula Sud 1	Aula Sud 2	Aula Sud 3	Lab
total volume [m3]	194	249	249	249	415	249	249	249	111
max n° of occupants	20	25	25	25	30	25	25	25	15
Air Changes per Hour	3.7	3.6	3.6	3.6	2.6	3.6	3.6	3.6	4.9

In order to fill properly the *ventilation schedule* object, values in Table 15 were adjusted according to people occupancy and seasonality as follows:

$$ACH = ACH_{ref} \cdot \frac{current\ occupants}{\max n°\ of\ occupants} \cdot C \qquad where \quad \begin{cases} C = 1\ for\ winter \\ C = 2\ for\ summer \end{cases} \qquad (19)$$

It is to be reminded that infiltration rate is also included in the air mass balance.

[17] Classes form 8am to 1pm and afternoon recreational/homework activities
[18] Data provided by *Escola Conde* administration office.

5.2.3 Electrical and gas equipment

Gas equipment is almost absent in the building, apart from the boiler system used to heat water in the bathrooms which does not contribute significantly to the internal gains. Electrical equipment consists in computers, lights and various plug-in appliances. The use of those is scheduled according to people occupancy. Hence, if a certain room in the pavilion is at his maximum occupation, it is consuming the maximum amount of power.

The following equipment has been introduced in the model:

- Computers: 350 W x 20 units.
- Lights: 5 W/m2; scheduled according to daylight period contained in the weather file.
- Various plug-in appliances: estimated in 400 W per classrooms.
- Stand-by appliances: estimated in 500 W for the entire building.

The daily electricity consumption profile and SEC report are presented below:

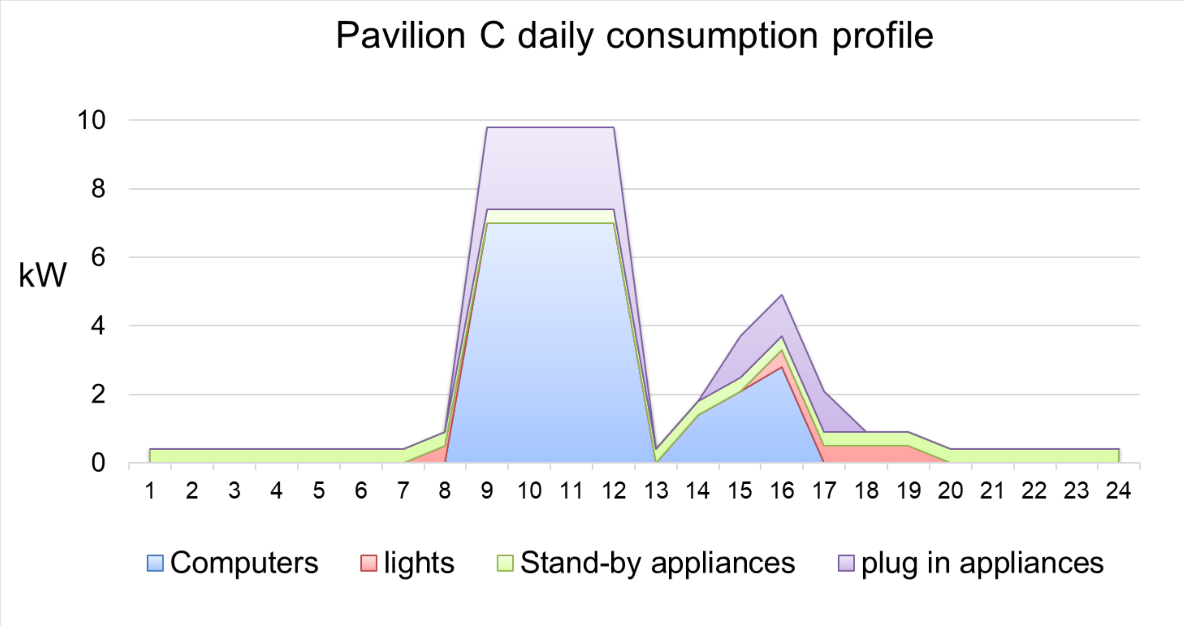


Figure 27 - *Pavilion C* daily electricity consumption profile.

Table 16 - *Pavilion C* Specific Energy Consumption report.

Pav. C SEC report	
Gross Floor Area [m2]	825
Estimated annual electricity consumption [kWh]	14304
SECelectricity [kWh/m2/year]	17.3

5.3 Administrative pavilion

Unlike the other buildings, administrative pavilion is developed on two floors. It is also the only one in the school that is air conditioned. It hosts offices, but it is also provided with a large library and a computer lab on the second floor.

Figure 28 - *Administrative pavilion* view. Source: Google Earth Pro; year: 2018.

Windows are large and numerous on all the facades, except for the north exposed one. As said for the pavilions with classrooms, windows are the major source of inefficiency because of heat dispersions, excess solar gains, air leakages and consequently the main reason of thermal discomfort. The window/wall ratio for this building is equal to 35%.

Figure 29 – *Administrative pavilion*, east façade. Source: Google Earth Pro; year: 2018

Some energy efficiency measures were adopted, especially in the recent years:

- New 6 cm EPS roof cover.
- Replacement of the old halogen lamps in the library with LED.
- Installation of cork insulation layer on the indoor part of the roof.

Except for these three measures, interventions on the building focused mainly on routine maintenance and occasional fixings after damages.

Spaces arrangement

The building presents eight[19] types of spaces each of them identifying a thermal zone, according to Table 17.

Table 17 - Space functions and names of the main thermal zones in *administrative pavilion.*

Space function	Thermal zones in the virtual geometry
adminstrative office	*2down, 2up, 3,*
director office	*11*
psychologist office	14
other offices	*4, 5, 6*
library	*10, 15, 16*
bar	*7*
entrance	*1*
computer lab	*12*

Some 3D views of the *SketchUp* model of administrative pavilion are provided below.

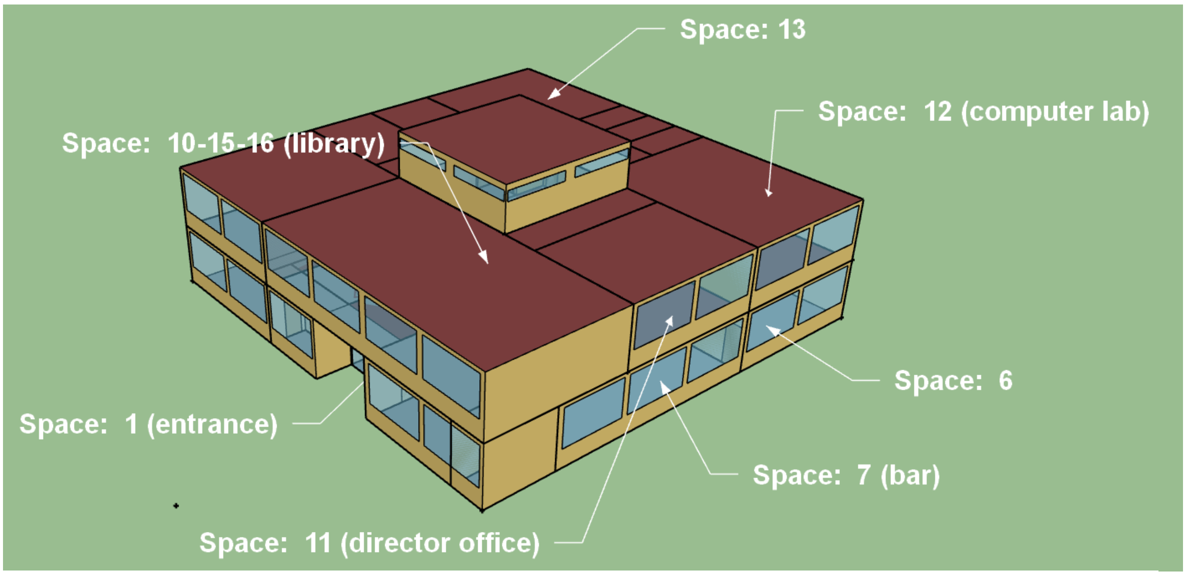


Figure 30 - Virtual view of south and east façade of *Administrative pavilions*

[19] Bathrooms, utility rooms and other small space were not included in the table (and as well in the analysis) due to their negligible average occupancy.

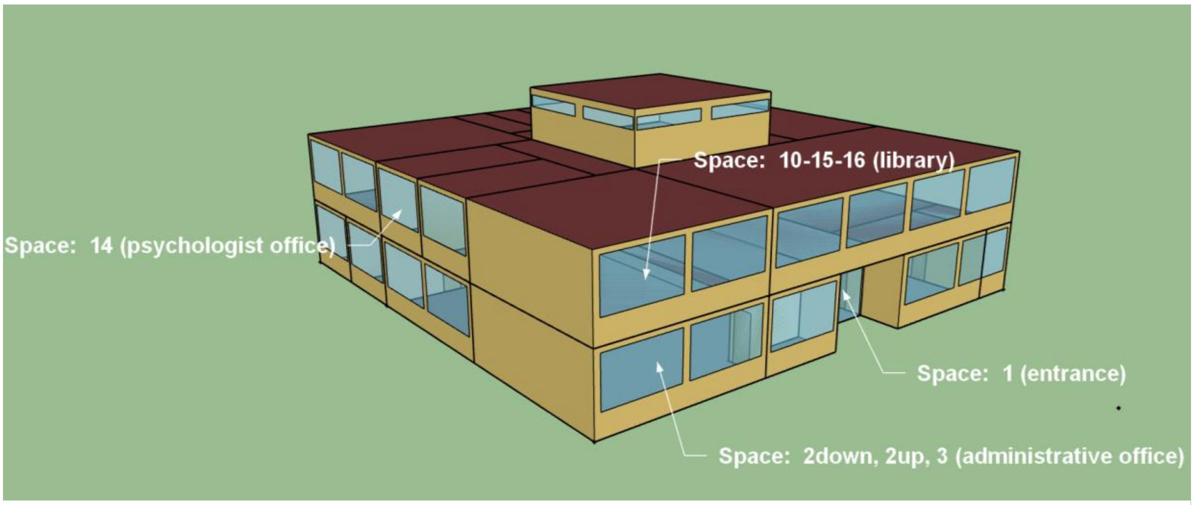


Figure 31 - Virtual view of west and south façade of *Administrative pavilion.*

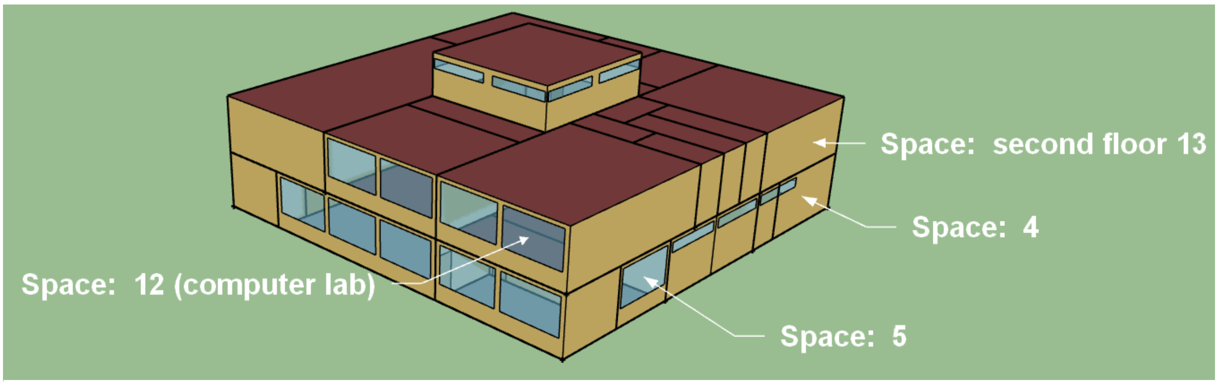


Figure 32 - Virtual view of east and north façade of *Administrative pavilion.*

5.3.1 People occupancy

This facility is occupied by people whose age is, on average, above 18, therefore their tolerance to discomfort is expected to be higher.

Working time is not the same for all the employees and some of them leave the building after launch. However, since children use to attend library and other spaces in this facility, people occupancy does not vary significantly during the working hours. Administrative pavilion is closed only during August, hence considering an average of 11 hours per day, the presence of people in this building is estimated in 2540 hours per year.

People occupancy profile for a design day is shown in Fig. 33.

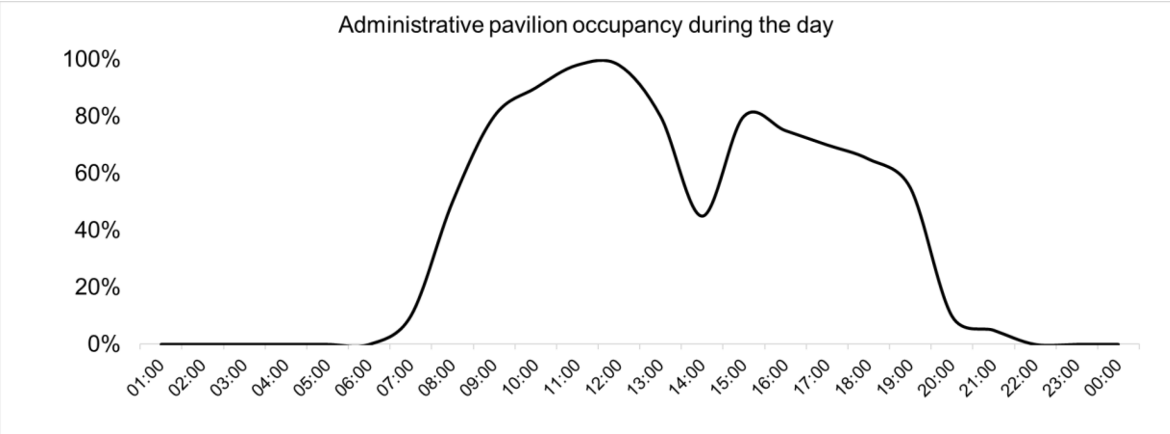


Figure 33 – *Administrative pavilion* daily occupancy. Source: *Escola Conde de Oeiras.*

5.3.2 Ventilation schedules

The procedure adopted to compute ACH values was the same adopted for pavilion C. Results of calculations are provided in Tables 18 and 19.

Table 18 - Minimum values of Air Changes per Hour to be guaranteed in 1st floor thermal zones of Administrative Pav.

1st floor

thermal zone	Entrance	2 down	2 up	3	4	5	6	7	8
total volume [m3]	258	214	117	39	87	78	78	232	58
max n° of occupants	15	12	4	2	3	4	3	12	3
Air Changes per Hour	2.1	2.0	1.2	1.9	1.2	1.9	1.4	1.9	1.9

Table 19 - Minimum values of Air Changes per Hour to be guaranteed in 2nd floor thermal zones of Administrative Pav.

2nd floor

thermal zone	Library	11	12	13	14
m3	525	117	194	156	58
max n° of occupants	30	5	20	8	3
Air Changes per Hour	2.1	1.5	3.7	1.9	1.9

5.3.3 Electrical and gas equipment

Gas equipment is almost absent in the building, with the exception of the boiler system used to heat water in the bathrooms which does not contribute significantly to the internal gains.

Electrical equipment consists in computers, lights and various plug-in and stand-by appliances. The use of those is scheduled according to people occupancy. Hence, if a certain room in the pavilion is at his maximum occupation, it is consuming the maximum amount of power.

The following equipment has been introduced in the model:

- Computers: 350 W x 45 units.
- Lights: 5 W/m2; scheduled according to daylight period contained in the weather file.
- Various plug-in appliances: like phone charger, estimated in 1 kW.
- Stand-by appliances, in which are included 2 refrigerators, wi-fi router, printer and other office equipment. Estimated in 1 kW for all the building.
- Bar equipment, for which the designed power is estimated in 4 kW.
- Air Conditioners, consisting in 5 AC units, label B with an annual consumption of 300 kWh. This value was then converted on a daily basis[20]. The daily electricity consumption profile and the annual data SEC report are presented below:

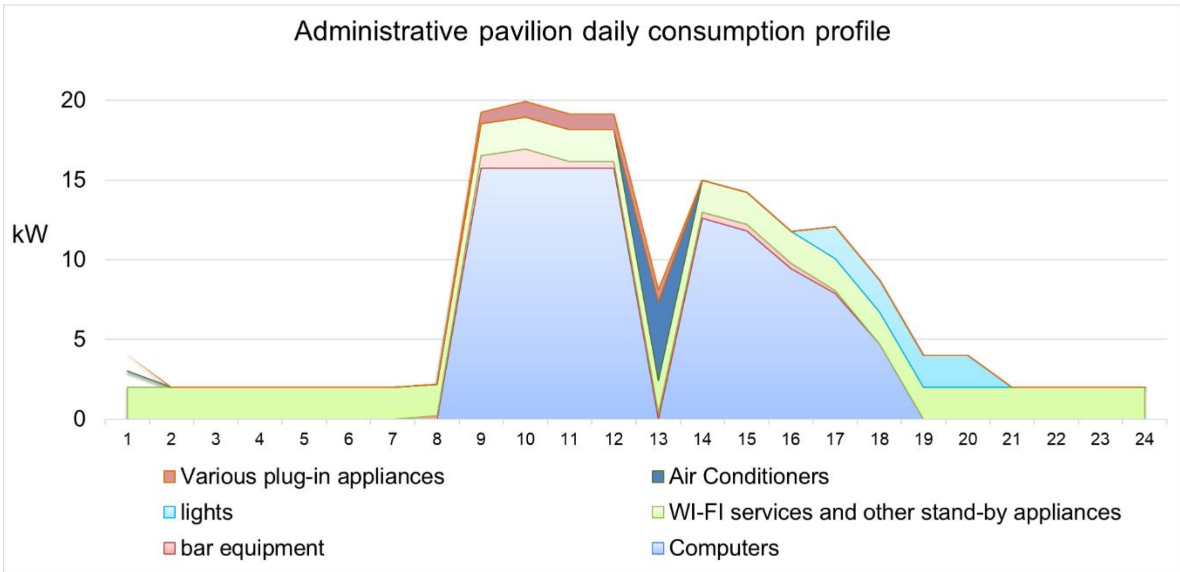


Figure 34 - *Administrative pavilion* daily electricity consumption profile.

Table 20 - Administrative pavilion Specific Energy Consumption report.

Admin. pav. SEC report	
Gross Floor Area [m2]	978
Estimated annual electricity consumption [kWh/year]	43100
SECelectricity [kWh/m2/year]	44.07

[20] 300 kWh per year → 1,25 kWh per day; considering 240 working days per year

5.4 Canteen

The canteen has a plant that is symmetrical to a line passing through the midpoint of its long side (Fig. 35). It has two main entrances one from north and one from south and a total area of 829 m^2. Kitchen stands in the exact centre of building.

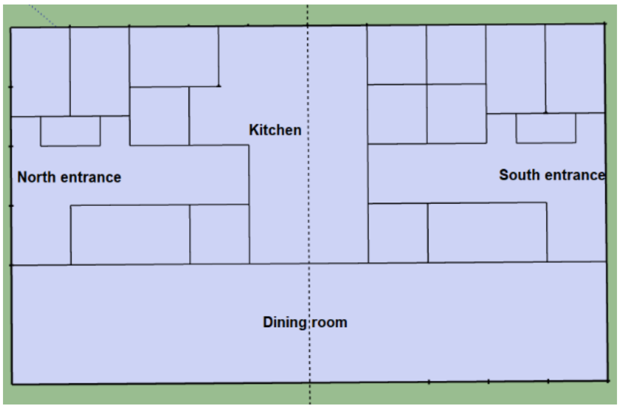


Figure 35 – Virtual plant view of *Canteen*.

As it can be seen in Fig. 36, the building receives shade from the trees that rise in front of north and south facades. Nevertheless, solar gains in this building are not the major source of heat.

Figure 36 – *Canteen* view. Source: Google Earth Pro; year: 2018.

The kitchen, because of his central position, provides a considerable amount of heat to surrounding rooms. Large glass surfaces characterize the west side of the building and provide dining room with light in the noon. Window/wall ratio was assessed around 28%.

This facility stands out form the others for a more marked need for modernization of the interior equipment. To give a practical example, the kitchen hoods in the bar and in the kitchen have suffered the effects of wear, should be replaced with new ones that are more efficient and could enhance air renovation rate.

Energy efficiency measures adopted consisted only in the installation of cork insulating layer in some of the rooms next to north façade, such as recreational area. Roof cover replacement did not take place yet.

In Fig. 37 is shown a view of the canteen building with the names of main thermal zones.

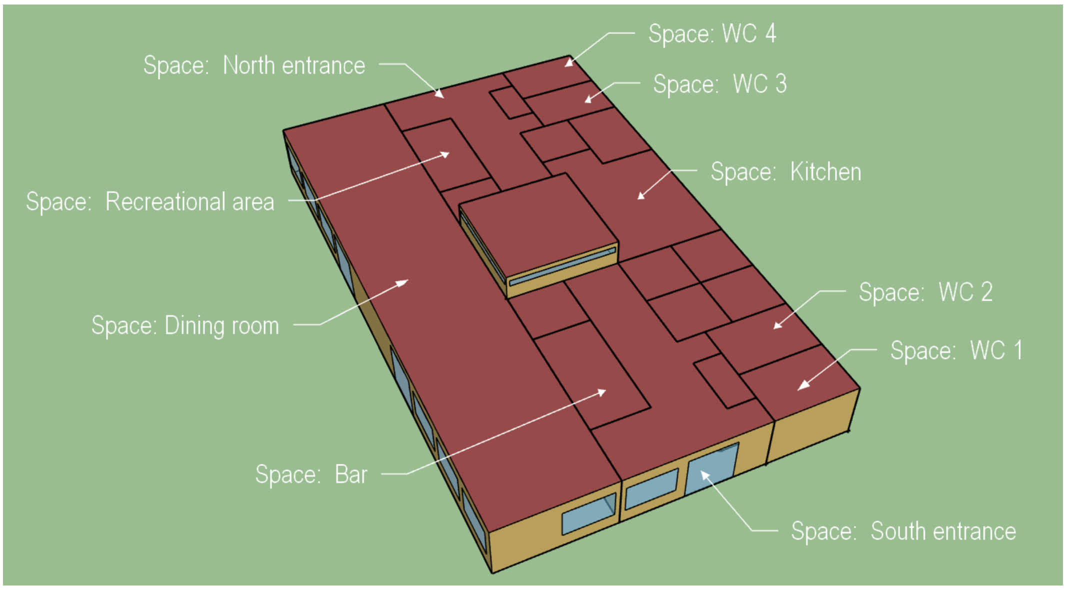


Figure 37 - Virtual view of the *Canteen*.

