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Abstract: A major rehabilitation programme of secondary school buildings has been carried out in the last few years in Portugal. With the introduction of HVAC systems in buildings that were previously naturally ventilated, an increase on energy consumption has been verified.
During the first occupancy periods of new and refurbished buildings, energy and indoor climate quality audits are important strategies to improve the buildings' energy use. In this context, this paper aims at showing the relations between the energy consumption and indoor environment quality (IEQ) parameters, obtained from the energy and IEQ audit in six representative modernised secondary schools - part of a larger R&D project untitled 3Es - geographically and climatically distributed in Portugal mainland.
The monitoring period during the mid-season 2013 varied between schools, between two and three weeks. Air exchange rates, more specifically infiltration rates, were quantified aiming at determining the current airtightness condition of the refurbished schools. A subjective IEQ assessment was also performed, focusing on occupants' feedback, providing insight on the potential linkages between energy use and occupants' comfort.
A reflection on the energy consumption indicators and the indoor conditions obtained in the classrooms was proposed, and some suggestions were anticipated.

Title Page with Author details

An integrated approach on energy consumption and Indoor Environmental Quality performance in six Portuguese secondary schools

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1. Introduction

1.1 Background

The physical and non-physical boundaries of school buildings environments have a critical effect on students' health and sense of well-being. School buildings are therefore a fundamental element of society [1]. The indoor environmental quality (IEQ) is a very important topic – not only children are particularly sensitive to low quality indoor environments because they are still under development [2] but also, classrooms have a high occupancy rate that may degrade users' health, comfort and performance conditions [3], [4]. Among the consequences of poor indoor air quality (IAQ) conditions in schools, recent studies have focused on students and teachers performance [3,4] and verified a notably increased student absenteeism.

To achieve and maintain satisfying IAQ levels, large buildings use mechanical ventilation systems. The "EE-TC-IAQ" dilemma (energy efficiency - thermal comfort - indoor air quality), as presented by Becker *et al.* (2007) [5], is still a challenge within the building sector. Other than external factors, such as climate, energy demand in buildings is determined by three main types of factors and the linkages between those – building services, building envelope and human factors [6].

Since the Kyoto Protocol and European Union's first commitment period, large efforts towards GHG mitigation have been undertaken globally [7], and specially within the European energetic context. Many European policies towards energy conservation and rational use of energy have focused on the building sector. The Energy Performance Buildings Directive (EPBD) 2002/91/EC [8] and its 2010 recast [9], assumed special relevance in this context. In the Portuguese legislation, the EPBD was ensured in the form of three decree-laws, in 2006 [10–12].

By the end of 2009, a large building modernisation programme of the secondary schools was taking place in Portugal, led by the state-owned company *Parque Escolar E.P.E.* (PE) [13]. Most existing school buildings, which were naturally ventilated at their origin, were refurbished in accordance to the new legislation [10–12], integrating both insulation elements on walls and/or ceilings and 'heating ventilation and air conditioning' (HVAC) systems to comply with the new requirements of thermal comfort (TC) and indoor air quality (IAQ).

1.2 Problem statement

Research on IEQ related specifically to new or refurbished school construction was relatively scarce until the end of last century. Today worldwide studies are being performed on this field. In [14], the authors presented a literature survey on the influence of different factors on human comfort in indoor environments, presenting various case studies, data analysis strategies, different building types – including secondary schools, and results.

They also mention studies that related outdoor climate and season with IEQ satisfaction. Wargocki and Wyon's extensive work on students' schoolwork performance has been continuously published [3] [15] [16], and the study of Shendell *et al.* (2004) [17] relating CO_2 concentrations to student attendance also included a relevant literature review on the topic.

CO_2 control in classrooms and different ventilation strategies [18] [19] [20] – as the one suggested by the most recent UK legislation (BB101) [21] – have been well thought-out, and the most recent studies on its consequences are being closely followed [22] [23] [24]. It is noteworthy that changes to the legislation in the UK were preceded by the intensive studies on adaptive comfort by Humphreys and Nicol [25][26][27]. Currently this legislation is again under public consultation [28].

The study performed by [29], in a Mediterranean climate, demonstrated that considering outdoor conditions, clothing levels and indoor air temperatures in buildings is crucial to correctly analyse occupants behaviours and preferences. In fact, it showed that people who moved from HVAC equipped spaces to others, non-equipped, had their temperature range preference enlarged beyond those defined in ISO 7730 [30]. In winter, the verified acceptable indoor temperatures were slightly lower and during summer, for high outdoor temperatures, the indoor ones were higher than those suggested in the standards, resulting in operating range temperatures between 22-27ºC and 19º-25ºC, in summer and winter, respectively, for category C (representative of the *highest acceptable range around the optimum temperature – 15% dissatisfied people*).

As such, it became relevant to reflect on the IAQ parameters of the current Portuguese legislation (2013) that rules HVAC requirements for schools (as those expressed in SCE [31,32] facing the previous one, RSECE [11], 2006). Some studies, based on field measurements (e.g. Santamouris *et al*., 2008 [33]) or simulation (Gameiro da Silva, 2009 in [2]), suggested that the 2006 requirements of outdoor air flow (30 m^3/h) proposed by the Portuguese legislation, could be oversized (significantly higher than those from ASHRAE 62/1:2010 [34]), therefore over consuming and potentially over charging the contracted power (a lower fresh air flow rate means necessarily a lower energy consumption of the adopted mechanical system). The simulation tool developed by the author demonstrated that a relaxation of the "optimum" daily average concentration of CO_2 from 1,8g/m^3 (1000 ppm) to 2,7g/m^3 (1500 ppm) significantly minimizes fresh air flow rates – practically by half.

1.3 Aim and scope of the paper

For the reasons previously presented, it was questionable if the energy bill associated with ventilation on Portuguese schools modernised by PE was being overcharged, and if this corresponded to an effective satisfaction on occupants comfort.

This concern with energy expenses has been clearly stated by Santamouris *et al.* (2007) in [35]: the *"increased use of air conditioning creates a serious peak electricity load problem to utilities and increases the cost of electricity".* This condition was familiar to the Portuguese educational sector. Previously to PE's intervention, most schools were naturally ventilated and therefore, had smaller energy bills. Due to the mechanization of the heating and ventilation system (cooling was not mandatory according to the 2006 legislation), monthly energy expenditures increased. Because some schools could have their HVAC systems turned off to reduce energy bills, an IEQ audit was mandatory to evaluate the indoor climate condition of the classrooms.

To sum up, this study aimed at assessing the energy and IEQ of recently refurbished classrooms. In parallel to the energy data collection (both from billed energy data and field monitoring campaign), an IEQ analysis of indoor environmental parameters (as air temperature, relative humidity, air velocity and CO_2 concentration values) was performed – measured every minute over a two-week period (on average), complemented with a subjective survey driven to the students occupying the monitored rooms.

The development of an inquiry/survey between school populations was a fundamental procedure to assess the school population sensitive response to the recently installed HVAC systems. This type of data collection allowed in 2013, Montazami and Nicol [23] revealing overheating problems in the UK schools – in their case studies, school teachers were asked to rate the level of thermal comfort (TC) and temperature inside classrooms.

Moreover, Fanger's thermal comfort indices (PPD and PMV) [36] were estimated based on data collection, from both monitored parameters and surveys – accounting for the metabolic rate and clothing insulation. These indices calculation allowed establishing a comparative evaluation between subjective results and those obtained from the measurements on the field, attending also the perception in terms of acceptability and preference. The TC and IAQ assessment methodology has been entirely reported in 2014 [37].

All in all, the EE-TC-IAQ dilemma was faced in a holistic approach [38,39].

Nomenclature

AER	Air exchange rates	MMV	Secondary school in Montemor-o-Velho
BJA	Secondary school in Beja	PBL	Secondary school in Pombal
BGC	Secondary school in Bragança	PD	Predicted of Dissatisfied
CCD	Census County Division	PE	Parque Escolar E.P.E.
EE	Energy efficiency	PMV	Predicted Mean Vote
EPBD	Energy performance of buildings directive	PPD	Predicted Percentage of Dissatisfied
GFA	Gross Floor Area	PTG	Secondary school in Portalegre
GRD	Secondary school in Guarda	RH	Relative Humidity
HDD	Heating Degree Days	SBI	School Building Indicator
HVAC	Heating Ventilation and Air Conditioning	Ta	Indoor Air Temperature
IAQ	Indoor Air Quality	TA	Thermal acceptability
IEQ	Indoor Environmental Quality	TC	Thermal Comfort
		TUFA	Total useful floor area

2. Case studies

Based on a PE's database, changes in energy demand of the school buildings between the pre- and post-intervention measures were characterised. From this characterization and a set of criteria, a group of eight representative schools was selected, in which a more detailed analysis of energy consumption and operation conditions was carried out [40]. Within the current paper, only six of these schools are presented in detail: those were both the energy and the IEQ assessment was performed, objectively and subjectively.

2.1 The schools climate condition

The six schools buildings are located in mainland Portugal, as presented in **Figure 1**. A summary of the reference climate data of each school is presented in **Table 1**.

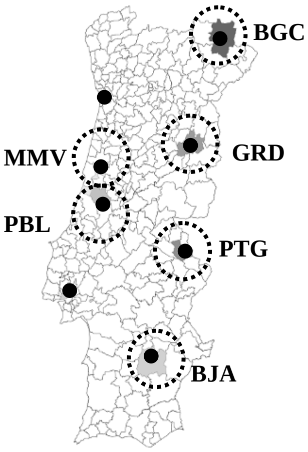


Figure 1 – Map of Portugal highlighting the 8 schools' selection (CCD[1] location) of the 3Es project [41], whose municipalities are signalled with the black dot. The dotted circles sign the six schools presented in this work.

Table 1 – Six schools' selection – CCD distribution and reference climate data

CCD	Acronym	Heating Degrees Days (HDD) [selection phase / new SCE]*		Distance to the oceanic coast (km)	CCD's Altitude (m)	Schools' Altitude (m)
Montemor-o-Velho	MMV	1410	1265	17,5	67	28
Beja	BJA	1290	1145	85	178	255
Pombal	PBL	1580	1226	28	126	75
Portalegre	PTG	1740	1496	165	246	475
Guarda	GRD	2500	2235	126	717	1028
Bragança	BGC	2580	2036	175	680	695

Note: The HDD presented in grey, resulting from the revised regulation (2013), account the schools altitude.*

From these data and in accordance with the climatological normal (1971-2000), **Figure A.1** in Appendix, it was clear that the schools with higher heating requirements were the schools located in Guarda (GRD) and Bragança (BGC). From the annual evolution of the mean, minimum and maximum monthly temperatures of these cities, it was verified that the school in Guarda (GRD) is located in the city presenting the lowest mean

[1] *CCD – Census County Division.*

monthly temperature. The school in Bragança (BGC) is positioned in the city with the lowest average of minimum temperatures. On the other hand, the school in Beja (BJA) is located in the city which has the highest average of maximum temperatures.

The schools in Portalegre (PTG) and Beja (BJA) are situated in the cities with lower rigorous climate during the heating season. Regarding the cooling period, the school subjected to lower maximum temperatures is the one located in Guarda (GRD).

Given the regular school year period, September – June/July, and through the observation of the figures below, it is expected that the schools in Guarda (GRD) and Bragança (BGC) have greater needs for heating than for cooling, contrarily to the schools in Beja (BJA), Portalegre (PTG) and Pombal (PBL), where the greatest cooling needs are expected.

2.2 IEQ monitored classrooms characterization

Table 2, **Table A.1** and **Table A.2** (in Appendix), provide a detailed characterization of the monitored schools/classrooms: (1) school ID; (2) classroom identification; (3) classroom area and volume; (4) number of occupants and occupancy density; (5) windows areas and window to floor ratio; (6) other comments related to the classroom operation and design.

The classrooms scheduling occupancy varied along the schools. In some cases (e.g., MMV and BGC), different classes and students used the monitored classrooms along the day, varying the number and age of the students. In these cases the occupancy density was estimated on the number of students during the monitoring/survey period. Data about windows dimensioning, in **Table A.1**, refer to the "key classrooms" in each school.

Table 2 – Summary table of the 6 schools classrooms characteristics' and windows dimension

School	Room	Area (m^2)	Ceiling (m)	Volume (m^3)	Number of students (during class period)	Occupancy density (pupil / m^2)	Window to floor Ratio
MMV	**MMV1**	41.75	3.00	125.2	22 (survey)	0.53 (survey)	0.20
	MMV2	47.06	3.00	141.2	24 (surveyed total 24)	0.57 (survey)	0.18
BJA	**BJA1**	46.38	3.36	155.9	26 (median)	0.57 (median)	0.19
	BJA2	46.21	3.36	155.3	26 (median)	0.57 (median)	0.19
PBL	**PBL1**	49.65	2.75 – 3.05	140.9	28 (dominant class)	0.56 (dom. class)	0.21
	PBL2	50.00	2.75 – 3.05	141.7	29 (dominant class)	0.58 (dom. class)	0.21
PTG	**PTG 1**	56.12	2.77	155.5	28 (dominant class)	0.50 (dom. class)	0.30
	PTG 2	56.81	2.77	157.2	21 (dominant class)	0.37 (dom. class)	0.22
GRD	**GRD1**	54.89	2.43	133.2	25 (dominant class)	0.46 (dom. class)	0.24
	GRD2	54.53	3.18	173.6	20 (dominant class)	0.37 (dom. class)	0.24
BGC	**BGC1**	47.50	3.00	142.5	23 (survey)	0.48 (survey)	0.18
	BGC2	48.56	3.00	145.7	19 (survey)	0.39 (survey)	0.13

Notes: MMV = Montemor-o-Velho; BJA = Beja; PBL = Pombal; PTG = Portalegre; GRD = Guarda; BGC = Bragança. The number of students and occupancy density presented for PBL are due during the second monitoring period, 2014 (section 3.1).

3. Research methodology

These integrated approach aimed at increasing the schools' energy efficiency while providing good indoor environmental conditions to the occupants has been formally presented in September 2014 [42], being recognized as a finalist project in the *Green Brain of the Year Contest 2014* (Middle East Technical University, Northern Cyprus Campus).

The entire methodology relating the IEQ assessment of the case studies has been previously published in [37], using the school in Beja (BJA) as case study, and some early results were also disclosed in [43] also exploring the school in Portalegre (PTG). A summary of the monitoring equipment and corresponding parameters is presented in **Table A.3** (in Appendix).

3.1 Monitoring campaign scheduling

The monitoring period varied between two and three weeks, for both the energy and IEQ campaign. Although provided with HVAC systems, namely air handling units (AHU) and variable refrigerant flow (VRF) units, during the monitoring period some schools classrooms' were in "free running" conditions.

The assessment of indoor environmental conditions was performed in two classrooms per school; data collection was observed and examined both in teaching and non-teaching periods. Within each school building, classrooms with different solar orientation (e.g. one room facing north and another facing south) were preferably chosen. When such was not possible, classrooms with different volume or occupancy/activity (e.g. "typical" teaching classroom vs. workshop) were selected. These criteria ensured diversity within the classrooms, allowing a more robust assessment. The monitoring campaigns' scheduling is summarized in **Table 3**. IAQ subjective surveys to the students were generally implemented on the last day of the monitoring period.

