

Promotion of Energy Efficiency Measures in EB23 Conde de Oeiras School

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Abstract

Public buildings represent an important opportunity to depict suitably how energy efficiency may impact on the two most crucial aspects: management costs and thermal comfort. 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 promote 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 was shown that all the thermal zones do not comply with comfortable acceptability limits provided by ASHRAE-55 2017 standards.

Therefore, once assessed the performance of three new type of double-glazing systems, it was identified as the best option the installation of *selective low emissivity glass with a thermal break aluminium frame*. Indeed, with this new type of fenestration 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.

Finally, it is proposed a simplified business plan of a long-term investment which targets to achieve the condition of energy independence. This includes: the design of a 150-kW photovoltaic plant that could supply 261 MWh, enough to satisfy the 95% of the future school needs.

Resumo

Os edifícios públicos representam uma oportunidade importante para descrever adequadamente como a eficiência energética pode impactar nos dois aspectos mais cruciais: custos de gestão e conforto térmico. A este respeito, muitas das escolas secundárias em Portugal enfrentam a deterioração estrutural das suas instalações. Entre todas, a EB23 Escola Conde de Oeiras, construída em 1982 no distrito de Lisboa, necessita melhorar seu desempenho energético atual, a fim de garantir condições ambientais aceitáveis para estudantes e funcionários. Para isso, é necessário definir uma série de medidas que possam fornecer efeitos imediatos e permanentes.

Com essas premissas, o presente estudo tem como objetivo identificar uma abordagem sistemática para promover medidas adequadas de eficiência energética para a Escola Conde de Oeiras. Para atingir esse objetivo, foi realizado o estudo detalhado de suas principais instalações em três fases principais, a saber: criação do modelo geométrico com Google SketchUp e OpenStudio, simulação térmica dinâmica de edifícios com Energy +, análise e discussão de resultados.

Os resultados provaram que o desconforto térmico é principalmente induzido pelo excesso de ganhos solares e pelo baixo grau de isolamento causado pelas superfícies de vidro. Como consequência, foi demonstrado que todas as zonas térmicas não cumprem os limites de aceitabilidade confortáveis fornecidos pelas normas ASHRAE-55 2017.

Portanto, uma vez avaliada o desempenho de três novos tipos de sistemas de vidros duplos, foi identificada como a melhor opção a instalação de vidro seletivo de baixa emissividade com uma estrutura de alumínio com ruptura térmica. De fato, com esse novo tipo de vão envidraçados, estimou-se uma redução média de 30% menos tempo de desconforto em quatro dos seis edifícios examinados. Além desta primeira medida, foi estudado, para várias espessuras de poliestireno expandido (EPS), se a realização do revestimento térmico poderia trazer benefícios ou não. O que surgiu foi que apenas para um tipo de edifício, ou seja, pavilhão com salas de aula, era vantajoso instalar 12 cm de camada isolante de EPS.

Por fim, propõe-se um plano de negócios simplificado para um investimento de longo prazo, visando atingir a condição de independência energética. Isso inclui: o projeto de uma central fotovoltaica de 150 kW que poderia fornecer 261 MWh, o suficiente para satisfazer 95% das necessidades futuras da escola.

1 Introduction and aim of the study

Despite being apparently in good condition, *Escola Conde de Oeiras*, a lower secondary school (5 and 6 grade) in Lisbon district, has some critical inefficiencies which affect significantly thermal 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 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 CO₂ 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 assessed both in a thermal comfort enhancement and economic convenience perspectives.

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, a resource 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 a pie-chart as follows

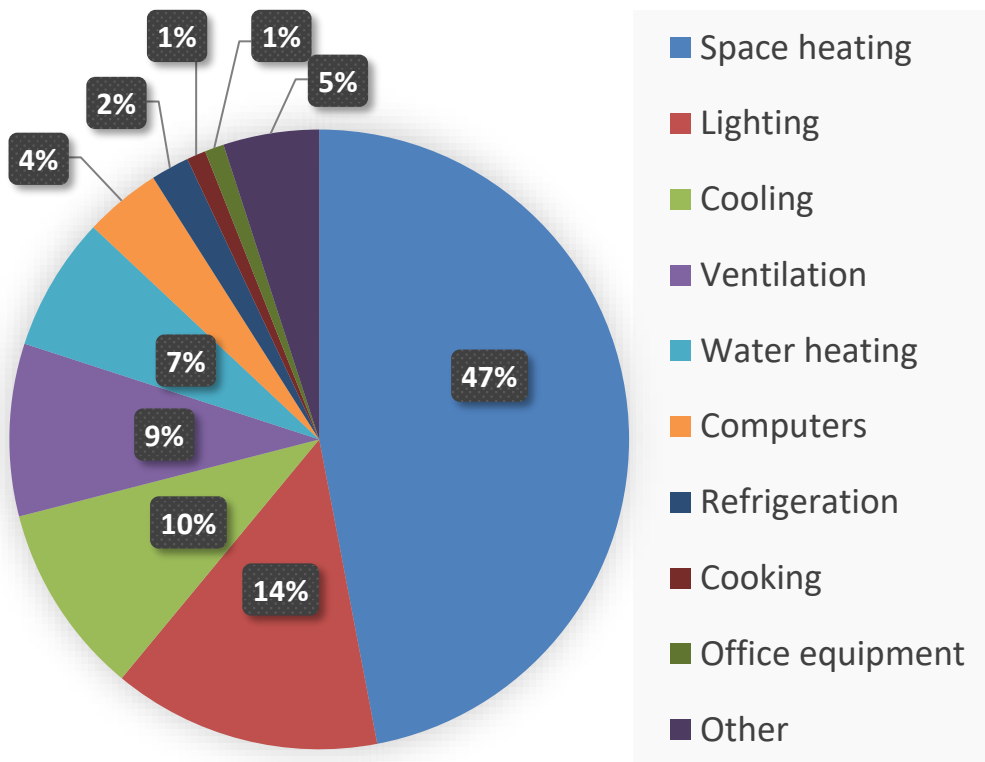


Figure 1 - Average energy use profile for U.S. schools [21].

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/m² 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 efficient 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*.

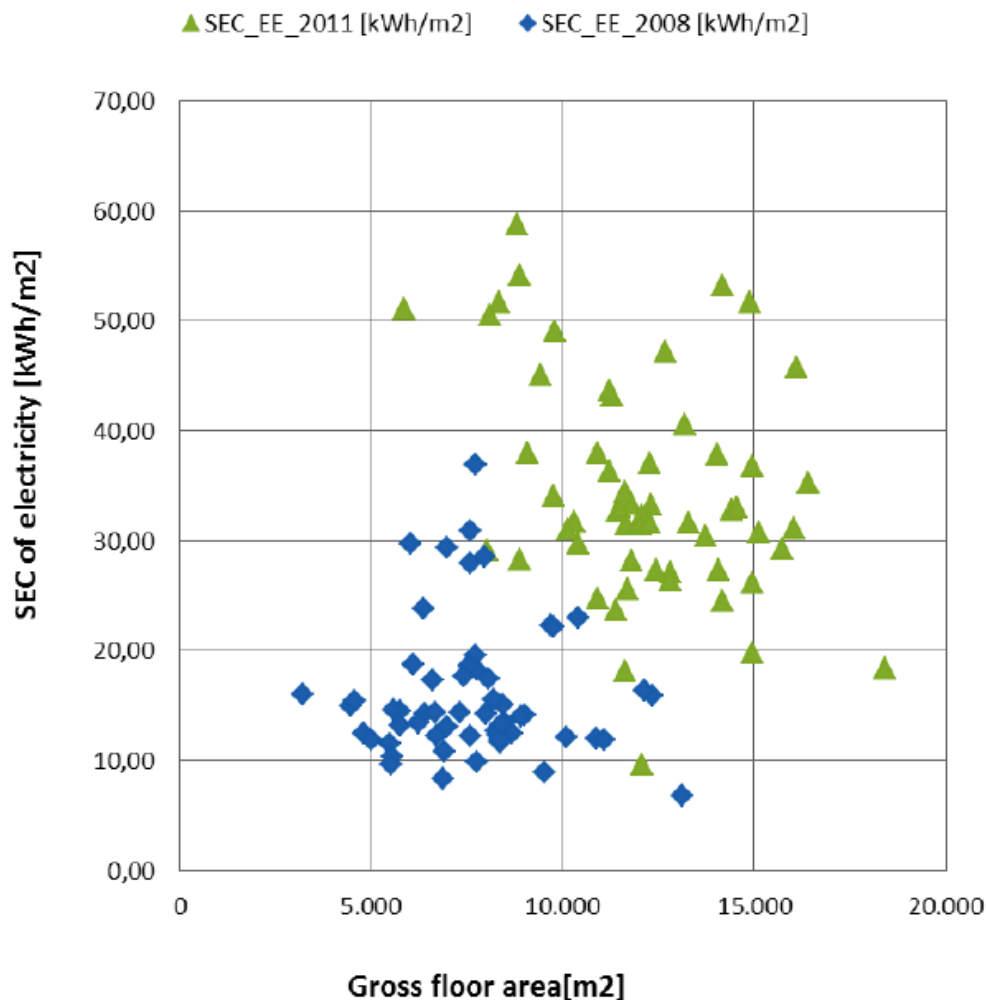


Figure 2 - Specific energy consumption of schools before (2008) and after (2011) the complete refurbishment [4].

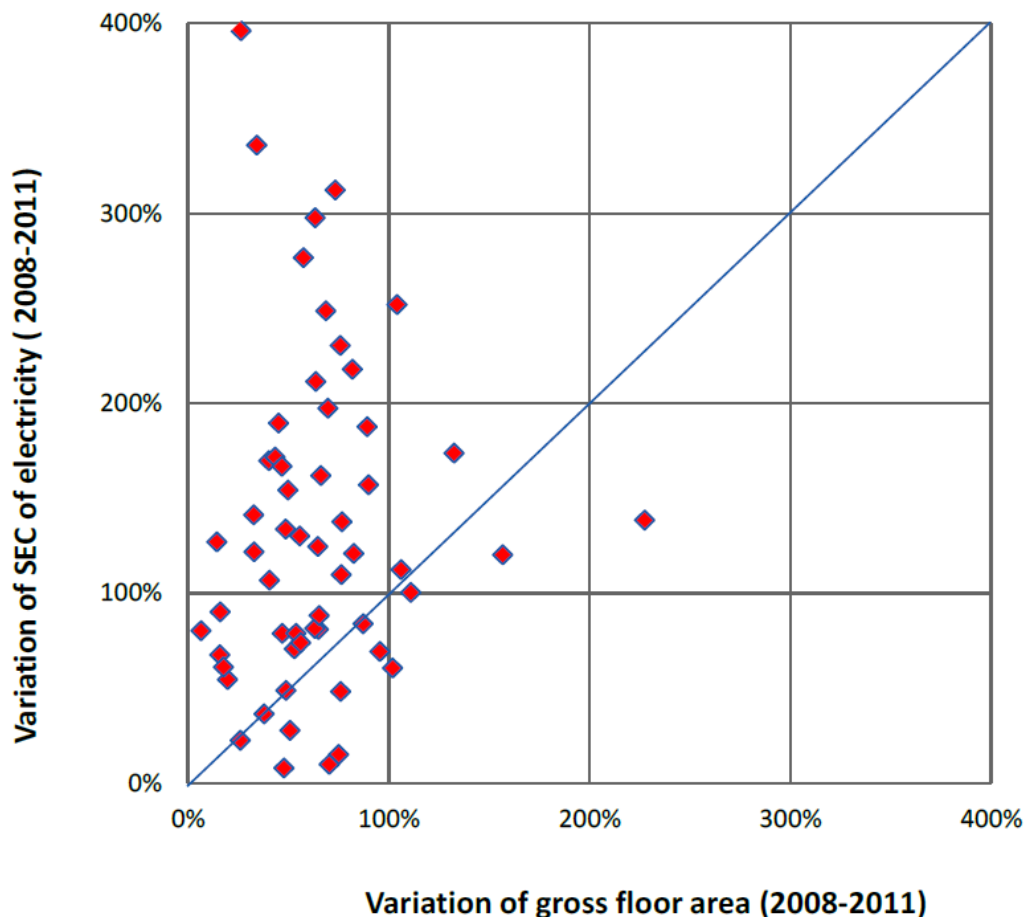


Figure 3 - Variation of Specific energy consumption vs. variation of gross floor area [4]

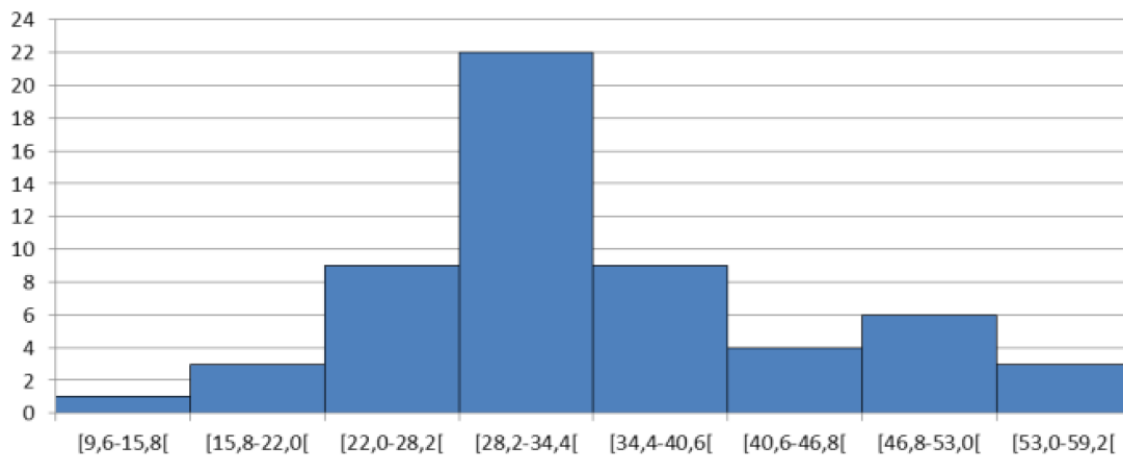


Figure 4 – Frequency distribution of the Specific energy consumption in all the 57 school, expressed in kWh/m²/year [4]

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/m² per year [4];
- The complete refurbishment implied the enlargement of the gross floor area assessed on avg. 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/m² per year with percentual increment of 231%;
- 22% of the school (Fig. 4) were in the range of specific consumption of 28,2-34,4 kWh/m²/year.

From these essential pieces of information many observations could be done. Above all, modernising the school facilities would lead to boost their consumptions. However, this is mainly due to the upgrade of the services provided, to the expansion of the infrastructures and to 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/m²/year, not guarantying space or 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. Wanting to adopt the same percentage for the Portuguese schools, it is obtained:

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

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

Even admitting the extremely simplified approach of these calculation, it is to be noted how the results above differ only by 5%. This could mean that during the refurbishment many of the 57 schools were equipped with HVAC systems. As a matter of fact, this statement is confirmed in [4].

What can be concluded after this brief discussion, is that developing an eventual modernization 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 more essential services such as 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 Methodology

Before presenting the case study, it seemed appropriate to describe which path was followed to reach the final outputs. Thus, are subsequently discussed tools and models which had characterized the study methodology.

3.1 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 design a geometry and then characterize it through 'its constructive solutions, the list of the equipment and its schedules and the climate information' [5].

Due to its availability and reliability, Energy+ is one of the most used software for thermal simulation 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.

3.1.1 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 in an open source version.

The intuitive interface (Fig. 5) allows the user to build very complex geometry in less time with respect to 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.

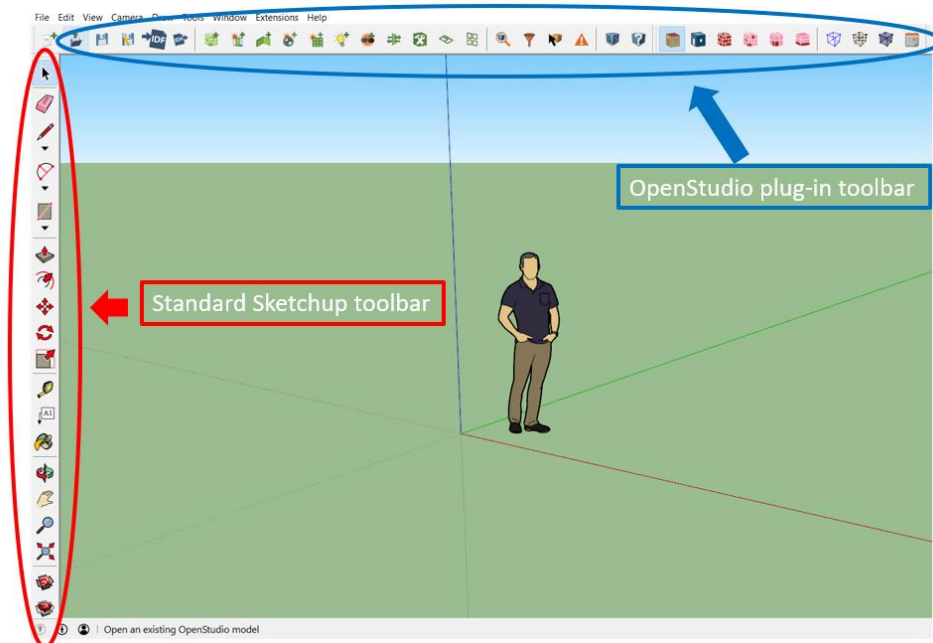


Figure 5 - Google SketchUp interface with its OpenStudio plug-in

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 *thermal zones*. This is done with the proper function available in OpenStudio plug-in toolbar present in SketchUp environment;
- 3) Assign *construction names* 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 material².
- 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.