5.4.1 People occupancy

Canteen works almost all day since during the morning children and employees could have a break in the bar whereas in the afternoon some of the rooms next to the northern entrance are used for recreational activities. Considering the daily occupancy profile in Fig. 38, presence of people in the building is estimated in 2180 hours per year.

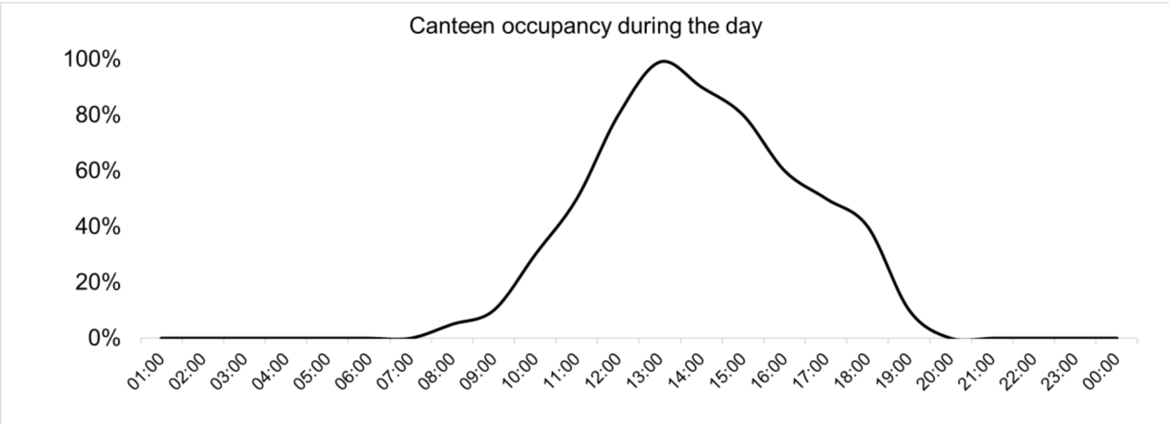


Figure 38 - *Canteen* daily occupancy.

5.4.2 Ventilation schedules

The procedure adopted to compute ACH values was the same adopted for pavilion C. Results of calculations are provided in Table 21.

Table 21 -Minimum values of Air Changes per Hour to be guaranteed in the main thermal zones of the Canteen.

Thermal zone	Kitchen	Dining room	South entrance	North entrance	Recreational area	Bar
m3	443	933	257	257	93	93
max n° of occupants	40	100	25	25	10	3
Air Changes per Hour	3.3	3.9	3.5	3.5	3.9	1.2

5.4.3 Electrical and gas equipment

Gas equipment has a large influence both in daily consumption and thermal comfort, hence it has to be included in the analysis.

Using the data from both from the gas bills (2014 to 2018) and the meter, Conde de Oeiras school estimates canteen gas consumption in a standard weekday around 4,1 m^3 which corresponds to 46,8 kWh (according to conversion factor seen in section 5.4.1). Hence, if gas equipment works at full load for three hours per day it results that:

$$P_{max,gas\ equip.} = \frac{46{,}8\frac{kWh}{day}}{3\frac{h}{day}} = 15{,}6\ kW \quad (20)$$

Hence, the value of designed power level to enter in the '*Energy+ gas equipment schedule*' was set to 15,6 kW.

Electrical equipment consists in electric stoves, microwave, lights and various plug-in and stand-by appliances. The use of those is scheduled according to people occupancy and dining times. The equipment [21] introduced in the *Energy+* model as well as daily consumption profile are presented below.

Table 22 – List of *Canteen* electrical appliances

Appliance	**Power (kW)**
Oven	9,5
Griddle for cooking	6
Fry machine	8
Cooling devices	3
Dishwasher	9
Coffee machines	3,5
Lights	1
Cold showcase	0,4
Hot showcase	0,6
Microwaves	2
Various plug-in appliances	1
Cooker hood	1

[21] Appliances and related powers were provided according to school's inventory and standard consumption of the most common devices available in the market.

Graphs describe a standard weekday in which power peak is reached approximately between 12 am and 1 pm. Obviously, these type of consumptions may vary a lot from day to day, but the purpose here was to depict a general overview of canteen gas/electrical equipment in order to set the proper input for the simulation.

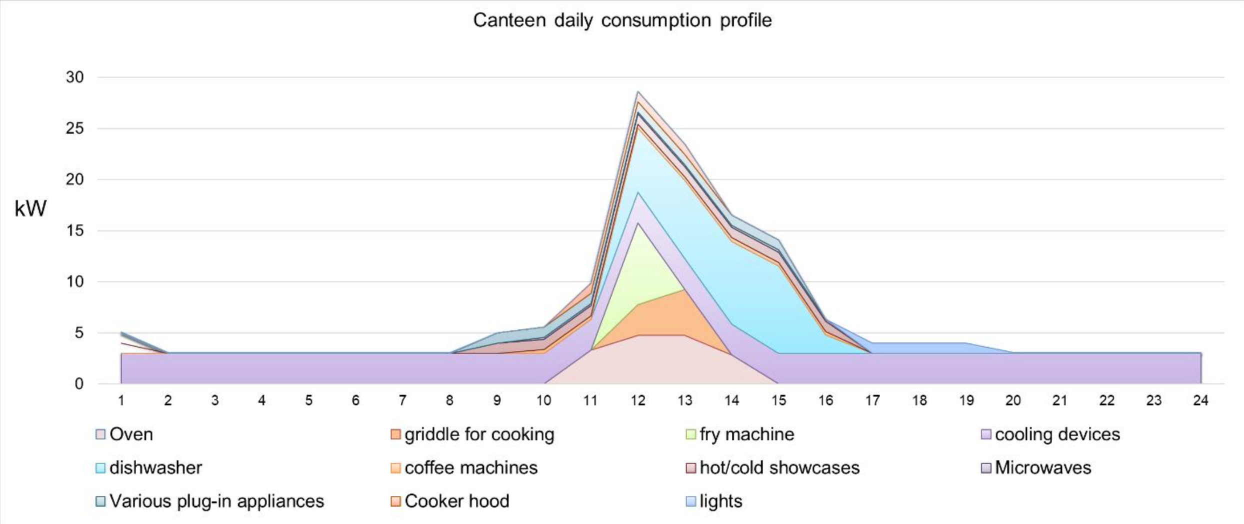


Figure 39 - *Canteen* daily electricity consumption.

Annual data on Specific Energy Consumption (SEC) are summarised in Table 23.

Table 23 - *Canteen* Specific Energy Consumption report.

Canteen SEC *report*	
Gross floor area [m2]	829
Estimated annual consumption [kWh/year]	36460
SECelectricity [kWh/m2/year]	43.98

5.5 Energy data analysis

It is intended to clarify, that all the pieces of information presented so far were estimated according to products datasheets made available from *Escola Conde* equipment inventory.

Thus, aiming to get closer to the actual annual consumption profile, gas and electricity bills of last five and three years, respectively, were collected. However, it has to be taken into account that this type of data does not make possible to distinguish the use of energy of each facility. Nevertheless, it may be useful to become acquainted with real data and to compare (in Table 24) *Escola Conde* with the Portuguese K-12 schools' average consumption, previously examined in chapter 2.

Table 24 – Specific Energy Consumption comparison.

	Escola Conde		Reference(***)
Year	2017	2016	2008
Electricity billed consumption [kWh]	155250	160998	/
SECelectricity [kWh/m2/year](*)	28.37	29.42	16.18
Avg. n° of students (**)	787	809	1179
SECelectricity per student [kWh/student]	197.3	199.0	286.5

(*): *Escola Conde* Gross Floor Area = 5473m2; including all the facilities (also the gym and football pitch)

(**): Calculated averaging data of two consecutive school periods

(***): Average values for the 57 schools discussed in chapter 2, before their complete refurbishment

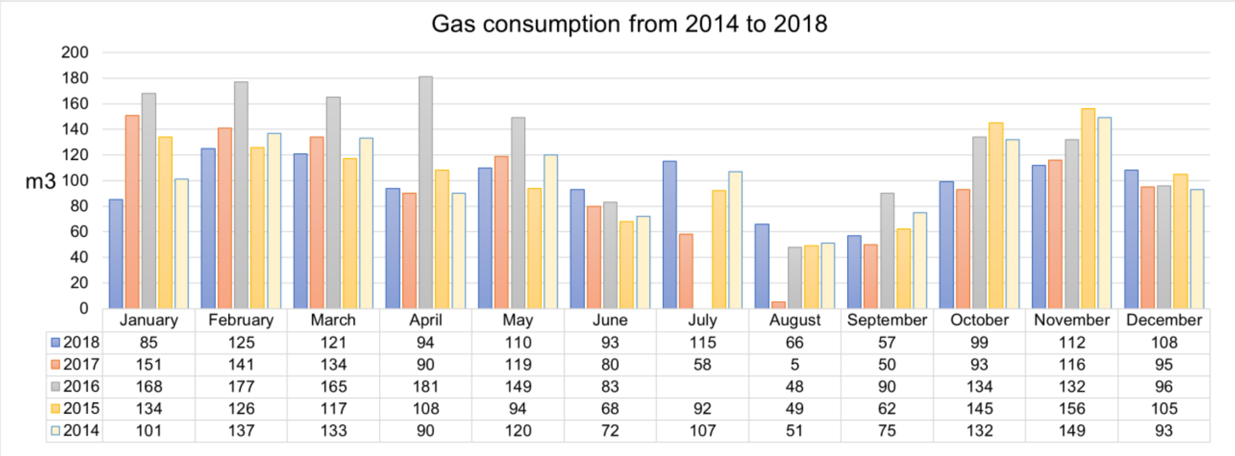
What can be observed from the comparison above is that *Escola Conde,* with around 32% less students than the average, registers almost twice consumption of electricity. This considering that those 57 schools were still not refurbished and consequently in a state of conservation similar to the one of the case study.

Of course, many objections could be raised since it is not specified whether those 57 schools were provided with the same infrastructures of *Escola Conde*. However, each of them was built after 1968 and supposedly with analogous criteria.

In any case, it would be legitimate to question the presence of any inefficiency in the management of energy resources in the case study framework. Aiming to pursue this objective, the present work will firstly provide more pieces of information about electricity and gas use and then expose the results of the thermal simulations of the virtual buildings which are part of *Escola Conde* complex.

5.5.1 Gas consumption

Conde de Oeiras gas consumption is essentially due to cooking and water heating. Hence, the buildings with higher gas needs are the canteen and the gym. As it can be observed in histogram in Fig. 40, consumptions rise similarly when school reach full occupancy in months with less holidays (February, March, April, October, November). In winter, use of hot water for showers in the gym, justifies the increased demand.



	January	February	March	April	May	June	July	August	September	October	November	December
2018	85	125	121	94	110	93	115	66	57	99	112	108
2017	151	141	134	90	119	80	58	5	50	93	116	95
2016	168	177	165	181	149	83		48	90	134	132	96
2015	134	126	117	108	94	68	92	49	62	145	156	105
2014	101	137	133	90	120	72	107	51	75	132	149	93

Figure 40 - Gas consumption from 2014 to 2018

Discontinuity in data was found for:

- April 2016, which consumption is way above the monthly average.
- July 2016 data that was not found.
- August 2017, which is very close to 0.

To make gas data comparable with electricity ones, it was necessary to convert it from m^3 to kWh. This was done adopting the following conversion factors suggested by *EDP,* (*Conde de Oeiras* suppliers from 2014 to 2017):

$$y\,kWh = x\,m^3 \cdot FCV \cdot PCS \tag{21}$$

$$where \begin{cases} Volume\ Conversion\ Factor\ (FCV) = 0{,}96759\,\frac{m^3}{kg} \\ Higher\ Heating\ Value\ (PCS) = 11{,}8\,\frac{kWh}{kg} \end{cases}$$

Hence, it is provided the Specific Energy Consumption summary including gas use. It was found out that school expense for natural gas is way over national average (Table 26).

Table 25 - Specific Energy Consumption report including gas use.

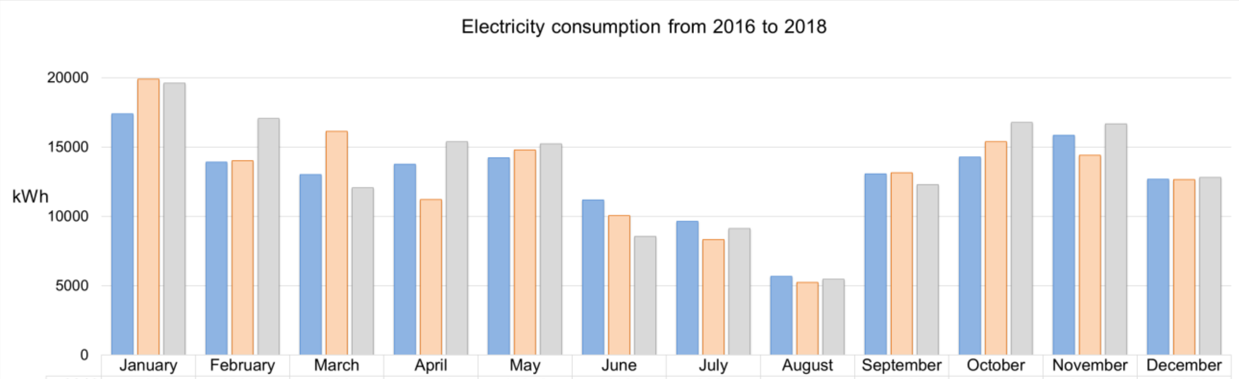
Gas SEC report			
Year	2018	2017	2016
Gas price, vat excluded [€/m3]	7.39	7.56	8.47
Gas billed consumption [kWh]	13530	12925	16247
SEC(gas+electricity) [kWh/m2/year]	30.84	30.73	32.39

Table 26 – Portuguese gas tariffs [23].

	€/GJ	€/kWh	€/m3
2017	25.55	0.09198	1.050
2016	25.48	0.091728	1.047
2015	22.82	0.082152	0.938
2014	20.31	0.073116	0.835

5.5.2 Electricity consumption

Electricity is the most demanded type of energy in this school. Consumptions did not change significantly in the period 2016-2018 as it can be seen in the histogram of Fig. 41.



	January	February	March	April	May	June	July	August	September	October	November	December
2018	17391	13925	13017	13756	14216	11182	9634	5684	13069	14276	15836	12671
2017	19900	14006	16117	11199	14803	10061	8316	5235	13145	15381	14416	12665
2016	19594	17063	12057	15382	15222	8561	9121	5460	12293	16775	16660	12810

Figure 41 - Electricity consumption from 2016 to 2018.

End-uses are numerous and tough to quantify in percentages, however most of the needs come from administrative pavilion (office equipment like computers, printers etc.) and the canteen (cooling devices, oven, microwave etc.). Another source of consumption is the football pitch next to pavilion A which is rented to local teams even when school is closed. Regarding electricity price, the school adopts a tariff with four time slots: *Ponta (Peak), Cheias (Standard), Vazio (Off-Peak), SuperVazio* (Super Off-Peak). Pie chart in Fig. 42 shows the tariff distribution in 2018 and the prices of each slot.

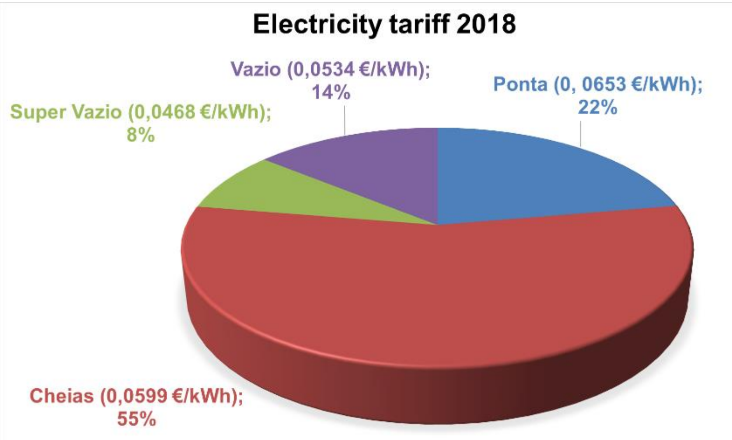


Figure 42 - Electricity tariff of 2018.

However, this represents only the variable part of the total electricity cost. Considering, that the contracted power is currently 84 kVA, fixed costs are predominant.

6 Simulations of the virtual buildings in their actual conditions

At this point, since all the aspects of the energy analysis have been discussed, it may be helpful to summarize them as follows:

- Creation of the geometry of *pavilion C, Administrative pavilion* and *canteen*.
- Definition of thermal balance variables to input in Energy+ environment (materials, constructions, people occupancy, ventilation schedules, gas equipment etc.)
- Attribution of weather file, containing climate data of Lisbon district.

Nevertheless, before exposing the results the reader must know more about what type of output is expected.

Firstly, for all the mentioned buildings, the time in which occupants perceive sensation of thermal discomfort will be quantified. In this way it will be possible to compare the current condition with scenarios in which energy efficiency measures have been implemented. Besides, *Escola Conde* replaced roof covers in *pavilion C* and *administrative pavilion* in August 2019 therefore it was considered appropriate to compare the results obtained simulating the building before and after the replacements.

Successively, the attention will be focused on *Energy+* output with the aim of addressing the main causes of thermal discomfort. What will be found out is fundamental to understand the reasons to adopt energy efficiency measures exposed in chapter 7.

6.1 Pav C results

Thermal discomfort

It is now possible to analyse and discuss the results obtained from the simulation of the virtual *pavilion C* in real climate conditions. In this regard, since in August 2019 roof covers in fibrocement were replaced with new ones in EPS, the output of the following two configurations will be provided:

- Scenario A: pavilion with fibrocement roof cover.
- Scenario B: pavilion with EPS roof cover (current condition).

In the histograms below hours of discomfort are expressed in percentages of the total time occupants spent in the thermal zones. In this regard, for all the zones shown in the charts it is assumed that the presence of at least one person is guaranteed for 2043 hours per year. Hence, small rooms that do not meet this requirement were not considered in the analysis.

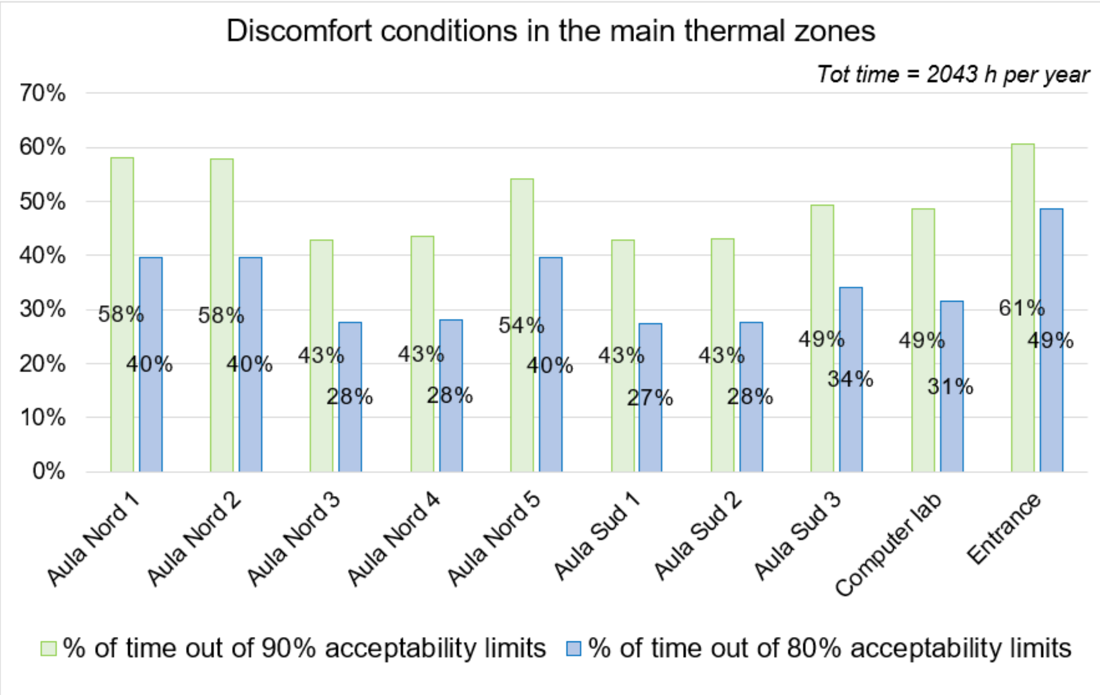


Figure 43 - Thermal discomfort condition in the main thermal zones of *Pavilion C*, before roof replacement (Scenario A).

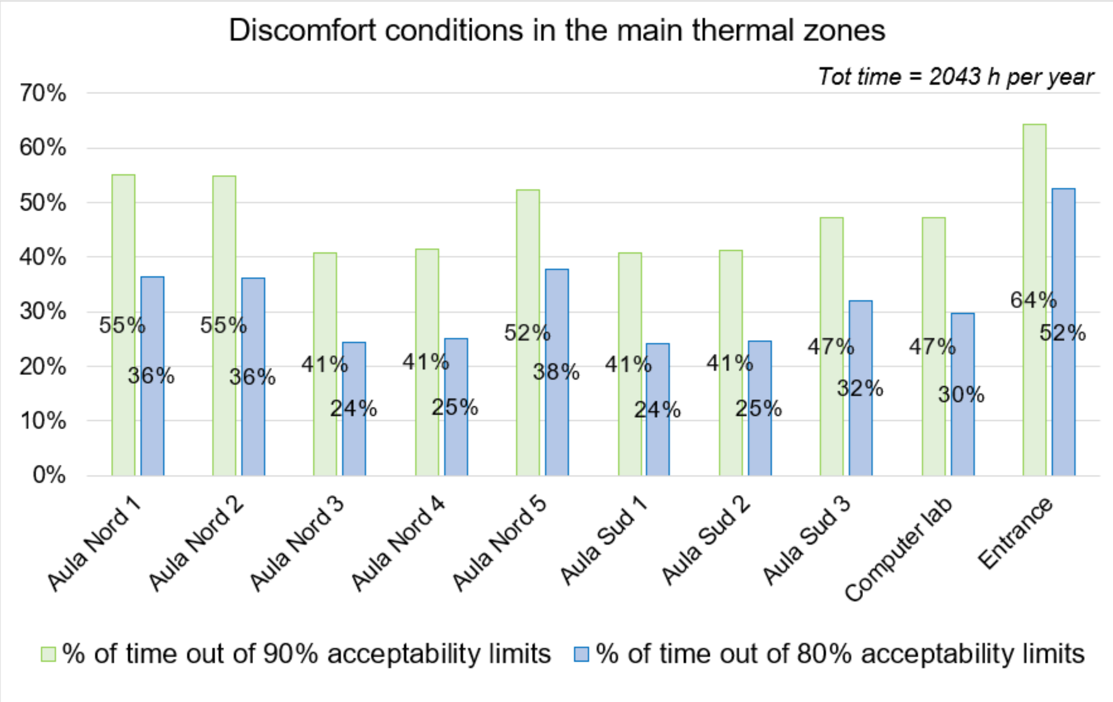


Figure 44, Thermal discomfort condition in the main thermal zones of *Pavilion C*, after roof replacement (Scenario B).