Table 3 – Summary of the scheduling of monitoring campaigns

School	1st monitoring campaign	2nd monitoring campaign	IAQ survey
Montemor-o-Velho (MMV)	16/05/2013 – 06/06/2013*	–	06/06/2013
Beja (BJA)	29/04/2013 – 13/05/2013	–	13/05/2013
Pombal (PBL)	03/04/2013 – 16/04/2013	21/05/2014 – 03/06/2014	03/06/2014
Portalegre (PTG)	02/05/2013 – 14/05/2013	–	10/05 & 13/05/2013
Guarda (GRD)	27/09/2013 – 17/10/2013	–	17/10/2013
Bragança (BGC)	24/09/2013 – 18/10/2013	–	18/10/2013

Note: In this school, due to problems with the monitoring equipment, the campaign was extended up to 11/06/2013*

3.2 Energy consumption

For each of the studied schools, the energy audit started with preliminary data collection of the facility; later, the inspection of the building and the installation of monitoring equipment took place. The preliminary data collection analysis consisted in a review of the energy bills[2] and typical occupancy values, aiming at analysing energy use quantities and patterns. The architectural and engineering plans of the building and its systems were assessed in detail, in conjunction with data inventory of the different energy related systems (HVAC, pumps, lighting, domestic hot water, etc.).

After the preliminary analysis, a tour over the schools complex was performed, consisting of an on-site visit to visually inspect each of the energy systems and trying to get answer for the questions raised during the preliminary review. The audit team also met with the operation and maintenance staff to establish a common understanding of the audit process.

The on-site energy consumption measurements were performed on specific equipment and systems, to evaluate their load profiles and identify potential energy efficiency measures, at the time the IEQ monitoring was performed. This stage allowed the quantification of energy flows and the assessment of the energy performance of the facility.

The information gathered during the facility inspection and the monitored measurements were reviewed and organized, allowing the interpretation of energy use per school per year and per student. Likewise, understanding the utility bill permitted other conclusions on energy tariffs and building management system (BMS)'s programing – these two steps are out of the scope of the study here presented.

3.3 TC and IAQ

The field campaigns were performed in the six schools during the spring – autumn period (excluding summer vacation) during 2013. The school in PBL was monitored a second time, in May 2014, once when it was first monitored, it was not possible to conduct the subjective assessment. In order to address the linkage between students' thermal comfort trends and indoor environmental conditions, both subjective and objective data analyses were carried out outside the heating season. Most of the schools in this period were in free-running mode (to reduce energy consumption due to cost constraints).

"The IAQ and TC factors were analysed by means of field measurements of the following parameters: air temperature (T_a), air relative humidity (RH) and concentration of carbon dioxide (CO_2). Data were registered every 60 sec for the total monitoring periods". As stated in [37] and [43], due to regular class action, and considering students behaviour, the measurements were not registered totally in accordance with ISO 7726 [44] – *"the equipment were integrated in the room furniture, at a height of circa 0.6 m above the floor"* or over

[2] As recommended in *Thumann, A., & Younger, W.J.*, 2003 [70], the goal was to collect two school years data. However, due to the recent refurbishment, it was only possible to collect one year data pre-intervention and one year after the intervention.

the suspended ceiling [37]. A summary of the occupants' characterization and classrooms' conditions during the questionnaires is presented in **Table A.4** and **Table A.5** (in Appendix).

3.4 Classrooms' AER

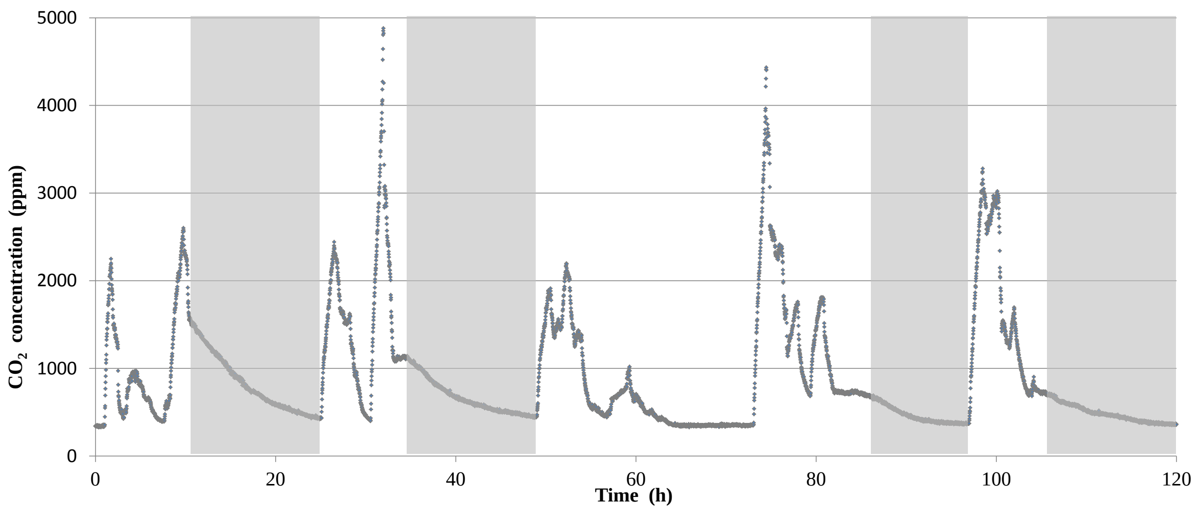
Quantifying infiltration rates in buildings is important for two main reasons: air infiltration strongly affect a building's energy balance, and it provides insight on the minimum building ventilation levels – *"the lack of which has been associated with health problems and lower productivity*" [45].

In this research, this issue was deepened by approaching CO_2 metabolic decay values as a method to determine air exchange rates (AER) or fresh air flow rates (Q) during late evening/ night periods (occupancy vacancy). This prompt method – using CO_2 as tracer gas – has been widely reported in the literature [46], [47], [48], and it is quite discreet (not intrusive) since it is introduced in the rooms in a natural way, through the air exhaled by occupants. As explained in [49], after the occupants have left the room, the CO_2 concentration decays exponentially (in naturally ventilated spaces or when HVAC systems are spent), approaching an equilibrium asymptotic value, as time passes.

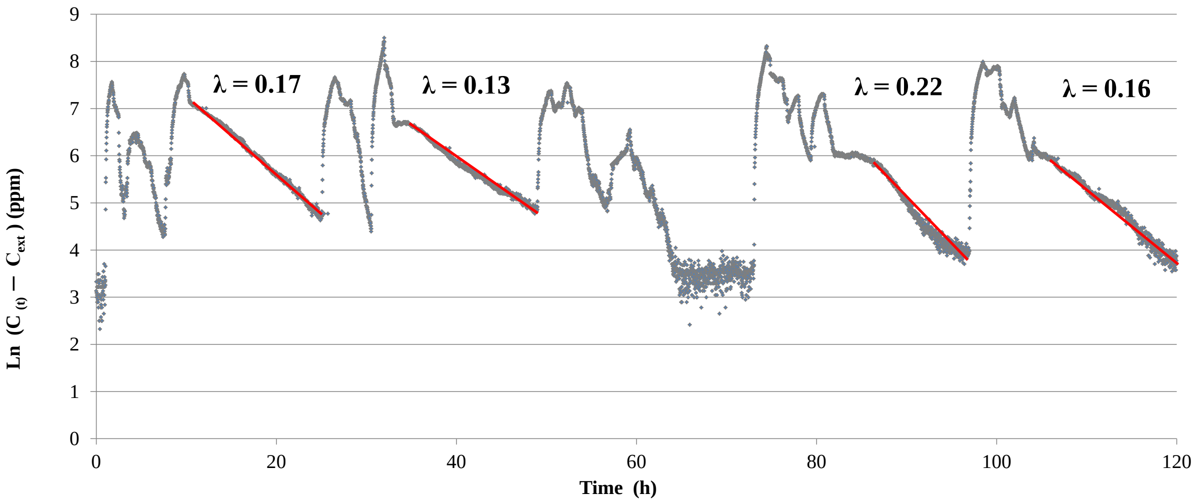
AER is estimated by regressing the logarithm of concentration above outdoors against time (as also reported by [50]), calculated as

$$log_e\,[C_{int}\,(t) - C_{ext}\,] = log_e\,[C_{int}\,(t_0\,) - C_{ext}\,] - \lambda\,(t - t_0\,)\,, \qquad (1)$$

where $C_{int}(t)$ is the observed CO_2 concentration at time t ; $C_{int}(t_0)$ is the estimated initial concentration; λ is the estimated AER; and C_{ext} is the outdoor concentration, i.e. the equilibrium concentration after the decay – assuming that the volumetric flow rate is constant and that it is achieved the equilibrium *"between the rate of generation and the net outflow of CO_2"* [51].



a)



b)

Figure 2 – Five-day CO_2 concentration in GRD1 (30 Sep – 04 Oct 2013), a); Linear regression during the same CO_2 monitoring period (4 concentration-decay validated), b); Shadowed areas identify non occupancy periods

Figure 2 synthetizes the proposed method – herein, part of the GRD1 classroom CO_2 monitoring is presented as an example. A five-day concentration period (corresponding to one of the weeks monitored in this school) is presented in ***a)***. For the same period each of the five non-occupancy periods were evaluated, resulting in four concentration-decay chosen periods, ***b)***. The obtained values for AER and fresh air rates (Q) for all the monitored schools are presented in **Table 6** (section 4.2.1.3).

4. Results

4.1 Energy consumption data

As expected from the schools' installed systems, schools in the 3Es project consume both electrical energy (EE) and natural gas (NG) in which NG represents on average 24% of the schools' energy consumption [52].

A yearly and seasonal energy consumption synthesis of the six schools, expressed both in EE and NG, is presented in

Figure 3. The seasonal billed energy data was organized according to the climatic condition of the schools: summer period considered billed data from July until September; winter period from January to March (BJA, 3 months energy data) and December to April (GRD and BGC, 5 months energy data) – for the remaining schools winter energy data was based on 4 months billed data.

In

Figure 3 the total energy consumption is presented in bold, above each bar in the graph, while EE values are centred in the corresponding part of the bar. The NG value can be inveigled from the difference between these two values.

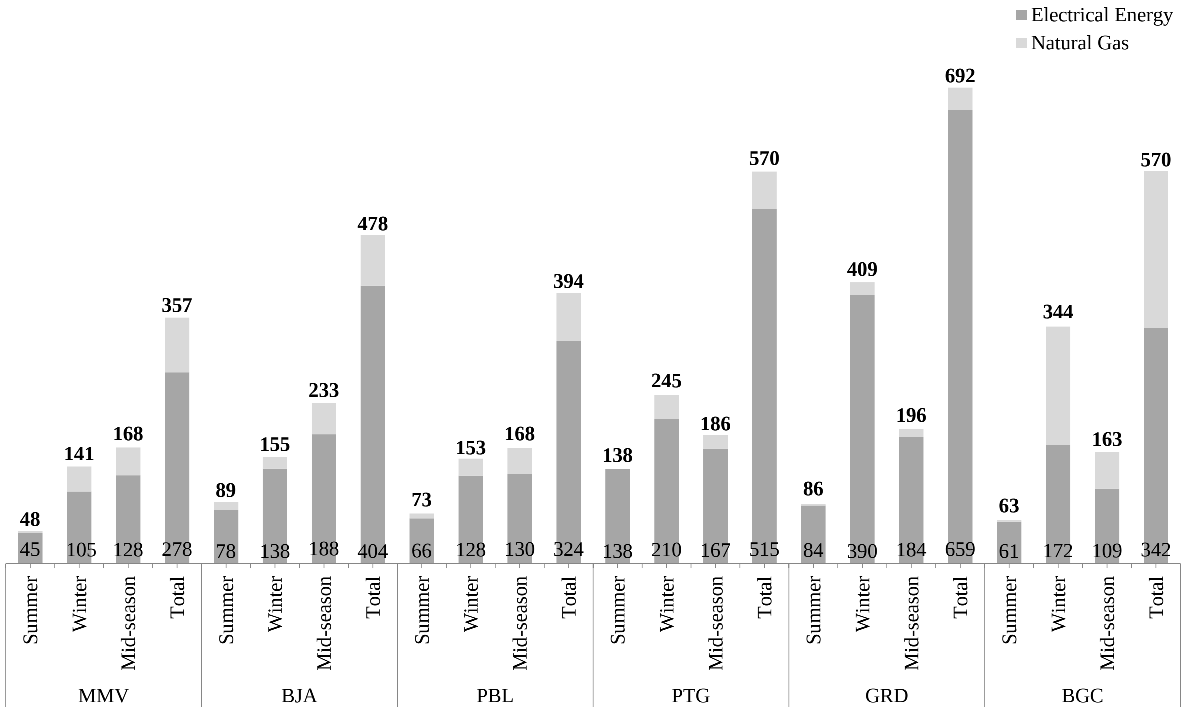


Figure 3 –Syntax table of the 6 schools' energy consumption (data relating one scholar year data e.g. September/2012 – August /2013) [MWh]

In terms of absolute values of the total energy consumption, GRD was the school presenting the highest energy consumption/costs, followed by BGC; MMV presented the bottom annual, summer and winter season lowest energy consumption. GRD and BGC also presented the highest energy cost during winter.

Building up on the importance of school building indicators (SBI), three different SBI are presented in **Figure 4**, along with the median and 25% percentile value of the sample (typical value and good practice value).

Since it was not possible to disaggregate the amount of energy consumption by end-use in all the schools, it was decided to "simply" explore schools' energy consumption in terms of floor area and the number of students. The schools' area is explored both in gross floor area (GFA) and total useful floor area (TUFA).

Figure 4 is quite pertinent: by putting together three different SBI it was found that there are only two permanent positions – the school best performing across the rankings, PBL and PTG, the school worse performing in terms of both the GFA and TUFA.