² 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.

3.1.2 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:

$$q'' = -k\nabla T \quad (3)$$

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

For convection, the rate equation is of the form:

$$q'' = h(T_s - T_\infty) \quad (4)$$

Were T_s is the temperature of a surface, T_∞ is the temperature of a fluid and h ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) 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 gray surface):

$$q'' = \epsilon\sigma(T_s^4 - T_{sur}^4) \quad (5)$$

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 ($\sigma = 5,67 \times 10^{-8} \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$) 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 (6) shows the formulation for the Crank-Nicolson scheme:

$$C_p\rho\Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{1}{2} \left[\left(k_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \right) + \left(k_W \frac{T_{i+1}^j - T_i^j}{\Delta x} + k_E \frac{T_{i-1}^j - T_i^j}{\Delta x} \right) \right] \quad (6)$$

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 7.

$$\Delta x = \sqrt{c\alpha\Delta t} \quad (7)$$

Where 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 8.

$$C_p^*(T) = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \quad (8)$$

3.1.3 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 [5]:

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

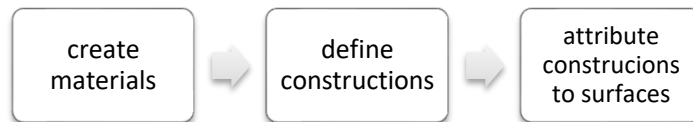
The model built adopting this simplified approach could be considered validated according to the results provided in Appendix C.

3.1.3.1 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. 6) presents field that needs to be filled knowing the actual thermophysical properties.

'Constructions' (Fig. 7) 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

Field	Units	Obj1
Name		brick15cm
Roughness		Rough
Thickness	m	0,15
Conductivity	W/m-K	0,28
Density	kg/m3	900
Specific Heat	J/kg-K	840
Thermal Absorptance		0,9
Solar Absorptance		0,7
Visible Absorptance		0,7

Figure 6 - material object in Energy+ environment

Field	Units	Obj1
Name		CONSTRUCTION 1
Outside Layer		MATERIAL 1
Layer 2		MATERIAL 2
Layer 3		MATERIAL 3
Layer 4		

Figure 7 - 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.

Field	Units	Obj1
Name		Surface_35
Surface Type		Floor
Construction Name		solaio controterra
Zone Name		Thermal Zone: Aula nord 1
Outside Boundary Condition		Ground
Outside Boundary Condition Object		
Sun Exposure		NoSun
Wind Exposure		NoWind
View Factor to Ground		
Number of Vertices		
Vertex 1 X-coordinate	m	4,80000000E+00
Vertex 1 Y-coordinate	m	1,80000000E+00
Vertex 1 Z-coordinate	m	0
Vertex 2 X-coordinate	m	4,80000000E+00
Vertex 2 Y-coordinate	m	-7,20000000E+00
Vertex 2 Z-coordinate	m	0
Vertex 3 X-coordinate	m	-2,4

Figure 8 - 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.

[0001] SurfaceConvectionAlgorithm:Inside		
[0001] SurfaceConvectionAlgorithm:Outside		
[0001] HeatBalanceAlgorithm		
[0001] ZoneAirMassFlowConservation		
[0001] Timestep		
[0001] RunPeriod		
[0001] Site:GroundTemperature:BuildingSurface		
[0006] ScheduleTypeLimits		
[0012] Schedule:Compact		
[0002] Schedule:Constant		
[0016] Material		
[0002] Material:NoMass		
[0002] Material:AirGap		
[0009] WindowMaterial:SimpleGlazingSystem		

Explanation of Object and Current Field

Object Description: Default outside surface heat transfer convection algorithm to be used for all zones

Field Description: SimpleCombined = Combined radiation and convection coefficient using simple ASHRAE model TARP = correlation from models developed by ASHRAE, Walton, and Sparrow et. al. MoWITT = correlation from measurements by Klems and Yazdanian for smooth surfaces DOE-2 = correlation from measurements by Klems and Yazdanian for rough surfaces AdaptiveConvectionAlgorithm = dynamic selection of correlations based on conditions

ID: A1

Field	Units	Obj1
Algorithm		AdaptiveConvectionAlgorithm

Figure 9 – 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.

3.1.3.2 Air mass balance

The air mass flow is 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 DOE³ were used (table 3).

Table 2 - Infiltration flow rate input for all zones assuming the building level air change is distributed equally in all zones

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)
BLAST	BLAST 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 = 1 cm⁴;
- 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 m³;

$$\text{flow rate through the openings} = 0,01m \cdot 14m \cdot 0,1 \frac{m}{s} = 0,014 \frac{m^3}{s} \quad (9)$$

$$\text{Air Changes per Hour} = 0,014 \frac{m^3}{s} \cdot 3600s \cdot \frac{1}{249} = 0,202 \quad (10)$$

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 for all other rooms.

These flows are always present regardless of room occupancy.

³ Department of Energy of the United States. DOE has given the major contribution in the development of Energy+ software.

⁴ Directly measured *in situ*.

Ventilation and Schedules

Unlike infiltration, air flow rates due to ventilation are much more complex to evaluate since they depend on occupant's 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 the 'schedules'.

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

In Fig. 10 it can be observed an occupancy schedule. Various fields are present, namely:

- 'Name': the name of the schedule. This will be recalled by other objects;
- 'Schedule type ...': it is the type of values entered in the next fields. It can be set to 'Temperature' (if the schedule is for a thermostat), to Watt, Ampere and so on. In this case the enter values are 'dimensionless' quantities;
- 'Through...': indicates the period in which the next values are related to;
- 'For...': defines the day type. It can be set to weekdays, weekends, all-days holidays etc.
- 'Until...' defines the time of the day which the next values refer to;
- Input parameter.

Field	Units	Obj1
Name		School Occupancy
Schedule Type Limits Name		Fraction
Field 1	varies	Through: 6/20
Field 2	varies	For: Weekdays
Field 3	varies	Until: 07:00
Field 4	varies	0
Field 5	varies	Until: 08:00
Field 6	varies	0
Field 7	varies	Until: 09:00
Field 8	varies	.8
Field 9	varies	Until: 11:00
Field 10	varies	.95
Field 11	varies	Until: 13:00
Field 12	varies	.95
Field 13	varies	Until: 14:00
Field 14	varies	.2
Field 15	varies	Until: 17:00
Field 16	varies	.7
Field 17	varies	Until: 18:00
Field 18	varies	.2
Field 19	varies	Until: 19:00
Field 20	varies	.1
Field 21	varies	Until: 21:00

Figure 10 – Schedule object in Energy+ environment

Hence, considering the explanation above, the schedule in Fig. 10 is described as follow: *'in weekdays from January 1st to June 20th there 0% occupants before 8 am, 80% between 8am and 9am, 95% between 9am and 11am ...'*.

This was the logic adopted for the definition of natural ventilation schedules. The discussion about the choice of the values of Air Changes per Hours due to natural ventilation will be presented later in the dedicated sections 4.2.2, 4.3.2, 4.4.2

3.1.3.3 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. 11). 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.

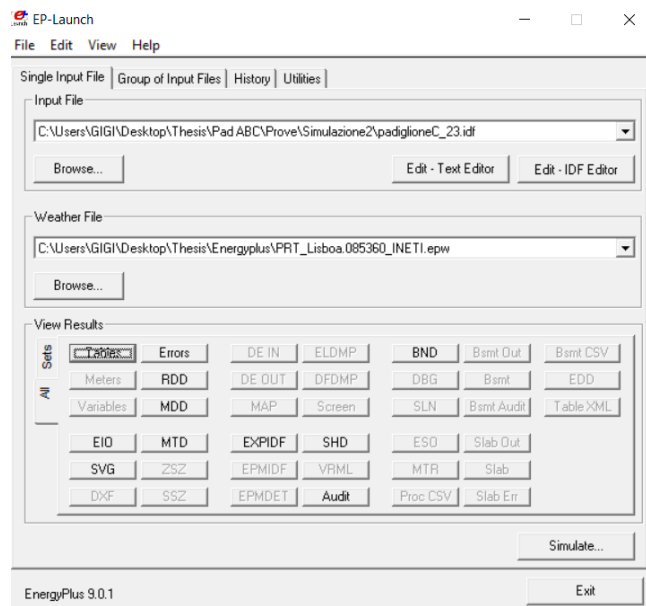


Figure 11 – Energy+ launch menu

3.1.3.4 Internal gains

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

People

The definition of 'people' object is one of the most crucial steps of the analysis for two reasons:

- quantification of internal gains;
- thermal comfort assessment.

In the Energy+ environment it is possible to define the amount out heat that each person dissipates due to the surrounding environment. This quantity depends on several factors such as: metabolic rate and type of activity. Average values are given in Table 3:

Table 3 – Reference values for people activity level [16]

Activity	Activity w/Person EnergyPlus Value	Level Ener- Schedule	Activity W/m2	Level	met*
Seated, quiet	108		60		1
Standing, relaxed	126		70		1.2
<i>Walking (on level surface)</i>					
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
<i>Office Activities</i>					
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 energy is defined in *Activity level schedule name* that appears in *People* object (Fig. 12).

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		30
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	0,0000000382
Enable ASHRAE 55 Comfort Warnings		Yes
Mean Radiant Temperature Calculation Type		ZoneAveraged
Surface Name/Angle Factor List Name		
Work Efficiency Schedule Name		
Clothing Insulation Calculation Method		DynamicClothingMo delASHRAE55
Clothing Insulation Calculation Method Schedule Name		
Clothing Insulation Schedule Name		
Air Velocity Schedule Name		
Thermal Comfort Model 1 Type		AdaptiveASH55

Figure 12 – *People* object in *Energy+* environment

As mentioned, with *people* object is possible to assess thermal comfort conditions choosing among different models⁵. *Energy+* computes the hours in which the environment does not comply with the standard (in this case the standard will be set to ASHRAE 55-2017).

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.

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 13 - *Electric equipment* object in *Energy+* environment.

⁵ The two major thermal comfort models will be discussed in section 4.2

3.2 Thermal comfort assessment

The famous Vitruvius, writer, engineer and architect of the Roman era, argued that the pursuit of thermal comfort had given birth to the science of architecture [6]. 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 as 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 two section, the reader will be provided with the description of the two most widely used models: Predicted Mean Vote and Adaptive.

3.2.1 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 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. 14.

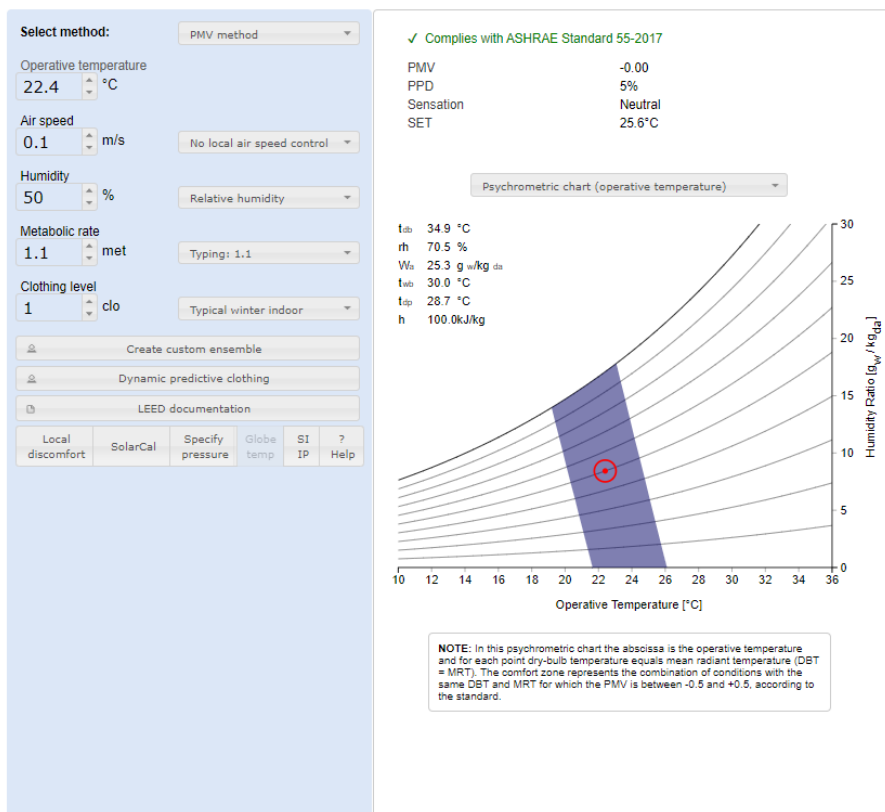


Figure 14 - CBE thermal comfort tool displaying PMV model [19].

According to the ISO 7730, the optimal range to be guaranteed is $-0,5 < PMV < +0,5$

Nevertheless, since various authors [7] assess 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. 14 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.

For these reasons, scientists Richard de Dear and Gail Brager developed in 1998 the Adaptive Model of Thermal Comfort and Preference [8]

3.2.2 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 higher tolerance than the people who do not. This happens also for a natural self-thermoregulation of the human body that tend 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 has to share a space whose conditions approaches to thermal discomfort. To deal with that, they first response is to adopt one or more strategies. In naturally ventilated buildings is common to adjust the windows [9] and 'those occupants who take these sorts of actions tend to feel cooler at warmer temperatures than those who do not' [10]

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' [8].

A visual example of thermal comfort tool [11] set to adaptive method is provided in Fig. 5.

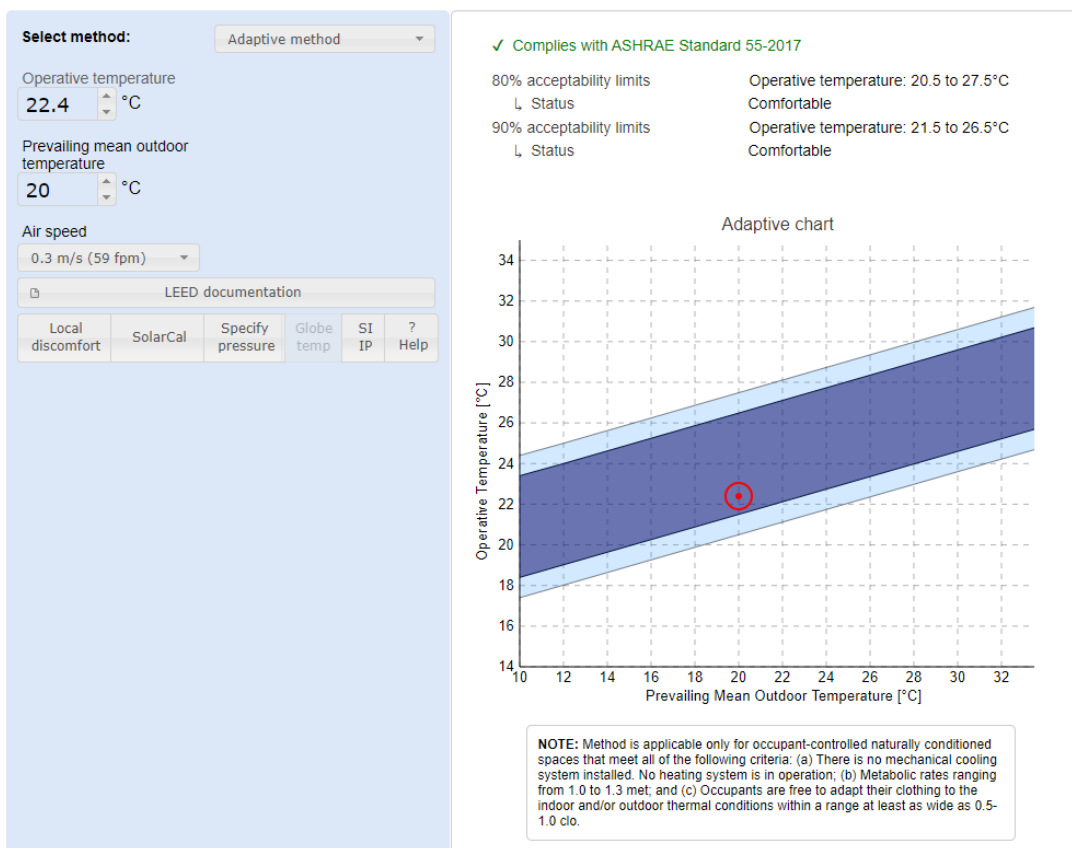


Figure 15 – CBE thermal comfort tool displaying *Adaptive* model [19].

As far as the present study is concerned, the Adaptive model regulated by ASHRAE-55 standards will be adopted to assess thermal comfort conditions. This will be done using the *people object* in the Energy+ environment (Fig. 16). With these settings the software will compute for each thermal zones of the model, the number of hours in which conditions are outside acceptability limits of 90% (dark-blue area of the graph in Fig. 15) and 80% (light-blue area in Fig. 15).

Field	Units	Obj1
Name		People kitchen
Zone or ZoneList Name		Thermal Zone: COZ
Number of People Schedule Name		School Occupancy
Number of People Calculation Method		People
Number of People		30
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	0,000000382
Enable ASHRAE 55 Comfort Warnings		Yes
Mean Radiant Temperature Calculation Type		ZoneAveraged
Surface Name/Angle Factor List Name		
Work Efficiency Schedule Name		
Clothing Insulation Calculation Method		DynamicClothingModelASHRAE55
Clothing Insulation Calculation Method Schedule Name		
Clothing Insulation Schedule Name		
Air Velocity Schedule Name		
Thermal Comfort Model 1 Type		AdaptiveASH55

Figure 16 – Selection of thermal comfort Obj model in *people* object of *Energy+* environment.