As expected, north exposed classrooms suffer more discomfort due to lack of solar gains, which are essentially the major heat source of this building, during winter.

With the new roof cover in EPS (results in Fig. 44) situation slightly improved with an overall -3% of discomfort time for all the classrooms.

Yearly thermal balance analysis

Causes of discomfort might be different, in particular the most recurrent are exceedingly cold/hot environment and poor air quality. Since for these set of simulations it has been assumed for all the spaces that in any time is always guaranteed enough ventilation to comply with ISO 16798 air quality standard, causes of discomfort should converge to the lack of control on temperature in the thermal zones.

In Tables 27 and 28 are presented extracts of yearly thermal balance for *pavilion C*. This information was contained in *'Sensible heat gain summary'* included in the *Energy+* output summary.

It was possible to prove and quantify the presence of an uncontrolled amount of heat gains and losses through the envelope. In particular *Window heat addition* and *infiltration heat removal*, highlighted in red, have in absolute terms the biggest influence on the thermal balance.

It could be noted how roof replacement affected positively the *infiltration heat removal* and negatively the *window heat removal*. This can be explained in the enhanced air tightness of the roof.

Table 27 – Extract from annual thermal balance of *pavilion C*, before roof replacement.

Extract from annual thermal balance - Scenario A	
HVAC Zone Eq & Other Sensible Air Heating [kWh]	0
HVAC Zone Eq & Other Sensible Air Cooling [kWh]	0
People Sensible Heat Addition [kWh]	24050
Lights Sensible Heat Addition [kWh]	1181
Equipment Sensible Heat Addition [kWh]	10089
Window Heat Addition [kWh]	117074
Infiltration Heat Addition [kWh]	904
Opaque Surface Conduction and Other Heat Addition [kWh]	1233
Window Heat Removal [kWh]	-32909
Infiltration Heat Removal [kWh]	-63780
Opaque Surface Conduction and Other Heat Removal [kWh]	-57841

Table 28 - Extract from annual thermal balance of *pavilion C*, after roof replacement.

Extract from annual thermal balance - Scenario B	
HVAC Zone Eq & Other Sensible Air Heating [kWh]	0
HVAC Zone Eq & Other Sensible Air Cooling [kWh]	0
People Sensible Heat Addition [kWh]	23821
Lights Sensible Heat Addition [kWh]	1181
Equipment Sensible Heat Addition [kWh]	10089
Window Heat Addition [kWh]	116565
Infiltration Heat Addition [kWh]	905
Opaque Surface Conduction and Other Heat Addition [kWh]	1153
Window Heat Removal [kWh]	-33659
Infiltration Heat Removal [kWh]	-61428
Opaque Surface Conduction and Other Heat Removal [kWh]	-58627

Since *pavilions A, B* and *C* are not provided with HVAC systems, energy savings were not registered.

A discreetly high value of *People heat addiction* is justified with an high occupants density of the classrooms (on average 3 m^2/person) whereas lights and electrical equipment give a small contribution to the total balance due to their limited use.

'Opaque surface conduction and other heat addiction/removal' indicates the effect of conduction (through walls, roof and ground) mechanisms in the thermal balance. As shown in Tables 27 and 28, large heat losses occur through the opaque surfaces. A reason for that could be found in the very small thickness of internal walls made with uncovered 15 cm bricks.

6.2 Administrative pavilion results

Thermal discomfort

Roof replacement also concerned *administrative pavilion*, therefore results from both scenario A and B are provided as done with *pavilion C*.

In the histograms of Fig. 45 and 46 hours of discomfort are expressed in percentages of the total time occupants spent in the thermal zones. In this regard, for all the zones shown in the charts it is assumed that the presence of at least one person is guaranteed for 2540 hours per year. Hence, the spaces (small rooms, bathrooms, closet etc.) that do not meet this requirement were not considered in the analysis.

The reader will easily spot the air-conditioned zones: *administrative office, library, director and psychologist office*.

With the new roof, improvements in the range of 1-3% were found for some rooms, mainly for those on 2nd floor. However, hours of discomfort still represent the majority of time for not conditioned room.

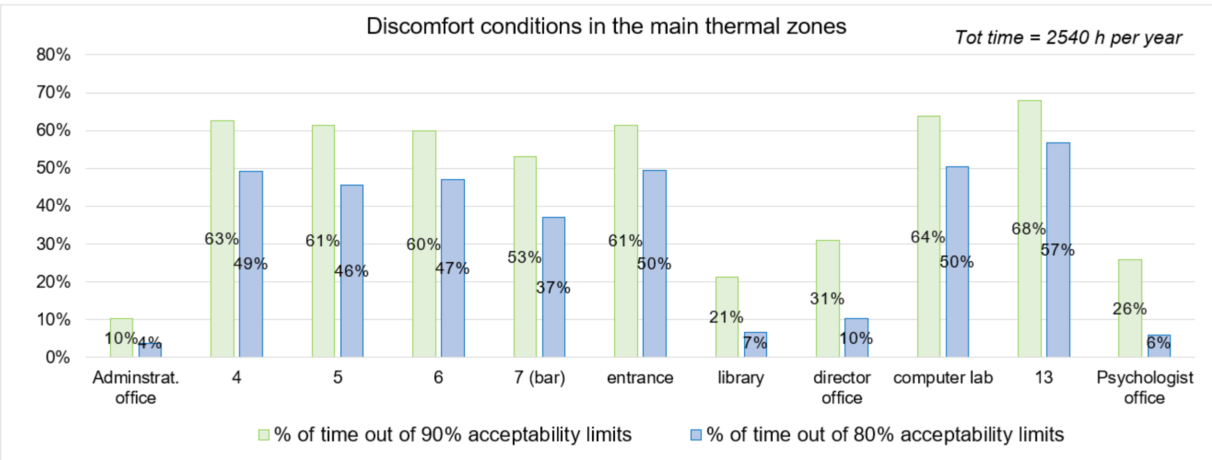


Figure 45 - Thermal discomfort condition in the main thermal zones of *Administrative pavilion*, before roof replacement (Scenario A).

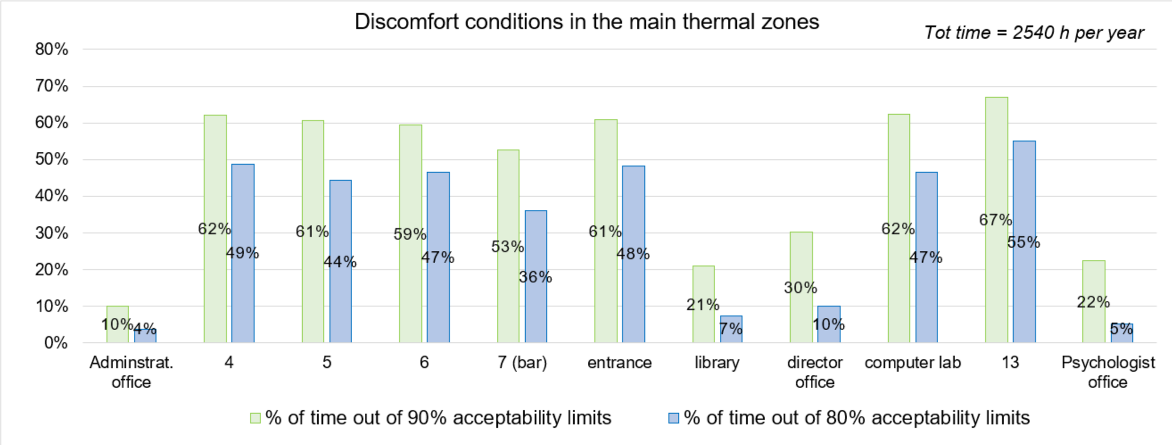


Figure 46 - Thermal discomfort condition in the main thermal zones of *Administrative pavilion*, after roof replacement (Scenario B).

Annual thermal balance data

Similar causes of thermal discomfort were found for *administrative pavilion* with some differences. As done for *pavilion C*, extracts of yearly thermal balance for the two scenarios are here presented.

Table 29 - Extract from annual thermal balance of *Administrative pavilion*, before roof replacement.

Extract from annual thermal balance - Scenario A	
HVAC Zone Eq & Other Sensible Air Heating [kWh]	4293
HVAC Zone Eq & Other Sensible Air Cooling [kWh]	-9976
People Sensible Heat Addition [kWh]	15495
Lights Sensible Heat Addition [kWh]	808
Equipment Sensible Heat Addition [kWh]	25777
Window Heat Addition [kWh]	121733
Infiltration Heat Addition [kWh]	1945
Opaque Surface Conduction and Other Heat Addition [kWh]	8513
Window Heat Removal [kWh]	-36926
Infiltration Heat Removal [kWh]	-87472
Opaque Surface Conduction and Other Heat Removal [kWh]	-46664

Table 30 - Extract from annual thermal balance of *Administrative pavilion*, after roof replacement.

Extract from annual thermal balance - Scenario B	
HVAC Zone Eq & Other Sensible Air Heating [kWh]	3345
HVAC Zone Eq & Other Sensible Air Cooling [kWh]	-10476
People Sensible Heat Addition [kWh]	15308
Lights Sensible Heat Addition [kWh]	808
Equipment Sensible Heat Addition [kWh]	25777
Window Heat Addition [kWh]	121733
Infiltration Heat Addition [kWh]	1809
Opaque Surface Conduction and Other Heat Addition [kWh]	8358
Window Heat Removal [kWh]	-36926
Infiltration Heat Removal [kWh]	-86220
Opaque Surface Conduction and Other Heat Removal [kWh]	-43514

First, HVAC systems introduce another variable in the global thermal balance and this time it is possible to quantify energy savings obtained after roof cover replacement. In scenario B, which is the current condition, were registered 22% of savings for space heating and an increase of 4,7% for cooling needs. These may be considered the most tangible effects of the roof replacement on the air-conditioned thermal zones.

As expected, people heat addiction is smaller than pavilion C due to lower occupants' density, whereas for electric equipment this is not true. Indeed, numerous plug-in devices provide a considerable amount of heat, estimated in 25777 kWh per year.

Heat gains/losses through windows and infiltrations have very high values and consequently, these seem to be the major sources of discomfort.

Regarding the conduction mechanisms through opaque surfaces, the new roof has brought modest results quantified in -6,7% heat losses and -1,8% of heat gains.

6.3 Canteen results

Thermal discomfort

Since roof cover replacement did not occur in the canteen building hence only one scenario has been studied. In histogram of Fig. 47 are shown once again the thermal zones in which presence of people is guaranteed at least for 2180 h per year.

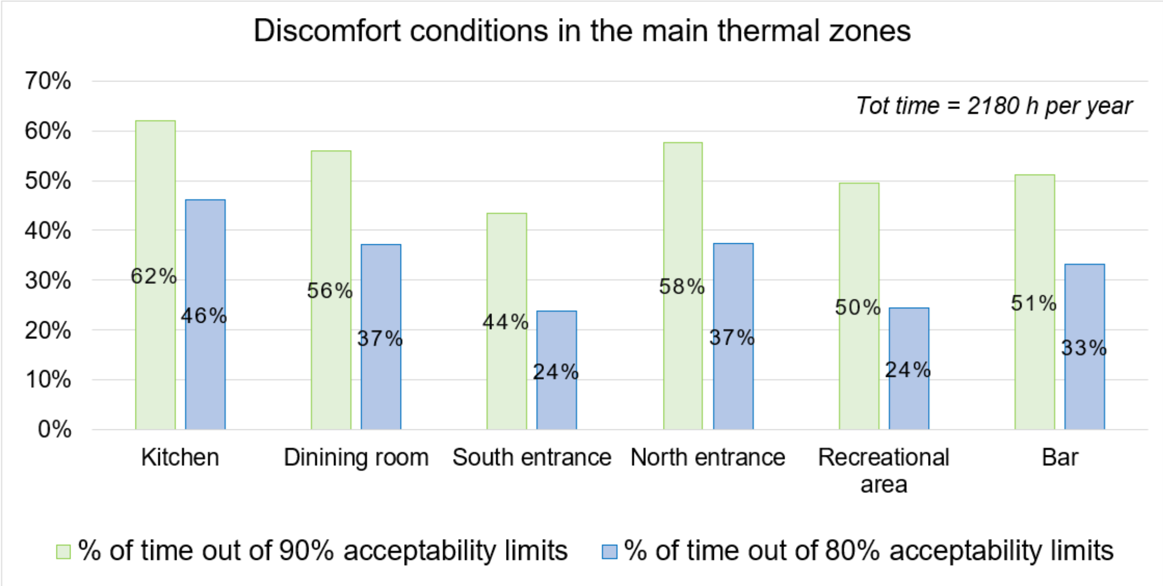


Figure 47 - Thermal discomfort condition in the main thermal zones of *Canteen.*

As was mentioned before, kitchen occupies a central position and influences thermal balance of all the surrounding zones. For this reason, all the heat generated by the gas equipment, especially during launch time, flows into the dining room and the entrances making them uncomfortable.

Recreational area is mainly occupied in the afternoon justifying lower percentages of discomfort. Moreover, is one of the few rooms provided with cork insulation on the indoor side of the roof.

Entrances tends to be very crowded between 12:30 am to 3:00 pm, and for this reason they were included in the analysis.

Annual thermal balance

Finally, it is shown the extract from *Canteen* thermal balance. From that, it can be seen how *Equipment heat addition*, assessed in 33904 kWh per year, is not a minor factor for this facility.

Window Heat addition is less severe than *Pav. C* and *Adm. pav.* essentially because fenestrations are mostly located in the west side of the building.

On the other hand, losses due to conduction are larger and this is likely to be caused by the lower performance of the old roof, still not replaced.

Table 31 - Extract from annual thermal balance of *Canteen*.

Extract from annual thermal balance	
HVAC Zone Eq & Other Sensible Air Heating [kWh]	0
HVAC Zone Eq & Other Sensible Air Cooling [kWh]	0
People Sensible Heat Addition [kWh]	17687
Lights Sensible Heat Addition [kWh]	848
Equipment Sensible Heat Addition [kWh]	33904
Window Heat Addition [kWh]	63262
Infiltration Heat Addition [kWh]	423
Opaque Surface Conduction and Other Heat Addition [kWh]	435
Window Heat Removal [kWh]	-20306
Infiltration Heat Removal [kWh]	-25431
Opaque Surface Conduction and Other Heat Removal [kWh]	-70821

7 Promotion of energy efficiency measures

In the previous chapter were acknowledged the factors which affects thermal balance more significantly, namely: *window heat addiction/removal*, *infiltration heat removal*, *opaque surface conduction heat removal*. Consequently, the energy efficiency measures to identify must allow the reduction of solar gains and in the same time provide a better air tightness to limit air infiltration. For this reason, three main energy efficiency measures (EEM) have been compared:

- EEM-A: windows replacement.
- EEM-B: addition of an interior EPS insulating layer in all the external walls.
- EEM-C: best option of A combined with best option of B.

The following section will consist in a costs/benefits analysis for each of the above measures which aims to point out the best solution in terms of energy savings and thermal comfort achievement.

Finally, it will be examined the possibility to make the measures above part of a more ambitious investment plan which aims to school's energy independence.

7.1 EEM-A: windows replacement

As mentioned before, windows play a fundamental role in the thermal balance and it is necessary to improve their current efficiency. To reach this scope there are numerous ways that involve the use of different combination of frames, glasses and gas gap.

In the Tables 32 and 33 are listed the principal alternatives for frames and glasses with the related typical transmittances values provided by ISO 10077.

Table 32 - Standard values for frame transmittance.

Frame	Uf [W/m2/K]
standard aluminium	6 to 7
PVC/WOOD	1,8 to 2,2
thermal break aluminium	2,2 to 3,8

Table 33 - Standard values for glass transmittance.

Glass	Ug [W/m2/K]
Single glazing	4,8 to 5,8
Double glazing	1 to 2,8
Triple glazing	>1

The first step was to reduce the range of the possible choices focusing only windows on thermal break aluminium frame and double glass. This was done for two main reasons:

- for large windows (as the ones of the case study), most of the manufacturers do not suggest PVC material due to his low yield strength. Wood is much more expensive than others material and is commonly used in the residential sector. Thus, aluminium was considered the best compromise. Aluminium frames with thermal break (typically a resin or plastic material interposed between the outside and inside surface of metal) allow to reduce significantly conductive energy losses.
- single glazing is the current type of glass present in all the windows. Since the aim is to achieve a better efficiency would not make sense to invest a large amount of money to have limited improvements. Since triple glazing systems would have provided more insulation that needed, it was opted for double glasses.

Once addressed the focus on double glazing systems, it was necessary to identify the optimal glass thermophysical properties. In this regard, the impact of three factors was studied: *U value*, *Solar Heat Gain Coefficient (SHGC)* and *Visible Transmittance (VT)*.

SHGC represent 'the fraction of incident solar radiation admitted through a window' [13]. According to the National Fenestration Rating Council (NFRC) it has to be evaluated for the whole window system (frame and glass). SHGC for old windows may be estimated in 0,85 whereas for modern performing windows the value can be below 0,25. *VT* indicates 'the fraction of visible light transmitted through the window' [13]. Single glazing tends to have a *VT* value above 0,8 whereas double and are in the range 0,3 to 0,7.

To sum up, it was sought a new fenestration type with the following characteristics:

- low U values, to enhance insulation and reduce heat losses.
- low *SHGC*, to contain solar gains excess.
- high *VT*, to maximize daylight.

To restrict the numerous options available in the market, it was decided to compare the three types of double-glazing systems, namely: *standard clear, low-emissivity (low-e) and selective* (also referred as *selective low-e*). To know which one was the best fit for *Escola*

Conde de Oeiras it was decided to take one sample for each of these categories. In Table 34 is provided the products data sheets.

Table 34 – Data sheets for the three possible glass alternatives.

Source: Pilkington catalogue; technical data assessed according to EN 410 and EN 673 Price per m^2 includes the two-glass surface and the argon fill. Argon fill cost estimated in 16 €/m^2 [21].

	Standard clear	*Low-e*	*Selective low-e*
Product name	Optifloat™ Clear	K Glass™	Optitherm™ S1
Manufacturer	Pilkington	Pilkington	Pilkington
Glass thickness	4 mm	4 mm	4 mm
Gap	Argon - 16 mm	Argon - 16 mm	Argon - 16 mm
SHGC	0,7	0,6	0,4
VT	0,79	0,75	0,6
U factor [W/m2/K]	2,6	1,5	1
Price [€/m2]	60	94	105

In the following sections are going to be quantified the costs and benefits of these three solutions to seek the best compromise. This will be done simulating the virtual buildings with the new window configuration with the *SimpleGlazingSystems* object (Fig. 48) in the *Energy+* environment.

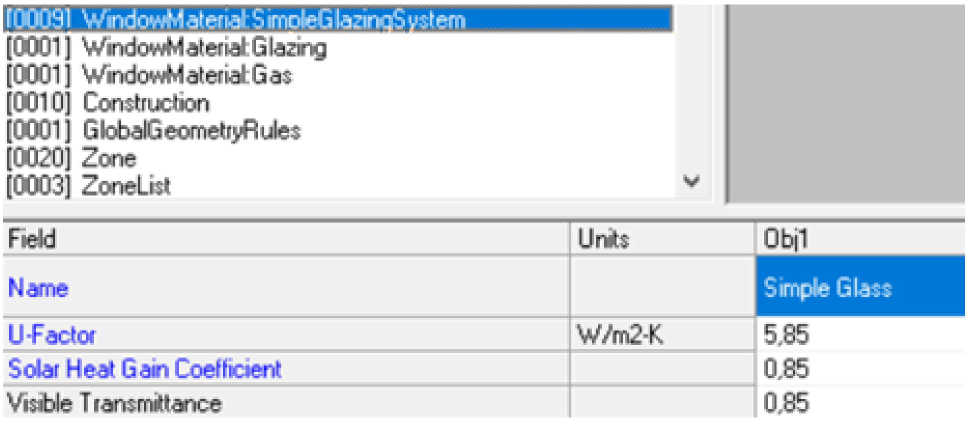


Figure 48 - *Simple Glazing System* object in Energy+ environment.

7.1.1 Energy performance comparison

In this section is illustrated how the three new possible windows configurations could affect the buildings performances in terms of energy and thermal comfort.

In the first graph (Fig. 49) are shown three[22] voices: *Infiltration heat removal*, *window heat addition* and *window heat removal*. According to what demonstrated in chapter 5, these represent the largest contributions in the thermal balance of each building and are directly influenced by the windows properties.