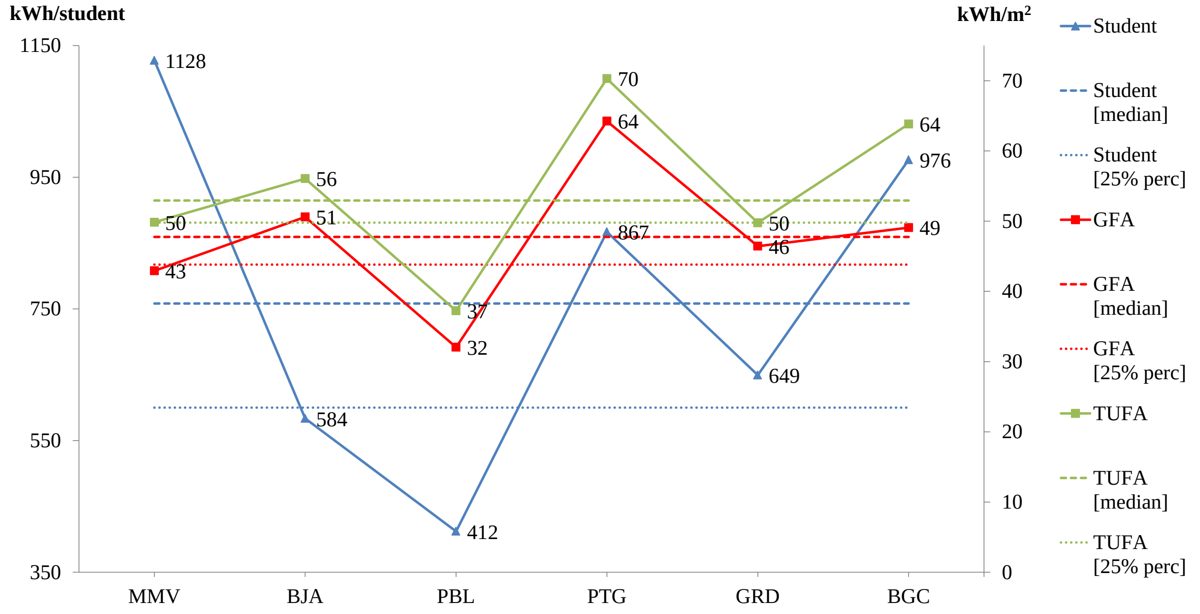


Figure 4 – SBI for the 6 schools selection: energy consumption related to GFA and TUFA expressed in kWh/m^2; energy consumption related to No. of students expressed in kWh/student

When addressing the SBI expressed in kWh/student, the school worse performing is MMV, followed by BGC and PTG. This means that although MMV does not seem to be very energy consuming (when observing its area it practically fits the 25th percentile, i.e. it fits the good practice value) it is not so efficient when the school population is taken into account.

Aiming at tuning climate differences, the relation between the Heating Degree Days (HDD) and the energy consumption of each school was investigated through the development of a combined unit – kWh/m^2/year/HDD, as shown in **Figure 5**. Alike the initial surface normalization, when integrating HDD, differences between GFA and TUFA were also found, but not so significant. In both cases the school with better performance is GRD; followed by PBL and BGC that change positions 2nd to 3rd and vice versa, when the SBI goes from GFA to TUFA. According to this indicator the school with the worst performance is BJA – which is just the 3rd worst performing within the "simple" SBI [kWh/m^2].

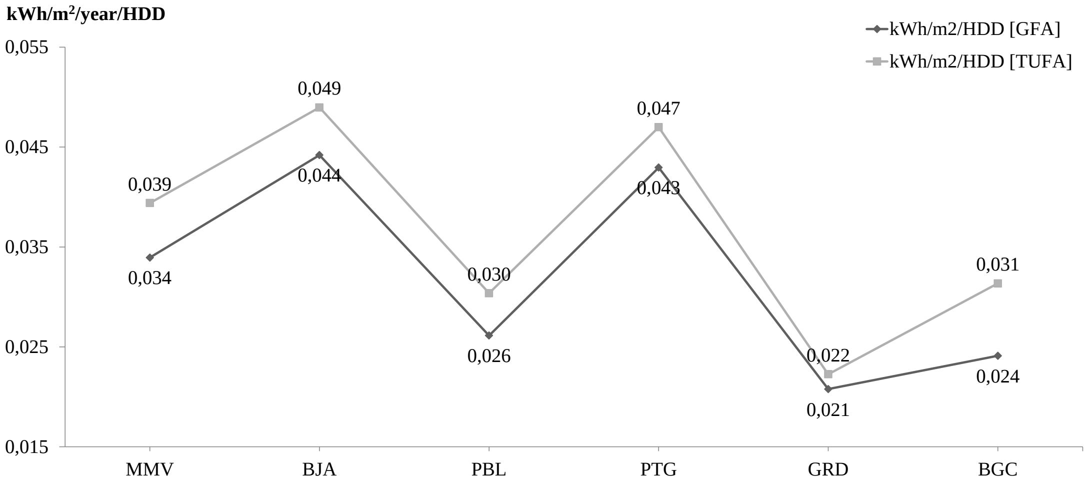


Figure 5 – Weather data SBI normalization for the 6 schools selection.

The relation between the HDD, i.e. climate austerity and the energy consumption of each school was further investigated. The results are presented in **Figure 6**. The image unveils that there is not a strong relation between the two variables – energy consumption and HDD. This means that, in this particular set of data, evaluating the schools' energy performance by their climate condition is not a correct judgement.

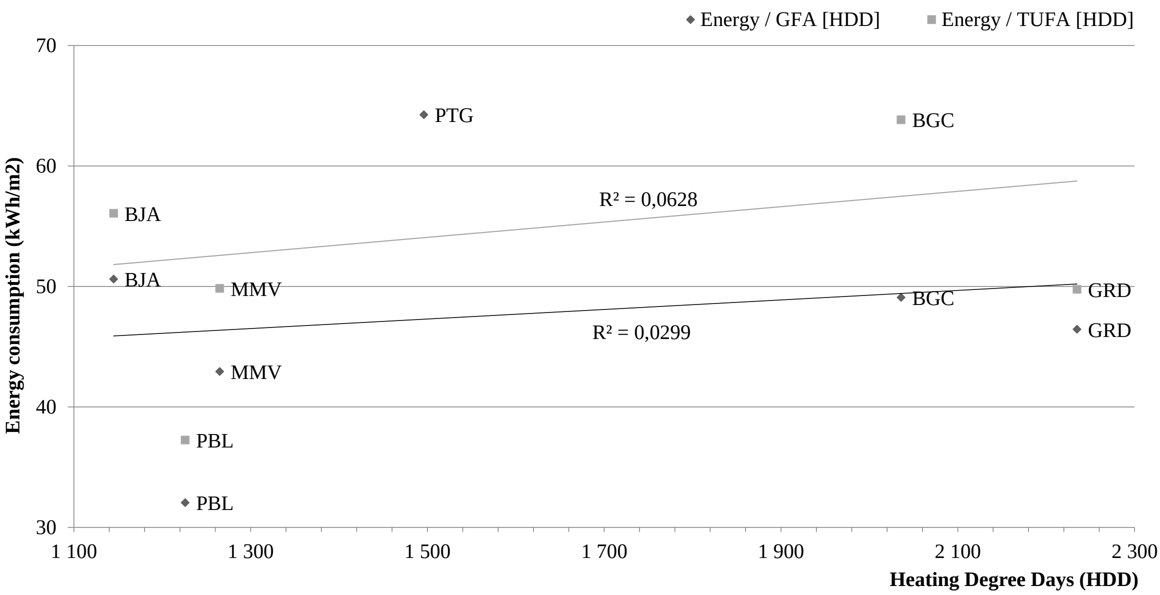


Figure 6 – Energy consumption (kWh/m^2) versus heating degree-days (HDD)

4.2 IEQ assessment

4.2.1 Results from objective assessment

4.2.1.1. Classroom indoor air temperature and relative humidity

The indoor air temperatures (Ta) distribution in both monitored classrooms in each school is presented in **Figure 7**. Only in a very few occasions Ta was below the lowest references values (≤ 20ºC), e.g. BJA's. Ta above 30ºC was only registered in one school, GRD. Indoor air temperatures in the interval 28-30ºC were also only detected in this school. In MMV, PTG, GRD and BCG it was verified a frequency increase in the interval 26-28ºC, corresponding to classrooms facing south. It is noticeable that only one school did not follow the trend, PBL, revealing lower temperatures in the classroom facing south, PBL2.

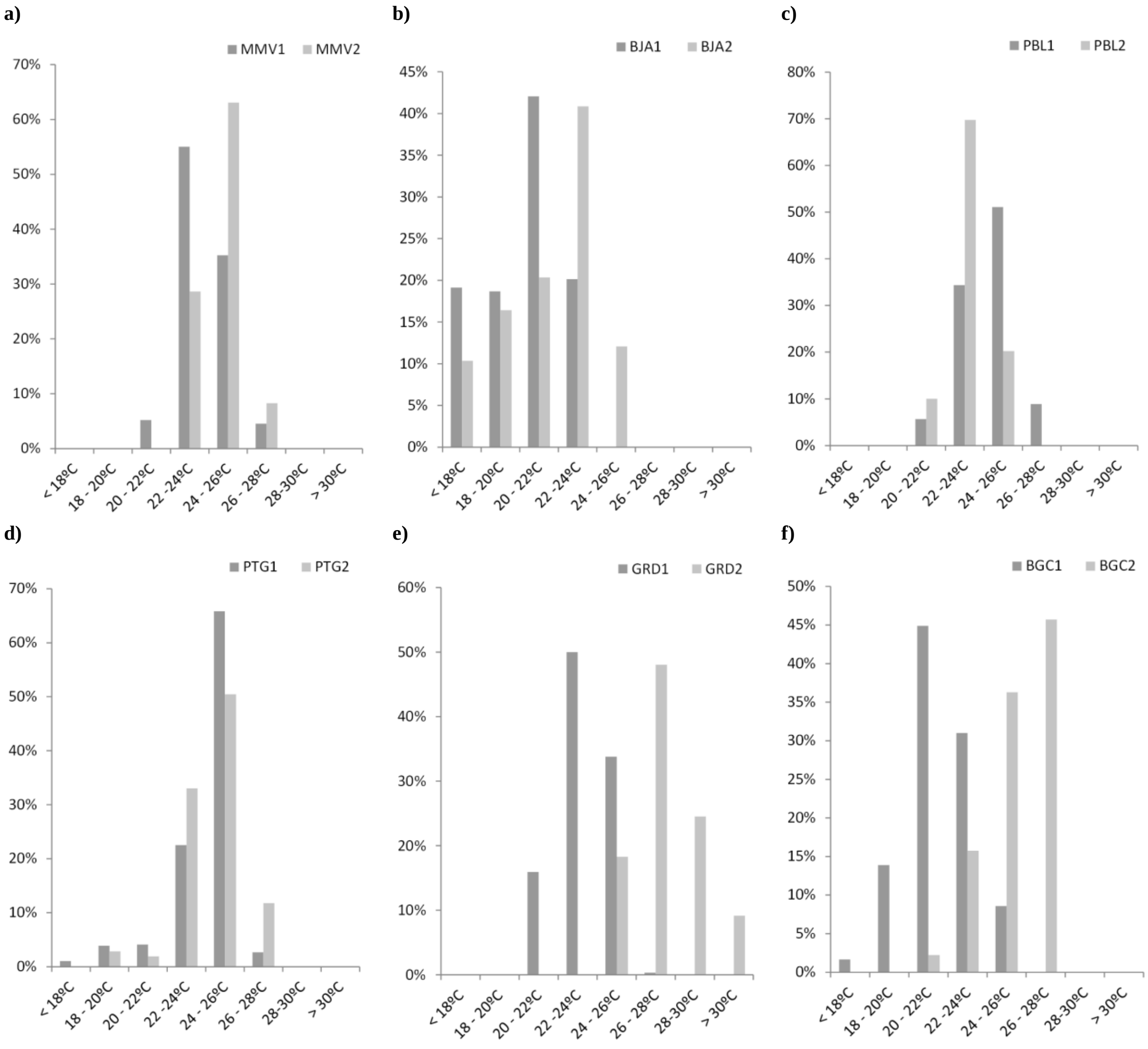


Figure 7 – Air temperature distribution intervals in the monitored rooms. (a) MMV; (b) BJA; (c) PBL (2014 monitoring); (d) PTG; (e) GRD and (f) BGC

One of the issues that might contribute to the results obtained in PBL classrooms is their occupancy characteristics (e.g. age or density). The results herein presented, relating PBL, correspond to the 2nd monitoring campaign, in 2013/14 scholar year. PBL1 was occupied by a 28-student 10th grade class, while PBL2 was mostly occupied by a 29-student 8th grade level class. Moreover, occupancy schedule in the PBL2 was "favoured", i.e., between morning and afternoon classes, longer lunch break periods were foreseen in PBL2.

Indoor Ta values higher than 26ºC were registered in MMV, PBL and PTG in less than 15% of the occupied periods. The most extreme values were found in GRD and BGC classrooms, both facing south (**Table**

4). In fact, Ta distribution frequency in GRD and BGC varied significantly between classrooms. It is noteworthy that these two schools were monitored practically at the same time, in the beginning of autumn 2013. In rooms facing NE (GRD1 and BGC1), the correspondent percentages to 20–24ºC interval were 66% and 76%, respectively. In classrooms facing South (GRD2) and SE (BGC2), the range 24–28ºC corresponded to 66% and 88% percentages. The asymmetric temperature difference between BGC1 and BGC2 is in accordance with the scholar population, which complained in BGC2 for being school hottest classroom.

Temperatures lower than 18ºC were only verified in three schools: BJA, PTG and BGC and only during short periods, 20%, 1% and 2% of the overall monitoring period, respectively. Furthermore, it was observed that in MMV, Ta varied between 22 and 26ºC, more than 90% of the occupancy periods, and surpassed 80%, either in PBL or PTG; in BJA, Ta varied between 20–24ºC more than 60% of the occupancy periods.

It is worth reminding that Ta analysis should be done considering external conditions, but it was not possible to run the monitoring campaigns all at the same time in all the schools. Furthermore, in many cases, school buildings were in free-running mode, at least during a significant part of the monitoring periods – HVAC systems were often activated during part of the morning time only, e.g. 7:00-10:00, to compensate night cooling, or were simply turned off due to energy costs constraints.

Nevertheless, building on **Table 4**, it can be stated that mean temperature values, registered during the occupancy periods, were quite satisfying (i.e., respecting the reference norms), excluding GRD2 and BGC2.

Table 4 – Summarizing table of the Ta (ºC) statistic data during the occupancy periods in the monitored classrooms (*as defined in* ***Appendix C****, C1 – C8 in* [53])

Statistic data	**MMV1**	**MMV2**	**BJA1**	**BJA2**	**PBL1**	**PBL2**	**PTG1**	**PTG2**	**GRD1**	**GRD2**	**BGC1**	**BGC2**
Highest	26.9	26.2	23.0	25.9	27.4	25.5	26.3	27.3	26.2	30.7	25.5	27.5
lowest	20.7	22.7	16.1	17.4	21.2	20.8	17.4	19.6	20.4	24.8	16.4	21.3
average	**23.8**	**24.8**	**20.3**	**21.6**	**24.4**	**23.3**	**24.1**	**24.3**	**23.4**	**27.5**	**21.6**	**25.6**
St dev	1.2	1.0	1.8	2.1	1.3	0.9	1.7	1.5	1.2	1.6	1.7	1.4

Note: PBL = 2nd monitoring campaign, 2014

Relative humidity (RH) in the classrooms was almost always within the reference values (30%–70%). In fact, this was the monitored parameter with best results within the analysed classrooms. Since the percentages of compliance values were quite satisfying, no further attention is addressed on this subject.

4.2.1.2. Classroom IAQ and CO2 concentration values

Like indoor particulate matter [54], [55], CO_2 concentration values are related to occupancy. The threshold limits specified by the current Portuguese legislation for CO_2 in the indoor air are 2250 mg/m^3 (1250 ppm), average concentration value during the various occupancy periods.

The results of the percentage of compliance with CO_2 parameters were not fully satisfying, because they were analysed using 1250 ppm as the upper limit (and not as an average threshold as suggested in the current legislation, 2013 [56]). This was intentionally done towards contrasting the precedent legislation, 2006 [11] – 1000 ppm upper concentration limit. When investigated in light of the 2013 legislation [56], the results obtained in some of the schools, even under the absence of mechanical ventilation systems in action, were not so bad: along the various occupancy periods the values varied between 387–3526 ppm in the six monitored schools (**Table 5**).