4 Case study: Escola Conde de Oeiras

Built in 1982, Conde de Oeiras is a primary 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.

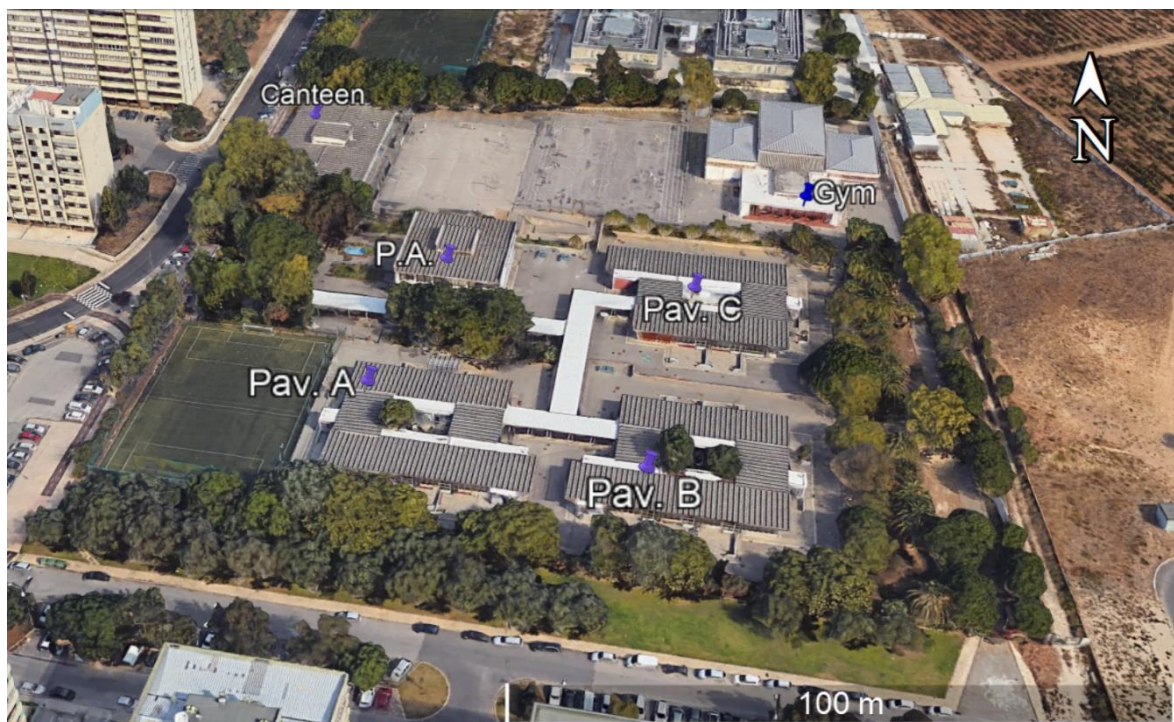


Figure 17 - Escola Conde de Oeiras view 1. Source: Google Earth Pro; year: 2018.

The 11-a side football pitch and playground in front of the gym are also included 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 4, school can be considered medium-sized according to the Portuguese average [4].

Table 4 - 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

4.1 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 affects negatively various factors such as 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 [11].

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 [11].

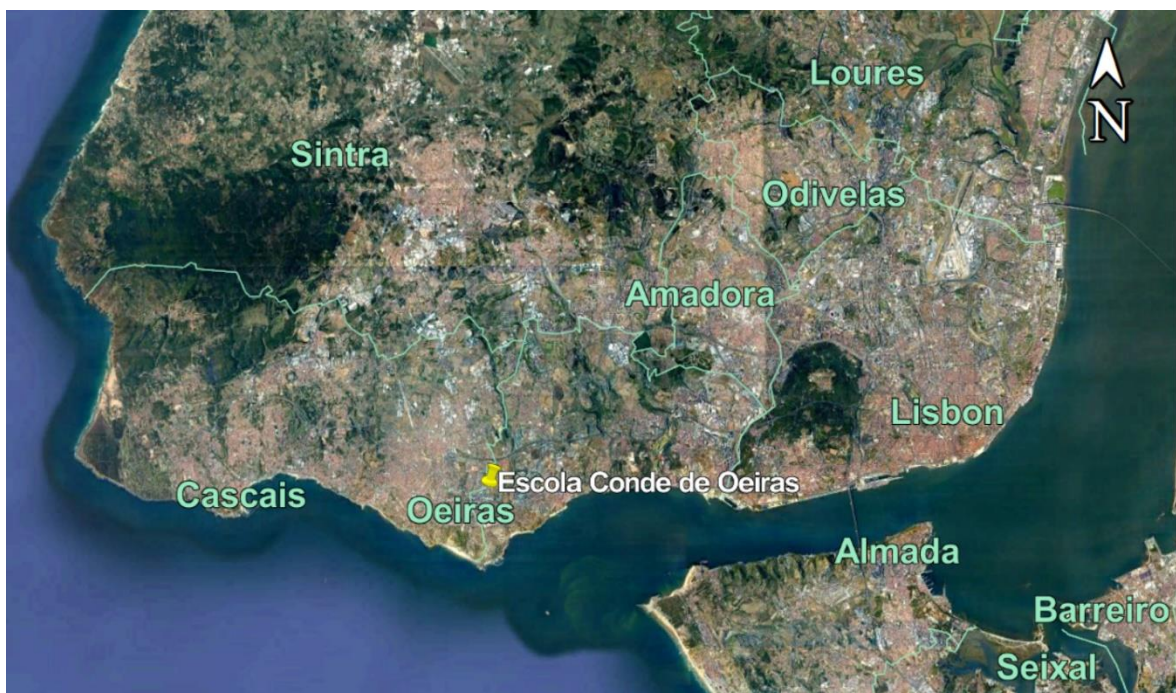


Figure 18 - *Escola Conde de Oeiras* view 2. Source: Google Earth Pro; year: 2018

4.2 Pavilions with classrooms

Pavilions A, B and C share the same constructions and are almost identical and for this reason they are presented together in this paragraph. The only difference between the pavilions is essentially 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 19 – *Pavilion C* view. Source: Google Earth Pro; year: 2018.

As can be noted in the Sketchup model of Fig. 21 and in the real view of the north façade of Fig. 20, the main feature of these buildings is a large overall window/wall ratio (44,5 %).



Figure 20 – *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 fixtures and glasses have remained the same since 1982. 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. 6) 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 m² 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. 21 it is provided a view of pavilion C in which are indicated all the thermal zones.

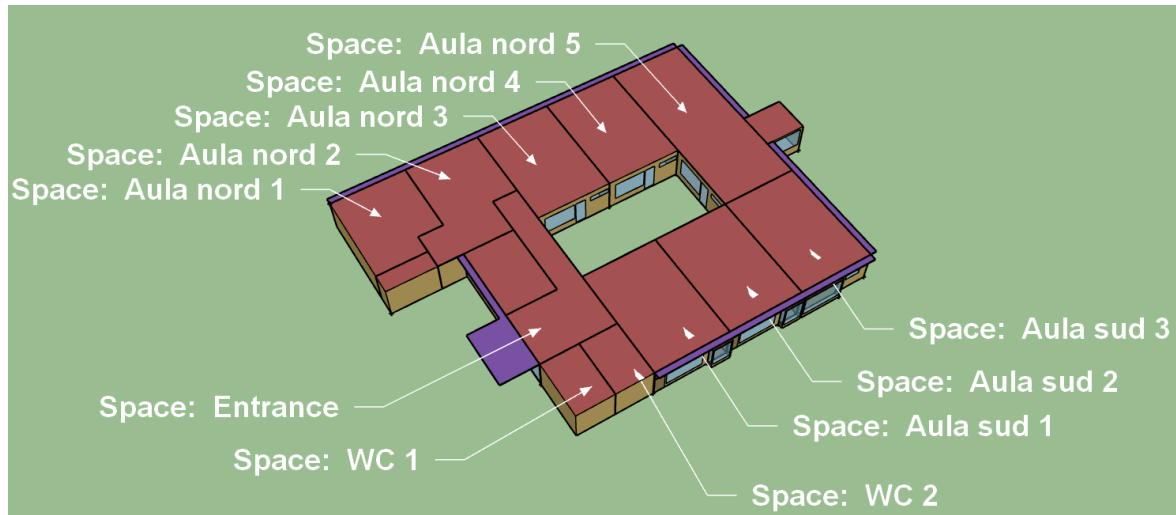


Figure 21 – Virtual view of *pavilion C*.

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

4.2.1 People occupancy

People occupancy in Pavilions A, B, C varies according to school timetable⁶. Despite not having classes, in the noon some children spend time in the classrooms doing homework or various extracurricular activities. Figure 22 represents a design day occupancy profile valid for a standard weekday. This building is not used during July, August and holidays.

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.

4.2.2 Ventilation schedules

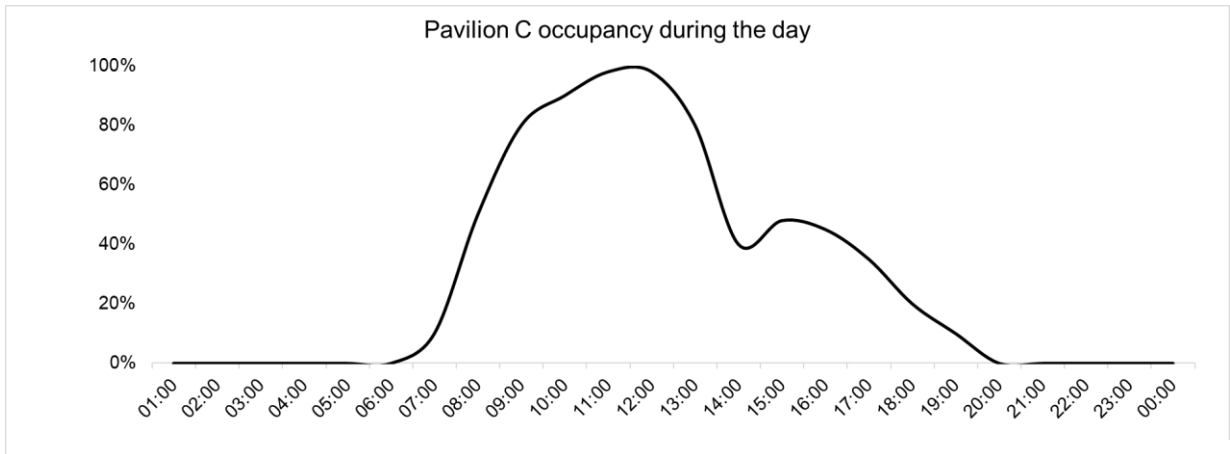


Figure 22 - pavilion C daily occupancy. Source: Escola Conde de Oeiras.

To compute the minimum Air Changes per Hour (ACH) to be guaranteed in each classrooms of the pavilion C, standard values from ISO EN 16798-2 were adopted.

For adapted⁷ people 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 index of 15%. Hence, the following value were calculated for pavilion C.

	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 input to fill properly the *ventilation schedule* object, values in table 5 were adjusted according to people occupancy and seasonality as follows:

$$ACH = ACH_{min} \cdot \frac{occupants}{max\ n^{\circ}\ of\ occupants} \cdot C \quad where \quad \begin{cases} C = 1 \text{ for winter} \\ C = 2 \text{ for summer} \end{cases} \quad (11)$$

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

⁶ Classes form 8am to 1pm and afternoon recreational/homework activities

⁷ People who use to live in the same environment or climate area for long periods of time.

4.2.3 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:

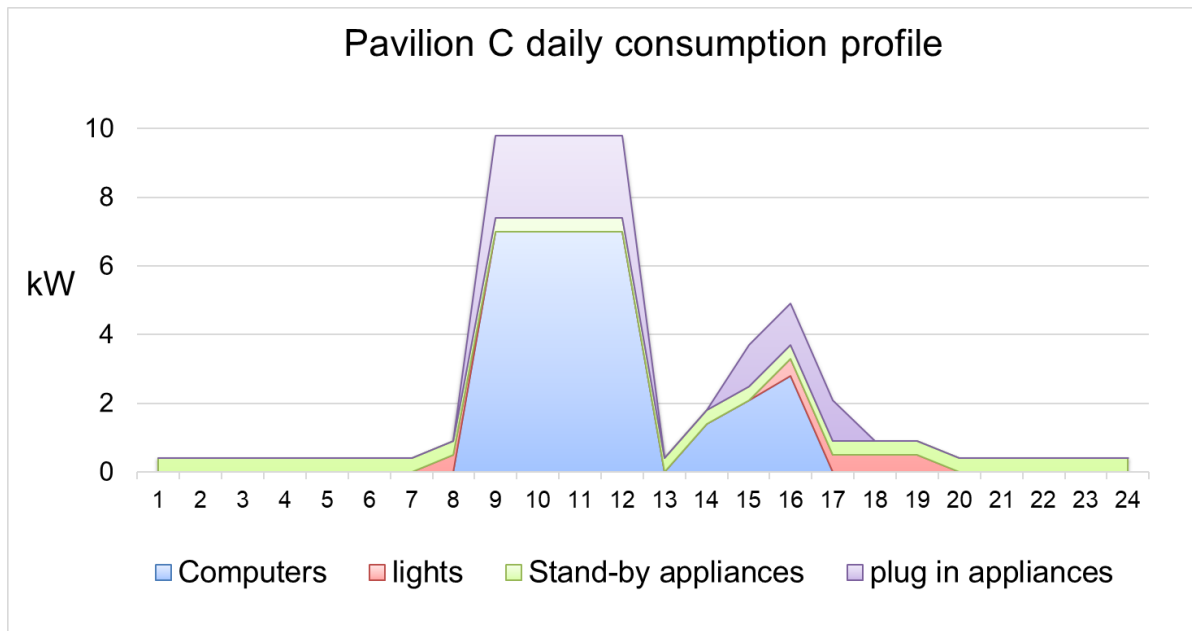


Figure 23 - Pavilion C daily electricity consumption profile.

Table 6 - Pavilion C Specific Energy Consumption report.

Pav. C SEC report	
Gross Floor Area [m ²]	825
Estimated annual electricity consumption [kWh]	14304
SECelectricity [kWh/m ² /year]	17.3

4.3 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 for the students on the second floor.



Figure 24 - *Administrative pavilion* view. Source: Google Earth Pro; year: 2018.

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



Figure 25 – *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 two measures, the interventions on the building focused mainly on routine maintenance and eventual repairs in case of failure.

Spaces arrangement

The building presents eight⁸ main types of spaces which each of them identifying a thermal zone, according to table 7.

Table 7 - Space functions and names of the main thermal zones in *administrative pavilion*.

Space function	Thermal zones in the virtual geometry
administrative 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.

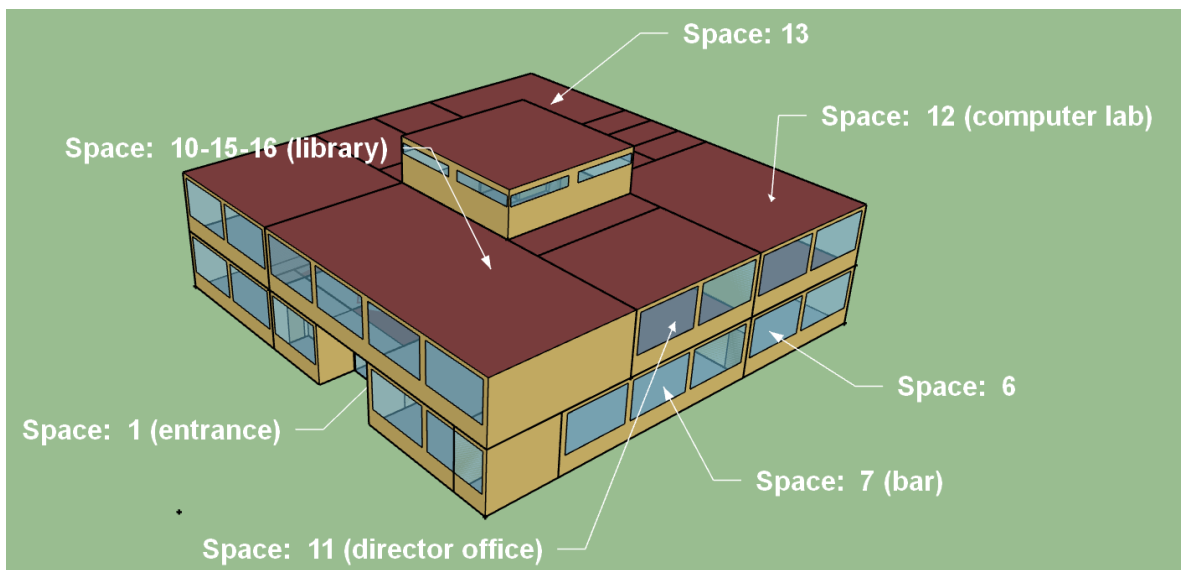


Figure 26 - Virtual view of south and east façade of *Administrative pavilions*

⁸ 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.