[22] Other variables were excluded because due to their small contribution (ex. *Infiltration heat addition*) or because they were not directly affected by the windows replacement (ex. *People internal gains, equipment heat addiction etc.*

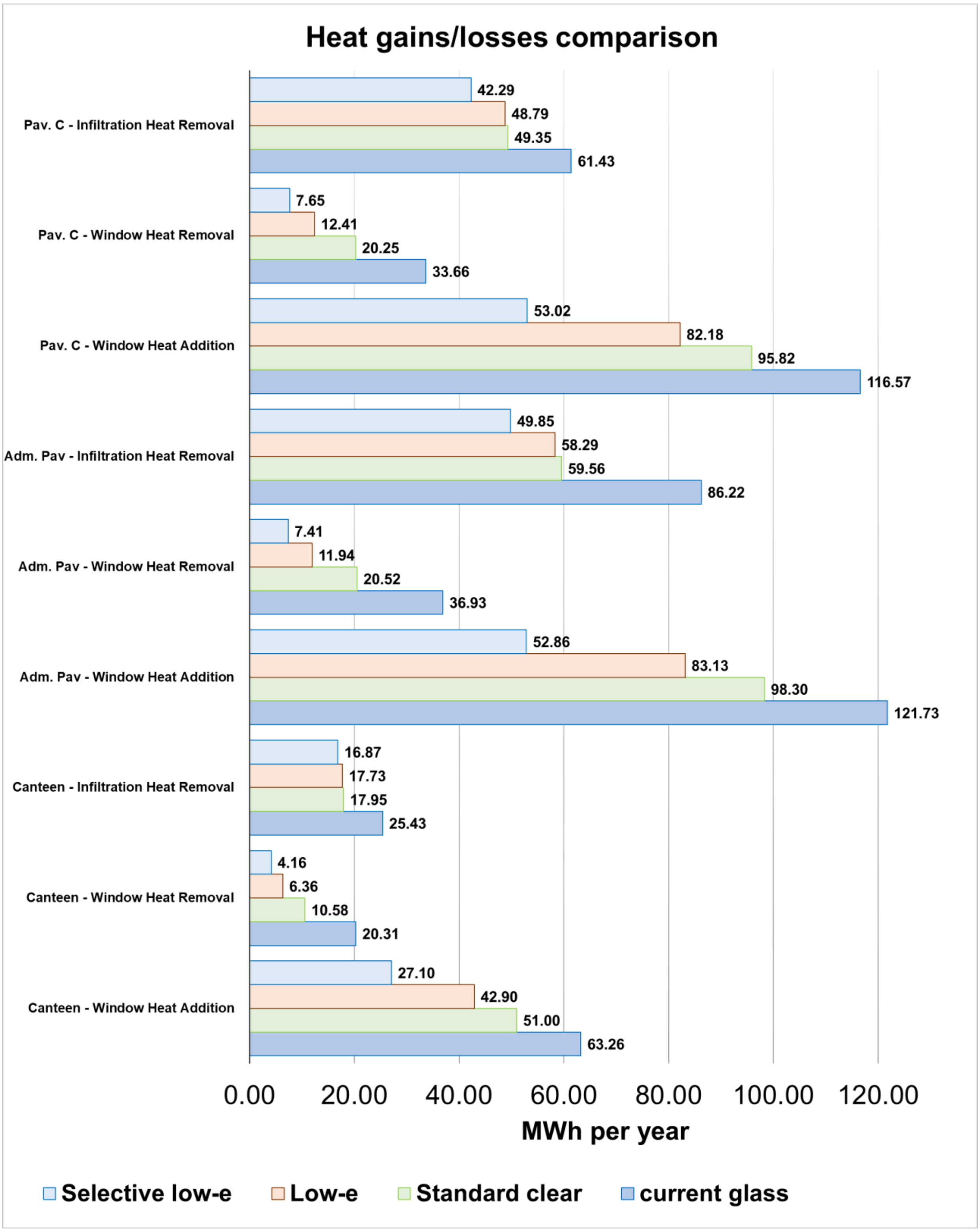


Figure 49 – Heat gains/losses comparison for the examined double-glazing systems

To compute heating and cooling needs it was introducing in the model an ideal HVAC system that meets the needs of the thermal zones whenever indoor temperature in a thermal zone exceeds the thermostat setpoint. This was done by mean of the '*HVACTemplate: IdealLoadsSystem'* object of Energy+ (see Appendix B for more details).

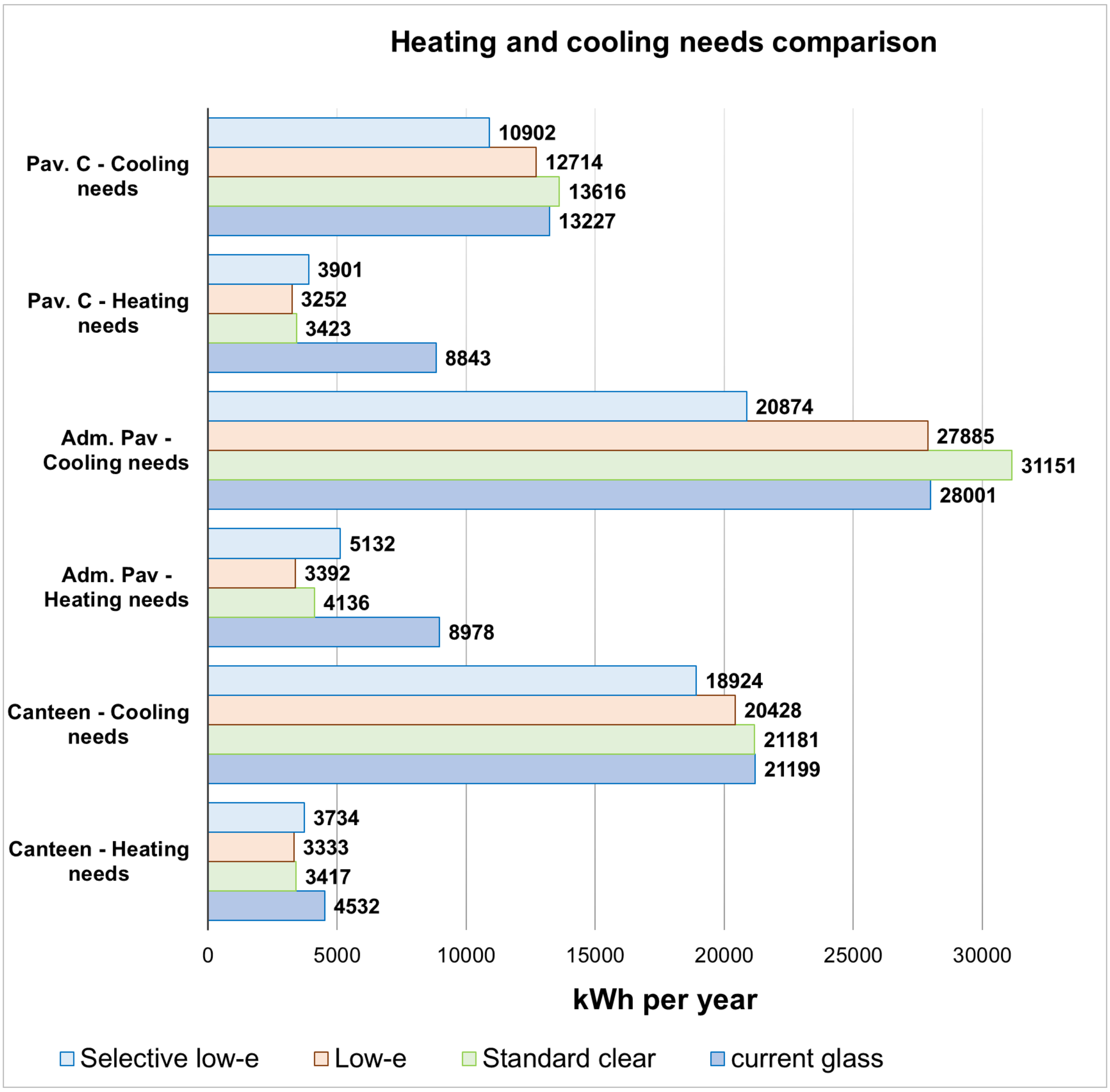


Figure 50 – Heating and cooling needs comparison for the examined double-glazing systems.

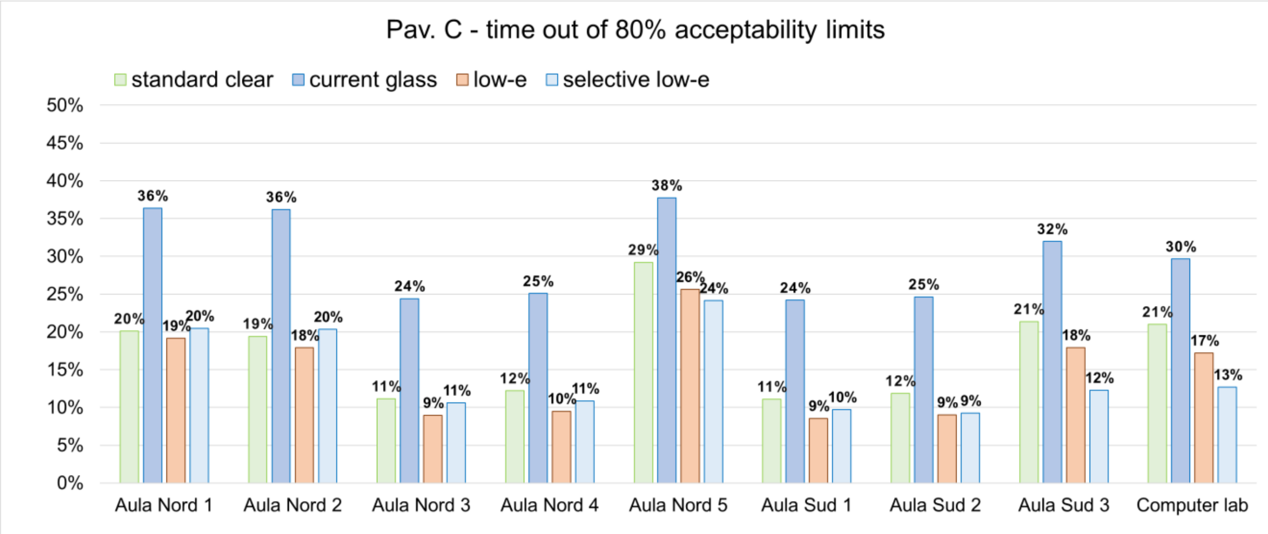


Figure 51 - Thermal discomfort condition in *Pav. C* thermal zones for the examined double-glazing systems.

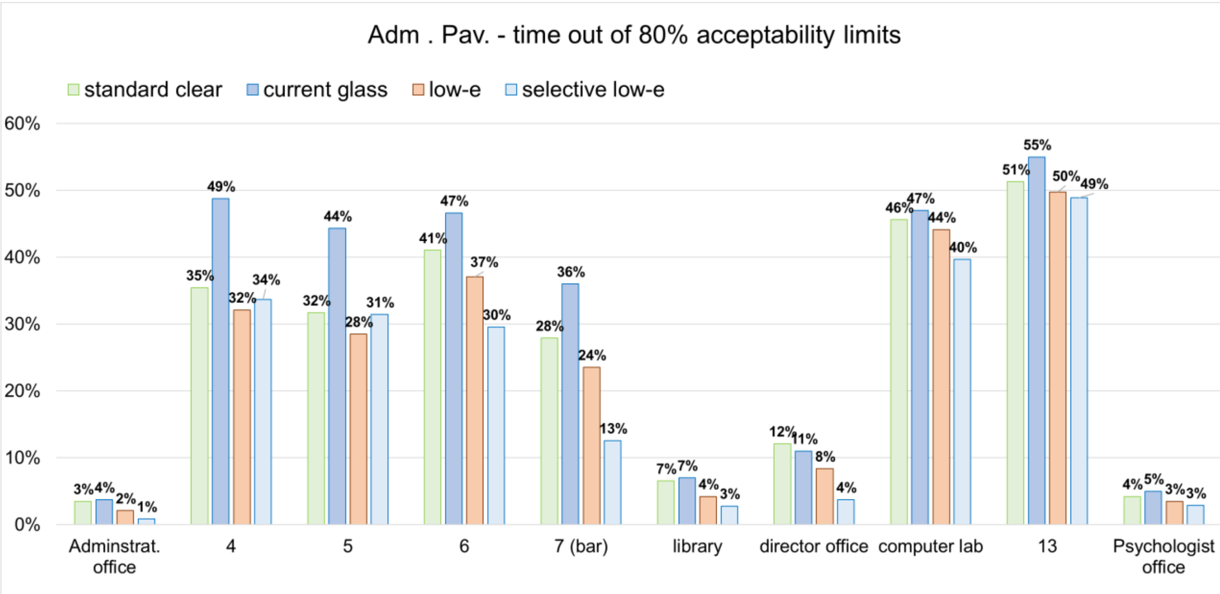


Figure 52 – Thermal discomfort condition in *Adm. pav.* th. zones for the examined double-glazing systems.

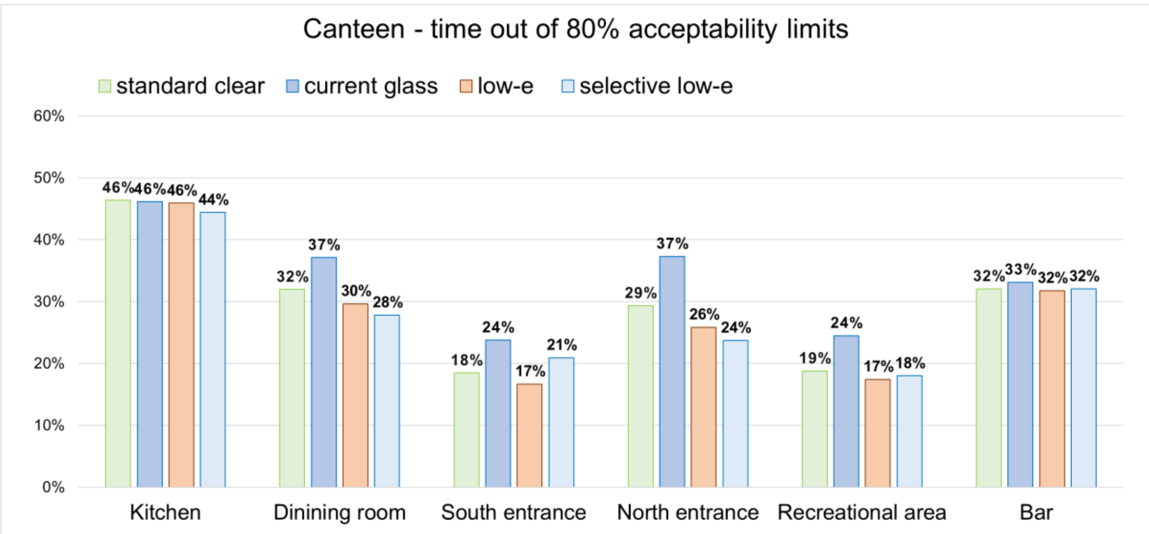


Figure 53 - Thermal discomfort condition in *Canteen.* th. zones for the examined double-glazing systems.

7.1.2 Natural light assessment

Referring to Table 34 in section 7.1, the three types of glass have specific values of *VT* (visible transmittance) and *SHGC* (solar heat gain coefficient).

Obviously, it is preferred to have *SHGC* as low as possible to limit excess of solar gains which is the main source of discomfort, especially in the classrooms. On the other hand, lowering *SHGC* will decrease *VT* as well: selective glasses with very low value of *SHGC*, are opaquer and consequently may not provide enough natural light during the day. This problem could be quite serious for north exposed windows. In this regard, it is important to verify whether the new windows comply with the standard EN ISO 12464 discussed 3.3.

Assuming that 300 lux (minimum lighting requirement for classrooms) could always be provided, it crucial to assess whether these lux came from artificial or natural lighting. Adopting equation (5) in 3.3 *medium daylight factor* η_m has been calculated for *Aula Nord 1, Aula Nord 2.* These classrooms are the most critical for the following reasons:

- all windows are exposed to north.
- total glazed surfaces are smaller than all other classrooms.

Detailed features of both classrooms are shown in Table 35 that follows.

Table 35 – *Aula Nord 1* and *Aula Nord 2* features.

	Aula Nord 1	**Aula Nord 2**
Glazed surfaces	6,51 m^2	12,81 m^2
Walls net surface	97,17 m^2	83,32 m^2
Floor surface	60,48 m^2	60,48 m^2
Ceiling surface	60,48 m^2	60,48 m^2
Standard clear[23], *VT* coefficient	0,85	
Standard clear, reflection coefficient	0,1	
Low-e glass, *VT* coefficient	0,75	
Low-e glass, reflection coefficient	0,15	
Selective low-e glass, *VT* coefficient	0,6	
Selective low-e glass, reflection coefficient	0,2	
Walls reflection coefficient (assumed white)	0,8	
Floor and ceiling reflection coefficient (assumed brown)	0,1	

Applying equation (5) in 3.3, results in Fig. 54 were obtained. In the histogram are shown values of *medium daylight factor* η_m the three types of glass.

It is easy to spot that even with the current standard clear single glass, *Aula Nord 1* cannot meet requirements due to its small glass area (6,51 m^2). However, natural light would be considered at least sufficient even for selective low-emissivity glass.

[23] 'Standard clear' represents value of η_m obtained both for the current 'standard clear single glazing system' and 'standard clear double-glazing system' since these are assumed to have the same VT coefficient.

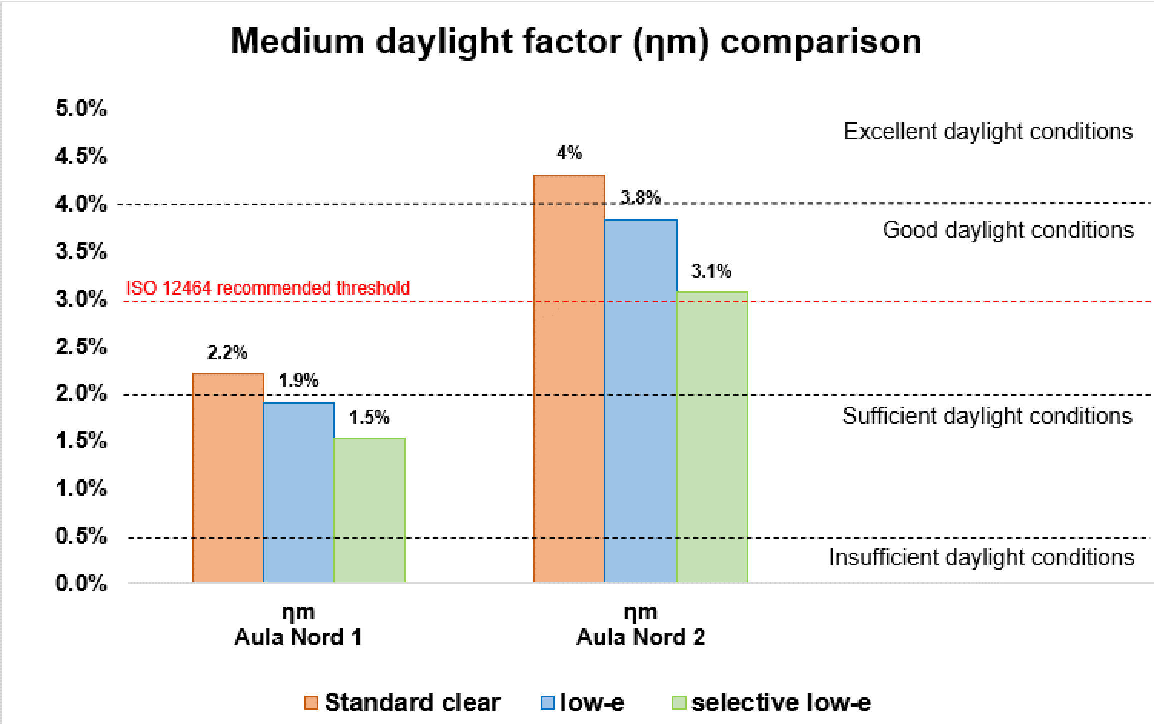


Figure 54 – Medium daylight factor comparison for *Aula Nord 1* and *Aula Nord 2*.

The second smallest glass area belongs to *Aula Nord 2*. In this case with selective low-e glass it is still possible to have medium daylight factor above 3%.

Since all other classrooms have larger glazed surfaces and most of them are not north exposed, it can be stated that they are very likely to comply with ISO 12464 requirements.

7.1.3 Acoustic performance comparison

New windows are expected to be more efficient in terms of noise insulation. In order to quantify these upgraded performances and to assess whether they are good enough to meet ISO 12354 requirements, it was followed the procedure discussed in section 3.4. Thus, *Façade Standardised Level Difference* ($D_{2m,nT,w}$) was calculated with equation (7) and (8) shown in chapter 3. Input variables for those equations are summarised Table 36.

Table 36 – Inputs for acoustic performance assessment.

Input values for Aula *Nord 1* and *Aula Nord 2*	
$R_{w,walls}$	56 dB
$R_{w,single\ glazing}$	25 dB
$R_{w,double\ glazing}$	36 dB
Gross north façade wall surface (*Aula Nord 1* and *2*)	23 m²
North façade glass surface (*Aula Nord 1)*	6,5 m²
North façade glass surface (*Aula Nord 2)*	12,8 m²
Further assumptions	
R_w standard values referenced in UNI 11175	
$\Delta L_{fs} = 0$ (in eq. 7); (flat façade case)	
$K=0$ (in eq. 8); (no heavy elements connected to the façade)	

The values of $D_{2m,n,T,w}$ calculated with ISO 12354 procedure (discussed in section 3.4) for *Aula Nord 1* and *Aula Nord 2* are shown in Fig. 55.

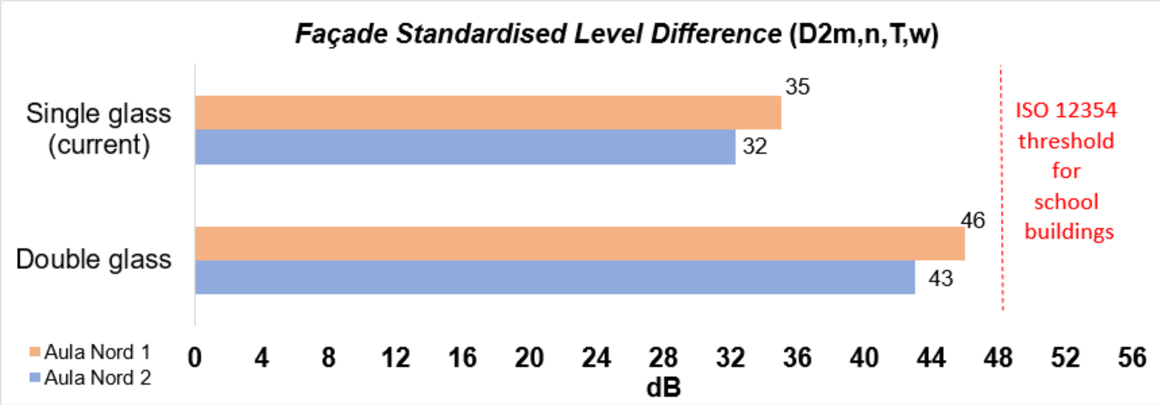


Figure 55 – Façade standardised level difference for single and double glass solutions.