Table 5 – Summary table of the average and maximum CO_2 (ppm) concentration average values during the occupancy periods (*as defined in **Appendix C**, C1 – C8 in* [53])

Room	**Average**			**Max**	**PD (%)**
	min and max values	**St dev.**	**% compliance** (average ≤1250 ppm)		(average PD ± stdev)
MMV1	718 – 3303	742	53.3	7142	27.8 ± 11.3
MMV2*	1380	0	**0**	2623	26.7
BJA1	387 – 2235	686	50.0	6223	23.6 ± 14.5
BJA2	458 - 3103	830	40.0	7645	26.3 ± 15.2
PBL1	1389 - 3255	658	**0.0**	8076	36.5 ± 8.1
PBL2	1081 - 3029	546	**10.0**	7747	36.6 ± 7.6
PBL1 (2nd Period)	743 - 1876	379	66.7	4598	23.5 ± 7.4
PBL2 (2nd Period)	736 - 1311	175	77.8	2765	20.4 ± 4.0
PTG1	976 - 2112	426	37.5	3775	28.5 ± 7.1
PTG2	856 - 1757	312	50.0	4615	24.1 ± 6.0
GRD1	561 - 3526	729	**13.3**	6804	33.0 ± 11.0
GRD2	975 - 2195	305	46.7	3336	24.9 ± 5.2
BGC1	531 - 2684	543	47.4	3871	26.7 ± 8.9
BGC2	552 - 1938	619	50.0	2922	21.7 ± 13.1

*Note: * Due to the monitoring unpredicted interruption, only one monitoring period was obtained, therefore there is not an average interval, but only one single value.*

As shown in **Table 5**, in terms of the current national regulation [56], the CO_2 reference value was fulfilled only 50% of the time (average ≤ 1250 ppm), what still expresses a general unsatisfying result in terms of IAQ. Most significantly is the case of the schools in which none of the monitored rooms presents a satisfying concentration value (e.g. Guarda, average CO_2 percentage of compliance lower than 50%).

Moreover, the maximum recorded CO_2 values were always above 1800 ppm (at times reaching values above 5 000 ppm, 33% of the maximum CO_2). As suggested in [37], *"by plotting the average indoor CO_2*

*concentration values in the expression PD (%) = 395*EXP (-15.15*C_{CO2}^-0.25)* [57], *where the PD is expressed in terms of CO_2 concentration values in excess to outside air (ppm)"*, the PD values, presented in **Table 5**, were obtained. Since outdoor CO_2 concentration values were not measured, a value of 380 ppm was estimated.

The school with the best results was PBL. In contrast, GRD1 is one of the rooms with worst performance in terms of IAQ, which might be justified by the very low ceiling (< 2.50 m) and volume (<133 m^3) of the room, consequently, being more difficult to dilute CO_2 due to human occupancy.

The values presented for MMV2 (**Table 5**) are less significant because they correspond to a single sample. The results obtained for PBL1 and PBL2 were also considered less significant in the analysis, because the 2nd monitoring campaign in this school did not confirm the bad performance of the first monitoring period. It is noteworthy that during the 2nd campaign (the consecutive scholar year), an increase of the room occupancy was verified and the results were still better. One of the reasons might be due to the period of the campaign, May/June 2014, in which higher temperatures outside could motivate opening the windows more often.

Deepening this analysis, based upon the EN15251 [58], the CO_2 evaluation was expressed in concentration above the outdoor CO_2 concentration. It was verified that in all the classrooms, during a significant percentage of the occupied time, the values fall into the optimum category that is normally used for "recommended for spaces occupied by very sensitive and fragile persons with special requirements". In theory, the six schools under study should fit between categories II and III (new buildings and major renovations; existing buildings). These results, summarized in **Figure 8**, revealed that there was significant improvement potential of IAQ, since schools unveil great IAQ levels in the worst performing category.

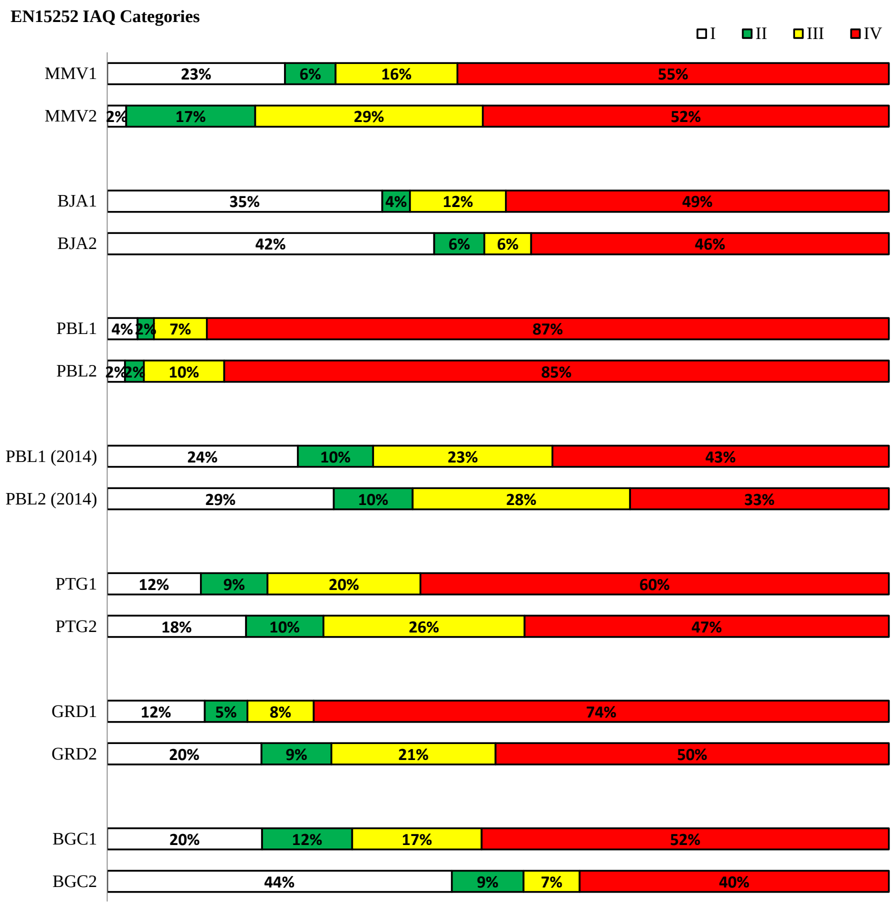


Figure 8 – Concentration evaluation expressed in percentage of time during occupancy periods in IAQ categories, according to the values of Table B4 in EN15251, expressed in concentration above outdoor concentration (considered 380 ppm)

4.2.1.3. Classrooms' AER

In **Table 6** the obtained values for AER and fresh air rates (Q) are presented. Only robust AER estimations were considered (regressions achieving high R^2), like the example illustrated in **Figure 2**.

Table 6 – Summary table of the AER and Fresh air rate (Q)

Classroom	N	Air Exchange rate (λ, h^{-1})					Fresh air flow rate (Q= V x λ)
		Min	Max	Average	ST Dev	Coefficient of variation (%)	m^3/h
MMV1	7	0.10	0.14	**0.11**	0.02	15	14.3
MMV2	1	-	-	**0.20**	-	-	28.1
BJA1	7	0.14	0.18	**0.16**	0.01	8	25.6
BJA2	5	0.12	0.19	**0.14**	0.03	20	22.4
PBL1	6	0.08	0.13	**0.11**	0.02	23	15.1
PBL2	4	0.09	0.15	**0.12**	0.02	20	17.2
PTG1	4	0.10	0.28	**0.18**	0.09	49	28.4
PTG2	2	0.12	0.22	**0.17**	0.08	46	26.1
GRD1	8	0.03	0.29	**0.15**	0.09	62	19.6
GRD2	7	0.03	0.14	**0.07**	0.04	55	12.8
BGC1	6	0.16	0.31	**0.21**	0.05	26	27.2
BGC2	-	-	-	-	-	-	-

Note: N = sample size; Q = fresh air flow rate; V = classroom volume (m^3); λ = air exchange rate (h^{-1}).

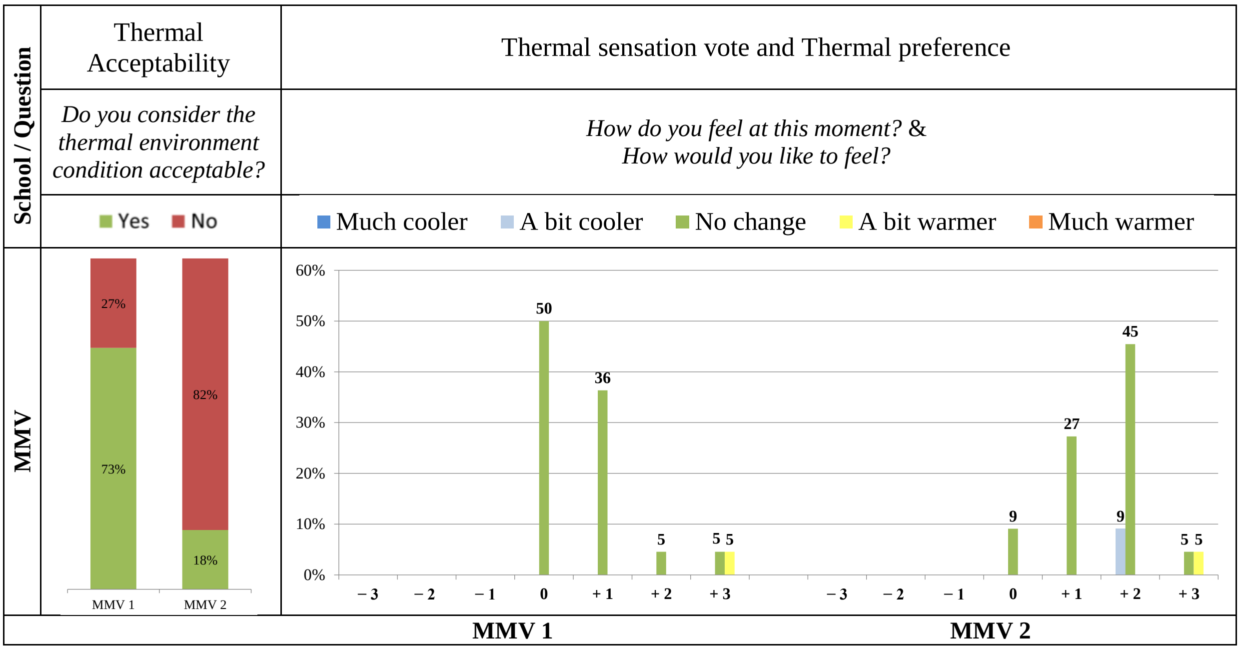
Some observations regarding these results are noteworthy. A single value is presented for MMV2 and no values are presented for BGC2, due to the fact that the monitoring equipment was early turned off. Also, the high coefficient of variation of some classrooms shows the misleading character of the average as a statistical indicator (e.g., GRD1 and GRD2). In fact, either in GRD and PTG, the high degree of relative dispersion of the sample exposes the difficulty/ambiguity of presenting a solid value that represents each of the schools. Looking at GRD, the standard deviation (ST Dev) obtained in GRD1 is higher than the average value obtained for GRD2. In this particular case, such different results might be related with the classrooms location within the and with the impact of the wind flows in such a complex building. Building on these observations, a mean AER value is not presented for all the schools.

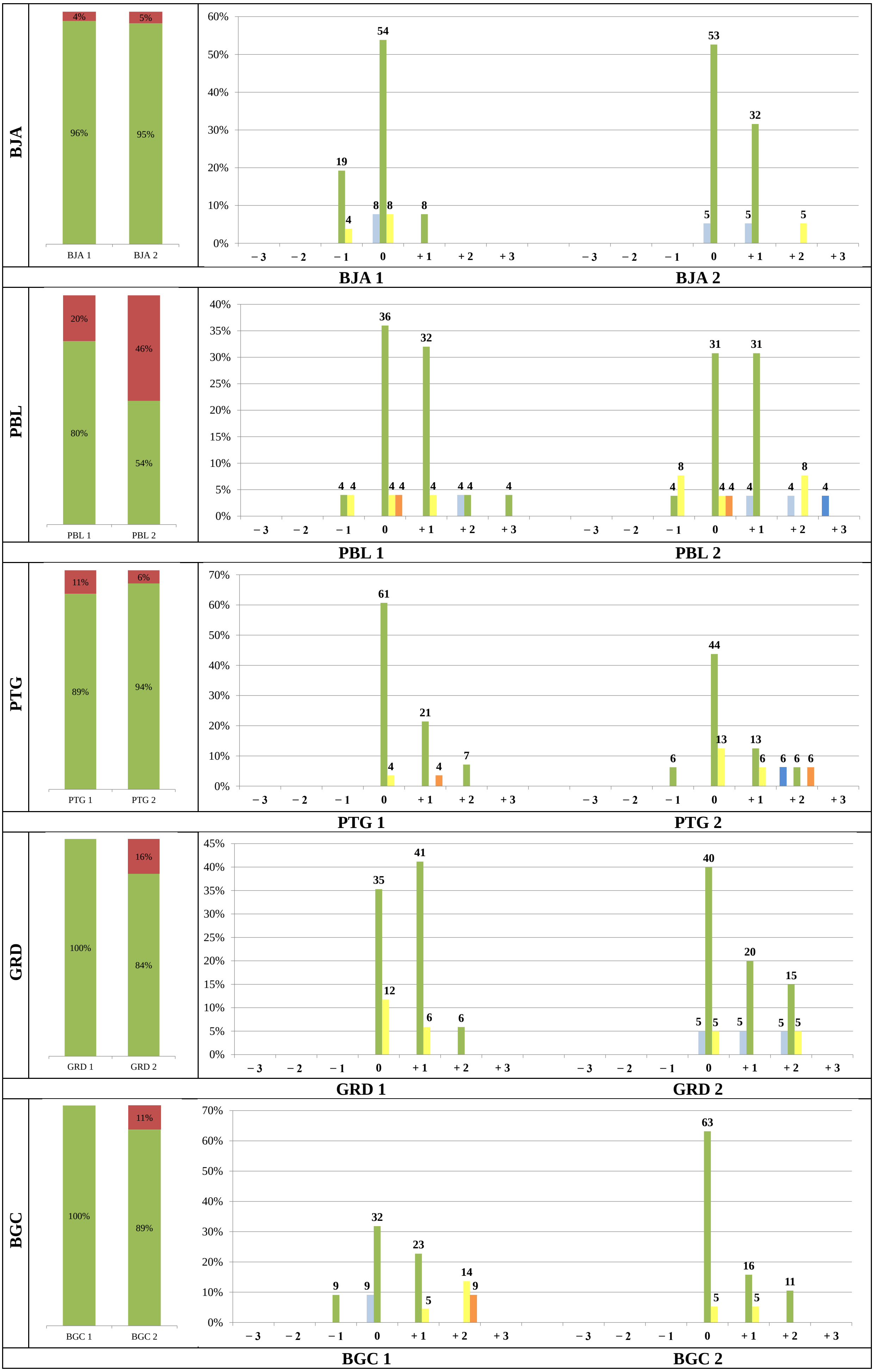
The results herein presented are significantly lower than those reported in previous studies, e.g., in Michigan schools [50] 0.6 ± 0.3 per hour. This shows the current airtightness condition of the refurbished schools.