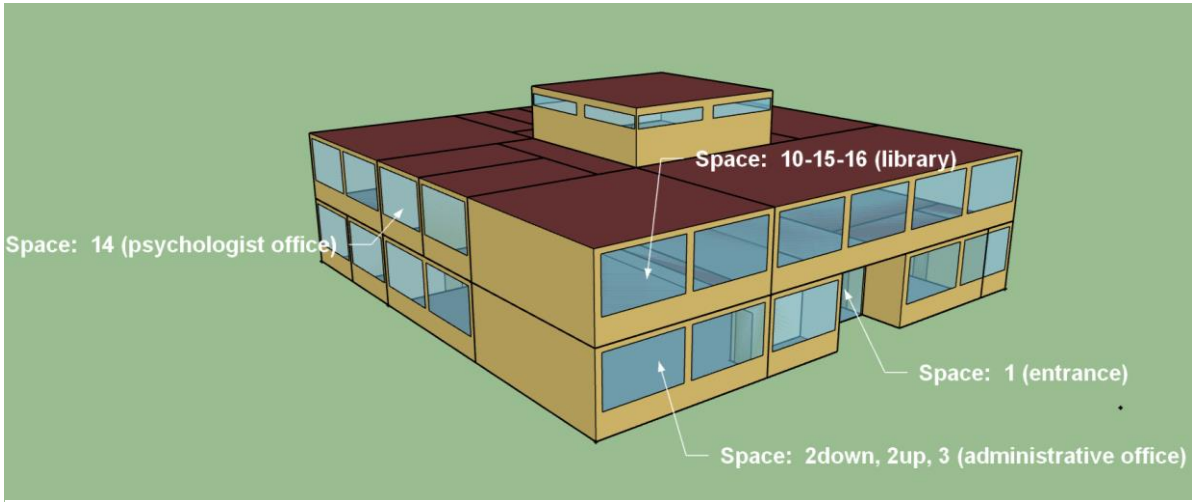


Figure 27 - Virtual view of west and south façade of *Administrative pavilion*.

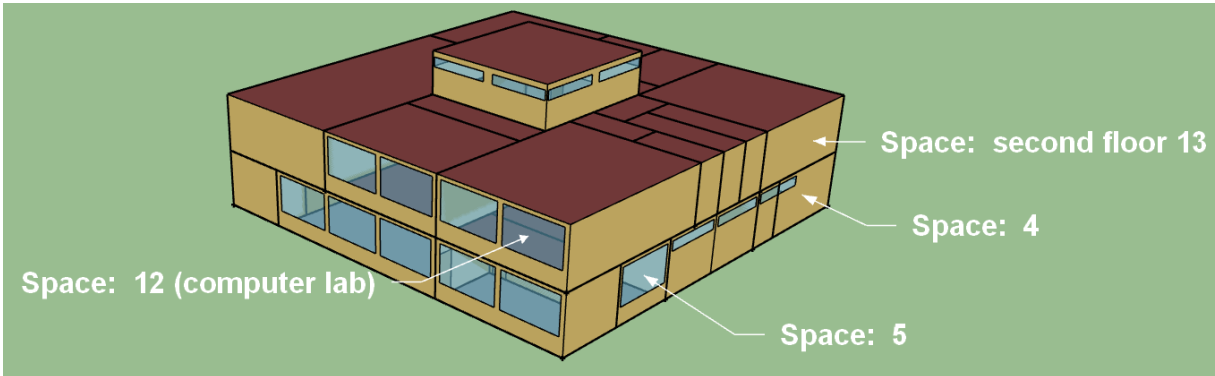


Figure 28 - Virtual view of east and north façade of *Administrative pavilion*.

4.3.1 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 break. However, since children use to attend library and other spaces within this facility, people density does not vary significantly during the day. 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. 29.

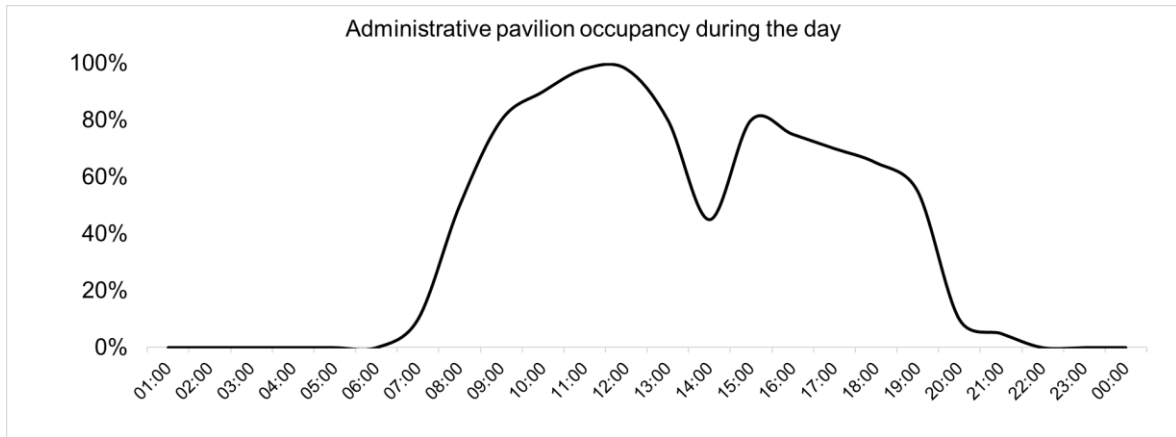


Figure 29 – Administrative pavilion daily occupancy. Source: Escola Conde de Oeiras.

4.3.2 Ventilation schedules

The procedure adopted to compute the minimum ACH values was the same adopted for pavilion C. Results of calculations are provided in tables 8 and 9.

Table 9 - 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 8 - Minimum values of Air Changes per Hour to be guaranteed in 2st 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

4.3.3 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 basis⁹. The daily electricity consumption profile and the annual data SEC report are presented below:

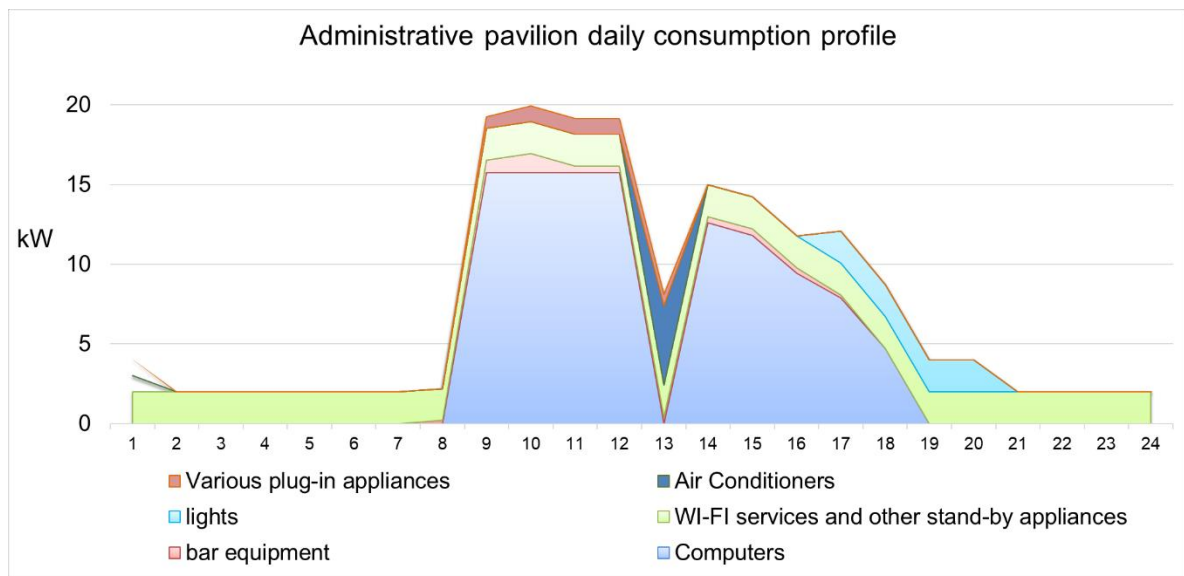


Figure 30 - Administrative pavilion daily electricity consumption profile.

Table 10 - Administrative pavilion Specific Energy Consumption report.

Admin. pav. SEC report

Gross Floor Area [m ²]	978
Estimated annual electricity consumption [kWh/year]	43100
SECElectricity [kWh/m ² /year]	44.07

⁹ 300 kWh per year → 1,25 kWh per day; considering 240 working days per year

4.4 Canteen

The canteen presents a plant symmetrical with respect to line passing through the midpoint of its long side (Fig. 31). It has two main entrances one from north and one from south and a total area of 829 m². Kitchen stands in the exact centre of building.

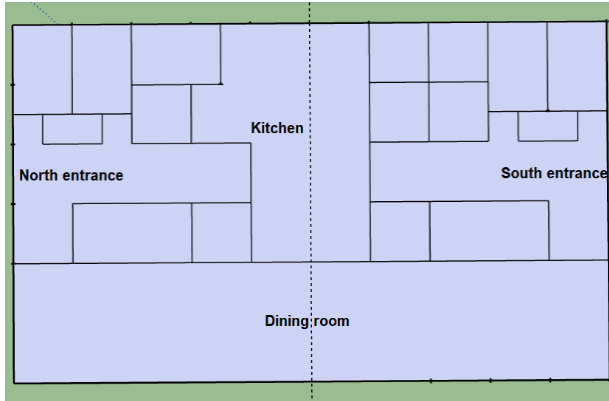


Figure 31 – Virtual plant view of *Canteen*.

As it can be noticed in Fig. 32, the building receives a good 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 32 – *Canteen* view. Source: Google Earth Pro; year: 2018.

Indeed, 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 from 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. 33 is shown a view of the canteen building with the names of the most relevant thermal zones.

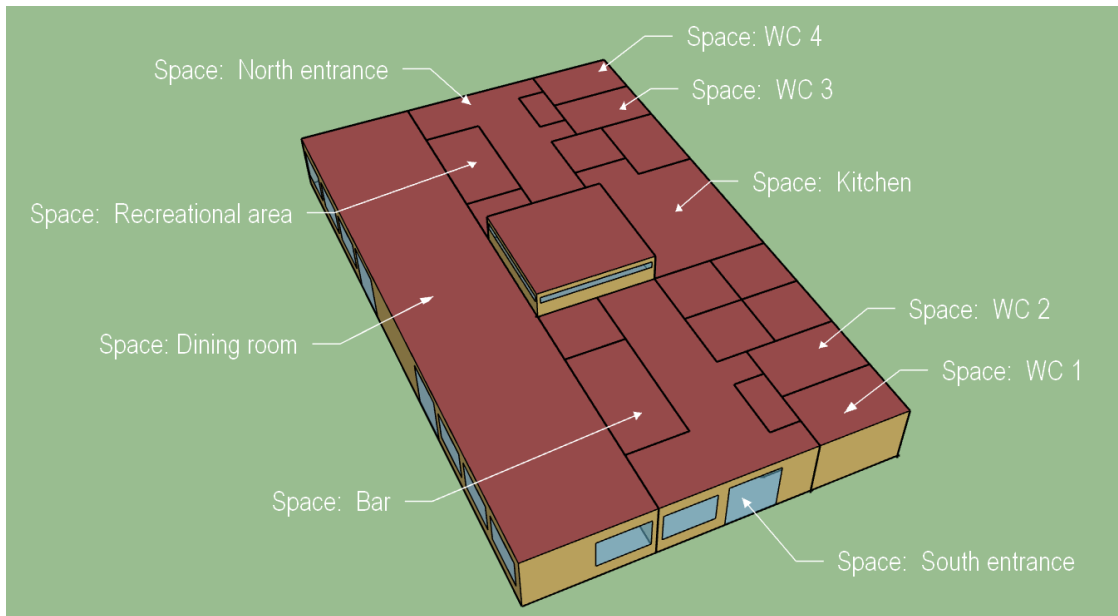


Figure 33 - Virtual view of the *Canteen*.

4.4.1 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 below, presence of people in the building is estimated in 2180 hours per year.

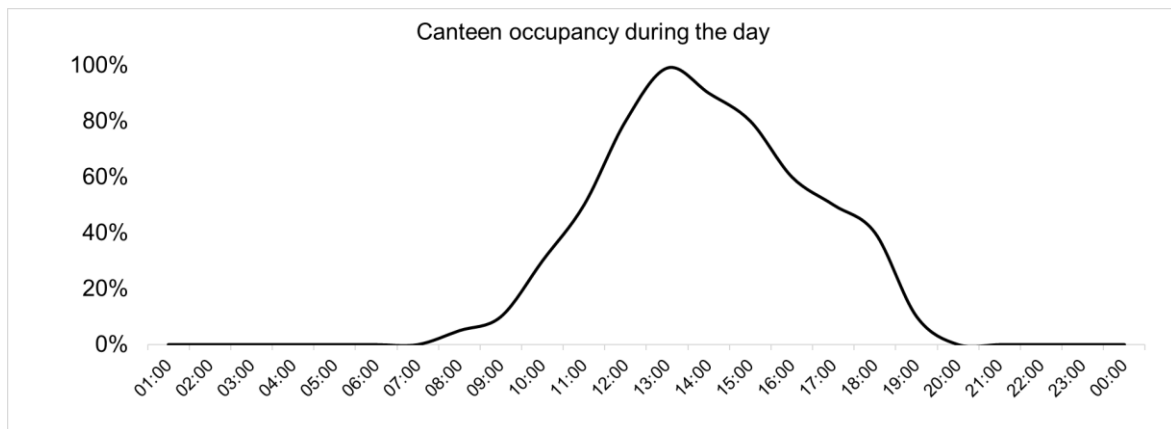


Figure 34 - *Canteen* daily occupancy.

4.4.2 Ventilation schedules

The procedure adopted to compute the minimum ACH values was the same adopted for pavilion C. Results of calculations are provided in tables 11.

Table 11 -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

4.4.3 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 m³ 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:

$$P_{max,gas\ equip.} = \frac{46,8 \frac{kWh}{day}}{3 \frac{h}{day}} = 15,6 kW \quad (12)$$

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 equipment¹⁰ introduced in the *Energy+* model as well as daily consumption profile are presented below.

Table 12 – 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

¹⁰ 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.

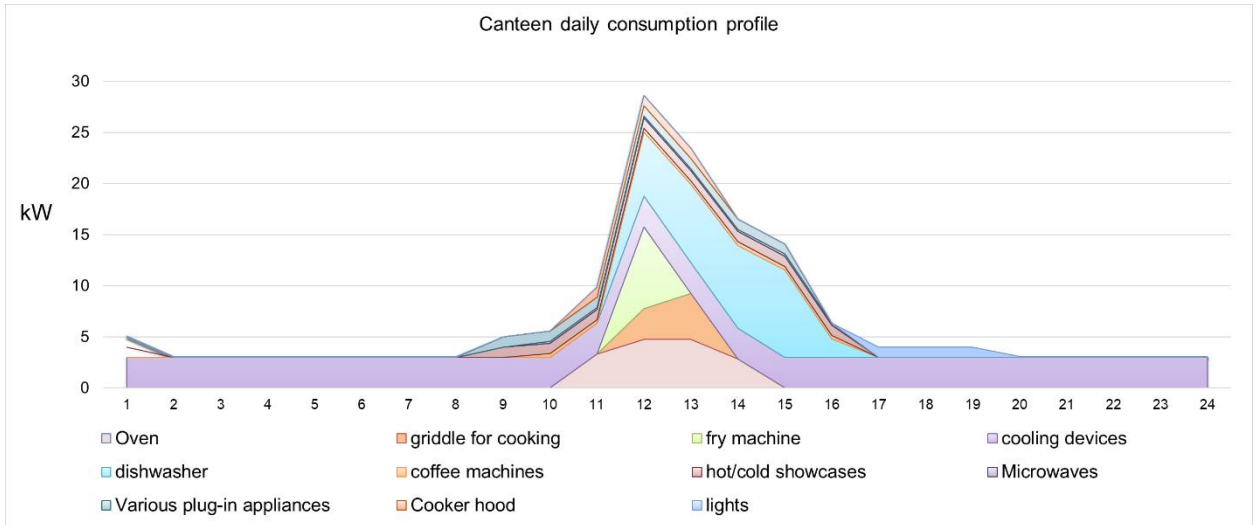


Figure 35 - *Canteen* daily electricity consumption.

Annual data on Specific Energy Consumption are summarised in table 13.

Table 13 - *Canteen* Specific Energy Consumption report.

<i>Canteen SEC report</i>	
Gross floor area [m ²]	829
Estimated annual consumption [kWh/year]	36460
SECElectricity [kWh/m ² /year]	43.98

4.5 Energy data analysis

It is intended to clarify, that all the pieces of information presented so far were obtained through estimates based on the inventory equipment specifications.

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 consulting this type of data does not make possible the distinction between energy use of the singular. Nevertheless, it may be useful to become acquainted with real data and to compare *Escola Conde de Oeiras* with the Portuguese school's average discussed in chapter 2. For this purpose, table 14 was outlined.

Table 14 – Specific Energy Consumption comparison.

	Escola Conde		Reference(***)
	2017	2016	2008
Year	2017	2016	2008
Electricity billed consumption [kWh]	155250	160998	/
SECElectricity [kWh/m ² /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 3, 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 will expose the results of the thermal simulations of the virtual buildings which are part of *Escola Conde* complex.

4.5.1 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 .36, 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.