For both classrooms a significant improvement of acoustic performance was observed, but not high enough to reach the ISO threshold. This is due to the fact that glass surfaces are very large and their apparent sound reduction index ($R_{w,single\ glazing}$/$R_{w,double\ glazing}$) hardly reach values above 36 dB. Indeed, even under the hypothesis of perfect airtightness, only triple glass windows with wide gas gaps may reach values of R_w>40 dB.

However, glass surface dimension affects $D_{2m,n,T,w}$ value not as much as can be expected because the dB scale is logarithmic. As a matter of fact, *Aula Nord 1* which has north façade windows with a glass area of 6,5 m^2 can provide only 3 dB of noise insulation more than *Aula Nord 2* windows (which are almost twice bigger).

All in all, installing of a new double-glazing system would bring a meaningful contribution for acoustic comfort as well as for thermal and visual comfort.

7.1.4 Project evaluation

As regards for the energetic performance, savings from heating and cooling needs will be quantified in euro according to natural gas and electricity tariffs of 2018. However, it is to be clarified that for *canteen* and *pav. C*, which are not provided with HVAC, heating/cooling needs variation will not imply an actual cost reduction.

For all the options will be computed *Net Present Value* (NPV) and *Payback period* (PBP).

Variables and assumption adopted for the calculation are here listed:

- Electricity price: 0,2 €/kWh [14];
- Natural gas price: 0,079 €/kWh [14].
- Interest rate: 5%[24];
- Economic benefits: tax deduction up to 60% of the total investment, according to 2006/32/CE European directive and the Portuguese 'Plano Nacional de Ação para Eficiência Energética' (PNAEE).
- Annual cash flows increase by 2% [15] each year according to avg. energy cost inflation.
- Annual cash flows were calculated with two methods:
    (1) Space heating provided by natural gas and space cooling by electricity.
    (2) Both space heating and cooling provided by electricity.
- Fixed cost, like the ones due to contracted power supply or network maintenance, are assumed unchanged.

Investment details:

- Investment period: 40 years
- Aluminium thermal break frame price: 200 €/m^2 [16];
- Glass price: see Table 24.
- Installation cost: 90 €/window [16];
- Glass surfaces and n° of windows:

Table 37 - Surface and n° of windows of school buildings.

	Pav. A,B,C	Adm. pav	Canteen	Total
glass surface [m2]	267 x 3	197	116	1114
n° of windows	46 x 3	31	20	189

24 Typical value for low risk investment that are not subjected to market fluctuations.

Table 38 – Project evaluation summary for installation of *Standard clear double-glazing system*.

Option A: Standard clear double glazing system

	Pav. A,B,C (1)	Pav. A,B,C (2)	Adm. pav (1)	Adm. pav. (2)	Canteen (1)	Canteen (2)	Total (1)	Total (2)
Gross investement [€]	220828	220828	54010	54010	32041	32041	306879	306879
Net investment (-60% due to tax deduction) [€]	88331	88331	21604	21604	12816	12816	122752	122752
Investment period [years]	40	40	40	40	40	40	40	40
1st year cash flow due to energy savings [€]	1274	3683	304	406	110	276	1689	4365
estimated annual energy cost inflation	2%	2%	2%	2%	2%	2%	2%	2%
Interest rate	5%	5%	5%	5%	5%	5%	5%	5%
NPV [€]	-59179	-4077	-14641	-12313	-10290	-6491	-105714	-22881
PBP [years]	>70	44	>70	>70	>70	>70	>70	65

Table 39 - Project evaluation summary for installation of *low-emissivity double glazing system*.

Option B: low-e double glazing system

	Pav. A,B,C (1)	Pav. A,B,C (2)	Adm. pav (1)	Adm. pav. (2)	Canteen (1)	Canteen (2)	Total (1)	Total (2)
Gross investement [€]	248082	248082	60708	60708	35995	35995	653574	344785
Net investement (-60% due to tax deduction) [€]	99233	99233	24283	24283	14398	14398	261430	137914
Investment period [years]	40	40	40	40	40	40	40	40
1st year cash flow due to energy savings [€]	1983	4468	564	1391	303	750	2849	6609
estimated annual energy cost inflation	2%	2%	2%	2%	2%	2%	2%	2%
Interest rate	5%	5%	5%	5%	5%	5%	5%	5%
NPV [€]	-53876	2992	-11382	7536	-7464	2757	-97005	13285
PBP [years]	>70	38	>70	26	>70	30	>70	34

Table 40 - Project evaluation summary for installation of *selective* low-emissivity *double glazing system.*

Option C: selective low-e double glazing system

	Pav. A,B,C (1)	Pav. A,B,C (2)	Adm. pav (1)	Adm. pav. (2)	Canteen (1)	Canteen (2)	Total (1)	Total (2)
Gross investement [€]	256899	256899	62875	62875	37275	37275	676822	357048
Net investment (-60% due to tax deduction) [€]	102760	102760	25150	25150	14910	14910	270729	142819
Investment period [years]	40	40	40	40	40	40	40	40
1st year cash flow due to energy savings [€]	3123	5319	2108	2678	632	749	5863	8746
estimated annual energy cost inflation	2%	2%	2%	2%	2%	2%	2%	2%
Interest rate	5%	5%	5%	5%	5%	5%	5%	5%
NPV [€]	-31305	18936	23072	36117	-7464	2228	-33834	57281
PBP [years]	>70	30	16	11	>70	34	68	24

7.1.5 Results discussion

Outcomes of thermal simulations highlighted some aspects to be discussed. Above all, using natural gas to provide space heating service will make the investment less profitable. In fact, only *option C* can guarantee positive NPV's even though for all the facilities. Contrariwise, electricity, due to his higher price, will make the PBP shorter than 40 years even with *option B*. In any case, economic benefits of *option A* are not enough to justify the expenses. Moreover, adopting high performance glass as *selective low-e* instead of *standard clear double glass* would increase the total gross investment only by 15%.

Replacing windows in pavilions A, B and C will lead to an overall cost of more 220.000 €, but these facilities could obtain very large benefits in terms of thermal comfort as illustrated in Fig. 51 and this may be considered as a good reason to promote this EEM.

Regarding the canteen, a negligible enhancement is registered for thermal comfort. This is mainly because of the intensive use of gas equipment in the kitchen that makes the surrounding thermal zones uncomfortable as well. However, investment will still give positive NPV with *option B* and *C*.

All in all, it seems that *selective low-e glass* must be preferred to the others because of his better performance in terms of solar gains reduction (*SHGC=0,4*) and insulation (*U=1* $W/m^2/K$). Smaller values of *SHGC* are not recommended, especially in pavilions with classrooms, since these would imply the reduction of glass visible transmittance (less natural light available during the morning) and of the positive warming effect of the sun during winter.

As mentioned before, pavilions A, B, C and canteen money savings are 'virtual' because space heating/cooling is not provided. Thus, all these results represent what would happen if these services were regularly supplied. About that, some words should be spent it was not considered in the calculation that a reduction of energy needs may lead to a smaller request in terms of contracted power. Currently the school sustain an average monthly (fixed) cost of 100 euro to have access to 84 kVA that might be reduced of 30% to 40%. This will make the investment more convenient because of the shorter PBP.

7.2 EEM-B: external walls with EPS insulation

Thermal coat represents one of the most widespread energy efficiency measures, especially in the coldest locations. This is mainly due to the fact that with relatively low costs it is possible to improve the performance of important construction elements, such as walls, roofs and floors.

In chapter 5 it was observed the impact, albeit modest, that roof replacement had in terms of thermal comfort improvements. In that case though, the intervention had the highest priority because of the carcinogenicity of the old material that put the occupants' health at risk.
To assess whether realizing an external thermal coat would be advantageous or not, a set of simulations was carried out for three different thickness of expanded polystyrene[25] (EPS): 4 cm, 8 cm and 12 cm. It was hypothesized to adopt the same material as the one used for new roofs.

Following the same approach of section 7.1, output comparison and project evaluation will be illustrated and discussed.

[25] Thermophysical properties available in Appendix A

7.2.1 Performance comparison

Energy savings for different EPS thicknesses are illustrated in the chart below.

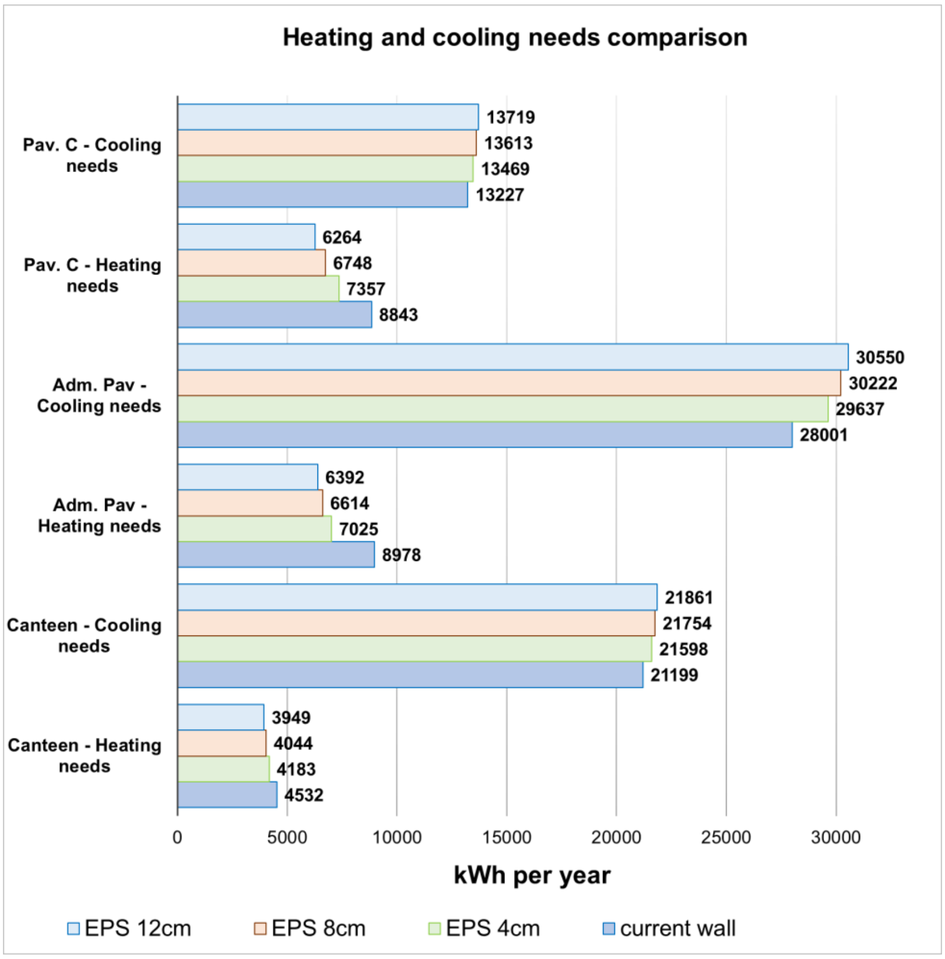


Figure 56 - Heating and cooling needs comparison for the examined EPS thicknesses.

In terms of heating needs maximum savings, achievable with 12 cm EPS, assess around 29% both for *administrative pavilion* and *C pavilion*, 13% for *canteen*.

Regarding cooling needs, maximum increments assess round 4% for *pav.* C, 8% for *administrative pavilion*, 3% for canteen

Thermal comfort improvements are negligible, as shown in histograms of page 84.

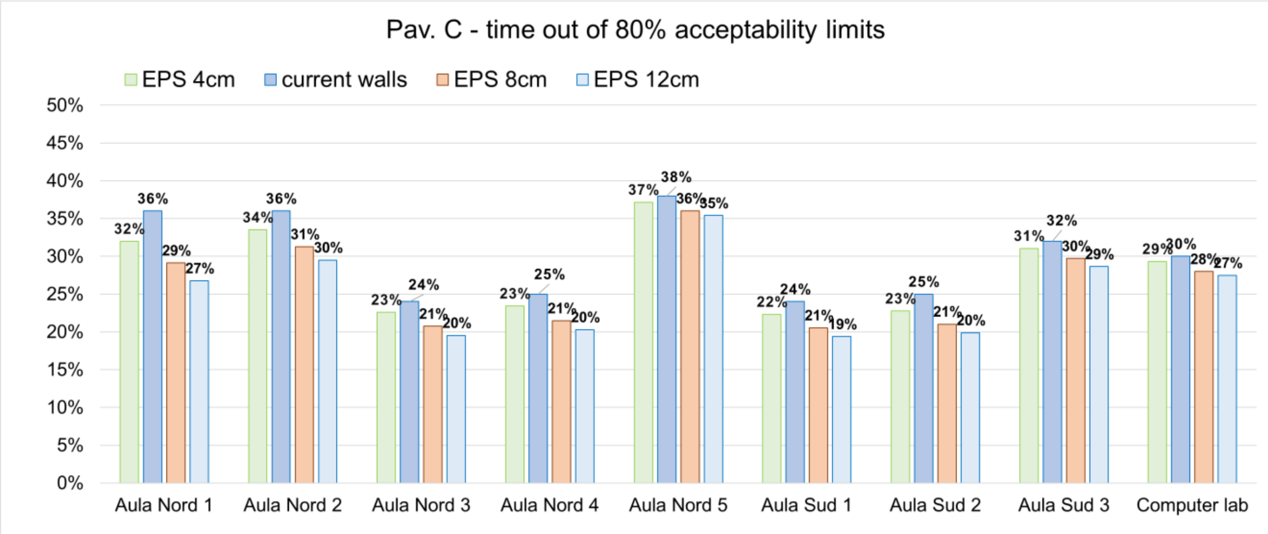


Figure 57 - Thermal discomfort condition in *Pav. C* thermal zones for the examined EPS thicknesses.

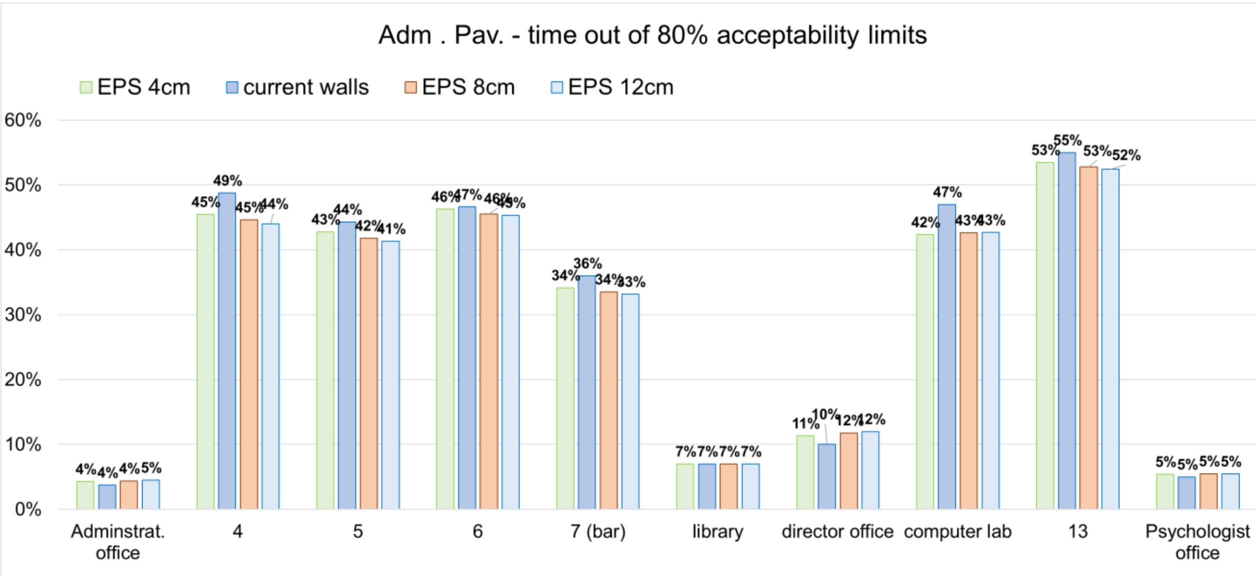


Figure 58 - Thermal discomfort condition in *Adm. pav.* th. zones for the examined EPS thicknesses.

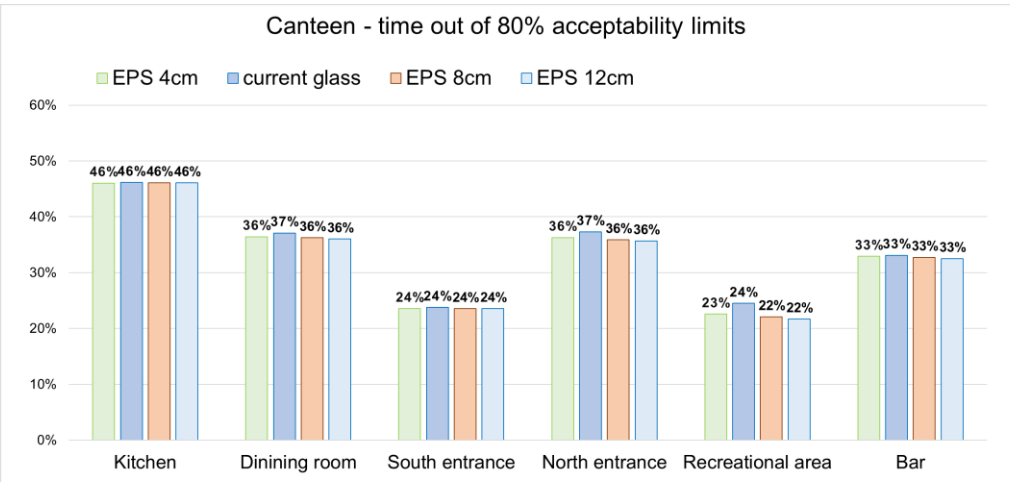


Figure 59 - Thermal discomfort condition in *Canteen.* th. zones for the examined double-glazing systems.

7.2.2 Project evaluation

Embracing the same assumption and methodology seen in 7.1.2, NPV and PBP were computed with same methodology.

Investment detail:

- EPS prices [16] :
  thickness 4 cm: 3 €/m^2.
  thickness 8 cm: 5,5 €/m^2
  thickness 12 cm: 8 €/m^2.
- installation price: 55 €/m^2 [16];
- net wall area to be covered:

Pav. A,B,C : 335,83 x 3 m^2 - $\left(\frac{Window\ area}{Wall\ area}\Big|_{pav\ A,B,C} = 44{,}5\%\right)$

Adm. pav. : 396,56 m^2 - $\left(\frac{Window\ area}{Wall\ area}\Big|_{Adm.\ pav} = 35\%\right)$

Canteen: : 333,27 m^2 - $\left(\frac{Window\ area}{Wall\ area}\Big|_{Canteen} = 28\%\right)$

Project evaluations results are illustrated in the Tables 41, 42 and 43.

Table 41 - Project evaluation summary for installation of *4cm EPS insulating layer.*

Option A: 4cm of EPS insulating layer

	Pav. A,B,C (1)	Pav. A,B,C (2)	Adm. pav (1)	Adm. pav. (2)	Canteen (1)	Canteen (2)	Total (1)	Total (2)
Gross investement [€]	58434	58434	23000	23000	19330	19330	100765	100765
Net investment (-60% due to tax deduction) [€]	23374	23374	9200	9200	7732	7732	40306	40306
Investment period [years]	40	40	40	40	40	40	40	40
1st year cash flow due to energy savings [€]	250	911	-211	77	-64	-12	-25	976
estimated annual energy cost inflation	2%	2%	2%	2%	2%	2%	2%	2%
Interest rate	5%	5%	5%	5%	5%	5%	5%	5%
NPV [€]	-17652	-2540	/	-7431	/	/	/	-19115
PBP [years]	>70	51	/	>70	/	/	/	>70

Table 42 - Project evaluation summary for installation of *8cm EPS insulating layer.*

Option B: 8 cm of EPS insulating layer

	Pav. A,B,C (1)	Pav. A,B,C (2)	Adm. pav (1)	Adm. pav. (2)	Canteen (1)	Canteen (2)	Total (1)	Total (2)
Gross investement [€]	60953	60953	23992	23992	20163	20163	105108	105108
Net investment (-60% due to tax deduction) [€]	24381	24381	9597	9597	8065	8065	42043	42043
Investment period [years]	40	40	40	40	40	40	40	40
1st year cash flow due to energy savings [€]	320	1251	-315	35	-89	-16	-84	1270
estimated annual energy cost inflation	2%	2%	2%	2%	2%	2%	2%	2%
Interest rate	5%	5%	5%	5%	5%	5%	5%	5%
NPV [€]	-17059	4240	/	-8402	/	/	-35951	-13065
PBP [years]	>70	32	/	>70	/	/	>70	>70

Table 43 - Project evaluation summary for installation of *12cm EPS insulating layer.*

Option C: 12cm of EPS insulating layer

	Pav. A,B,C (1)	Pav. A,B,C (2)	Adm. pav (1)	Adm. pav. (2)	Canteen (1)	Canteen (2)	Total (1)	Total (2)
Gross investement [€]	63472	63472	24983	24983	20996	20996	109451	109451
Net investment (-60% due to tax deduction) [€]	25389	25389	9993	9993	8398	8398	43780	43780
Investment period [years]	40	40	40	40	40	40	40	40
1st year cash flow due to energy savings [€]	375	1528	-374	9	-106	-19	-104	1517
estimated annual energy cost inflation	2%	2%	2%	2%	2%	2%	2%	2%
Interest rate	5%	5%	5%	5%	5%	5%	5%	5%
NPV [€]	-16800	9562	/	-9787	/	/	/	-9064
PBP [years]	>70	24	/	>70	/	/	/	69

7.2.3 Results discussion

What appears after first sight on the output is that walls insulation would provide an almost negligible enhancement in terms of energy performance. In this regards, two clarifications have to be done:

- Due to the climate location, cooling needs are more than twice the heating needs. This implies that even a significant reduction in heating consumption would produce limited savings in absolute terms. To give a practical example, results in Fig. 56 confirm a contraction of 29% in heating needs for *administrative pav.* and *pav. C*, but in absolute terms this corresponds to a global saving of around 5 MWh/year, less than 6% of the global consumption
- High window/wall ratios of the buildings influence negatively the achievable insulation.