4.2.2 Results from subjective assessment

4.2.2.1 Answers from the questionnaires

Figure 9 and F**igure A.2** (in Appendix) present the answers to: Thermal Acceptability (TA) - *Do you consider the thermal environment condition acceptable?*; thermal comfort (TC) questions, such as *How do you feel at this moment?; or How would you like to feel?*; and IAQ votes to *Air stiffness*, *Air smells* and *General air quality*.





BJA
4%
5%
96%
95%
BJA 1
BJA 2
BJA 1
BJA 2
PBL
20%
46%
80%
54%
PBL 1
PBL 2
PBL 1
PBL 2
PTG
11%
6%
89%
94%
PTG 1
PTG 2
PTG 1
PTG 2
GRD
16%
100%
84%
GRD 1
GRD 2
GRD 1
GRD 2
BGC
11%
100%
89%
BGC 1
BGC 2
BGC 1
BGC 2

Figure 9 – Summary table of the 12 classrooms' conditions (average) during the questionnaire

4.2.2.2 *Estimation on comfort indices based on schools' data collection*

The complete procedure of estimation of comfort indices Fanger's thermal comfort indices based on schools' data collection has been previously exposed in [59]. Likewise, *"aiming at comparing PMV and PPD indices, with the results obtained from the questionnaires"*, three results for each classroom were obtained. All the simulations and values can be found in [53] (Appendix F).

Figure 10 presents a synthesis of the simulated results in the six schools. The survey in PBL was driven during the second monitoring period. Regularly, PMV index is expressed between -3 and +3. Herein, the interval was reduced since all the simulated values fit -2 and +2, emphasizing the small deviation estimated.

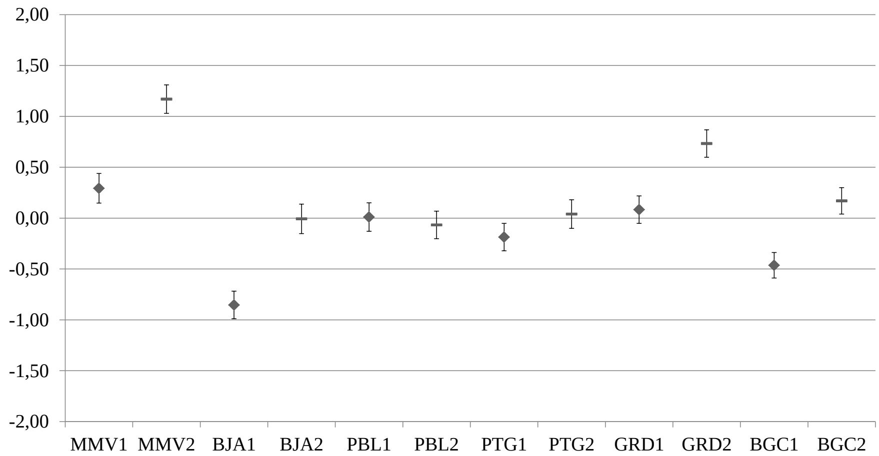


Figure 10 – PMV calculated votes (mean and standard deviation) based on simulation

4.2.2.3 *Indoor air quality analysis based on CO_2 concentration values*

Following the reasoning previously presented in **section 4.2.1.2** (IAQ and classrooms' CO_2 concentration values), i.e. *"by plotting the metered average indoor CO_2 concentration values in the expression PD (%) = 395*EXP (-15.15*CCO2^-0.25)"*, the percentage of dissatisfied (PD) was determined.

As in [59], in **Figure 11**, PD with IAQ in classrooms during the questionnaires (CR 1752-1998 [60]) is plotted together with PD derived from the questionnaires. Considering this pollutant concentration levels, it would be expected a higher value of PD (with the exception of room MMV2 for which monitored values were not available). *"This study confirms other studies where the subjective assessment is made by "outsiders" and not by the actual occupants, whose vote was more "sensitive", i.e. not accommodated* [61]*"* in [59].

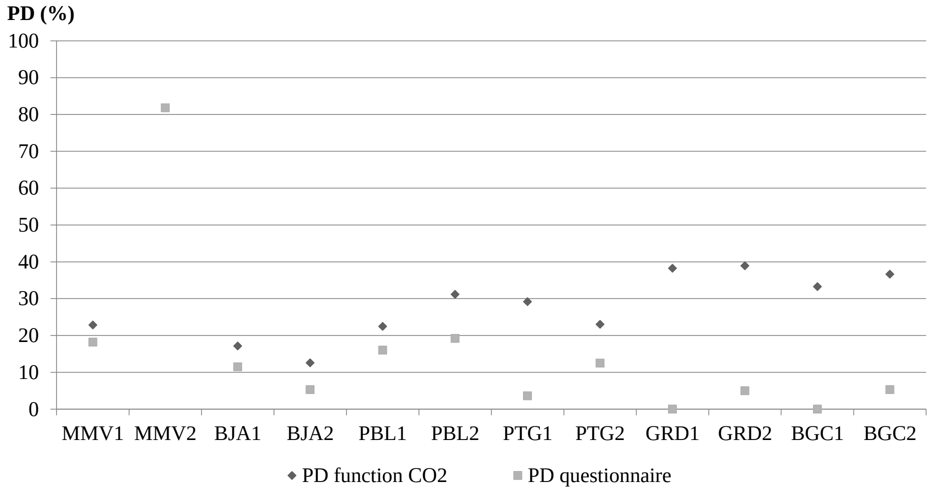


Figure 11 – Percentage of dissatisfied estimated on CO_2 concentration excess in relation to outside air (CR 1752-1998) plotted together with PD values from the questionnaire

5. Discussion

Within this paper, six out of the eight secondary schools integrating the 3Es Project, were studied in terms of their energy consumption and IEQ performance.

When first tackling their energy performance, different approaches of data normalization were explored. Aiming at creating a feasible and precise School Building Indicator (SBI), through the exploitation of different variables (area/ no. students/ HDD), different results were obtained.

This study reinforces the complexity of benchmarking as presented in previous studies [52] [62]. In fact, the approach suggested in [62], of one climatic indicator integrating a potential weather adjustment – $kWh/m^2/HDD$, proved to be clearly misleading.

Based on the indicator kWh/m^2, expressed in GFA or TUFA, the median and 25th percentile results of the six-school sample allowed establishing a typical (typ) and a good practice (gp) value. Based on [62], in **Figure 12**, TUFA values (the less favourable values) are compared with the ones presented in the literature relating to consumed energy values in secondary schools.

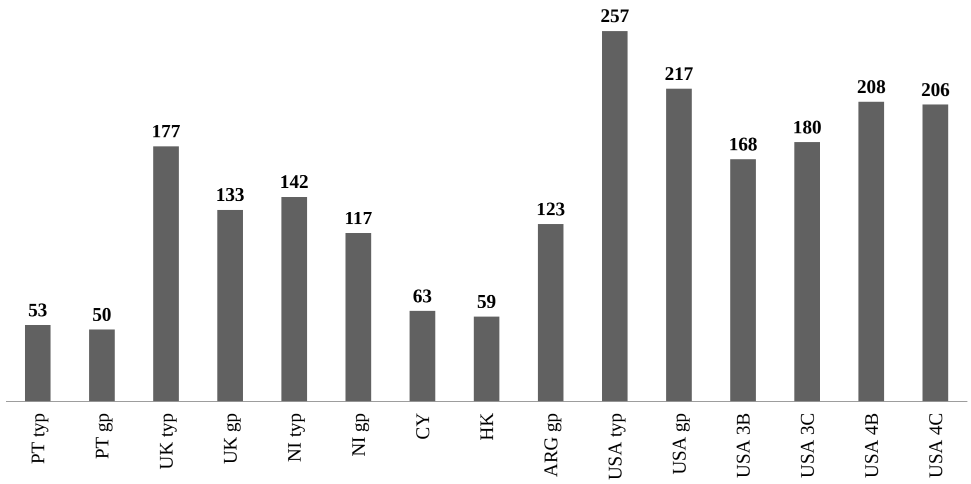


Figure 12 – Secondary schools' annual global energy consumption values per country (kWh/m^2)

The following notes are worth mentioning: (i) Portuguese, United Kingdom (UK) and Northern Ireland's values correspond to the median (typ - typical) and 25% percentile (gp – good practice) values; (ii) Cyprus (CY) and Hong Kong (HK) values are not referred (average values?); (iii) Argentina (ARG) gp values correspond to a mean value; United States of America (USA)'s values were determined by the authors of [62], based on data available in [63], for the 8 climatic zones (typ and gp also correspond to the median and 25% percentile values of all the climate zones) – the four climate zones here presented are the ones closer to the Portuguese condition.

The Portuguese SBI indicator of 53 kWh/m^2 (typ) is definitely much lower than all the other observed data. One of the reasons explaining these results might be due to the non-continuous operation of the HVAC systems in schools (mostly due to energy and operation costs). The implications of this general low HVAC systems operation were shown in the previous sections.

As seen in **Figure 10**, not all the obtained values respect the conditions recommended by the standards – EN 15251:2007, Category II: PPD <10 and PMV ± 0.5 (table A.1, Annex A). Namely MMV2, BJA1 and GRD2 with calculated PPD of 34.0, 20.6 and 16.5% respectively. All the others are slightly above 5.0% but lower than 10%.

In **Figure 13**, the subjective evaluation of the thermal environment is plotted along with the PMV values calculated for each of the classroom (as previously presented in **Figure 10**). A summary of the thermal conditions (indoor Ta, ºC) of the classrooms during the questionnaires' period, plotted with PMV simulations (in grey) and thermal sensation votes (TSV, in black), mean and standard deviation votes is presented. Generally, TSV in classrooms "accompanies" indoor Ta (ºC), e.g., in BJA2 (Ta = 25.2 ºC), and TSV = 0.47 while in GRD2 (Ta = 26.8 ºC) and TSV= 0.75.

Although TSV overestimates PMV in all cases except for MMV1, in 75% of the cases thermal acceptability (TA), reported in **Figure 9**, was higher than 80%, even when T_a was higher than 25.0 ºC, as in BJA2 and GRD2. In GRD2, Ta was higher than 26.5 ºC, but only 15% voted *A bit cooler* and TA = 84%. In contrast, in PBL when Ta was slightly above 24 ºC, TA was quite reduced, 54%. Curiously, in cases of lower TA as in MMV, either in classroom 1 or 2 (TA= 73% and 18%), TSV were still satisfactory: in MMV1, 95% voted *No change*, besides Ta was higher than 25 ºC. And in PBL2, were only 54% stated accepting the thermal environment, only 12% voted *A bit cooler* or *Much cooler*.

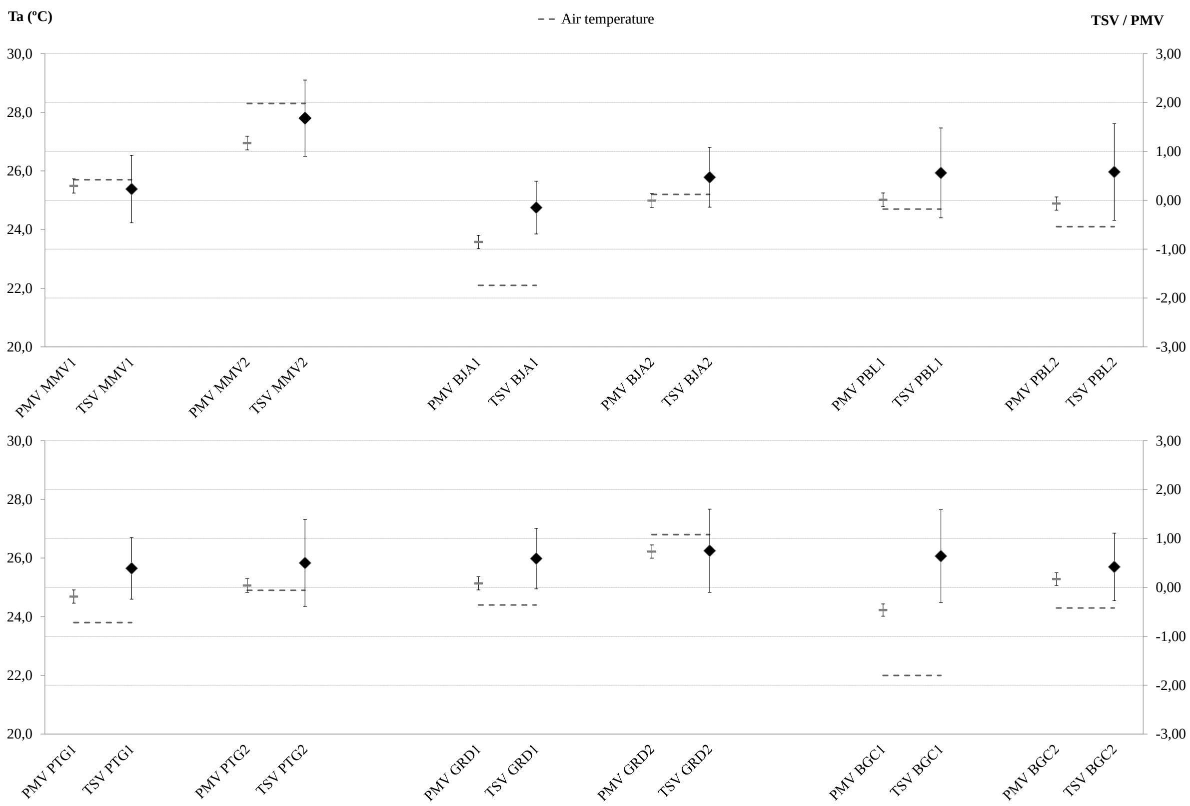


Figure 13 – Air temperature values plotted against TSV and PMV (mean and standard deviation)

Generally, TSV are spreader than PMV. Attempting separately the mean values for each of the classrooms, it can be seen that in classrooms BJA1, students perceived the thermal environment more comfortable than it would be expected from the calculated PMV - they did not perceive the environment so *cool* (Ta_{BJA1} = 22.1 ºC). The same reasoning can be drawn in classroom MMV1, but from the opposite perspective – in this case, students (TSV mean vote) did not perceive the environment so *Warm* (Ta_{MMV1} = 25.7 ºC).

In 67% of the schools, it was verified that the distribution of the votes tended to narrow with a decrease in the temperature (when comparing both monitored classrooms in each school), excepting PBL and BGC. This finding is divergent from to the one of H. Yun *et al*. (2014), [64] − which may be explained by the smaller Ta difference in our case studies (< 3ºC) in comparison to a higher Operative Temperature difference in [64] (~ 8ºC) or by the differences of the sample size. In PBL the Ta difference is very small (< 1ºC) to allow any conclusive remarks. The only exception is in fact BGC, where $TSV_{BGC1} = 0.64 \pm 0.95$ and $TSV_{BGC2} = 0.42 \pm 0.69$ ($Ta_{BGC2} > Ta_{BGC1}$).