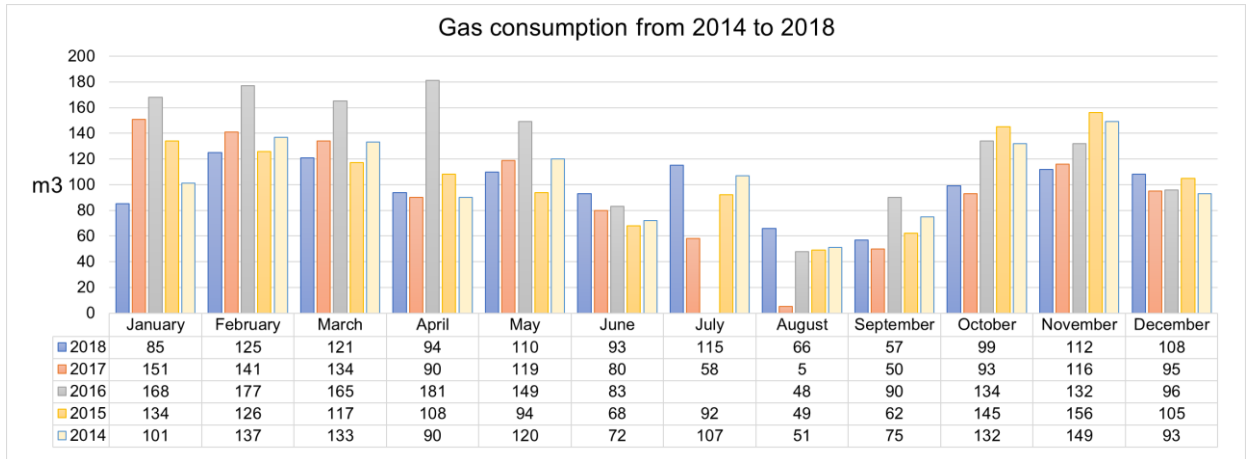


Figure 36 - Gas consumption from 2014 to 2018

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):

$$y \text{ kWh} = x \text{ m}^3 \cdot FCV \cdot PCS \quad (13)$$

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

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 16).

Gas SEC report

Year	2018	2017	2016
Gas price, vat excluded [€/m ³]	7.39	7.56	8.47
Gas billed consumption [kWh]	13530	12925	16247
SEC(gas+electricity) [kWh/m ² /year]	30.84	30.73	32.39

Table 15 - Specific Energy Consumption report including gas use.

	€/GJ	€/kWh	€/m ³
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

Table 16 – Portuguese gas tariffs [22].

4.5.2 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. 37.

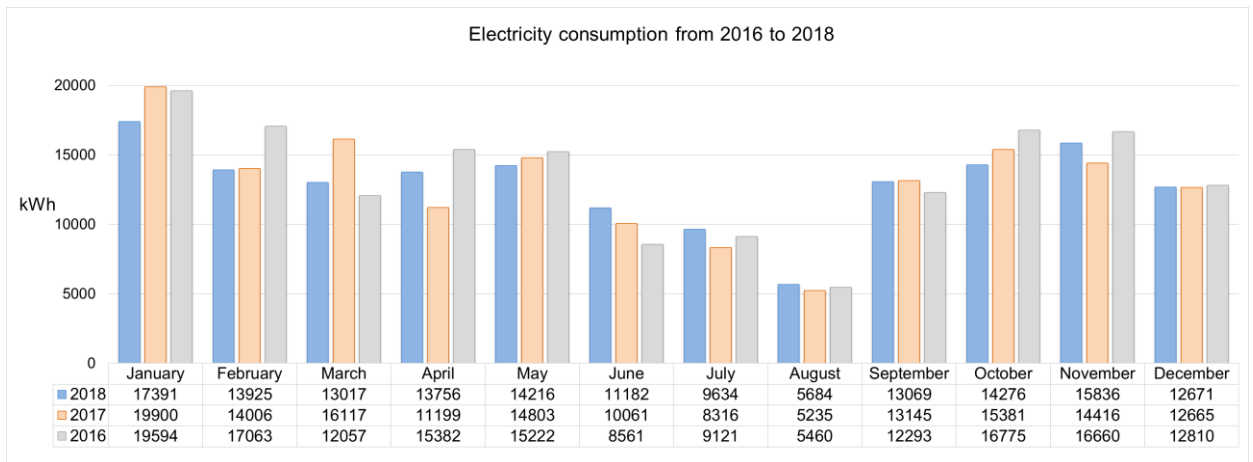


Figure 37 - Electricity consumption from 2016 to 2018.

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. 39 shows the tariff distribution in 2018 and the prices of each slot.

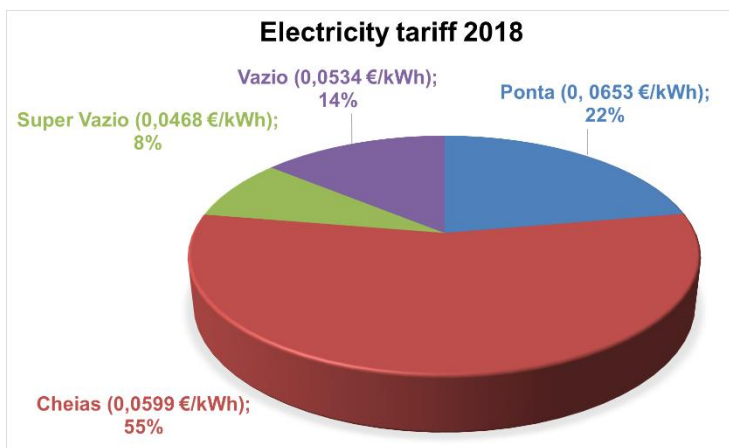


Figure 38 - Electricity tariff of 2018.

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.

5 Simulations of the virtual buildings in their actual conditions

At this point all the parameters of the energy analysis have been set and 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 6.

5.1 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 percentages¹¹ 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, the spaces (small rooms, bathrooms, closet etc.) that do not meet this requirement were not considered in the analysis.

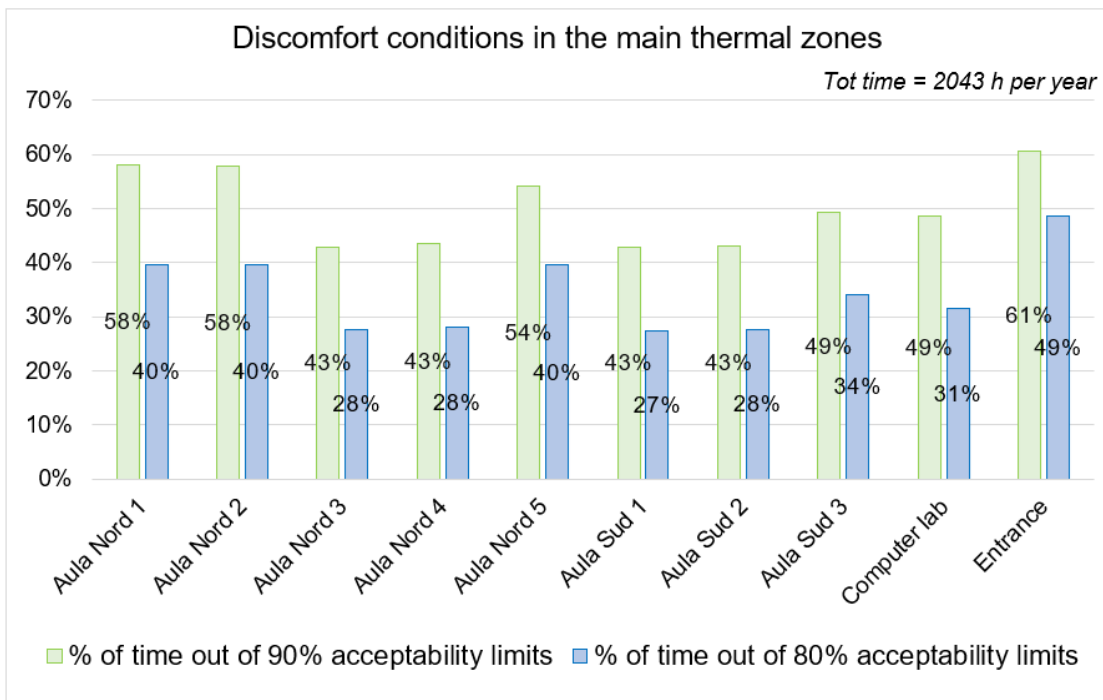


Figure 39 - Thermal discomfort condition in the main thermal zones of *Pavilion C*, before roof replacement (Scenario A).

¹¹ The acceptability limits are coherent with discussion provided in section 4.2.2.

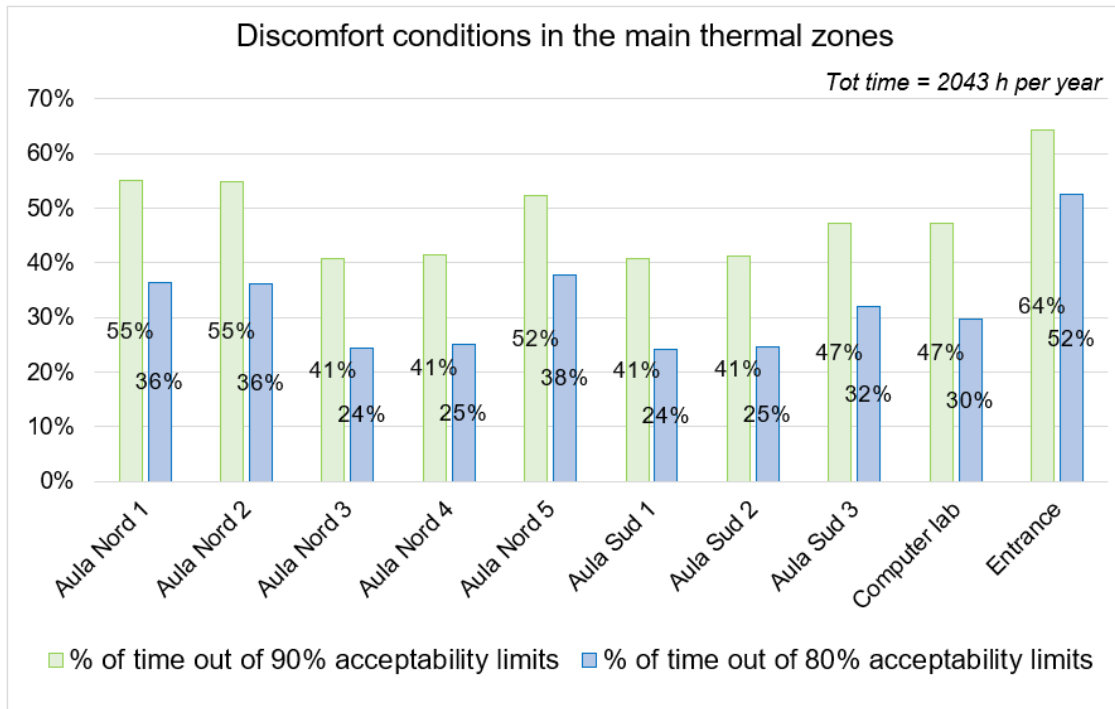


Figure 40, Thermal discomfort condition in the main thermal zones of *Pavilion C*, after roof replacement (Scenario B).

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 which results are shown in Fig. 40 situation slightly improved with an overall -3% of discomfort time for all the classrooms.

However, these percentages do not comply with ASHRAE-55 standards that requires no more than 4% of discomfort time.

Yearly thermal balance analysis

Causes of discomfort might be different, in particular the most are recurrent are: exceedingly cold/hot environment and poor air quality. Since it has been assumed for all the spaces that in any time is always guaranteed the minimum air renovation rate, causes of discomfort should converge to the lack of control on temperature within the thermal zone.

In Tables 17 and 18 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.

Table 17 – 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

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 18 - 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 addition* is justified with an high occupants density of the classrooms (on average 3 m²/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 addition/removal*' indicates the effect of conduction (through walls, roof and ground) mechanisms in the thermal balance. As shown in Tables 17 and 18, 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.

5.2 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. 41 and 42 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

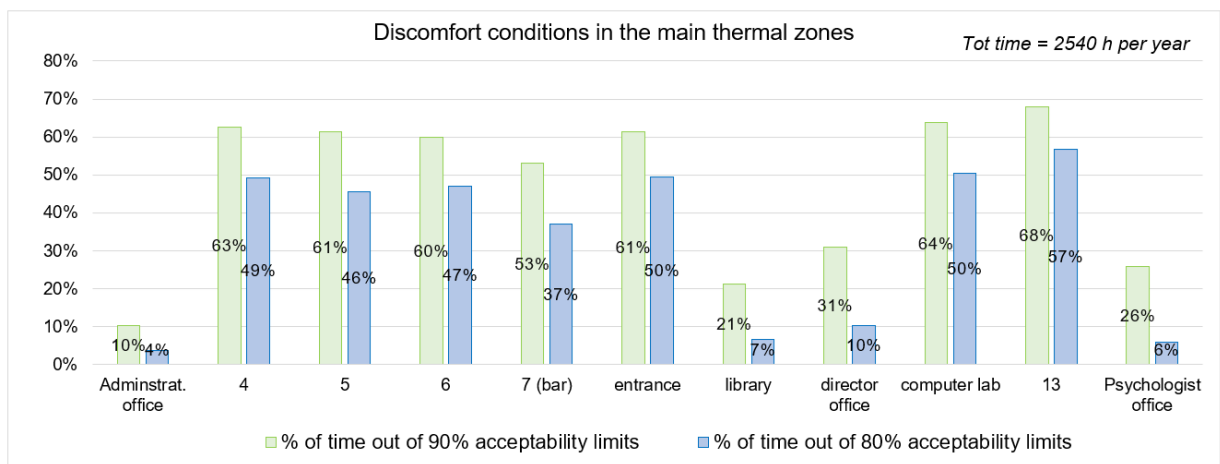


Figure 41 - Thermal discomfort condition in the main thermal zones of *Administrative pavilion*, before roof replacement (Scenario A).

for those on 2nd floor. However, hours of discomfort still represent the majority of time for not conditioned room. Regarding the zones provided with HVAC systems, the percentages are still higher than the threshold value of 4% indicated by AHRAE-55 standards

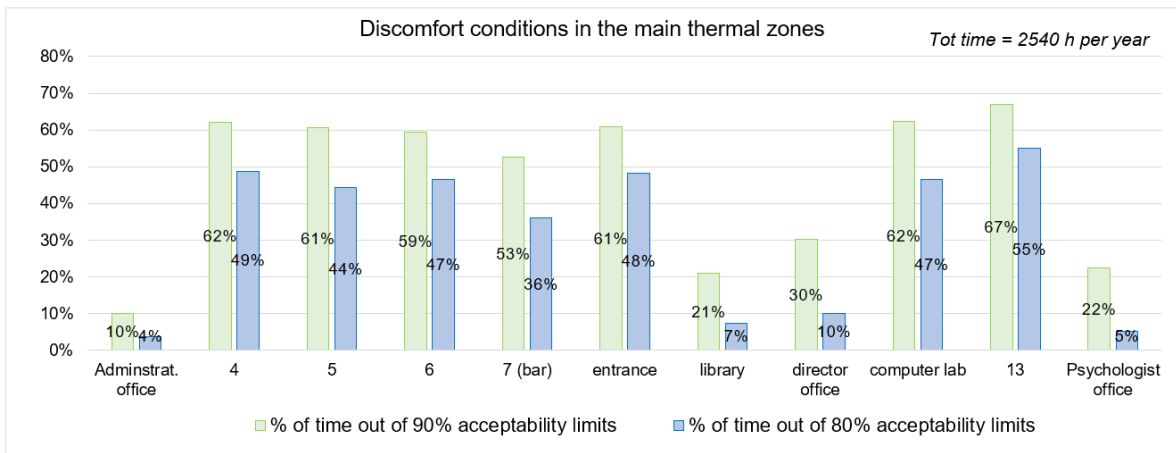


Figure 42 - Thermal discomfort condition in the main thermal zones of *Administrative pavilion*, after roof replacement (Scenario B).

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 19 - 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 20 - 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 addition 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.

5.3 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. 43 are shown once again the thermal zones in which presence of people is guaranteed at least for 2180 h per year.

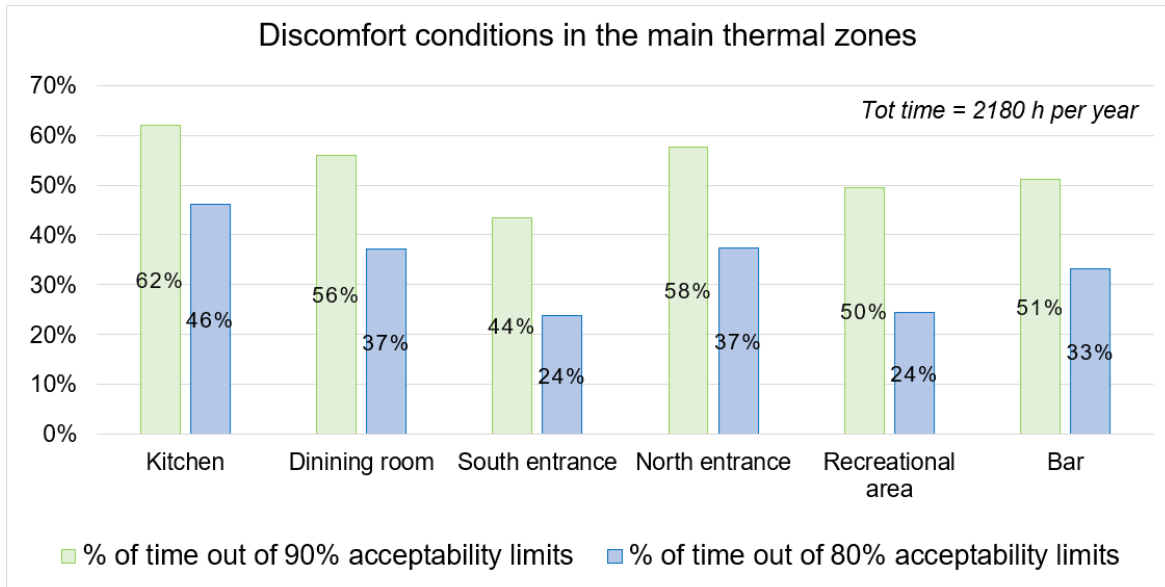


Figure 43 - Thermal discomfort condition in the main thermal zones of *Canteen*.

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 21 - 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

6 Promotion of energy efficiency measures

In the previous chapter were acknowledged the factors which affects thermal balance more significantly, namely: *window heat addition/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.