Successively, it was acknowledged that using natural gas to provide space heating would make all the options not profitable since NPV's are always negative, even considering an investment period longer than 70 years. Moreover, since all the cash flows for the *canteen* are negative, implementing this measure should not be recommended at all. *Administrative pavilion behaves* similarly since its annual potential incomes, albeit positive, are never above 1% of the net investment implying PBP's of hundreds of years.

With an electrically powered HVAC system things would be different, but only for *pavilions A, B* and *C*. In fact, it is possible to achieve a positive NPV within the 40 years with *option B* and *C*.

To sum up, it could be stated that, according with those results, the most convenient alternative is the installation of 12 cm EPS insulating layer only in the pavilions with classrooms.

7.3 EEM-C

In this passage is intended to evaluate a scenario in which both the previous measures are employed. Specifically, it has been studied the implementation of a *selective low-e double glazing system* for every fenestration (best option among EEM-A) combined with the installation, only for pavilions with classrooms, of *12 cm EPS insulating layer* (best option among EEM-B).

Furthermore, results from simulations will be exposed aggregating the energy savings for each of the six[26] buildings which are part of school complex. In this way the reader may appreciate more concretely the benefits that could be obtained from these measures.

Thermal comfort percentages will not be included again because of their similarity with those seen in section 7.1.1.

Successively, a final project evaluation will be presented.

7.3.1 Global savings

As Fig. 60 highlights, through the increased buildings efficiency achieved with a new double-glazing system and a thermal coat it is possible to limit the total annual consumption due to space heating and cooling from 129 MWh to 91,5 MWh per year, hence by 29%.

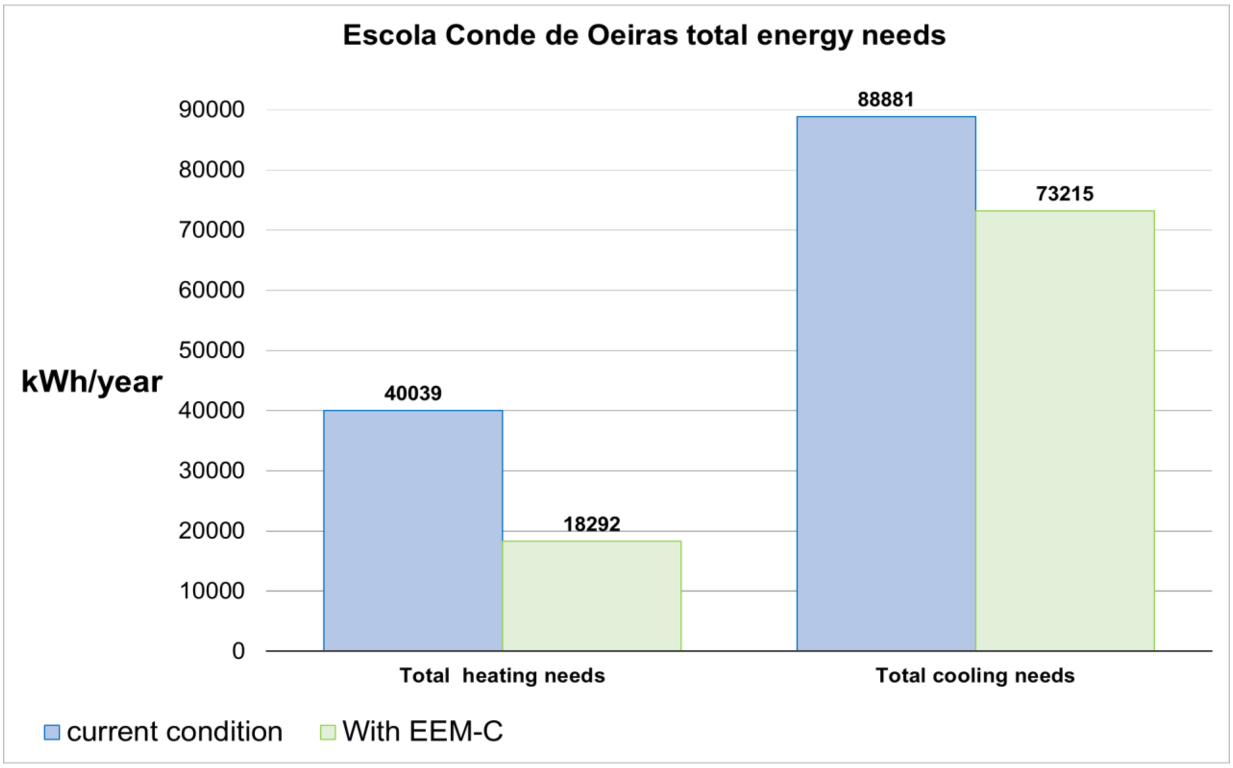


Figure 60 - Aggregated total energy savings.

Once again it is important to remark that these 'potential' savings do not represent an actual positive income, since the school does not provide heating or cooling services.

[26] Pavilions A, B, C; Canteen; Administrative pavilion

In addition to that, heating and cooling needs were estimated through the use of an ideal HVAC systems that works with 100% efficiency. This implies that, in absolute terms, calculated needs for the current condition and for the new one with EEM implemented are expected to be larger. In other words, assuming an average HVAC efficiency of 85% consumptions would become:

$$Tot\ needs_{cc} = \frac{1}{0,85} \cdot (tot\ heating\ needs + tot\ cooling\ needs)_{cc} = 151 \frac{MWh}{year} \quad (22)$$

$$Tot\ needs_{nc} = \frac{1}{0,85} \cdot (tot\ heating\ needs + tot\ cooling\ needs)_{nc} = 108 \frac{MWh}{year} \quad (23)$$

(cc = current condition; nc = new condition)

However, since

$$\left. \frac{Tot\ needs_{nc}}{Tot\ needs_{cc}} \right|_{ideal\ HVAC} = \left. \frac{Tot\ needs_{nc}}{Tot\ needs_{cc}} \right|_{real\ HVAC} = 29\%$$

It results that

$$(Tot\ needs_{cc} - Tot\ needs_{nc})|_{real\ HVAC} > (Tot\ needs_{cc} - Tot\ needs_{nc})|_{ideal\ HVAC}$$

Consequently, the adopted assumption of Ideal systems underestimates the savings. This can be considered as another positive aspects in favour of the promotion of EEM-C.

7.3.2 Project evaluation

Keeping the assumptions made in 7.1.2 and 7.2.2 a final project-evaluation was carried out. Annual cash flows were still evaluated with the two methodologies explained in 7.1.2 and always considering and Ideal HVAC system.

Results are available in the Table 44.

Table 44 – Project evaluation summary for the combined installations of *selective low-emissivity double glazing system* (in all the facilities) and *12cm EPS thermal coat* (only in *pavilions A,B and C*).

EEM-C: selective low-e doub. glaz. + 12 EPS th. coat only in pav. A,B,C

	Total (1)	Total (2)
Gross investement [€]	**420520**	**420520**
Net investment (-60% due to tax deduction) [€]	**168208**	**168208**
Investment period [years]	**40**	**40**
1st year cash flow due to energy savings [€]	**5836**	**9129**
estimated annual energy cost inflation	**2%**	**2%**
Interest rate	**5%**	**5%**
NPV [€]	**-34689**	**40651**
PBP [years]	**69**	**28**

8 Indoor air quality assessment for *Aula Nord 3* in *pavilion C*

Up to this point, two energy efficiency measures have been analysed with the purpose of enhancing thermal comfort conditions. Besides, it has been observed their positive impact on acoustic insulation. It was also verified that these measures were compatible with ISO 12464 requirements for visual comfort.

Thus, the last aspect of indoor environmental comfort to be investigated is Indoor Air Quality. Installing new highly-performant windows that minimize air infiltration rate can significantly increase ventilation needs. This is due to the fact that old poor sealing windows allow a certain amount of air to flow through the gaps bringing two main benefits:

- dilution of internal air and consequent lowering of CO2 concentrations.
- prevention of mould growth and water vapour condensation on glass surfaces.

For these reasons, it was considered worthwhile to perform a set of simulations specifically for *Aula Nord 3* in *pavilion C* in order to analyse how the variation of windows performances affects CO_2 concentration.

8.1 Current condition *vs.* Post-intervention assessment

In this section the CO_2 concentrations predicted by *Energy+* will be analysed. Output of simulations were obtained adopting the assumptions shown in Table 45, discussed and justified in the respective reference sections.

Table 45 - Summary of assumptions adopted for *pavilion C*.

Assumption	Reference section
Classroom Max n° of occupants = 25	5.4.1
Occupants' released heat due to metabolic activity = 110 W	4.1.3.4
Occupants' CO_2 production rate = 20 l/h	3.2.2
Classroom Infiltration rate = 0,3 ACH (current condition)	4.1.3.2
Classroom Infiltration rate = 0,05 ACH (post-intervention)	4.1.3.2
Classroom (Natural) Ventilation rate = 0,9 ACH	4.1.3.2

Under these hypotheses, two types of simulations were conducted:

- daily simulations. Carried out on 8-9-10 October 2019, during these days, experimental measurements of [CO_2] were collected (available in Appendix C). The purpose of these simulations is to show the how [CO_2] levels vary during the day.
- annual simulations. These were performed to estimate the percentage of time, in a year, in which CO_2 concentrations are above the limits recommended by the EN ISO 16798.

For both types of simulations, will be compared concentrations obtained for the current condition (pre-intervention) with the ones obtained post-intervention[27].

[27] Implementation of EEM-A (windows replacement) and EEM-B (12cm-EPS thermal coat).

8.1.1 Daily simulation results

Outputs of daily simulations are shown in Fig. 61 below. In the graph are exposed the predicted CO_2 concentration for

- the current condition (black curve).
- post-intervention assuming unchanged ventilation rate (yellow line).
- post-intervention assuming ventilation rate equal to 7 l/s per person (brown line). This value corresponds to the ventilation rate needed to assess IEQ_{II} (see section 3.2).
- post-intervention assuming ventilation rate equal to 10 l/s per person (blue line). This value corresponds to the ventilation rate needed to assess IEQ_{I} (see section 3.2).
- ISO 16798 threshold concentrations (dotted lines).

Assuming that occupants' behaviour will not change after the windows replacement, the current natural ventilation rate of 0.9 *ACH* will not be enough to guarantee an acceptable Indoor Air Quality (IAQ). Indeed, CO_2 concentrations registered post-intervention (yellow line in Fig. 61) are going to exceed category-III threshold seen in EN ISO 16798 standard.

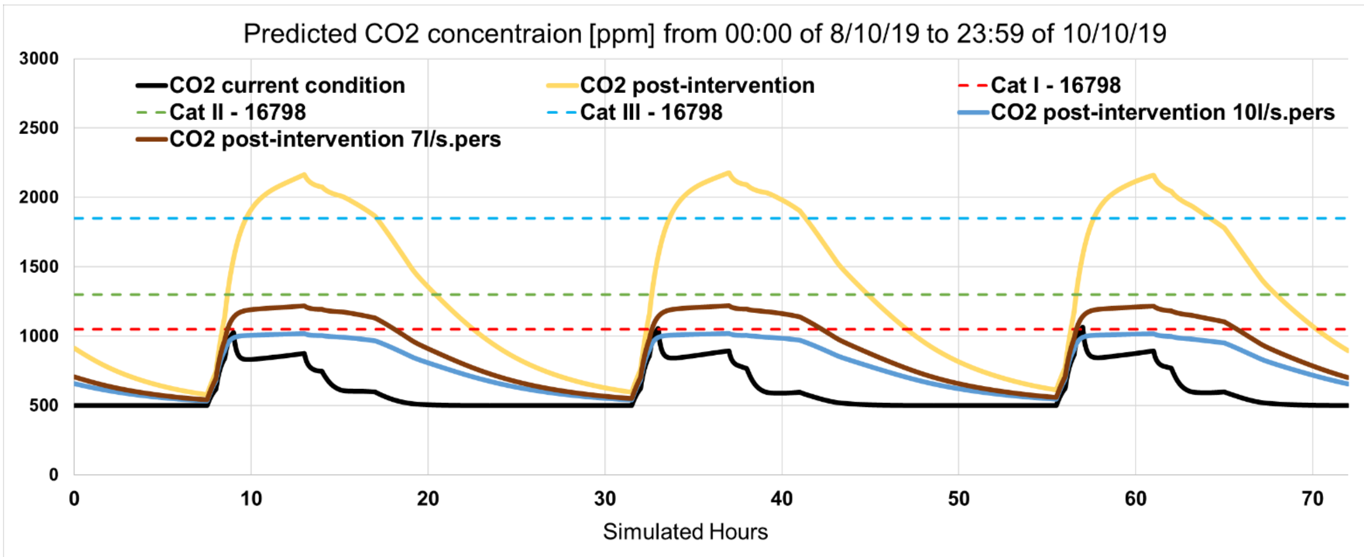


Figure 61 – Predicted CO_2 concentrations for daily simulations.

It is to be reminded that for K-12 schools the recommended IAQ should at least assess between category I and category II. Consequently, it is necessary to increase the ventilation rates.

As seen in section 3.2, ISO 16798 states that an inlet mass flow rate of air equal to 10 l/s per person is enough to achieve category I. This has been proven launching a simulation and using this input value for ventilation. Blue curve in the graph outlines the respective [CO_2] levels obtained. It can as well be noticed how decreasing ventilation rate to 7 l/s per person (brown curve in Fig. 61) would still be enough to remain in category II.

8.1.2 Annual simulation results

The objective of annual simulation was to quantify the percentage on the total time in which volume concentration of CO_2 was above 1050 ppm and 1350 ppm. As total time is considered the hours in a year in which at least 1 occupant is inside the classroom. This total time is estimated in **2043 h per year**. Hence the percentages are calculated as follows:

$$\% = \frac{time\ with\ [CO_2] > N\ \ ppm}{tot\ time} \tag{24}$$

Considering a background CO_2 concentration of 500 ppm, through the annual simulation is possible to assess which category characterises the Indoor Air Quality for classroom *Aula Nord 3*. As it was defined in Table 8 in 3.2.2, having $\Delta CO_{2,max} = CO_{2,max} - CO_{2,background}$ it yields:

IEQ_I $\Delta CO_{2,max}$=550 ppm → $CO_{2,max} \leq$ 1050 ppm

IEQ_{II} $\Delta CO_{2,max}$=800 ppm → $CO_{2,max} \leq$ 1350 ppm

IEQ_{III} $\Delta CO_{2,max}$=1350 ppm → $CO_{2,max} \leq$ 1900 ppm

Thus, when predicted [CO_2] level is above 1350 ppm, indoor air quality corresponds to Category III (IEQ_{III}) which is not recommended by EN ISO 16798 for K-12 schools.

Output of annual simulations is displayed in Fig. 62 below.

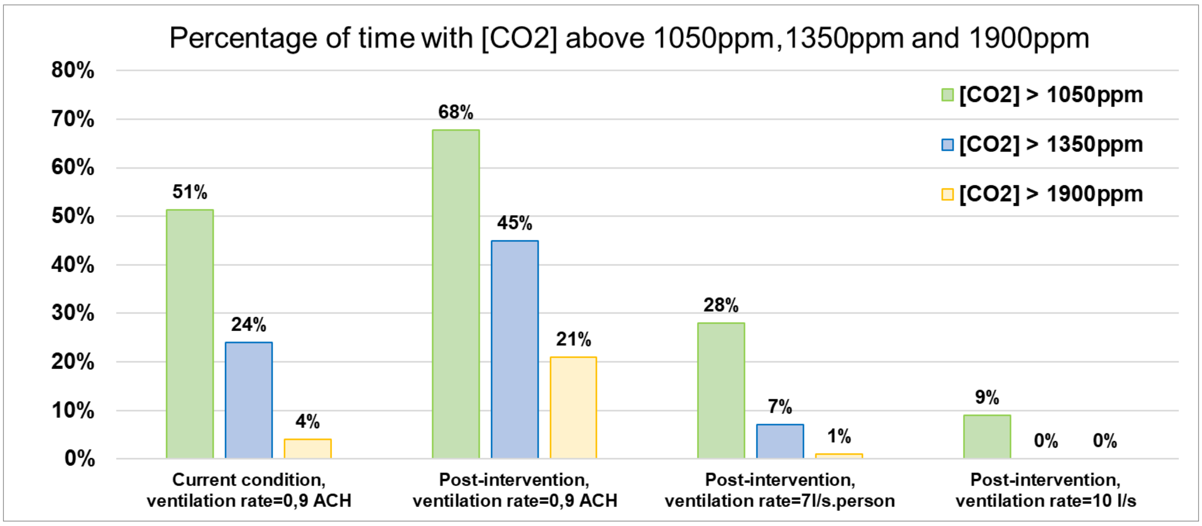


Figure 62 - Annual simulations results.

The histogram shows how, keeping the current ventilation rate of 0.9 ACH unchanged, the air quality assessed post-intervention worsens significantly. Indeed, the percentage of time in which the CO2 concentrations are above the thresholds that define category II reaches 45%. Raising ventilation rates to 7 l/s and 10 l/s per person this percentages are reduced to 7% and 0%, respectively.

To sum up, outputs of the daily and annual simulations demonstrate that, in order to guarantee air quality levels suitable for a school environment, it is strictly indispensable to provide larger ventilation rates.

Nevertheless, relying exclusively on natural ventilation could bring some important drawbacks:

- occupants have to be forced to change their behaviour and be always concerned in opening and closing windows with a certain frequency.
- drastic increments of natural ventilation rates are likely to decrease thermal comfort especially in cold months.

For these reasons, it is necessary to consider the design of a proper mechanical ventilation system that can meet the required needs. In the following sections, advantages and disadvantages of the two main types of mechanical ventilation will be discussed in order to identify the best option for the case study.

8.2 Mechanical Extract Ventilation (MEV) systems

Mechanical controlled ventilation is the solution that could provide air exchange, hygiene, comfort and energy saving at the same. In highly occupied spaces these became crucial, especially for schools. Nowadays, achieving satisfying levels of indoor environmental quality often involves the design of MEV systems.

As far as the case study is concerned, two MEV types were taken into account as possible options:

- Double-flow Centralised-MEV or (C-MEV).
- Double-flow Decentralised-MEV or (D-MEV).

These will be compared in the next two sections considering their main advantages in terms of suitability, energy efficiency, installation feasibility and costs.

Before describing the comparison between C-MEV and D-MEV, it is intended to highlight why only 'double-flows' instead of 'single-flow' solutions where examined.

Single flow solution has a very simple functioning: forced ventilation is provided by unit that introduces or extracts air. Essentially, they are mainly used to introduce a certain quantity of air that can suit needs of a certain rooms. They do not have a heat exchanger; therefore, they are suggested only for temperate climates that do not have large temperature variations.

There are also 'single cross-flow' solutions available on the market. They have a single pipe which operates with alternate intake and extraction cycles. For a pre-set period of time (i.e. 1 minute) they extract stale air and then, for the next minute, they release air into the environment. In order to get good ventilation effectiveness, single crossflow devices must be installed in pairs, as required by the EN 13141-8 standard. This aspect makes their cost raise significantly.

Double-flows mechanical ventilation systems units are provided with a heat recovery system that manages the intake and return of air from individual rooms. They are designed to obtain high air filtration with a very low operating cost since they recover a large part of the energy necessary to maintain the internal conditions by exchanging heat between the supply air and the extracted air.

To sum up, double-flow technology offers better performances at lower costs, consequently they are much more appealing for the case study.

8.2.1 C-MEV

Whenever their installation is feasible, C-MEV systems represent the best solution in terms of energy efficiency. A centralised system allows a particularly effective air exchange in all areas of the building. It consists in a central unit with a heat recovery system to which all the pipes are connected. All the components hidden, usually in a suspended ceiling; only suction/delivery vents are visible in the rooms.

An example of double-flow C-MEV is displayed in Fig. 63.

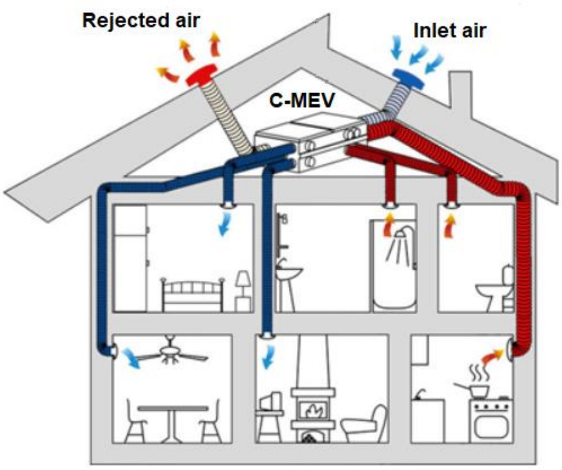


Figure 63 - Example of C-MEV system.

As it may be observed, this type system cannot be suitable for all kind of buildings due to its complexity. Seeking conciseness, advantages and disadvantages of C-MEV are gathered in Table 46.

Table 46 – Advantages and disadvantages of C-MEV systems.

Advantages	Disadvantages
High heat recovery efficiency	High costs due to complex design. Most of the times, C-MEV is not worthwhile in retrofitting.
Free cooling mode available[28]	Size of central unit requires a dedicated room
High air filtration efficiency	High maintenance costs: cleaning procedure requires use of aerosol and specific tools.
Absence of noise in the rooms.	User are supposed to control air flow rates: bad behaviour can compromise system efficiency.

Since *Pavilion C* is not provided with false ceiling, the distribution and heat recovery units should be located in one of the utility rooms. If so, the source of noise would be too close to some of the classrooms causing constant uneasiness for teachers and students. Another alternative would consist in locating the units in the patio. This would be eventually a worst solution than the first one, since the patio is frequently crossed by children during the day and consequently the central unit will be exposed to a constant risk of damage. For the

[28] Free cooling technology is able to interrupt heat recovery function allowing inlet cool air flow when needed.

above reasons, D-MEV appears to be the most suitable solution for *Escola Conde de Oeiras* due to its major flexibility and lower costs.

8.2.2 D-MEV

Rather than relying on a big-sized centralised unit connected to a net of pipes, a D-MEV system consists in a single machine that can be installed in a specific room. A heat recovery unit and air filtration traps are embodied in a compact device. An example of D-MEV is shown in Fig. 64.