IAQ subjective assessment did not differ much across the schools: *Air stiffness* votes were rather distributed in both monitored classrooms in each school. In a more detailed analysis, BGC was the school better performing in this evaluation with more than 68% of the votes between *Good* and *Exceptional*, followed by PTG, GRD and BJA. The school worse performing in terms of *Stiffness perception* was definitely MMV, particularly classroom MMV2. Although Ta was an estimation (since we were not able to register it), this was the classroom with higher Ta during the survey, Ta ≥ 28.3 ºC. *Air stiffness votes* might have been influenced by this factor. This condition might also have influenced *Air smells* votes, where again, MMV is the school with worst results. BGC is once more the school with more satisfying votes, followed by GRD and PTG. Classrooms in MMV and PBL reveal high contrast between them – MMV1 votes are far more satisfying than MMV2 and in PBL, PBL2 votes are far much better than PBL1.

General air quality votes were explored in **section 4.2.2.3** and **Figure A.2**. It is significant that in some schools, a substantial number of respondents were unable to define their votes (voting *Undefined*), e.g. PBL and GRD, circa 50%. Once again, MMV2 was the classroom with worst votes – this was already quite visible in **Figure 11**; however, it was not possible to compare these votes with predictable PD due to absence of monitored CO_2 data. BGC global assessment confirms the previous IAQ votes, with circa 70% of the students in both classrooms voting between *Good* and *Exceptional*, and registering the lowest *Undefined* votes from all the sample, <20% in both classrooms and only 5% negative votes in BGC2.

5.1 Conclusions

The work presented aimed at evaluating both the energy and IEQ performance TC and of recently refurbished Portuguese secondary schools running in free running conditions / natural ventilation mode or mechanically ventilated, mostly during mid-season. The energy consumption data unveiled quite low values when compared with other buildings of the same typology. The costs of this condition are expressed in the IEQ evaluation of the classrooms in these schools.

Herein, the indoor climate quality was tackled by the comparison between the subjective votes (TSV) and predicted votes, deriving from the objective monitoring of some environmental parameters, allowing the test in field, both in the "traditional" approach and in the adaptive one. This study strengthened findings of former studies conducted in classrooms – *"students in secondary schools in Mediterranean climate under free running conditions in mid-season"*[37]:

- stated accepting indoor T_a up to 25.2 ºC, in BJA (TA = 95%) or even above 26.5 ºC, in GRD (TA = 84%);
- expressed TSV for *no change*;
- confirmed that *thermal neutrality* is not the preferred state.

On the basis of these results, a trend was found for the thermal preference from *Slightly warm* environments in the mid-season: higher temperature ranges than those presented in the norms are accepted.

Concerning IAQ, focusing on CO_2 concentration levels, the perceived votes reveal students' adaptation to the environment exposure. Moreover, it was found that IAQ regulations are not being fulfilled. The concentration of this pollutant frequently exceeded the national and international reference limits.

In Portugal ventilation rates are dependent on indoor pollution sources and occupancy (like in North America, where these are regulated by ASHRAE 62.1-2010 [34]). In the UK, the recent version "Facilities Output Specification for School Buildings" [65] and BB101 [21] "provide guidelines on maximum CO_2 levels" (<5000 ppm and < 2000 ppm for more than 20 minutes at a time) and minimum ventilation rates to ensure adequate IAQ in classrooms", namely, that average ventilation rates shall be above 5 L/s-p (18 m^3/h) and ventilation rates above 8 L/s-p (28.8 m^3/h) shall be easily achieved by the occupants.

The AER values obtained in the schools under-study reveal their airtightness condition. AER need to be adjusted to remove indoor pollutants during non-occupancy periods. However, during occupancy periods, opening windows or HVAC systems are needed to maintain air quality levels. High CO_2 concentration values were found indoors because, in most cases, HVAC systems were turned off due to energy costs.

Drawing on these results, indications to school directors and teachers should be given in the sense of promoting /increasing AER when systems are not active, namely through window(s) and/or door opening, to improve IAQ conditions. Lesson breaks are a good opportunity for air renewal. Besides improving IAQ, adaptive actions as windows opening/closure or shading device manipulation, may help controlling microclimate conditions. In many situations these depend on the teacher's behaviour, more than students'[66]. Although adaptive opportunities in classrooms are relatively scarce, in Portuguese public schools, there is no obligatory uniform, for which students may add or remove layers of clothing.

Appendix

Table A.1 – Syntax table of the 6 schools classrooms and windows' characteristics

School / Room		Height (m)	Width (m)	Area (m^2)	Total Area (m^2) | (nº units)	Windows images
MMV1 & MMV2	**Window**	1.98	2.10	4.16	8.32 (2)	
	Window (opening)	1.98	1.05	2.08	4.16 (2)	
MMV1 and MM2 are located in different buildings. Room MMV1 is located in A3, NW oriented and MMV2 is located in A1, SE oriented. Windows are equal in both rooms: double casement windows. Window opening area corresponds to the area of a single casement.						
BJA1 & BJA 2	**Window**	1.80	1.20	2.16	8.64 (4)	
	Window (opening)	1.24	0.60	0.74	2.98 (4)	
BJA1 and BJA2 are both located in building A, facing N and S respectively. Windows are equal in both rooms: sliding windows with a superior hopper. Only the sliding windows were considered on window opening since it was verified that the hopper window was always obstructed by the blinding system.						
PBL1 & PBL2	**Window**	0.42 + 1.08	3.49	5.24	10.47 (2)	
	Window (opening)	0.42 + 1.08	1.11	1.67	1.67 (1)	
PBL1 and PBL2 are both located in building A, facing NW and SE respectively. Each glazed area) is composed of sliding windows and an upper glazed surface composed of two fixed glasses and one hopper. Window opening area was estimated as the area of one 'slid' and the mid centre hopper windows area.						
PTG2	**Window**	1.82	2.3	4.19	12.56 (3)	
	Window (opening)	1.20	0.77	0.92	2.73 (3)	
Room PTG2 is located in building C, S oriented and PTG1 is located in building F, N oriented. PTG1 has one more window, i.e. the total values presented for windows surfaces in PTG1 are 16.75 (4) and 3.67 (4) for window opening. Each glazed surface has a casement window = window opening area.						
GRD1 & GRD2	**Window**	0.60 + 1.20	3.6	6.48	12.96 (2)	
	Window (opening)	1.2	1.2	1.44	2.88 (2)	
Room GRD1 is located in building E, S oriented and GRD2 is located in building G, E oriented. Windows are equal in both rooms. Since the opening window is a tilt and turn unit, for window opening it was estimated the totality of the window opened as a casement window.						
BGC1	**Window**	1.53	1.39	2.12	6.36 (3)	
	Window (opening)	—	—	—	1.59 (3)	
BGC1 and BGC2 are both located in building A, facing W and E respectively. Windows are equal in both rooms: double hung (or double hopper) windows. BGC2 has one more window, i.e. the total values presented for windows surfaces in BGC2 are 8.48 (4) and 2.12 (4) for window opening. Window opening was roughly estimated as ¼ area of the windows area.						

Table A.2 – Schools' characterization synthesis: main construction elements of the 6 schools pre and post- intervention, as presented in [67], [68], [69] (Parque Escolar EPE publications).

School	Typology	Initial building construction characteristics (general notes)	"New" building construction characteristics (short notes)
GRD 1969	**Special Design**	**Plan of 1958** [68] 1960 | Preliminary draft Arch. António Maria Veloso Gomes 1965 | Project Arch. António Maria Veloso Gomes Special characteristic: winter playground area	**Intervention date:** July 2009 – December 2011 **Walls:** Thermal insulation on the outside over existing walls (60mm *ETICS*) **Ceilings**: OSB panels
PTG 1976/77	**Lyceum Pavilion Type**	**Standardized studies of 1968** [68], [69] General author: JCETS | Project Arch. Maria do Carmo Matos Normalized project, general construction references: ▪ lattice structure (7.20 m x 7.20 m); exposed concrete elements (pillars & beams) ▪ single structure dimensioning : pillars & beams (interspace between pillars) ▪ brick masonry elements exposed or covered w/ painted plaster ▪ 3 normalized types of bricks for walls ▪ 2 types of indoor openings (general doors & toilet doors)	**Intervention date:** September 2008 – June 2010 **Walls:** Thermal insulation (40+10mm) "PladurTerm-N (xpe)" or 40 mm rock wool covered w/ painted plasterboard) applied on the inside over existing walls – brickwork or concrete
BJA 1960	**Industrial and Commercial Technical School**	**Buildings for technical and vocational education – technical schools** [68] General author: JCETS Preliminary draft – Technical school type (1950) [69] Special characteristic: workshop area w/ significant dimension Normalized project, general construction references: ▪ spatial reorganisation – central corridor, both length regular classrooms and drawing classrooms, facing North & South ▪ classrooms resizing – 6.8 m x 7.5 m (vs. 6 x 9 m previous preliminary drafts) – more "squared" ▪ drawing classrooms w/ new length – 15 m (holding bigger size drawing boards) ▪ workshops length reduction – from 10 m to 7 m ▪ main classroom building - ceiling height reduction to 3.6 m (vs. 4 m previous height) ▪ workshops ceiling height reduction – 4.5 m ▪ general resizing of the buildings – classrooms 4 floors high & physical education 3 floors high **4^{th} Normalized project – Technical school type (1960') [69]** ▪ building blocks connected through outdoor covered galleries ▪ adaptability to the site slope	**Intervention date:** October 2008 –November 2009 **Windows:** Aluminium frames + double glazing **Shading devices**: Translucent and opaque interior blinds – classrooms; Exterior blinds – labs
PBL 1963/64			**Intervention date:** October 2008 – November 2009 **Walls**: 30 -50mm insulation (XPS or polyurethane projection foam), covered by an external cladding of GFRC, added to existing walls **Windows:** thermal cut aluminium frames + double glazing (tempered ext. glass)
BGC 1962			**Intervention date:** July 2009 – March 2012 **Ceilings**: Suspended microperforated plasterboard (thermal & acoustic) **Walls:** Thermal insulation on the inside over existing walls (60mm XPS covered w/ painted plasterboard)
MMV 1970's	**3x3 Pavilion Type**	**Type projects for secondary schools** [68] **General author | DGEE – Maria do Carmo Matos** Normalized project, general construction references: ▪ modular classroom sized $50m^2$, set in a regular grid 7.20 x 7.20m (structure) ▪ squared building blocks – 21.60 x 21.60 m, one or two floors high ▪ second module 0.60 m for furniture ▪ pillar-beam portico structure w/ reinforced concrete slabs ▪ no thermal insulation ▪ double pane brickwork exterior walls	**Intervention date:** July 2009 –November 2010 **Ceilings**: Suspended microperforated plasterboard (thermal & acoustic) **Windows**: Aluminium/ galvanized steel/iron frames (no thermal cut) + double glazing (different widths) **Walls**: Plaster + brickwork / concrete + thermal insulation + ventilated cavity+ brickwork + plaster compound (indoor – outdoor) **Shading devices**: Translucent interior blinds

Table A.3 – Summary table of the energy and Indoor Air Quality monitoring equipment

Parameter		**Unit**	**Equipment**
Indoor Air Quality	Air temperature	ºC	Extech SD800 Datalogger, Tinytag Talk 2 Datalogger & Tinytag Ultra 2 Datalogger
	Relative Humidity	%	
	CO_2 concentration	ppm	
Energy	Electrical power	kW	Qualistar Chauvin Arnaux 8334

Note: Natural gas consumption was not monitored. Data analysis was performed based on energy bills and utility meters reading.

Table A.4 – Summary table of the 6 schools / 12 classes answering the survey

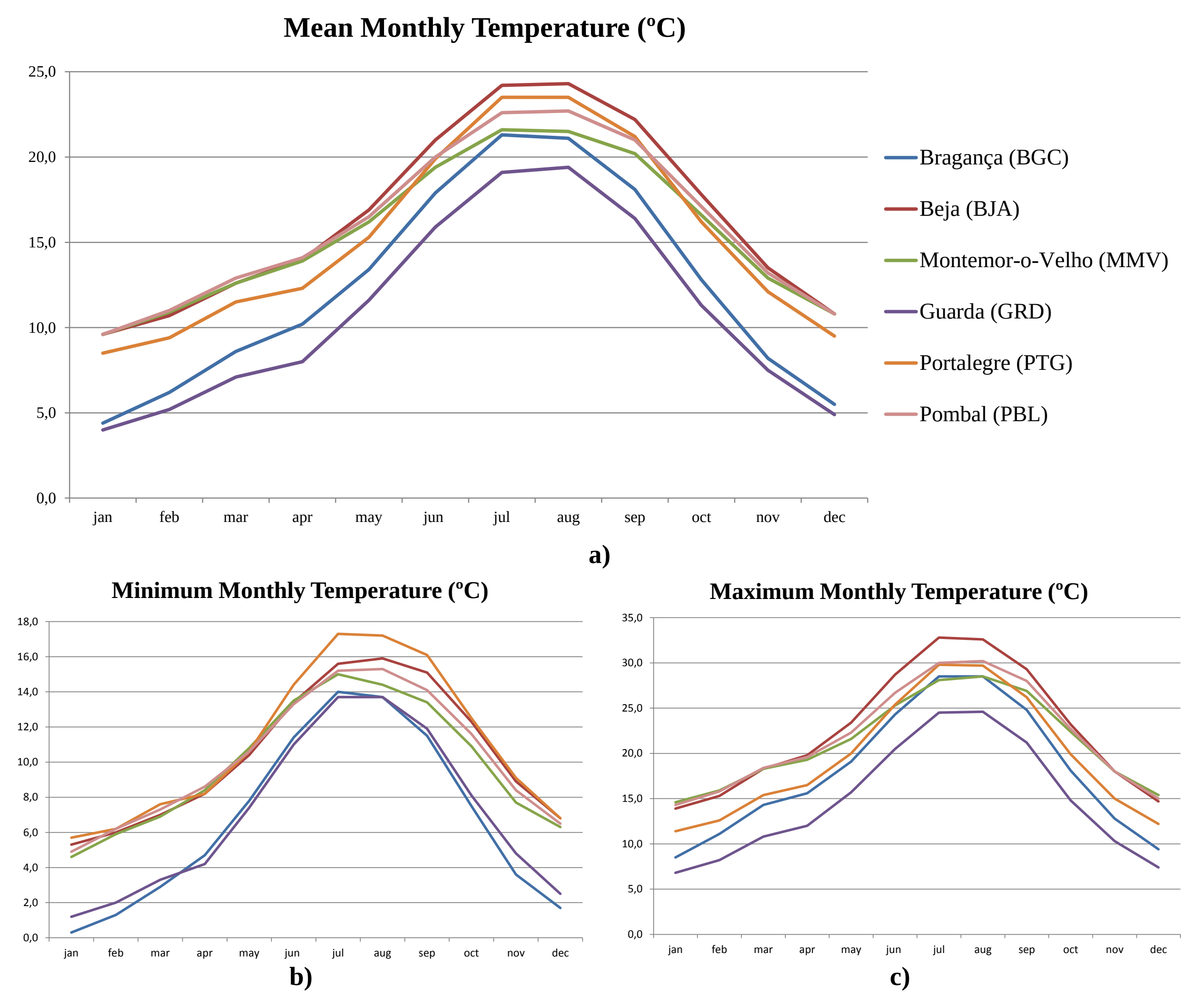
Room	CG	N	Anthropometric and gender data				Clo Insulation*		
			Gender (%)	Age (y)	Height (m)	Average BMI (kg/m^2)	M	F	Average
MMV1	11th	22	45 (M) / 55 (F)	16.5	1.67	22.0	0.53 ± 0.13	0.51 ± 0.11	**0.52 ± 0.11**
MMV2	9th	22	50 (M) / 50 (F)	15.2	1.67	20.9	0.59 ± 0.15	0.57 ± 0.15	**0.58 ± 0.15**
BJA1	11th	26	54 (M) / 46 (F)	16.7	1.71	21.1	0.46 ± 0.09	0.46 ± 0.05	**0.46 ± 0.07**
BJA2	10th	19	32 (M) / 68 (F)	15.6	1.64	21.7	0.44 ± 0.00	0.45 ± 0.05	**0.45 ± 0.04**
PBL1	10th	25	40 (M) / 60 (F)	15.6	1.67	22.0	0.43 ± 0.03	0.53 ± 0.10	**0.49 ± 0.10**
PBL2	8th	26	50 (M) / 50 (F)	14.2	1.62	21.3	0.51 ± 0.10	0.54 ± 0.10	**0.53 ± 0.10**
PTG 1	8th	28	25 (M) / 75 (F)	13.5	1.62	22.6	0.55 ± 0.17	0.54 ± 0.11	**0.54 ± 0.13**
PTG 2	10th	16	44 (M) / 56 (F)	15.5	1.68	20.7	0.55 ± 0.14	0.56 ± 0.16	**0.55 ± 0.14**
GRD1	11th	17	18 (M) / 82 (F)	16.0	1.64	20.5	0.65 ± 0.19	0.54 ± 0.11	**0.56 ± 0.12**
GRD2	9th	20	50 (M) / 50 (F)	13.9	1.67	19.7	0.61 ± 0.10	0.55 ± 0.15	**0.58 ± 0.13**
BGC1	9th	22	55 (M) / 45 (F)	13.6	1.64	19.1	0.62 ± 0.21	0.55 ± 0.10	**0.60 ± 0.16**
BGC2	9th	19	42 (M) / 58 (F)	14.1	1.65	22.1	0.59 ± 0.13	0.61 ± 0.09	**0.60 ± 0.11**