In the following sections will analysed costs and benefits that each of the above measures would imply in order to identify 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.

6.1 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 Table 23 are listed the principal alternatives for frames and glasses with the related typical transmittances values provided by ISO 10077.

Table 23 - Standard values for frame transmittance.

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

Table 22 - Standard values for glass transmittance.

Glass	U _g [W/m ² /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 glazing. This was done for two main reasons:

- for large windows (as the ones of the case study), builders and designers do not suggest PVC material due to his low yield strength. Wood is much more expensive than others material and is commonly use 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' [12]. 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' [12]. 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 24 are provided the products data sheets.

Table 24 – Data sheets for the three possible glass alternatives.

Source: Pilkington catalogue; technical data assessed according to EN 410 and EN 673
 Price per m² includes the two-glass surface and the argon fill. Argon fill cost estimated in 16 €/m²

	<i>Standard clear</i>	<i>Low-e</i>	<i>Selective low-e</i>
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. 44) in the Energy+ environment.

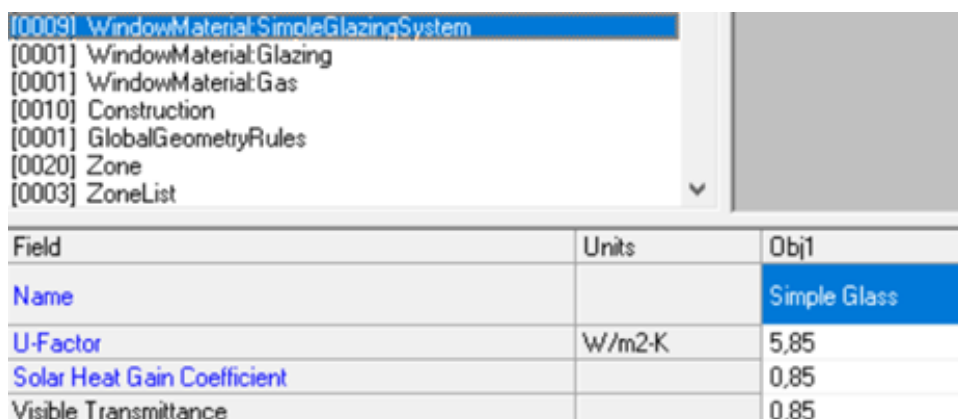


Figure 44 - *Simple Glazing System* object in Energy+ environment.

6.1.1 Glass 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. 45) are shown three¹² 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.

¹² 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 addition* etc).

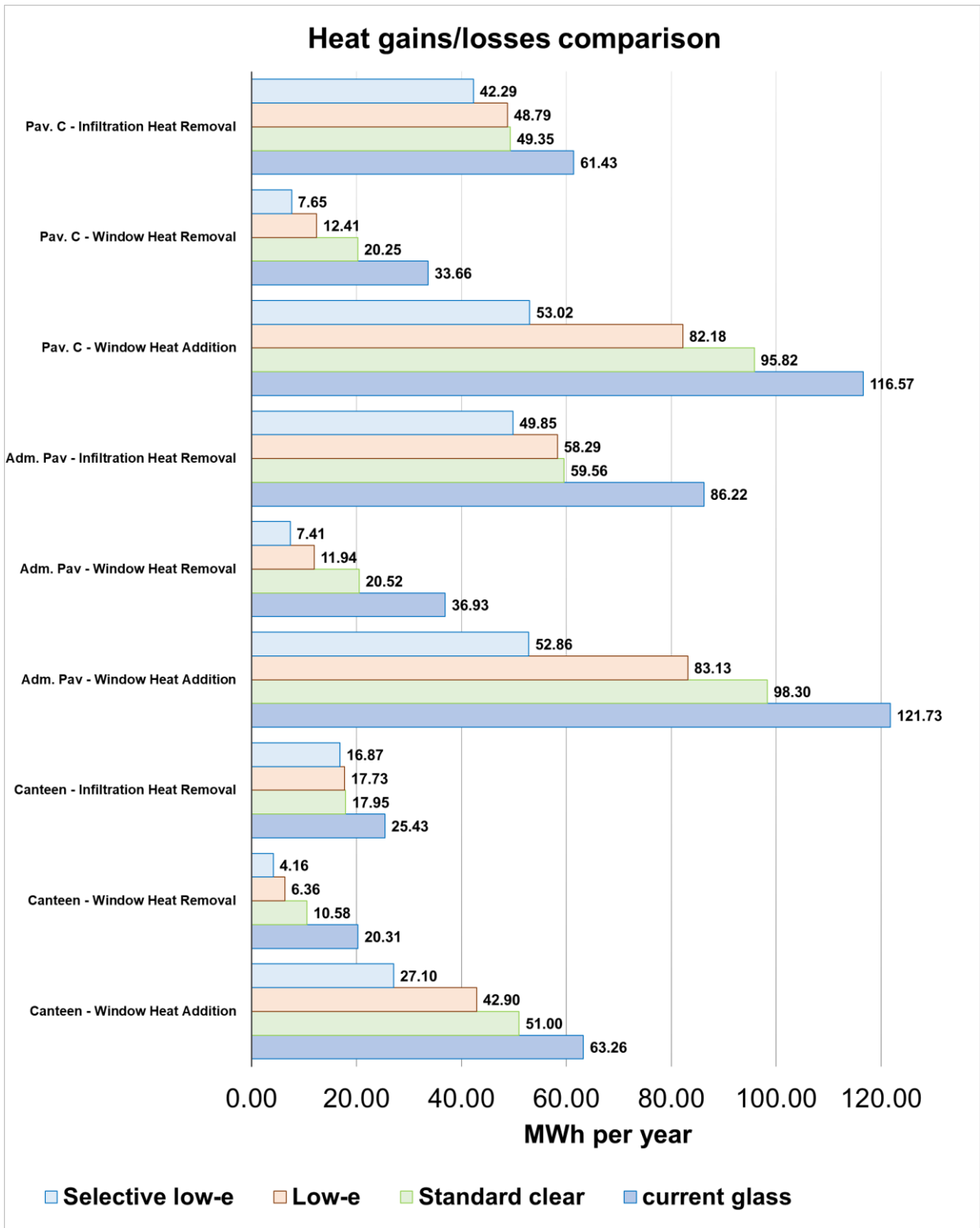


Figure 45 – Heat gains/losses comparison for the examined double-glazing systems

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).

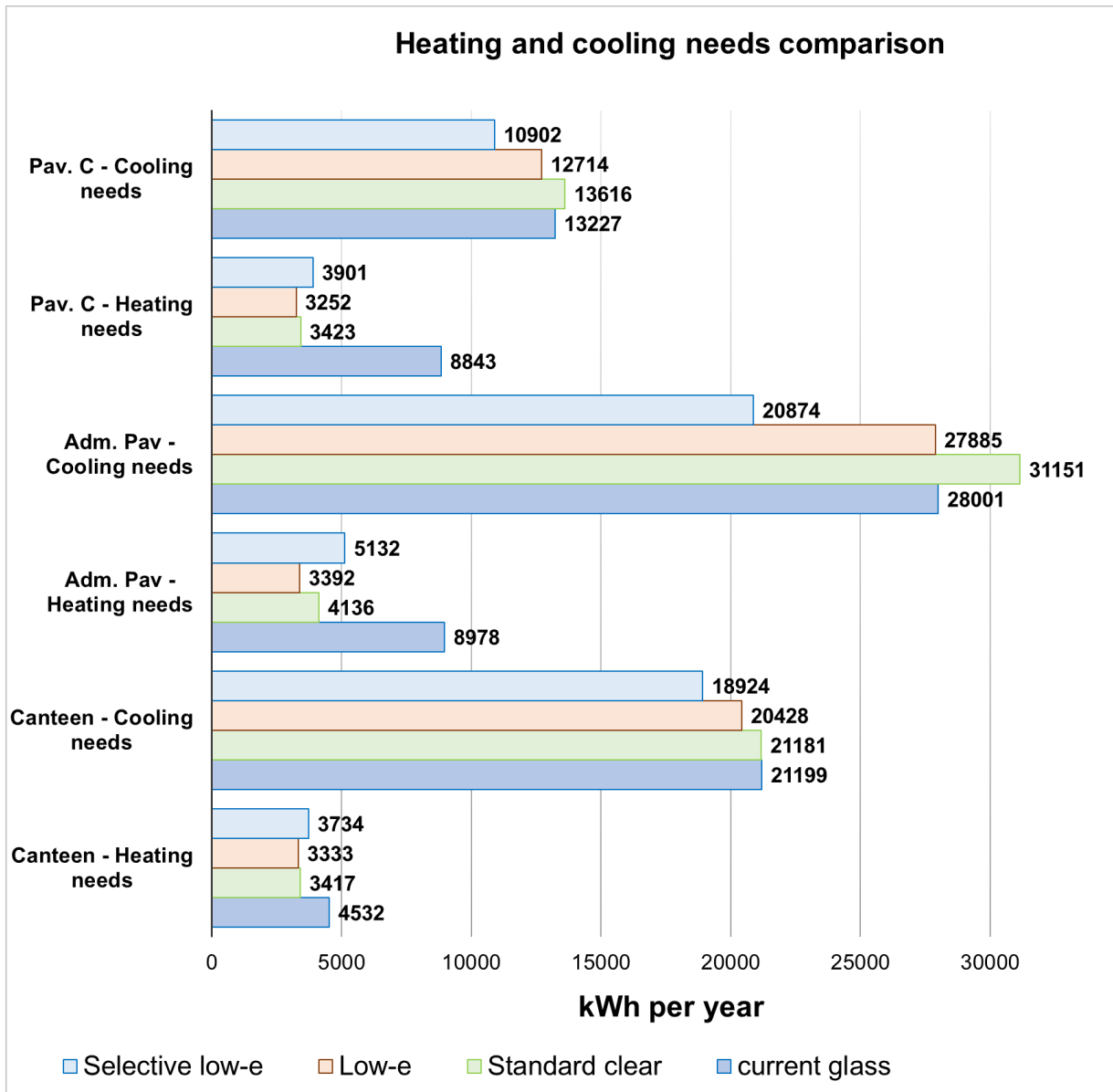


Figure 46 – Heating and cooling needs comparison for the examined double-glazing systems.

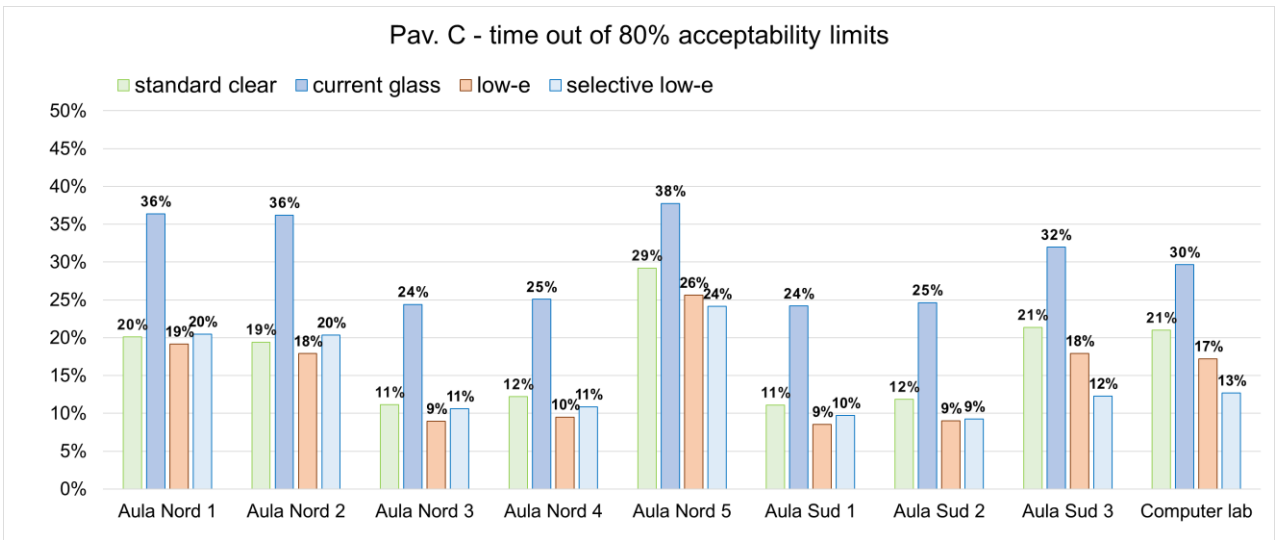


Figure 47 - Thermal discomfort condition in *Pav. C* thermal zones for the examined double-glazing systems.

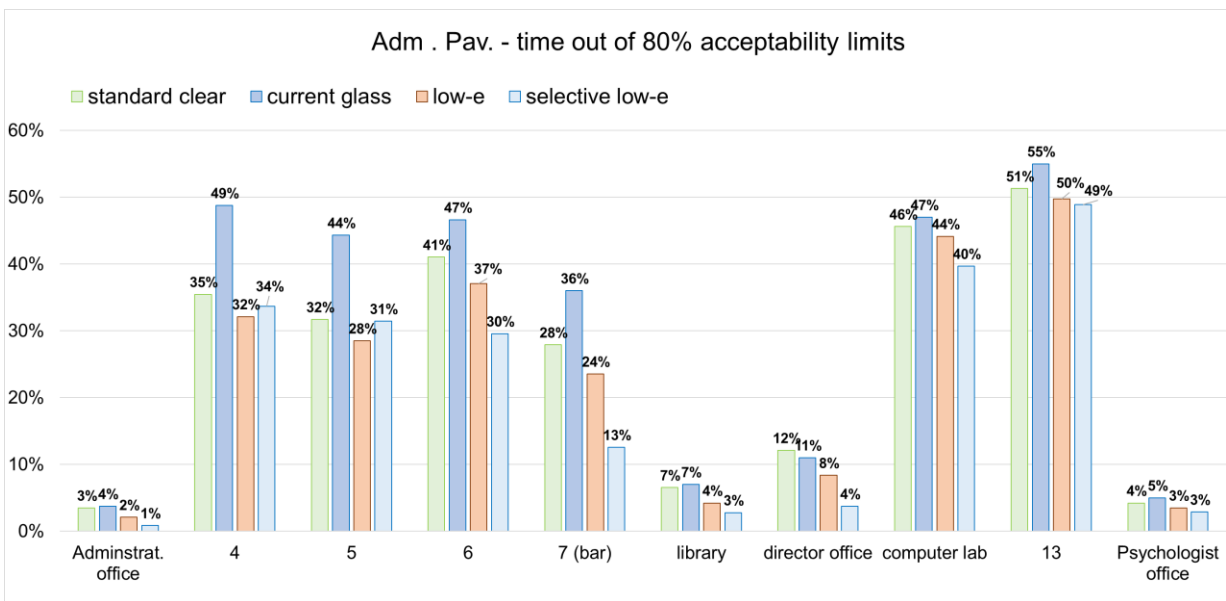


Figure 48 – Thermal discomfort condition in *Adm. pav.* th. zones for the examined double-glazing systems.

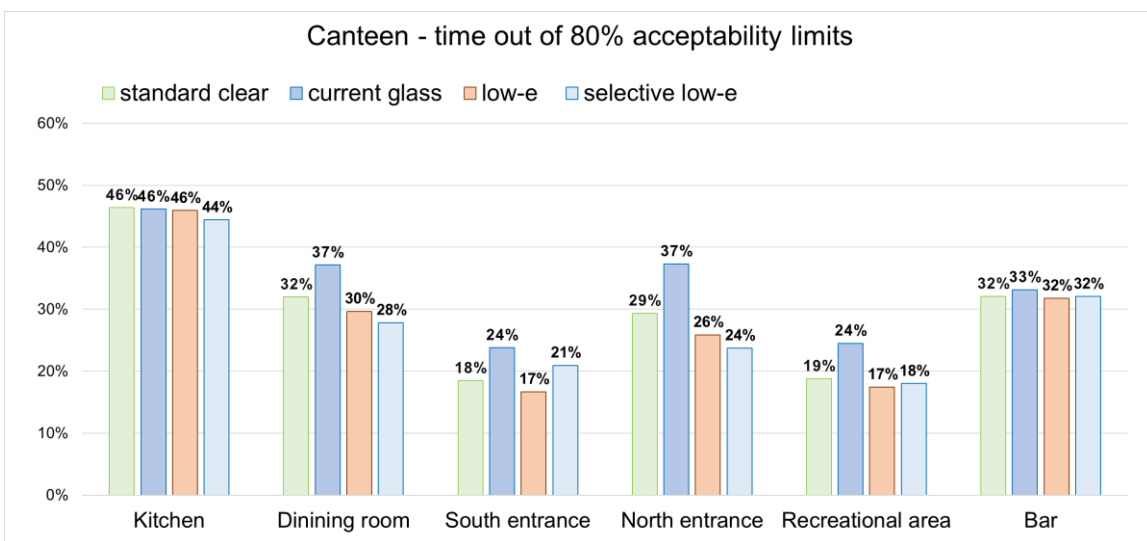


Figure 49 - Thermal discomfort condition in *Canteen.* th. zones for the examined double-glazing

6.1.2 Project evaluation

As regards for the energetic performance, heating and cooling needs savings 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, 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 [13]
- Natural gas price: 0,079 €/kWh [14];
- Interest rate: 5%¹³;
- 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% [14] 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 €/m² [15];
- Glass price: see Table 24;
- Installation cost: 90 €/window [15];
- Glass surfaces and n° of windows:

Table 25 - 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

¹³ Typical value for low risk investment that are not subjected to market fluctuations.