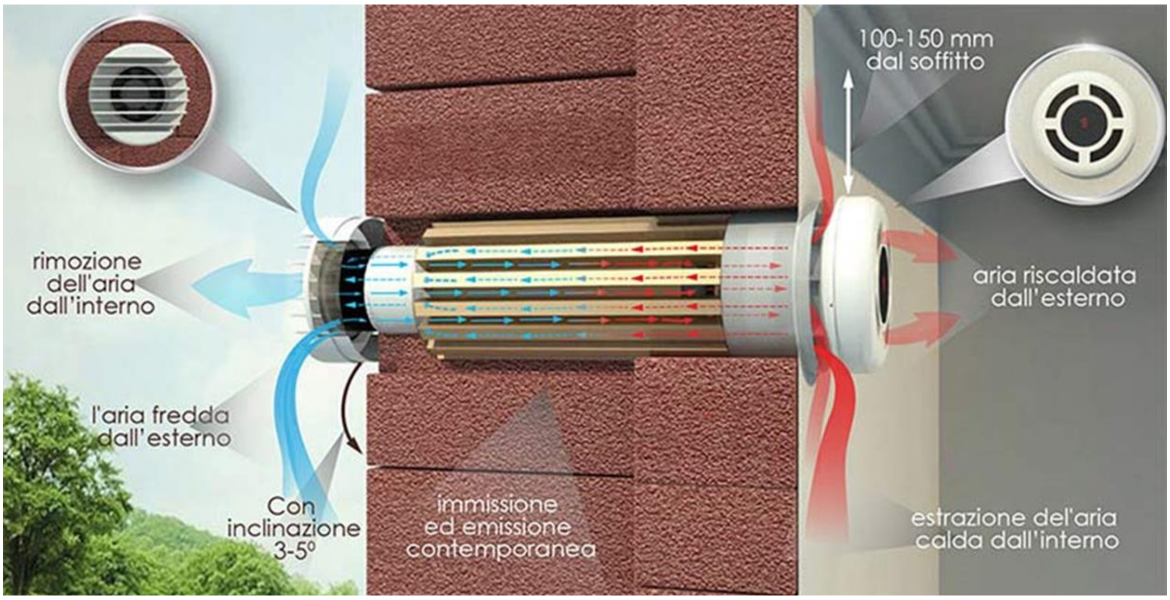


Figure 64 – Example of D-MEV system.

The reduced size makes this device particularly easy to install in any type of building. As done for C-MEV, in Table 47 are listed the main advantages and disadvantages of D-MEV systems.

Table 47 – Advantages and disadvantages of D-MEV systems.

Advantages	Disadvantages
Simple and cheaper design. No need of pipes or dedicate room.	Smaller heat recovery efficiency compared to C-MEV.
Flexibility. Installation is feasible in almost every type of building.	Smaller air filtration efficiency compared to C-MEV.
Low energy consumption.	Limited air flow rates. D-MEV not recommended for large rooms.
Avoided ventilation in unoccupied rooms.	Low cost devices could be quite noisy.

All the pieces of information gathered above explain why a decentralised solution is more suitable for the case study. Therefore, it is now time to provide a preliminary design of the system according to the ventilation requirements identified in sections 8.1.1 and 8.1.2 which essentially match the EN ISO 16798 prescriptions.

8.2.3 D-MEV installation in *Aula Nord 3*: expected results

As the graphs in sections 8.1.1 and 8.1.2 have shown, in order to guarantee an air quality level classified with Category II or higher, a mechanical ventilation system should provide an air flow rate equal or above 7 l/s per person. Considering an average classroom occupancy of 25 people, the corresponding **total air flow rate** to be supplied is **175 l/s** (**630 m^3/h**).

However, current D-MEV available on the market can supply air in a range between **20 to 250 m^3/h**. This implies that more than one device should be installed in each classroom. Therefore, the issue is to find a compromise between the actual ventilation needs and costs.

At this point, it is intended to bring a numerical example which characterise actual conditions of *Aula Nord 3*:

Table 48 – *Aula Nord 3* design data.

Aula Nord 3	
Surface	78 m^2
Volume	249 m^3
Max n° Occupants	25
CO_2 production rate	20 l/h per person
Air flow rate required for ISO 16798 IEQ_{II}	7 l/s per person (630 m^3/h) (2,5 ACH)

Table 49 – D-MEV datasheet.

D-MEV datasheet	
Manufacturer	Prana Italia s.r.l.
Model	200C ErP
Max D-MEV air flow rate	235 m^3/h (0,95 ACH)
Power consumption	12 to 54 W
Unitary D-MEV cost	860 € (last update March 2020)

Data from Tables 48, 49 were used as input to predict CO_2 concentrations and consequently to assess Indoor Air Quality as previously done in 8.1.1 and 8.1.2. In this case it was hypothesised the worst-case scenario in which occupants would never open the windows and consequently air exchange would only be relied on D-MEV devices. With these conditions the following three outputs were compared:

- CO_2 concentrations predicted throughout a year with installation of 1 D-MEV device in *Aula Nord 3*.
- CO_2 concentrations predicted throughout a year with installation of 2 D-MEV devices in *Aula Nord 3*.
- CO_2 concentrations predicted throughout a year with installation 3 D-MEV devices in *Aula Nord 3*.

All the installed devices are assumed to be equal to each other and to have the characteristics exposed in Table 52. Results are shown in Fig. 65 below.

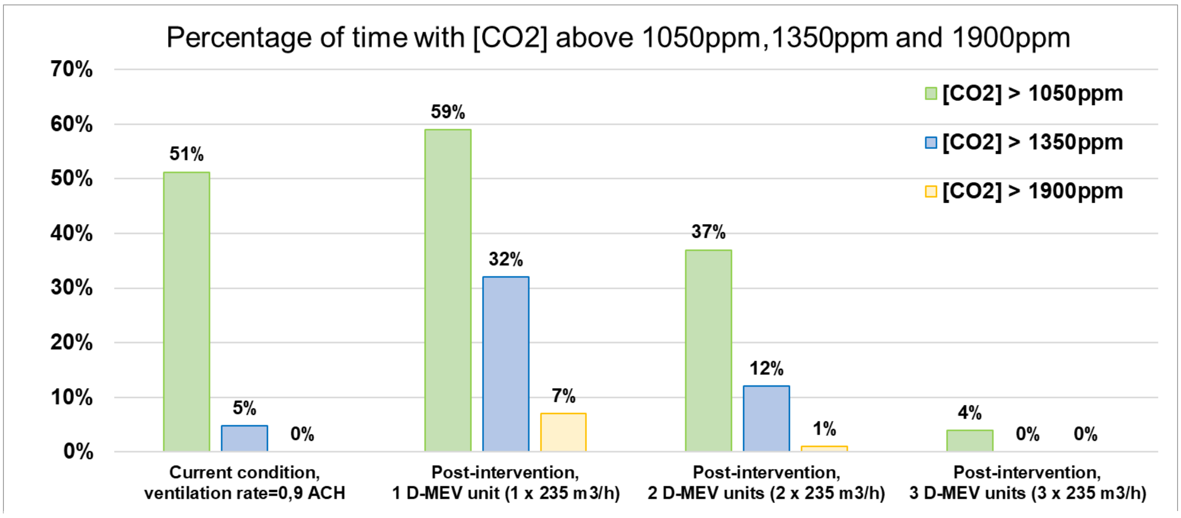


Figure 65 – Expected results after D-MEV installation.

Histogram shows how the installation of 1 D-MEV unit would not guarantee category II for indoor air quality, since almost 1/3 of the total time presents [CO_2] >1350 ppm.

Placing 3 D-MEV devices would certainly make *Aula Nord 3* achieve category I, but the overall cost would rise significantly (it should be considered that for each of the 3 pavilions there are 8 classrooms and 1 lab, all of them should be provided with 3 D-MEV units).

Therefore, installation of 2 D-MEV devices (see example in Fig. 66) is considered a fair compromise since only in 13% of the total time CO_2 concentrations will be above 1350 ppm. The flexibility of D-MEV solution can also avoid plant oversizing. Indeed, what is suggested to *Escola Conde de Oeiras* is a step-by-step approach:

1. installing 2 D-MEV units in *Aula Nord 3*.
2. collecting data from: occupants' comfort, energy consumption, system efficiency.
3. proceed with further installation in other classrooms basing on the data gathered in step 2.

This approach would not be feasible with a C-MEV system.

Figure 66 – Example of 2 D-MEV devices installed in a classroom.

8.3 Final investment plan

Having reached this point, we have all the information necessary to outline a complete report on the possible actions to be taken to improve the energy efficiency of *Escola Conde de Oeiras.*

From the thermal comfort analysis of the singular buildings emerged the necessity to guarantee better conditions for the students and employees. As demonstrated before, the current state of fact can be improved through an enhanced insulation of the building envelope which also leads to a reduction of energy needs. Indeed, the last project evaluation highlighted a relatively short PBP of 24 years and an NPV equal to 24% of the initial investment.

Nevertheless, considering the absence of space heating/cooling services, all the measures analysed in the present study may not be sufficient to guarantee acceptable conditions inside the thermal zones in every season of the year. For this reasons, windows replacement and thermal coat must be included in a wider investment plan which includes the design of efficient HVAC systems able to supply the required needs. Besides, these new assets must be economically and environmentally sustainable.

All these factors suggest pursuing the use of renewable sources to satisfy all needs, having as ultimate goal the achievement of energy independence. In other words, convert the current buildings into nZEB's which produce as much as they consume.

To accomplish nZEB objective, one of the possible ways could be designing a photovoltaic plant that is able to develop enough power to satisfy the energy requests of the entire school. Thus, the total demand will be disaggregated into three voices:

- Energy to supply HVAC system, currently estimated in 151 MWh per year but reducible to 108 MWh per year with EEM-C.
- Energy required from ordinary electric equipment, assessed around 155[29] MWh per year.
- Energy required from gas equipment, assessed around 13,5[30] MWh per year

With information above it was intended to provide the reader with a business plan of 150 kWh grid-connected PV plant that can satisfy the total demand.

The simplified approach used to carry out this investment plan may imply low accuracy in the results; however, the scope was essentially to acknowledge the order of magnitude of the capitals involved.

A higher interest rate was adopted due the unpredictable time required for the installation of all the new structures and because of their risk of damage throughout the years.

[29] Data from 2018 electricity bill.
[30] Data from 2018 gas bill.

Table 50 - Photovoltaic plant cost and specifications.

PV plant data	
Total school energy demand[31]	**277** MWh per year
Useful days per year[32]	**242**
Useful hours per day	**8**
Average daily energy demand	**143** kWh
Peak design power of the PV plant	**150** kW
Yearly PV energy production[33]	**261** MWh
PV plant overall cost, VAT included	**300'000** €

Table 51 - HVAC plan cost and specifications

HVAC plant data	
Plant energy demand[18]	**108** MWh per year
Number of thermal zones to supply[34]	**39**
Cost of each AC unit[35]	**1700** €
HVAC plant overall cost, VAT included	**70'000** €

Table 52 – Final business plan.

Final business plan	
Tot gross investment (PV plant + HVAC +EEM-C) [€]	**800'000**
Net investment (-60% due to tax deduction) [€]	**320'000**
Investment period [years]	**40**
1st year cash flow due to energy savings [€]	**74'379**
estimated annual energy cost inflation	**2%**
Interest rate	**15%**
NPV [€]	**247'430**
PBP [years]	**7**

The plan appears extremely profitable with a complete return of the capital after 7 years and Internal rate of return (IRR) of 27%.

If tax deduction is not considered, hence the school should consider the entire gross investment, the IRR decrease to 11% and PBP rise up to more than 50 years.

[31] Considering EEM-C implementation.
[32] 11 months per year and 22 days per month.
[33] Results provided by PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM (PVGIS) interactive tool.
[34] 27 thermal zones for *pav. A, B, C;* 10 for *Adm. pav.*; 6 for *Canteen*.
[35] Average cost for ducted air conditioner A++ that develops a power of 39'900 BTU for cooling and 48'000 BTU for heating.

9 Conclusions

Among all the possible ways to promote energy efficiency measures in buildings, the dynamical simulation it is often considered one of the most time-consuming for various reasons. Indeed, it may be laborious to collect information about materials used, scheduled activity of a certain facility, types and number of electronic devices. On the other hand, to develop essential refurbishment projects such as those required for a school, more complex tools are needed to define the crucial elements that need to be improved and optimize the available resources. As a matter of fact, the present work also aims to highlight potentialities and accuracy that software like *Energy+* can guarantee. Besides, it can provide a wide variety of outputs allowing to assess the performances of specific component of the building like windows, walls and roof. With these arguments, it was decided to study in detail the issues that *Escola Conde de Oeiras* is currently facing.

Already after the first visits, it was acknowledged, as probable causes of discomfort, the poor insulation degree and the excess of solar gains due to the old glass surfaces. To prove this hypothesis, it was computed the percentage of time out of acceptability limits for every thermal zone of each facility. Outcomes of simulations of the current[36] conditions showed, even considering less strict acceptability limits of 80%, a high presence of discomfort in most of the spaces with averages of 32% in pavilions with classrooms, 33% in *Administrative pavilion* and 34% in the *canteen*.

Among the various alternatives compared, a *selective low emissivity double glazing system* provided the best results. With this new windows configuration, it was estimated that percentage of discomfort time would reduce up to 14% for pavilions with classrooms, 21% for administrative pavilions and 28% for the canteen, without installing any HVAC systems. Successively, this intervention was evaluated under an economic perspective and what emerged was that it was also most convenient.

However, it was proven that windows replacement could also increase ventilation demand making indoor air quality way worse than the current condition. In this regards, it was intended to make the reader aware of this issue by discussing how Mechanical Extract Ventilation (MEV) technology works and which possible devices are currently available on the market. For *Escola Conde de Oeiras* it was acknowledged that a Decentralised-MEV device would best adapt to the building's characteristics.

Finally, hypothesizing to include these energy efficiency measure in a more ambitious and long term investment plan it is expected not only to reduce school environmental impact, but also to have the complete return of capital after 7 years and a Net Present Value of almost 250'000 € after 40 years, even assuming an interest rate of 11%.

With the achieved results, it is intended to promote a detailed feasibility study to be carried out in the near future.

[36] Scenario B: after roof replacement.

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Appendix A - Materials and constructions

In this appendix it is exposed a description of the construction elements and the associated simplifying hypotheses.

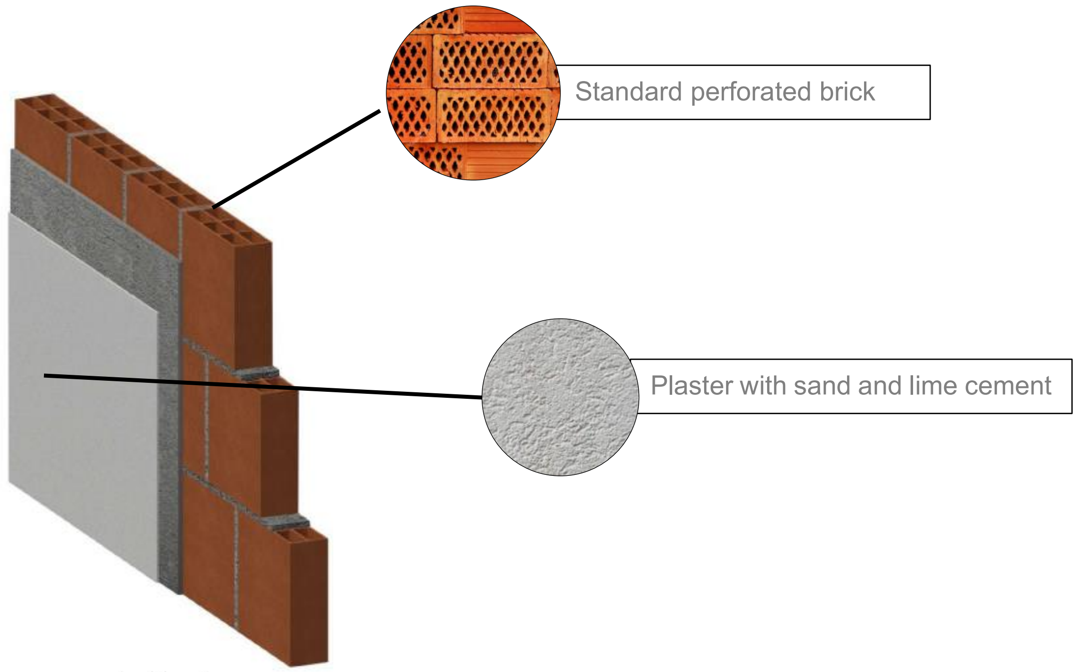
The constructive elements and the relative assumptions are listed below.

a) External and internal walls layering for all walls it was considered the following layers composition: *-plaster-brick-plaster*. To make the model simpler and to reduce simulation time it has been assumed the presence of a single brick with a width equal to: $Width_{brick} = Thickness_{wall} - (Thickness_{plaster})x2$.
   In all the major importance thermal zones the bricks are covered with plaster from both sides, however in some rooms, such as bathroom and other small spaces the bricks are uncovered. Since classrooms, offices, libraries are considered the most important thermal zones their internal wall layering is assumed as standard.
b) Roofing: some rooms present cork insulation for the ceiling, while some do not. In the pavilions with classrooms cork has been assumed present in all the ceilings (since only bathroom are not insulated). In the other buildings it has been respected the actual ceilings stratification for all the spaces. Moreover,
c) Flooring: equal for all the facilities, as already stated in the premise. As regards for the administrative pavilion, since this is the only building developed on two levels, it is the only that has two types of floor with different layering.
d) Glass surfaces are assumed to be made of the same type of glass. The school was built in 1982 and since then the windows and glass doors have never been replaced. Therefore, it was opted for the use of simple glass which at the time was the most available in the market. However, it has to be considered that some of the glass surfaces in classrooms are not transparent so the solar radiation entering the room is lower than a simple t glass. In any case, since in 1982 low-emissivity or selective glass were not in the market, it is here assumed that the solar heat gain coefficient is the same whether the glass surface is transparent or not.
e) Windows have the following characteristics: 90% of the surface is constituted by simple glass; 10% of the surface is occupied by a non-insulated aluminium frame with a transmittance value of U_{frame} = 7W/m^{2}K.

Given the assumptions above, materials were introduced in the Energy+ model filling all the fields in the *Material* object of Energy+ described in 4.1.3. Their thermophysical properties are shown in the next pages.

NOTA: The renderings that follows have an exclusively explanatory function. Therefore, they do not represent the actual shape of the constructive elements but are used to show their stratification more effectively.

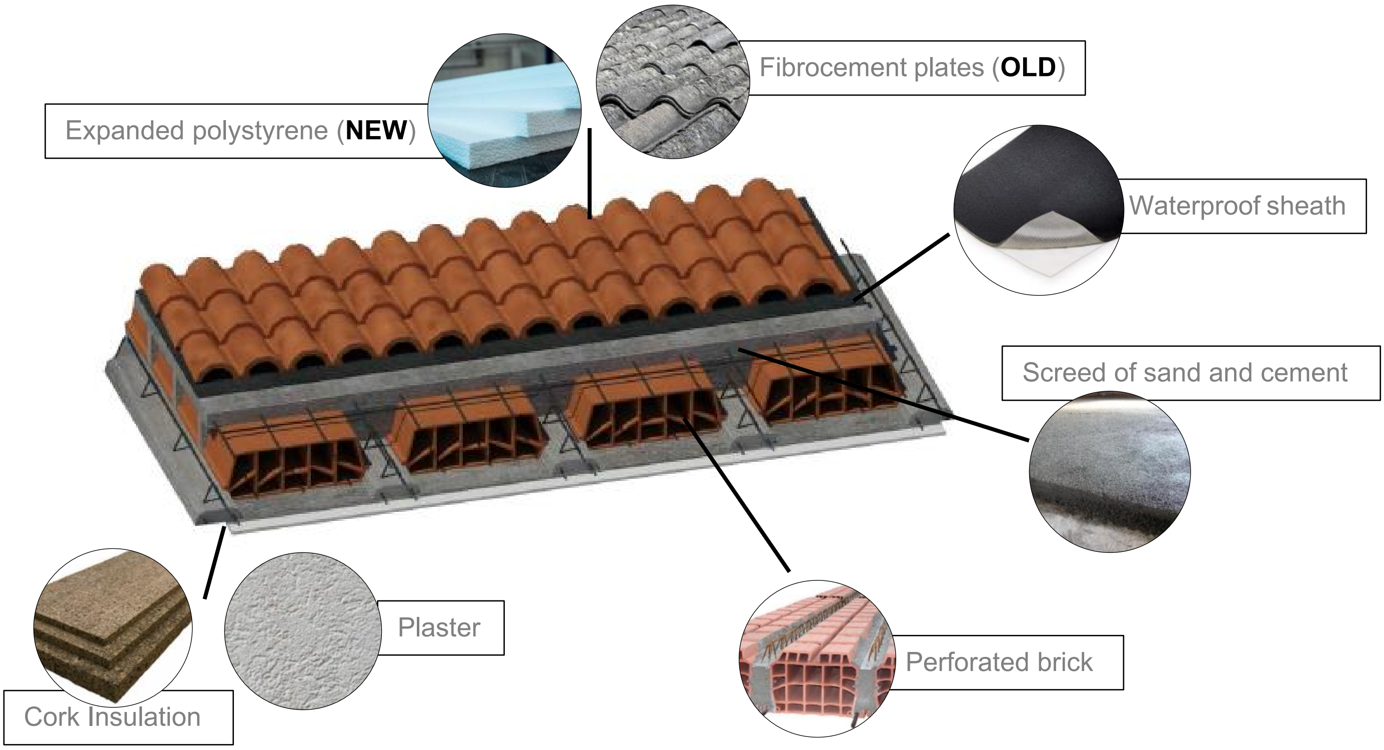
A.1 Walls



BRICK		Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
Pavilions A,B,C	external walls	34	Rough	0.28	900	840	0.9	0.7	0.7
	internal walls	15	Rough	0.28	900	840	0.9	0.7	0.7
Admin. Pavilion	external walls	36	Rough	0.28	900	840	0.9	0.7	0.7
	internal walls (1)	35	Rough	0.28	900	840	0.9	0.7	0.7
	internal walls (2)	33	Rough	0.28	900	840	0.9	0.7	0.7
	internal walls (3)	22	Rough	0.28	900	840	0.9	0.7	0.7
Canteen	external walls	28	Rough	0.28	900	840	0.9	0.7	0.7
	internal walls	13	Rough	0.28	900	840	0.9	0.7	0.7