*Notes: CG = Class grade; N = number of students/validated questionnaires; BGC1, one questionnaire was not considered due to doubtful answers & in one of the questionnaires, the gender was not identified; * Clo insulation was calculated according to Table C.2 in* [30]. *The wooden chair insulation (0.01 clo according to Table C.3) was not considered.*

Table A.5 – Summary table of the 6 schools /12 classrooms conditions during the questionnaires

Room	Date / Time	Ta (ºC)	RH (%)	CO_2 (ppm)	Ext Ta (ºC)	Notes
MMV1	06/06/ 2013 @ 11:15	25.7	45.5	1178	16.8	Survey after the beginning of the class at 11:05 (after a small interval between classes). At that time, students had been inside the room for less than 15min.
MMV2*	06/06/ 2013 @ 11:45	28.3	50	-	16.8	Survey by the end of the class initiated at 11:05. Students had been inside the room for more than 30 min.
BJA1	13/05/ 2013 @ 12:00	22.1	55.2	924	25.8	Survey after the beginning of the class at 11:45 (after a small interval between classes). At that time, students had been inside the room for circa 15min.
BJA2	13/05/ 2013 @ 15:50	25.2	41.4	753	28.1	Survey a few minutes before the end of the class initiated at 15:15. Students had been inside the room for more than 30 min.
PBL1 **PBL2**	03/06/ 2014 @ 10:30	24.7 24.1	55.2 58.7	1159 1647	17.2	Survey after the beginning of the class at 10:30 (after the morning interval between 10:10 - 10:25).
PTG 1	10/05/ 2013 @ 10:30	23.8	50.8	1523	20.6	Survey after the beginning of the class at 10:20 (after the morning break between classes 10:00 – 10:20). At that time, students had been inside the room for circa 5min.
PTG 2	13/05/ 2013 @ 10:00	24.9	35.1	1188	25.4	Survey a few minutes before the end of the class initiated at 9:15. Students had been inside the room for more than 30 min.
GRD1	17/10/ 2013 @ 12:05	24.4	59.7	2152	18.3	Survey after the beginning of the class at 12:00 (after a small interval between classes). At that time, students had been inside the room for circa 5-10min.
GRD2	17/10/ 2013 @ 09:50	26.8	49.3	2205	17.7	Survey a few minutes before the end of the class initiated at 9:20. Students had been inside the room for circa 30 min.
BGC1	18/10/ 2013 @ 10:25	22.0	68.1	1786	13.2	Survey after the beginning of the class at 10:20 (after the morning interval between classes). At that time, students had been inside the room for circa 5-10min.
BGC2	18/10/ 2013@ 13:05	24.3	65.9	2027	18.6	Survey a few minutes before the end of the class initiated at 12:00. Students had been inside the room for more than 60 min.

Notes: MMV2. Since monitoring in MMV2 was earlier interrupted in 17/05/2013, Ta herein presented has been estimated based on temperature differences between Ta in the room and external temperature in 07/06/2013.RH was estimated as 50%.

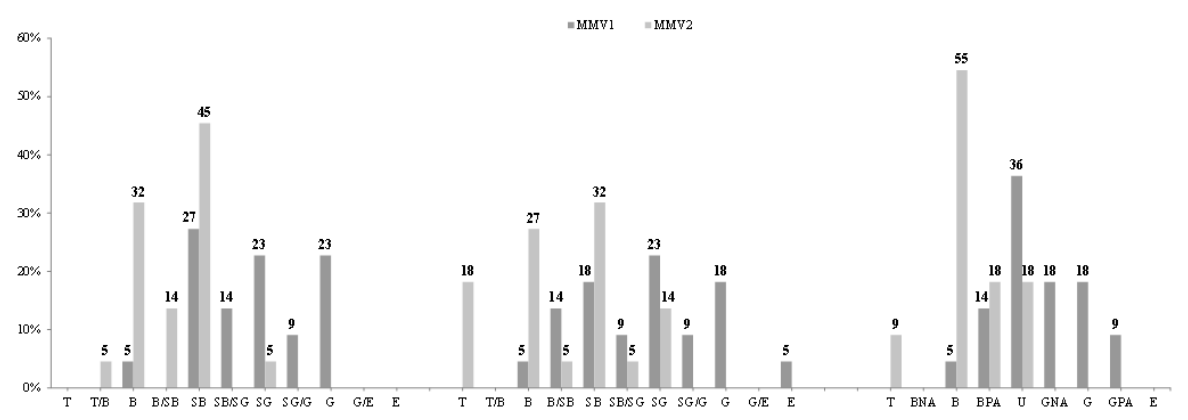


Note: Climatological data presented for Montemor-o-velho are those available for the nearest most representative city, Coimbra; the same goes for Pombal, data herein presented correspond to Santarém's climatological data.

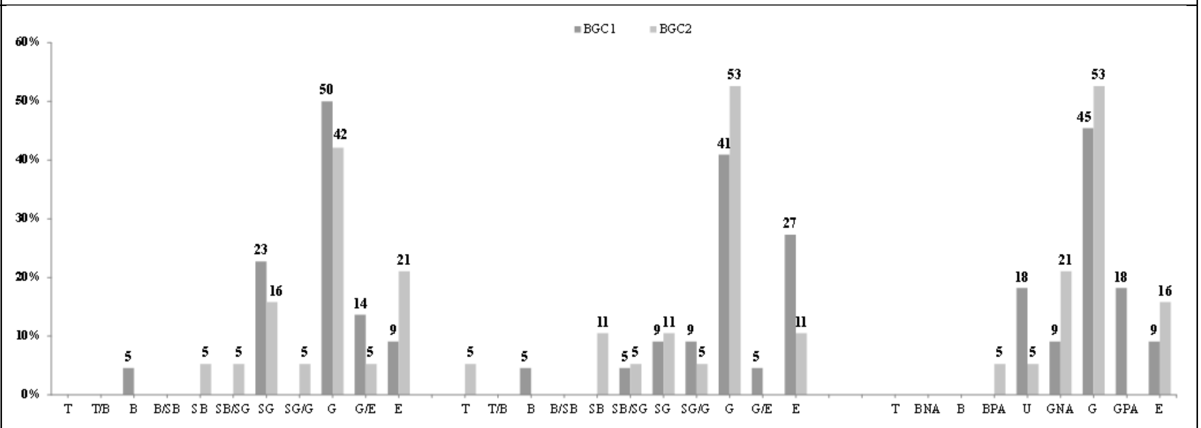
Figure A.1 – Mean Monthly Temperature a), Minimum Monthly Temperature b), and Maximum Monthly temperature c) for the cities corresponding to the 6 schools' CCD selection [Temperature values were obtained from www.ipma.pt]

	Air stiffness votes (*Clean Air/Polluted Air)*	*Air smells* votes	General air quality votes

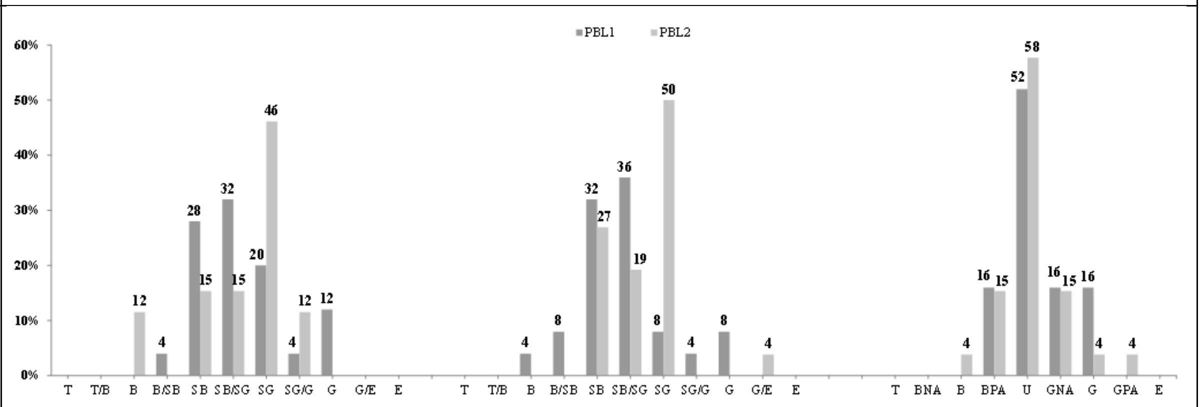
MMV



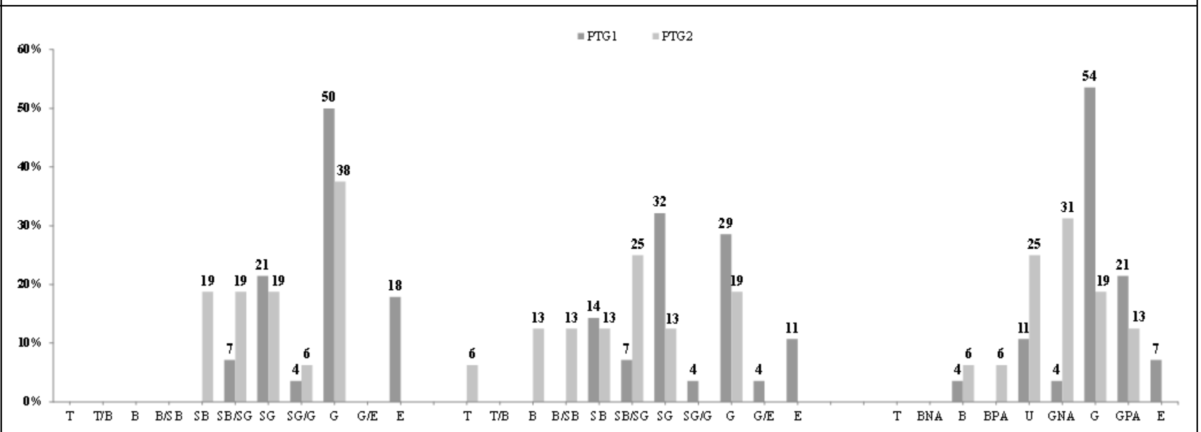
BJA

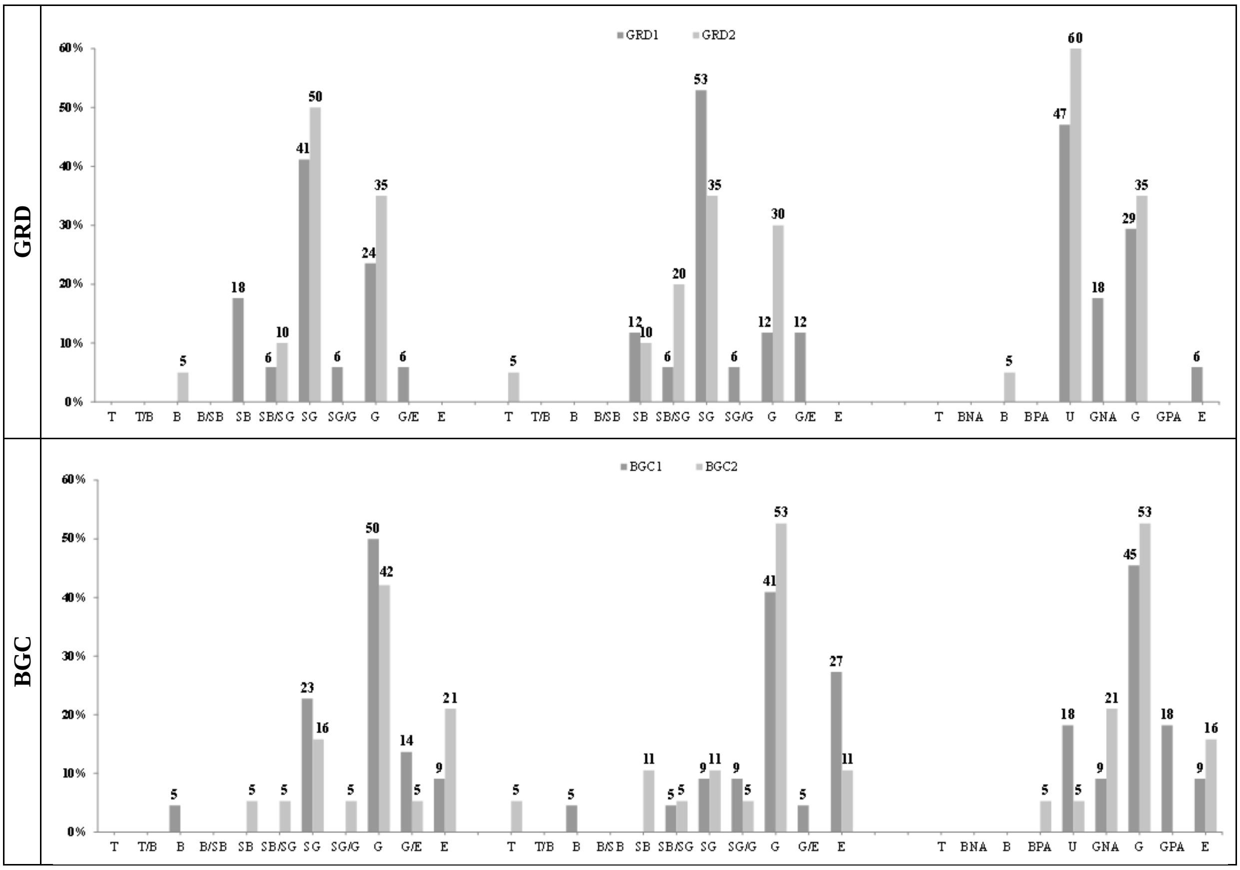


PBL



PTG





Note: T = Terrible; T/B = Terrible – Bad; B = Bad; BNA = Bad w/ negative aspects; BPA = Bad w/ positive aspects; B/SB = Bad –slightly bad; SB = Slightly bad; SB/SG = Slightly bad – Slightly good; SG = Slightly good; SG/G = Slightly good – Good; G= Good; G/E= Good exceptional; GNA = Good w/ negative aspects; GPA = Good with positive aspects; E = Exceptional.