Table 26 – 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 investement (-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 27 - 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 28 - 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 investement (-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

6.1.3 Results discussion

Outcomes of thermal simulations raise several observations. 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 even though for *administrative pavilion* only. 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 expenditure of more 220.000 euro because of large glass area. Nonetheless, these facilities could obtain very large benefits in terms of thermal comfort as illustrated in Fig. 48 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.

6.2 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 polystyrene¹⁴ (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.

¹⁴ Thermophysical properties available in Appendix A

6.2.1 Performance comparison

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

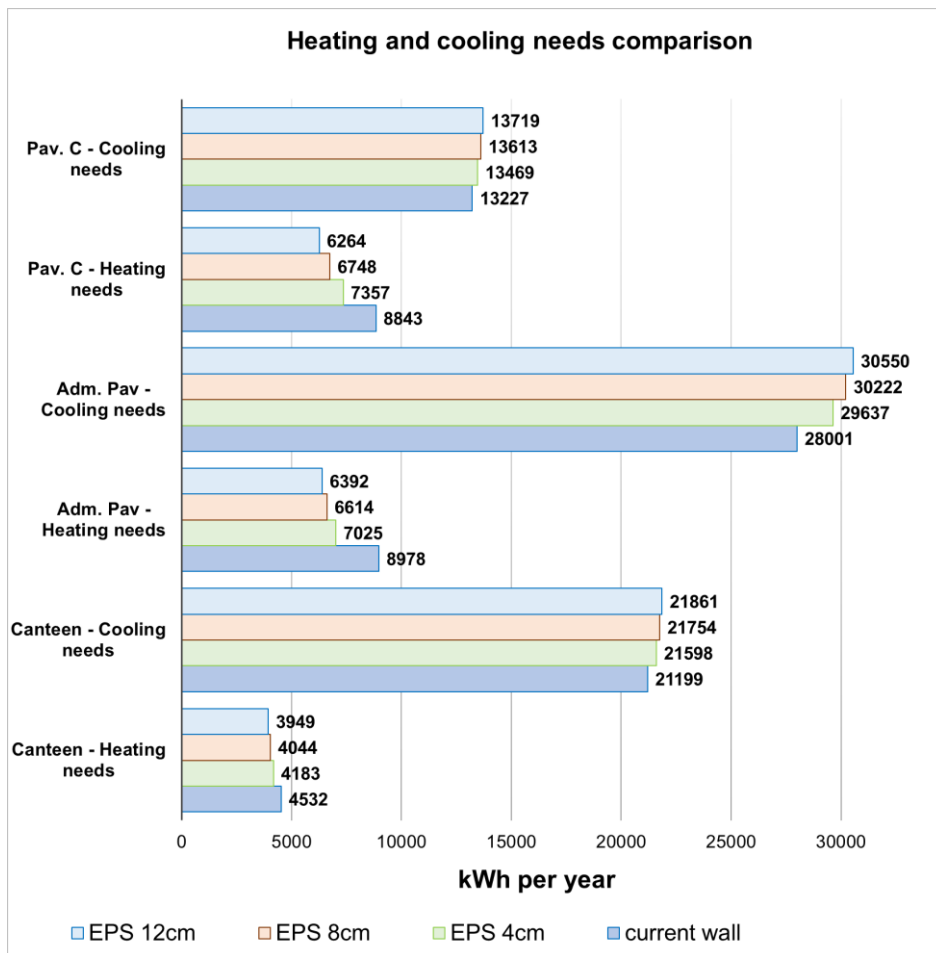


Figure 50 - Heating and cooling needs comparison for the examined EPS thicknesses.

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 63.

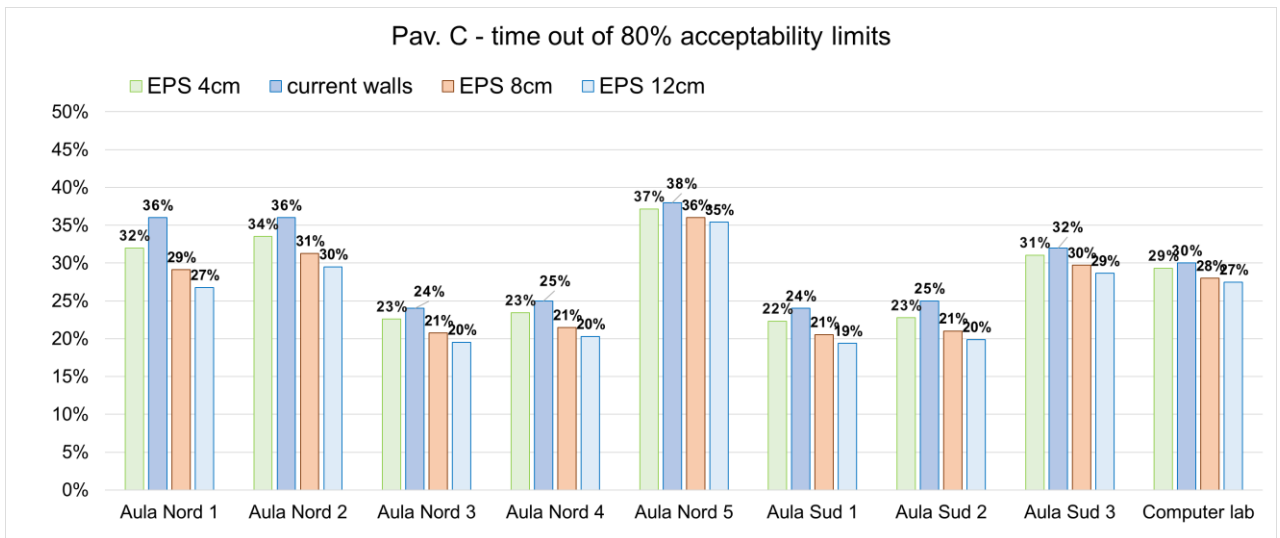


Figure 52 - Thermal discomfort condition in *Pav. C* thermal zones for the examined EPS thicknesses.

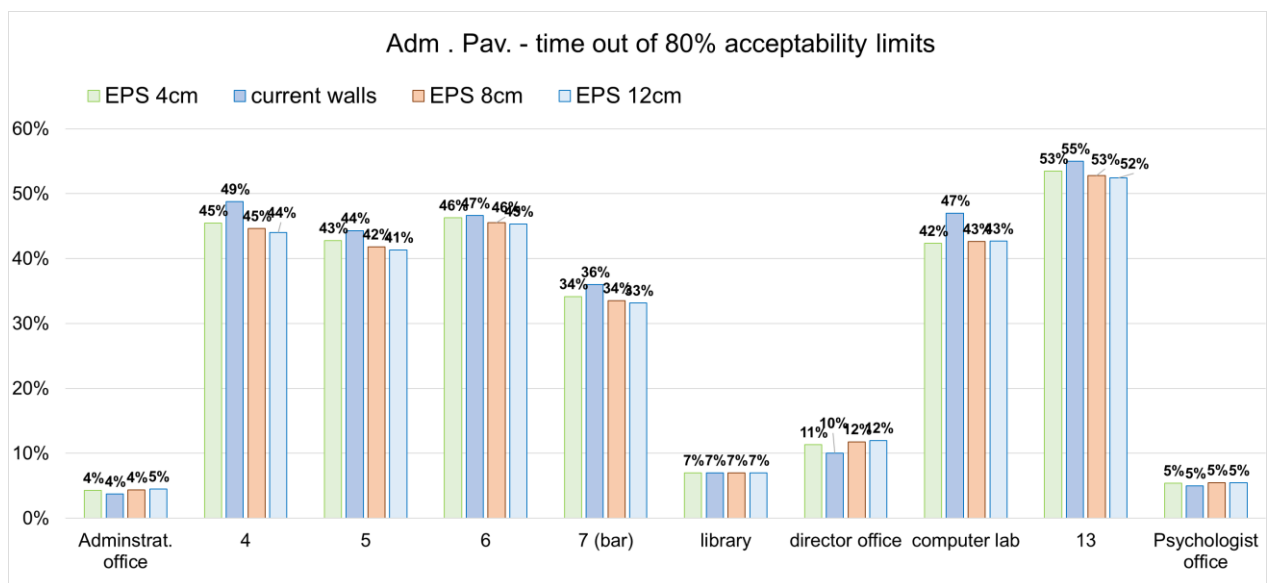


Figure 51 - Thermal discomfort condition in *Adm. pav.* th. zones for the examined EPS thicknesses.

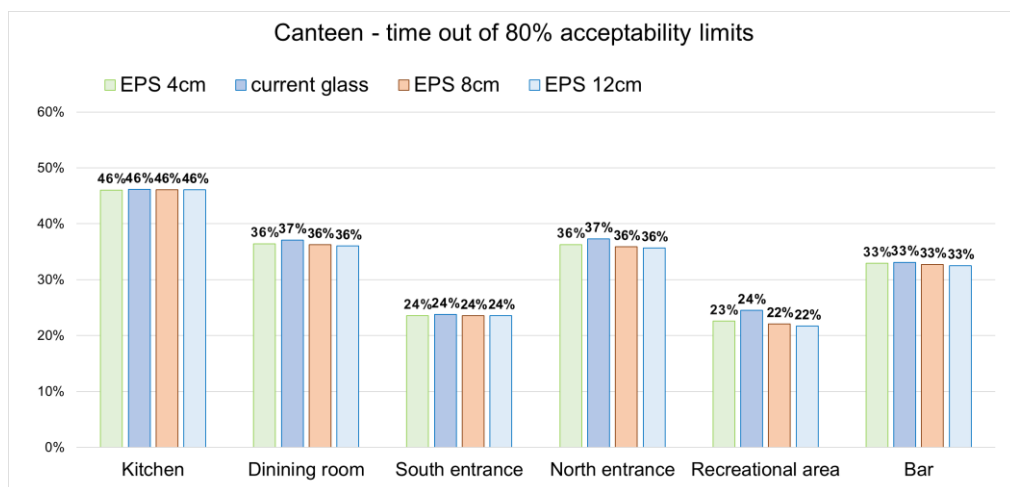


Figure 53 - Thermal discomfort condition in *Canteen*. th. zones for the examined double-glazing

6.2.2 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 [15] :
 - thickness 4 cm: 3 €/m²;
 - thickness 8 cm: 5,5 €/m²
 - thickness 12 cm: 8 €/m²;
- installation price: 55 €/m² [15];
- net wall area to be covered:

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

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

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

Project evaluations results are illustrated in the Tables 29, 30 and 31.

Table 29 - 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 30 - 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 31 - 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

6.2.3 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 negligible savings in absolute terms. To give a practical example in Fig. 51 results 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 is always negative even with an investment period longer than 70 years. Moreover, all the cash flows for the *canteen* are negative hence 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.

6.3 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 six¹⁵ 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.

6.3.1 Global savings

As Fig. 54 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%.

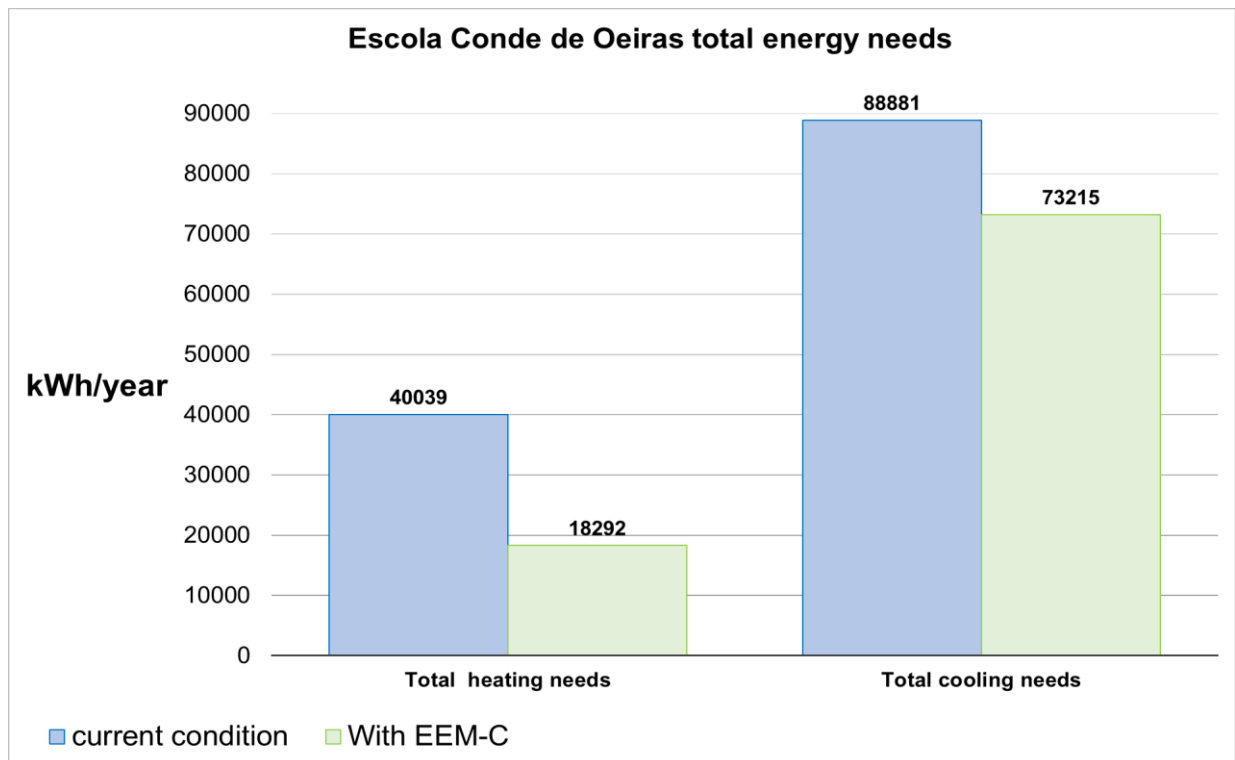


Figure 54 - Aggregated total energy savings.

¹⁵ Pavilions A, B, C; Canteen; Administrative pavilion

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

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:

$$Tot\ needs_{cc} = \frac{1}{0,85} \cdot (tot\ heating\ needs + tot\ cooling\ needs)_{cc} = 151 \frac{MWh}{year} \quad (14)$$

$$Tot\ needs_{nc} = \frac{1}{0,85} \cdot (tot\ heating\ needs + tot\ cooling\ needs)_{nc} = 108 \frac{MWh}{year} \quad (15)$$

(cc = current condition; nc = new condition)

However, since

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

It results that

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

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

6.3.2 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 32.

Table 32 - 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

6.4 Final business 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 urgent 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 for 96%¹⁶ of the time inside the thermal zones. 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 155¹⁷ MWh per year;
- Energy required from gas equipment, assessed around 13,5¹⁸ 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.

¹⁶ Percentage suggested by standards ASHRAE-55 2017.

¹⁷ Data from 2018 electricity bill.

¹⁸ Data from 2018 gas bill.

Table 33 - Photovoltaic plant cost and specifications.

<i>PV plant data</i>	
Total school energy demand ¹⁹	277 MWh per year
Useful days per year ²⁰	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 ²¹	261 MWh
PV plant overall cost, VAT included	300'000 €

Table 34 - HVAC plan cost and specifications

<i>HVAC plant data</i>	
Plant energy demand ¹⁸	108 MWh per year
Number of thermal zones to supply ²²	39
Cost of each AC unit ²³	1700 €
HVAC plant overall cost, VAT included	70'000 €

Table 35 – Final business plan.

<i>Final business plan</i>	
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.

¹⁹ Considering EEM-C implementation.

²⁰ 11 months per year and 22 days per month.

²¹ Results provided by PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM (PVGIS) interactive tool.

²² 27 thermal zones for *pav. A, B, C*; 10 for *Adm. pav.*; 6 for *Canteen*.

²³ Average cost for ducted air conditioner A++ that develops a power of 39'900 BTU for cooling and 48'000 BTU for heating.

7 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 the 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 *Escola Conde de Oeiras* is currently facing.

Already after the first visits, it was recognised, 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 current²⁴ 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.

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.

²⁴ Scenario B: after roof replacement.

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Appendix A - Materials and constructions

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

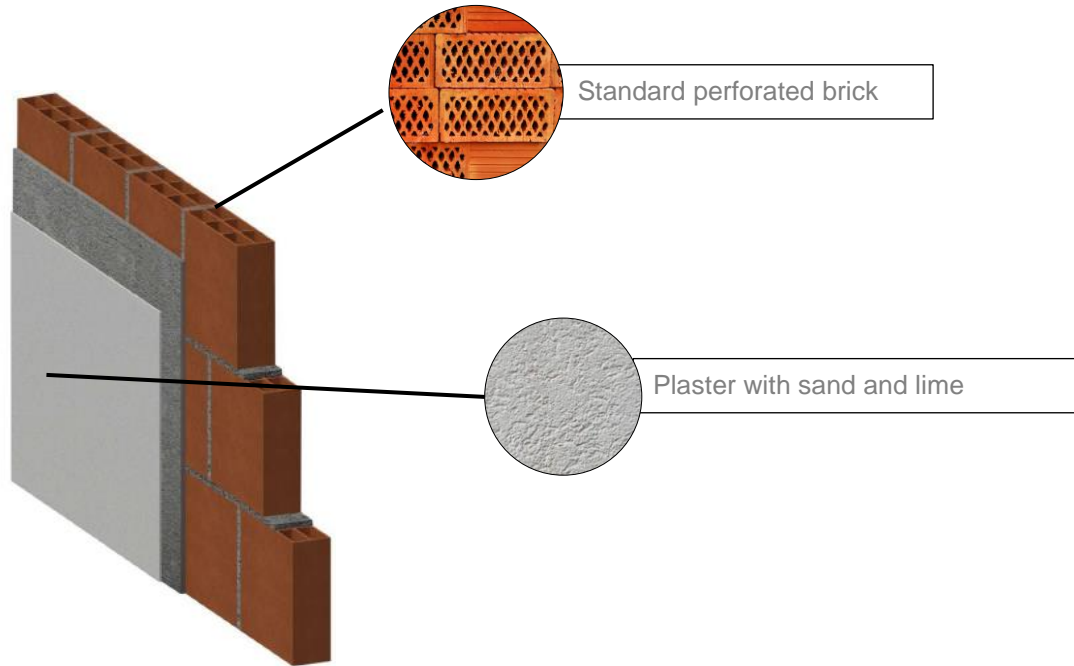
The constructive elements and the relative assumptions are listed below.