PLASTER		Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	external walls	2	Rough	0.9	1800	850	0.9	0.7	0.7
	internal walls	1.5	Rough	0.9	1800	850	0.9	0.7	0.7

A.2 Roofing



FIBROCEMENT	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	2	Rough	0.26	1450	870	0.9	0.7	0.7

POLYSTYRENE	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	6	Rough	0.034	30	1260	0.9	0.7	0.7

WATERPROOF SHEAT	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	0,5	Rough	0,5	1600	2500	0,3	0,3	0,3

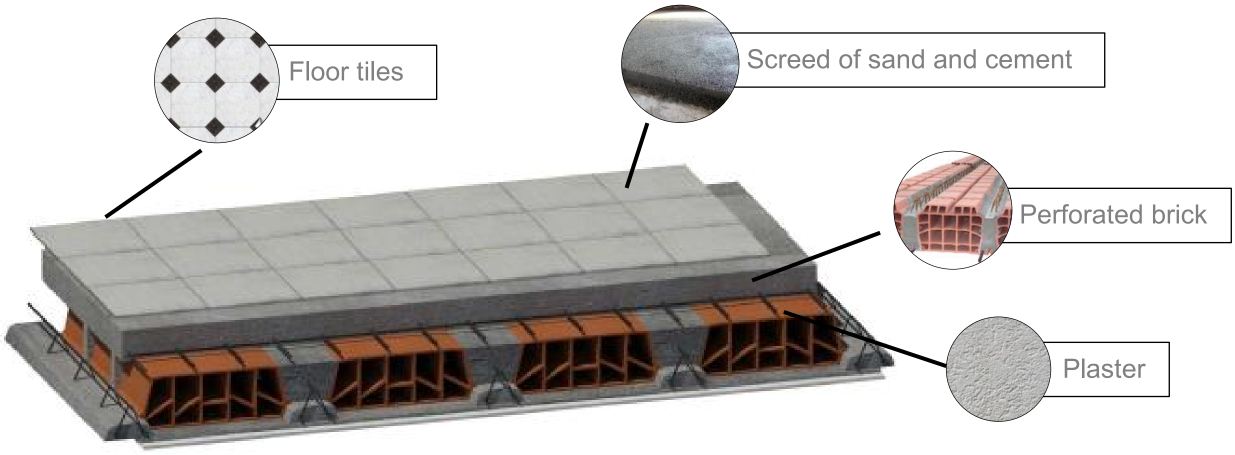
SCREED OF SAND AND CEMENT	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	4	Rough	0,93	1800	880	0,9	0,7	0,7

PERFORATED BRICK	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	26	Rough	0.535	1800	840	0.9	0.7	0.7

PLASTER	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	1,5	Rough	0,9	1800	840	0,9	0,7	0,7

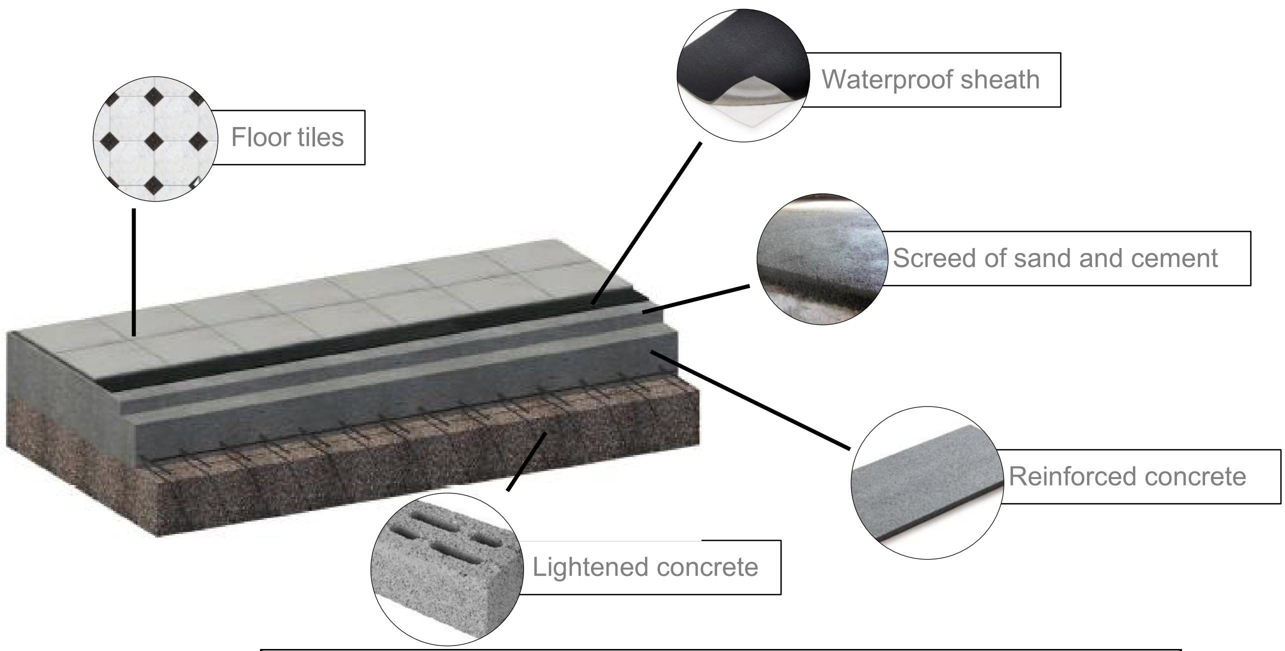
CORK	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	2	Rough	0,045	160	1900	0,9	0,5	0,5

A.3 Floor slab (only present in Adm. Pavilion)



FLOOR TILES	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
Administrative pavilion	2	Medium smooth	1	2300	795	0.9	0.5	0.5

A.4 Flooring



REINFORCED CONCRETE	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	Rough	0.3	0.8	1600	850	0.9	0.7	0.7

LIGHTENED CONCRETE	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m3]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	0.1	Rough	0.84	1400	840	0.9	0.7	0.7

A.5 Glass surfaces

Regarding the glass surfaces, two different method have been adopted for the estimation of their thermophysical characteristics. As will be shown shortly, both lead to similar results.

Method 1: detailed calculation with *Energy+*

With object 'WindowMaterial: Glazing' (Fig. 67 shows the *Energy+* interface) it is possible to input the measured characteristics of the glass and let the software calculate its thermophysical properties.

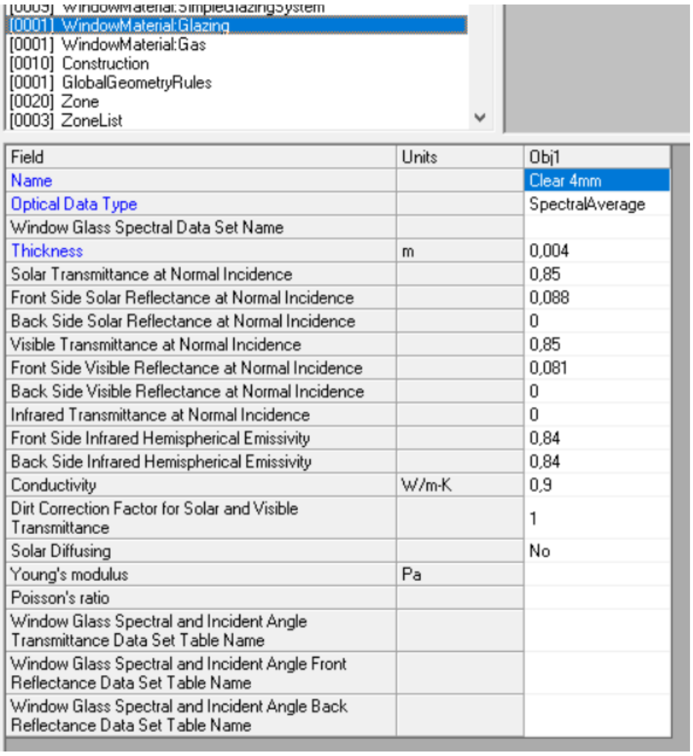


Figure 67 – *WindowMaterial: Glazing* object in the *Energy+* environment.

Once created the material, the user must assign it to a construction which has to be referred to the proper sub surface, that in this case is called '*Finestra normale nord*' (Italian translation of 'Standard north window').

Once simulation is completed the user can consult the results in HTML format and search, using the appropriate tool provided by his browser, the name of the construction he wants to check.

The software calculates a value of thermal transmittance (Glass U-factor) equal to 5,855 W/m^2/K and a Solar Heat Gain Coefficient (Glass SHGH) equal to 0,868.

Construction	Glass Area [m2]	Frame Area [m2]	Divider Area [m2]	Area of One Opening [m2]	Area of Multiplied Openings [m2]	Glass U-Factor [W/m2-K]	Glass SHGC	Glass Visible Transmittance
FINESTRA NORMALE NORD	6.51	1.11	0.00	7.62	7.62	5.855	0.868	0.851

Figure 68 – Output of Energy+ showing the calculated properties of glazed surfaces.

Method 2: Use of ISO standard values

Considering that most of the existing windows and doors consist of a frame in whole metal/not insulated or in wood with mostly single glazing for an estimate of the transmittance values of these components, the following values suggested by the ISO standards for single glazing can be chosen as a references:

- U_{glass} = 5,85 W/m^2/K for single glass (source: UNI EN ISO 10077-1).
- U_{frame} = 7 W/m^2/K for aluminium frames (source: UNI EN ISO 10077).

Hence, instead of using the object 'WindowMaterial:Glazing' that implies longer simulation times, it may be used a simplified approach with the object '*WindowMaterial:SimpleGlazingSystem'* (Fig. 69) of Energy+ which allows the user to input directly the values of Transmittance, SHGC and VT.

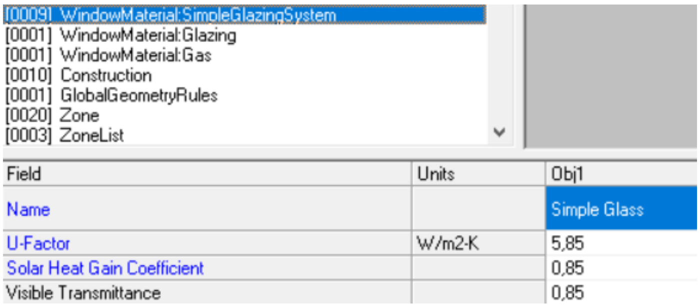


Figure 69 – *SimpleGlazingSystem* object in *Energy+* environment.

Table 53 summarizes the three main thermophysical properties of simple glass used for simulations.

Table 53 – Main thermophysical properties of simple glass.

SIMPLE GLASS	U factor [W/m2/K]	Solar Heat Gain Coefficient	Visible Transmittance
All buildings	5,85	0,85	0,85

Comparing the values of the thermophysical properties proposed by the ISO standard with those calculated with the detailed approach there is a minimal difference

Appendix B - Algorithms and other simulation parameters

It is here intended to briefly describe the algorithms and the principal parameters adopted to simulate physical heat transfer mechanisms in the model.

- Heat balance algorithm: *Conduction transfer function.* It provides a 'sensible heat only solution' and does not consider moisture storage or diffusion in the constructive elements [17].
- Inside surfaces convection algorithm: *Simple.* It applies constant heat transfer coefficients according to the surface orientation [17].
- Outside surfaces convection algorithm: *Adaptive convection algorithm.* It is a dynamic algorithm that selects among many different convections models the one that best applies [17].
- Sky Diffuse algorithm: *Simple sky diffuse modelling.* It assumes that shading objects or devices do not change their transmittance throughout the year. The it calculates the provided shadows according to daylight period contained in weather file.
- Zone air mass flow conservation: *Adjusted infiltration flow method.* It corrects the air mass flow balance within a thermal zone by including infiltration and ventilation coming from the surrounding zones.
- Timestep: *1 minute*. These values represent driving timestep for heat transfer and load calculations. It is the minimum value allowed by the software.
- Heating/cooling needs estimation: *HVAC Ideal Load system*. It is one of the objects available in the Energy+ environment. It allows the user to estimate the amount of heat to be add or removed in a thermal zone to meet the designed condition. With this object it possible to model a 100% efficiency HVAC system that works with a fixed thermostat. The thermostat temperatures were set to 20°C for heating and to 25°C for cooling thermostat. These values guarantee thermal comfort conditions for the widest range of outdoor temperatures, according to adaptive model. Whenever the registered temperature is above/below the designed value, it the system is switched on until temperature and humidity levels in the zone are inside the nominal range.

Appendix C - Experimental data feedback

To assess model accuracy, experimental measures of indoor air temperature and CO_2 concentration were collected in the second decade of October 2019 during three regular weekdays.

It is appropriate to clarify that this experimental data have no claim to validate the model 100%, but it is believed that they may represent an acceptable feedback for the work carried out in this study.

To evaluate the validation of a model, there are some variables which quantify model accuracy, which would determine how well simulated data would match real data during a certain time-frame. [18]. From these variables, statistical indices have been recommended by three main international bodies [19]:

- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guidelines 14 (St.14).
- International Performance Measurements and Verification Protocol (IPMVP).
- M&V guidelines for the US Federal Energy Management Program (FEMP).

The statistical indices used herein will be the Mean Bias Error (MBE) and the Coefficient of variation of the Root Mean Square Error (CvRMSE), defined by Equations (16-19):

$$MBE(\%) = \frac{\sum_i^n (S_i - M_i)}{\sum_i^n M_i} \times 100\% \tag{16}$$

$$RMSE_{period} = \sqrt{\frac{\sum_i^n (S_i - M_i)^2}{n}} \tag{17}$$

$$A_{period} = \frac{\sum_i^n M_i}{n} \tag{18}$$

$$Cv(RMSE)(\%) = \frac{RMSE_{period}}{A_{period}} \times 100\% \tag{19}$$

For a model to be considered calibrated, the mentioned international bodies define limit values for the previous statistical indices. For an hourly calibration, St.14 and FEMP consider a range of ±10%, while IPMVP considers a range of ±5% for the MBE. For the CvRMSE index, St.14 and FEMP consider a max limit value of 30%, while IPMVP considers a max limit value of 20%.

Comparing the average measured temperature data with the model results, shown in Fig. 70, an MBE value of 2.95% and a CvRMSE value of 4.29%, which are within the limits established above.

The equipment used to meter temperature and CO_2 concentration consisted in a detector[37] which was positioned inside one of the north exposed *pavilion C* classrooms, namely Aula Nord 3. Temperature and concentrations were registered with a 5 second timestep whereas for *Energy+* the minimum timestep possible is 1 minute. Recording period started at 00:00 of 8/10/2019 and ended at 23:59 of 10/10/2019. To obtain simulation output (either temperature and [CO_2]) from the model several assumptions[38] were adopted and each of them was discussed in previous sections of the present dissertation.

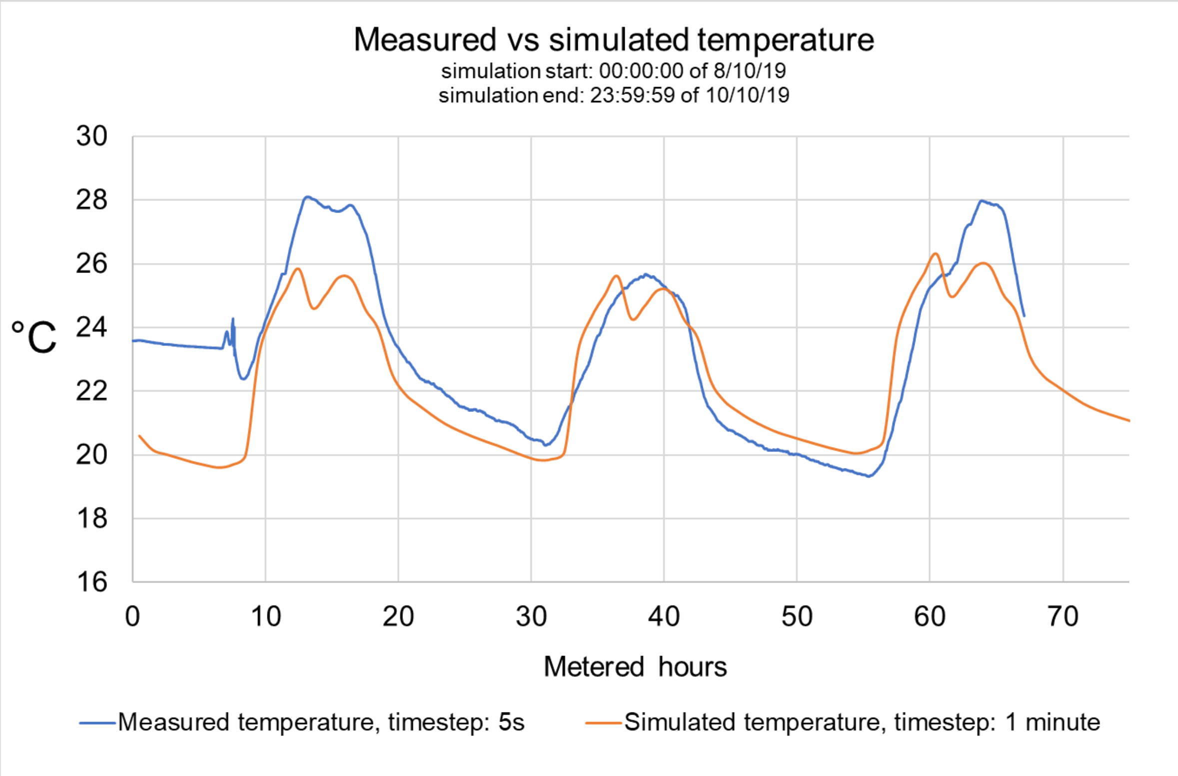


Figure 70 – Measured *vs.* simulated indoor temperature for classroom 'Aula Nord 3' in *pavilion C*.

As shown in Fig. 70, peak temperatures are reached around hours 15, 38 and 60 (approximately midday). The slight drops observed after all the peaks of the orange line and a little on the first peak of the blue line are probably due to people occupancy. Indeed, in the model it was scheduled that students start to leave the classroom at 1pm. This makes the indoor temperature decrease. Actually, this type of event does not occur systematically every day.

[37] Model: CMM-10. Manufacturer: PCE instruments.
[38] Summarised in Table 45, section 8.1.

In Fig. 71 is exposed the comparison between experimental CO_2 concentration data and the simulated one.

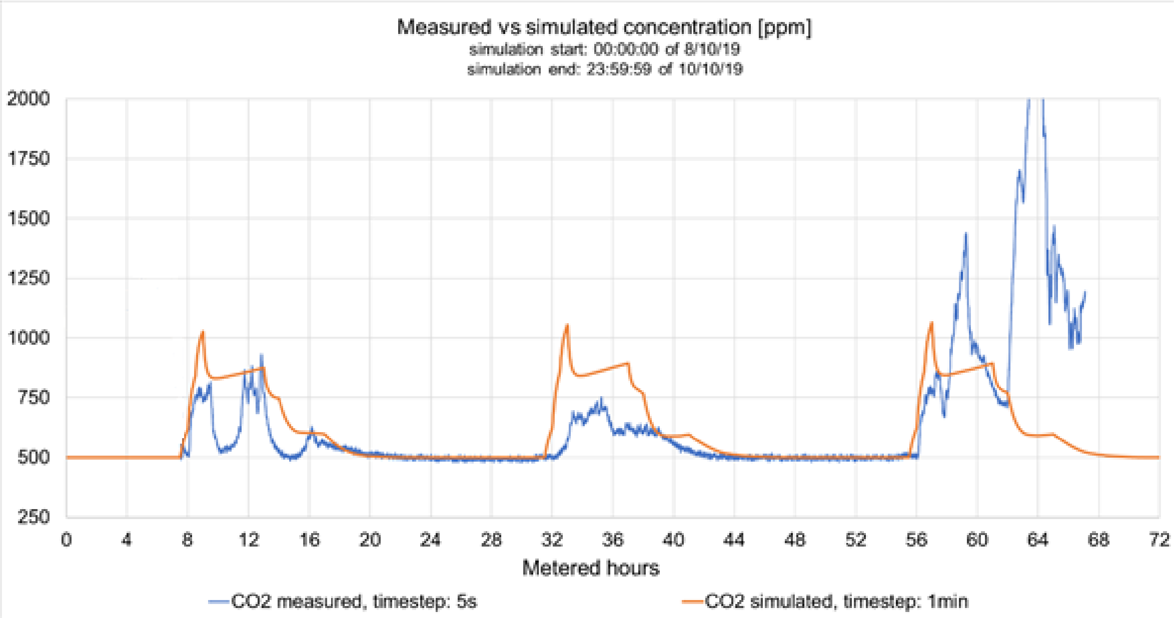


Figure 71 - Measured vs. simulated CO_2 concentration for classroom 'Aula Nord 3' in pavilion C.

Unlike the comparison shown in Fig. 70, there is a greater discrepancy between the values of the concentrations estimated by the model and those actually measured. However, the two curves are characterized by segments that are repeated throughout the day and can be identified as follows:

1. *Background segment* with [CO_2]=500 ppm. This CO_2 concentration characterises hours between 6pm and 8am.
2. *Growth* of [CO_2] until first peak is reached. [CO_2] rises since occupants populate the classroom without opening the windows.
3. *Fast drop*. Right after the peak, [CO_2] begins to decrease rapidly. This may be due to occupants' habit to open the window widely as soon as they perceive uneasiness in the environment.
4. *Stationary segment*. Clearly visible in day 2 where [CO_2] fluctuates around 650ppm after hour 36. After keeping the window wide open for a certain period of time, the occupants tend to close it completely or partially decreasing the inlet flow of diluting air.
5. *Final decrease*. When occupants start to move out from the classroom, [CO_2] gradually decreases up to the background level.

Day-to-day variability in trends is outlined by two principal aspects:

- irregular duration of stationary segments that can last various hours (as in day 2) or less than 30 minutes (day 1 and 3).
- inconsistent peak values of concentration. In day 1 peaks assess around 1000 ppm in the morning; in day 3 they reach more than 2000 ppm in the late afternoon.

The sources of these variability may be attributed to some of the following factors:

- number of people inside the room, which is not always constant since classrooms are used for lectures but also for small gatherings or extracurricular activities during the afternoon.
- window opening frequency, subjected to seasonality and occupant’s behaviour.
- weather condition (rain, sun etc.).
- metabolic rate of occupants, which affects directly their CO_2 production rate.