- 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: $Width_{brick} = Thickness_{wall} - (Thickness_{plaster}) \times 2$.
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 $U_{frame} = 7W/m^2K$.

Given the assumptions above, materials were introduced in the Energy+ model filling all the fields in the *Material* object of Energy+ described in 4.1.2.1. 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 (See bibliography []).

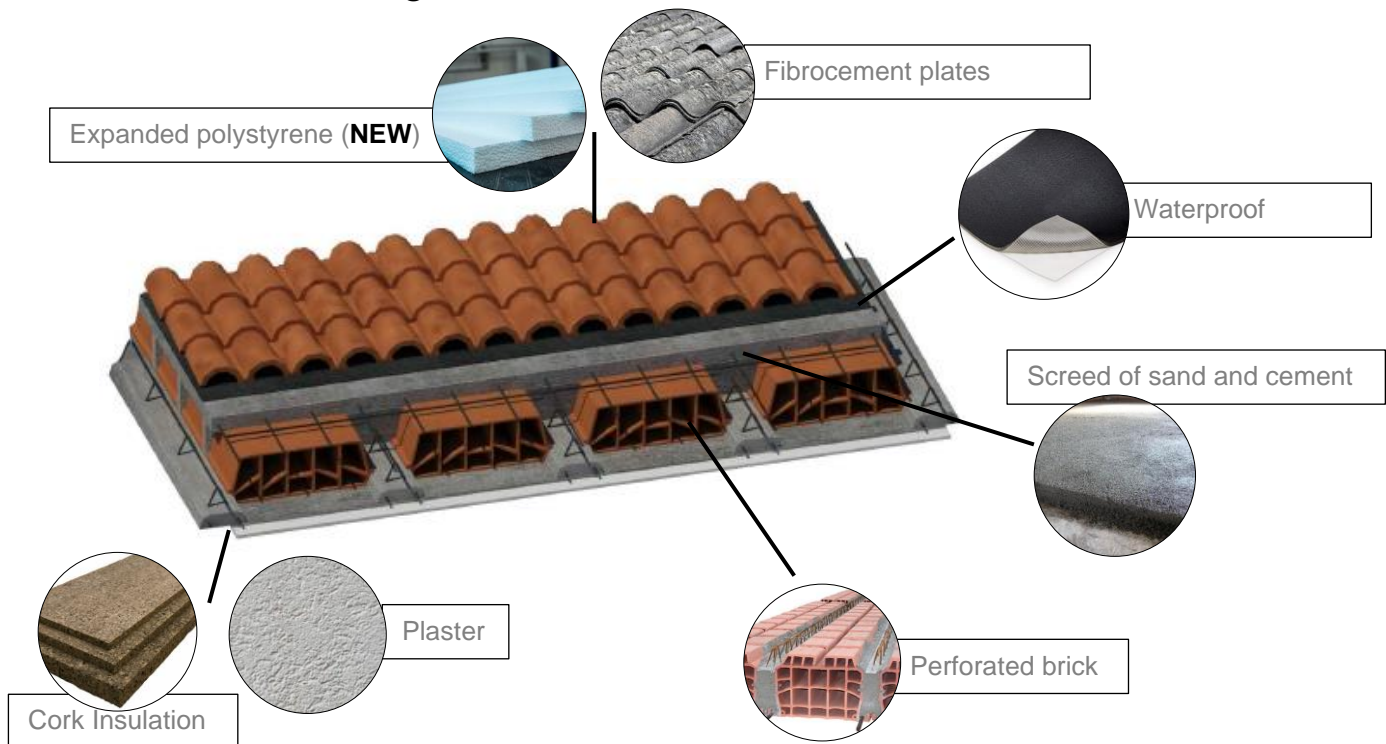
A.1 Walls



BRICK		Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m ³]	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

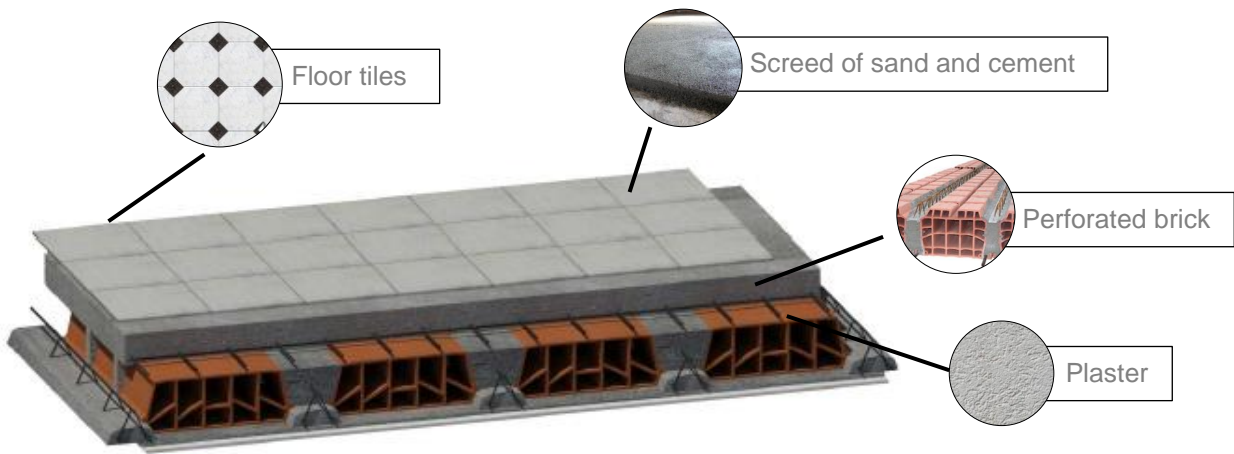
PLASTER		Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m ³]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	external walls	2	Rough	0.9	1800	850	0.9	0.7	0.7
	internal walls	1.5	Rough	0.9	1800	850	0.9	0.7	0.7

A.2 Roofing



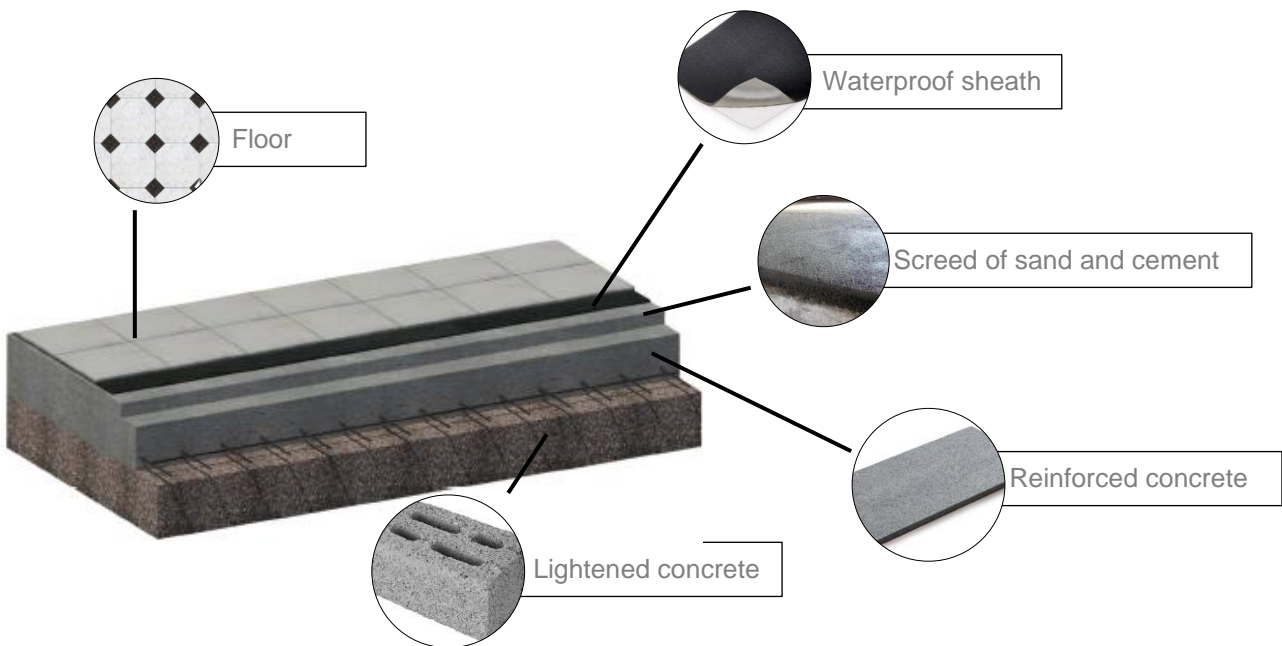
FIBROCEMENT	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m ³]	Specific Heat [J/kg/K]	Thermal Absorptance	Solar Absorptance	Visible Absorptance
All buildings	2	Rough	0.26	1450	870	0.9	0.7	0.7
POLYSTYRENE	Thickness [cm]	Roughness	Conductivity [W/m/K]	Density [kg/m ³]	Specific Heat [J/kg/K]	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/m ³]	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/m ³]	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/m ³]	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/m ³]	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/m ³]	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	Roughness	Conductivity	Density	Specific Heat	Thermal	Solar	Visible
	[cm]							
Administrative pavilion	2	Medium smooth	1	2300	795	0.9	0.5	0.5

A.4 Flooring



REINFORCED CONCRETE	Thickness	Roughness	Conductivity	Density	Specific Heat	Thermal	Solar	Visible
	[cm]							
All buildings	Rough	0.3	0.8	1600	850	0.9	0.7	0.7

LIGHTENED CONCRETE	Thickness	Roughness	Conductivity	Density	Specific Heat	Thermal	Solar	Visible
	[cm]							
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 methods 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. 55 shows the Energy+ interface) it is possible to input the measured characteristics of the glass and let the software calculate its thermophysical properties.

Field	Units	Obj1
Name		Clear 4mm
Optical Data Type		SpectralAverage
Window Glass Spectral Data Set Name		
Thickness	m	0,004
Solar Transmittance at Normal Incidence		0,85
Front Side Solar Reflectance at Normal Incidence		0,088
Back Side Solar Reflectance at Normal Incidence		0
Visible Transmittance at Normal Incidence		0,85
Front Side Visible Reflectance at Normal Incidence		0,081
Back Side Visible Reflectance at Normal Incidence		0
Infrared Transmittance at Normal Incidence		0
Front Side Infrared Hemispherical Emissivity		0,84
Back Side Infrared Hemispherical Emissivity		0,84
Conductivity	W/m-K	0,9
Dirt Correction Factor for Solar and Visible Transmittance		1
Solar Diffusing		No
Young's modulus	Pa	
Poisson's ratio		
Window Glass Spectral and Incident Angle Transmittance Data Set Table Name		
Window Glass Spectral and Incident Angle Front Reflectance Data Set Table Name		
Window Glass Spectral and Incident Angle Back Reflectance Data Set Table Name		

Figure 55 – *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/m²/K and a Solar Heat Gain Coefficient (Glass SHGC) equal to 0,868.

Construction	Glass Area [m ²]	Frame Area [m ²]	Divider Area [m ²]	Area of One Opening [m ²]	Area of Multiplied Openings [m ²]	Glass U-Factor [W/m ² -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

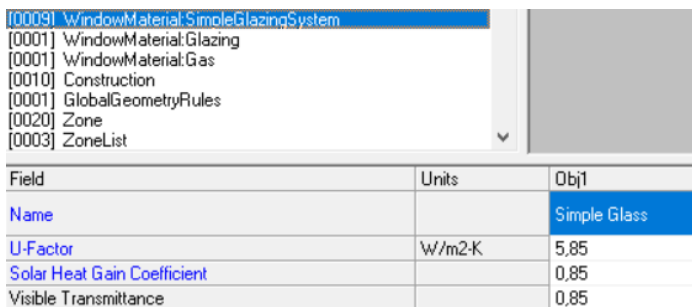
Figure 56 – Output of Energy+ showing the calculated properties of glazed surfaces.

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:

- $U_{\text{glass}} = 5,85 \text{ W/m}^2/\text{K}$ for single glass (source: UNI EN ISO 10077-1);
- $U_{\text{frame}} = 7 \text{ W/m}^2/\text{K}$ 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. 57) of Energy+ which allows the user to input directly the values of Transmittance, SHGC and VT.



Field	Units	Obj1
Name		Simple Glass
U-Factor	W/m2.K	5,85
Solar Heat Gain Coefficient		0,85
Visible Transmittance		0,85

Figure 57 – *SimpleGlazingSystem* object in *Energy+* environment.

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

Table 36 – 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 [16].
- Inside surfaces convection algorithm: *Simple*. It applies constant heat transfer coefficients according to the surface orientation [16].
- Outside surfaces convection algorithm: *Adaptive convection algorithm*. It is a dynamic algorithm that selects among many different convections models the one that best applies [16].
- 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 data on indoor air temperature was collected in the second decade of October 2019 during three regular weekdays.

It would be 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. [17]. From these variables, statistical indices have been recommended by three main international bodies [18]:

- 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):

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

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

$$A_{period} = \frac{\sum_i^n M_i}{n} \quad (18)$$

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

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 $\pm 10\%$, while IPMVP considers a range of $\pm 5\%$ 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 data with the model results, shown in Figure 58, an MBE value of 2.95% and a CvRMSE value of 4.29%, which are within the limits established above.

The equipment adopted to meter the above parameters consisted in a standard thermocouple positioned inside one of the north exposed *pavilion C* classrooms, namely Aula Nord 3. Temperature was registered with a 5 second timestep whereas for *Energy+* the minimum timestep possible is 1 minute, moreover since recording period started at 8pm, the simulated output was shifted 4 hours back in the graph of Fig. 58

In Fig. 58 that follows metered values and simulated ones are plotted for comparison purposes.

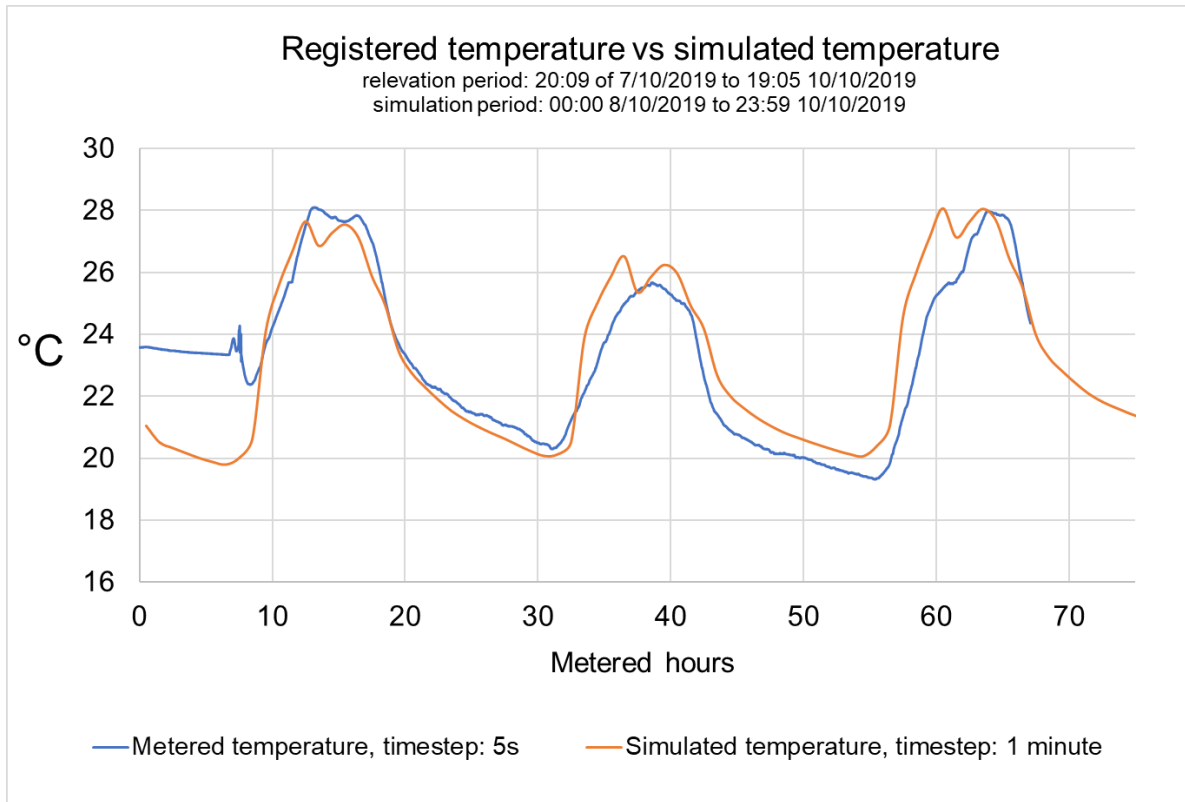


Figure 58 – Metered vs. simulated indoor temperature of classroom ‘Aula Nord 3’ in *pavilion C*.

Peak temperatures are achieved around 15, 38 and 60 hours hence approximately midday. The slight drops visible on 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. In the reality, this type of event does not occur systematically every day.