Figure A.2 –Answers from the IAQ questions. Summary table of the 12 classrooms

References

[1] L. Baker, H. Bernstein, The Impact of School Buildings on Student Health and Performance, The McGraw-Hill Research Foundation and the Center for Green Schools at the U.S. Green Building Council (USGBC), 2012. http://www.centerforgreenschools.org/impact-school-buildings-student-health-and-performance.

[2] F.R. d'Ambrosio Alfano, L. Bellia, A. Boerstra, F. Van Dijken, E. Ianniello, G. Lopardo, et al., REHVA - Indoor Environment and Energy Efficiency in Schools - Part 1, REHVA, 2010, Brussels, 2010.

[3] P. Wargocki, D. Wyon, The Effects of Outdoor Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children (RP-1257), HVAC&R Res. 13 (2007) 165–191. doi:10.1080/10789669.2007.10390950.

[4] Z. Bakó-Biró, D.J. Clements-Croome, N. Kochhar, H.B. Awbi, M.J. Williams, Ventilation rates in schools and pupils' performance, Build. Environ. 48 (2011) 1–9. doi:10.1016/j.buildenv.2011.08.018.

[5] R. Becker, I. Goldberger, M. Paciuk, Improving energy performance of school buildings while ensuring indoor air quality ventilation, Build. Environ. 42 (2007) 3261–3276. doi:10.1016/j.buildenv.2006.08.016.

[6] CIBSE, Energy efficiency in buildings - CIBSE Guide F, in: P. Bros (Ed.), Energy Effic. Build., CIBSE Publ, CIBSE Publications Department, Norwich, Norfolk, 2004: pp. 1–260.

[7] T. Hong, C. Koo, K. Jeong, A decision support model for reducing electric energy consumption in elementary school facilities, Appl. Energy. 95 (2012) 253–266. doi:10.1016/j.apenergy.2012.02.052.

[8] EPBD, Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings, Off. J. Eur. Communities. (2003) L1/65-L1/71. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:001:0065:0065:EN:PDF.

[9] EPBD (recast), Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)., Off. J. Eur. Union, 2010. (2010) L153/13-153/35.

[10] SCE, Decree-Law no. 78/2006. National Systemfor the Energy and IAQ Certification of Buildings (in Portuguese: Sistema Nacional de Certificação Energética e da Qualidade do Ar Interior nos Edifícios (SCE)), Official Gazette of the Portuguese Republic, Series A, (2006).

[11] RSECE, Decree-Law no. 79/2006. (2006). Regulation for the energy and HVAC systems in buildings (in Portuguese: Regulamento dos Sistemas Energéticos de Climatização em Edifícios— RSECE), Official Gazette of the Portuguese Republic, Series A, No. 67., (2006).

[12] RCCTE, Decree-Law no. 80/2006. (2006). Regulation for the characteristics of thermal behavior of buildings (in Portuguese: Regulamento das Características de Comportamento Térmico dos Edifícios—RCCTE), Official Gazette of the Portuguese Republic, Series A, No. 6, (2006).

[13] PE, Comunicado de imprensa 01/10/2009, (2009). http://www.parque-escolar.pt/.

[14] M. Frontczak, P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments, Build. Environ. 46 (2011) 922–937. doi:10.1016/j.buildenv.2010.10.021.

[15] P. Wargocki, D. Wyon, The Effects of Moderately Raised Classroom Temperatures and Classroom Ventilation Rate on the Performance of Schoolwork by Children (RP-1257), HVAC&R Res. 13 (2007) 193–220. doi:10.1080/10789669.2007.10390951.

[16] P. Wargocki, D. Wyon, Effects of HVAC On Student Performance, ASHRAE J. 48 (2006) 22–28.

[17] D.G. Shendell, R. Prill, W.J. Fisk, M.G. Apte, D. Blake, D. Faulkner, Associations between classroom CO2 concentrations and student attendance in Washington and Idaho., Indoor Air. 14 (2004) 333–41. doi:10.1111/j.1600-0668.2004.00251.x.

[18] K. Al-Rashidi, D. Loveday, N. Al-Mutawa, Impact of ventilation modes on carbon dioxide concentration levels in Kuwait classrooms, Energy Build. 47 (2012) 540–549.

[19] N.M. Salleh, S.N. Kamaruzzaman, R. Sulaiman, N.S. Mahbob, Indoor Air Quality at School : Ventilation Rates and It Impacts Towards Children- A review, in: 2nd Int. Conf. Environ. Sci. Technol. - IPCBEE, 2011: pp. 418–422.

[20] D. Mumovic, M. Davies, C. Pearson, G. Pilmoor, I. Ridley, H. Altamirano-Medina, et al., A comparative analysis of the indoor air quality and thermal comfort in schools with natural , hybrid and mechanical ventilation strategies, in: Clima 2007 WellBeing Indoors, 2007.

[21] Department for Education and Skills, Building Bulletin 101 Ventilation of School Buildings, 2006.

[22] D. Mumovic, J. Palmer, M. Davies, M. Orme, I. Ridley, T. Oreszczyn, et al., Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England, Build. Environ. 44 (2009) 1466–1477.

[23] A. Montazami, F. Nicol, Overheating in schools: comparing existing and new guidelines, Build. Res. Inf. 41 (2013) 317–329.

[24] D. Teli, P.A.B. James, M.F. Jentsch, Thermal comfort in naturally ventilated primary school classrooms, Build. Res. Inf. 41 (2013) 301–316.

[25] K.J. McCartney, J. Fergus Nicol, Developing an adaptive control algorithm for Europe, Energy Build. 34 (2002) 623–635. doi:10.1016/S0378-7788(02)00013-0.

[26] J.F. Nicol, M. a. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, Energy Build. 34 (2002) 563–572. doi:10.1016/S0378-7788(02)00006-3.

[27] H.B. Rijal, P. Tuohy, M. a. Humphreys, J.F. Nicol, a. Samuel, J. Clarke, Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings, Energy Build. 39 (2007) 823–836. doi:10.1016/j.enbuild.2007.02.003.

[28] Gov.UK, Guidelines on ventilation, thermal comfort and indoor air quality in schools, Building Bulletin 101, (2016). https://www.gov.uk/government/consultations/ventilation-thermal-comfort-and-indoor-air-quality-in-schools (accessed August 1, 2016).

[29] E.Z.E. Conceição, M.M.J.R. Lúcio, a. E.B. Ruano, E.M. Crispim, Development of a temperature control model used in HVAC systems in school spaces in Mediterranean climate, Build. Environ. 44 (2009) 871–877. doi:10.1016/j.buildenv.2008.06.015.

[30] ISO7730, EN ISO 7730: 2005 Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria., (2005). http://books.google.pt/books?id=cQisLgEACAAJ.

[31] SCE, Decree-Law no. 118/2013. (2013). Regulation for the Energy Certification of Buildings (in Portuguese: Sistema Certificação Energética dos Edifícios (SCE)), Official Gazette of the Portuguese Republic, Series 1, No. 159, (2013).

[32] Despacho no. 15793-CF/2013, Despacho (extrato) no. 15793-C/2013 (in Portuguese - following the Decree-Law no 118/2013, publishes the models associated with different types of pre -Certificate and Certificateof the SCE), (2013) 35088–(26–31).

[33] M. Santamouris, a. Synnefa, M. Asssimakopoulos, I. Livada, K. Pavlou, M. Papaglastra, et al., Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation, Energy Build. 40 (2008) 1833–1843. doi:10.1016/j.enbuild.2008.04.002.

[34] ASHRAE, ASHRAE Standard 62.1 -2010: Ventilation for Acceptable Indoor Air Quality, (2010).

[35] M. Santamouris, K. Pavlou, A. Synnefa, K. Niachou, D. Kolokotsa, Recent progress on passive cooling techniques. Advanced technological developments to improve survivability levels in low-income households, Energy Build. 39 (2007) 859–866. doi:10.1016/j.enbuild.2007.02.008.

[36] Fanger PO, Thermal comfort: analysis and applications in environmental engineering, McGraw-Hil, New York, 1972.

[37] L. Dias Pereira, D. Raimondo, S.P. Corgnati, M. Gameiro da Silva, Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: methodology and results, Build. Environ. 81 (2014) 69–80. doi:DOI: 10.1016/j.buildenv.2014.06.008.

[38] E.G. Dascalaki, V.G. Sermpetzoglou, Energy performance and indoor environmental quality in Hellenic schools, Energy Build. (2011) 718–727.

[39] M.G. Apte, D. Dibartolomeo, T. Hotchi, A.T. Hodgson, S.M. Lee, S.M. Liff, Simultaneous Energy Savings and IEQ Improvements in Relocatable Classrooms, Lawrence Berkeley Natl. Lab. (2003) 1–13.

[40] M. Gameiro da Silva, C.H. Antunes, H. Bernardo, H. Jorge, L. Cruz, E. Barata, et al., A preliminary assessment of energy performance in refurbished schools, in: 1st Int. Congr. Energy Environ. Bringing Together Econ. Eng., Porto, 2013.

[41] http://www.3es.pt/, (2013). http://www.3es.pt/.

[42] H. Bernardo, L. Dias Pereira, An integrated approach for energy performance and indoor environmental quality assessment in school buildings - Green Brain of the Year Contest 2014 (Finalist project), 2014. http://greenbrain.ncc.metu.edu.tr/2014-finalists/.

[43] L. Dias Pereira, L. Neto, M. Gameiro da Silva, Indoor air quality and thermal comfort assessment of two Portuguese secondary schools: main results, in: REHVA Annu. Conf. 2015, RTU PRESS, Riga, Latvia, 2015: pp. 49–56. doi:10.7250/rehvaconf.2015.007.

[44] ISO7726, EN ISO 7726:2001 Ergonomics of the Thermal Environment—Instruments for Measuring Physical Quantities, (2001).

[45] J. Dias Carrilho, L. Dias Pereira, N.S. Brito, M.R. Gomes, M. Mateus, B. Chenari, et al., NEW EXPERIMENTAL

TECHNIQUES AND WEB-ENABLED INSTALLATIONS FOR TEACHING AND RESEARCHING THE INDOOR ENVIRONMENT, in: 3º Encontro Jovens Investig. Do LAETA, Coimbra, Portugal, 2015: pp. 7–8. https://3ejil.wordpress.com/.

[46] C. Cornaro, A. Paravicini, A. Cimini, Monitoring Indoor Carbon Dioxide Concentration and Effectiveness of Natural Trickle Ventilation in a Middle School in Rome, Indoor Built Environ. 22 (2013) 445–455. doi:10.1177/1420326X11430099.

[47] E. Asadi, M. Gameiro da Silva, J.J. Costa, A systematic indoor air quality audit approach for public buildings., Environ. Monit. Assess. 185 (2013) 865–75. doi:10.1007/s10661-012-2597-x.

[48] M. Gameiro, J.J. Costa, A. Gaspar, A. Paulino, M. Bento, G. Botte, The influence of wind on the infiltration rates in a web-bases monitored office building, in: Roomvent 2011, Trondheim (Norway), 2011.

[49] J. Dias Carrilho, B. Chenari, M. Rocheta Gomes, G. Botte, M. Mateus, M. Gameiro da Silva, Development of a Live Laboratory for Research and Technology demonstration in Indoor Environment and Control Assessment, in: Energy Sustain. 2015 Sustain. Cities Des. People Planet, Coimbra, 2015. http://efs2015.uc.pt/index.php?module=sec&id=283&f=1.

[50] C. Godwin, S. Batterman, Indoor air quality in Michigan schools., Indoor Air. 17 (2007) 109–21. doi:10.1111/j.1600-0668.2006.00459.x.

[51] J. Dias Carrilho, M. Mateus, S. Batterman, M. Gameiro da Silva, Air exchange rates from atmospheric CO2 daily cycle, Energy Build. 92 (2015) 188–194. doi:10.1016/j.enbuild.2015.01.062.

[52] H. Bernardo, C.H. Antunes, A. Gaspar, Exploring the use of indicators for benchmarking the energy performance of Portuguese secondary schools, in: Energy Sustain. 2015 Sustain. Cities Des. People Planet, Coimbra, 2015.

[53] L. Dias Pereira, Modernised Portuguese Schools - From IAQ and Thermal Comfort towards Energy Efficiency Plans, PhD Thesis, University of Coimbra, 2016. https://estudogeral.sib.uc.pt/handle/10316/29419.

[54] U. Heudorf, V. Neitzert, J. Spark, Particulate matter and carbon dioxide in classrooms - the impact of cleaning and ventilation., Int. J. Hyg. Environ. Health. 212 (2009) 45–55. doi:10.1016/j.ijheh.2007.09.011.

[55] P. Blondeau, V. Iordache, O. Poupard, D. Genin, F. Allard, Relationship between outdoor and indoor air quality in eight French schools., Indoor Air. 15 (2005) 2–12. doi:10.1111/j.1600-0668.2004.00263.x.

[56] Portaria n.º 353-A/2013, Portaria n.º 353-A/2013 (in Portuguese: Regulamento de Desempenho Energético dos Edifícios de Comércio e Serviços (RECS) - Requisitos de Ventilação e Qualidade do Ar Interior), (2013).

[57] M.C. Gameiro da Silva, Requisitos de Ventilação em Edifícios Escolares – Parecer técnico elaborado para Parque Escolar EPE., ADAI, Departamento de Engenharia Mecânica da Universidade de Coimbra, 2009.

[58] CEN, EN 15251:2007 Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, (2007).

[59] L. Dias Pereira, M. Gameiro da Silva, E. Cardoso, Indoor air quality audit and evaluation on thermal comfort in a school in Portugal., Indoor Built Environ. 24 (2015) 256–268. doi:10.1177/1420326X13508966.

[60] DS/CEN/, CR 1752:1998. Ventilation for buildings - Design criteria for the indoor environment, (n.d.).

[61] E. Cardoso, Avaliação do Potencial de Utilização da Ventilação Natural em Edifícios Escolares, Coimbra, 2012.

[62] L. Dias Pereira, D. Raimondo, S.P. Corgnati, M. Gameiro da Silva, Energy consumption in schools – A review paper, Renew. Sustain. Energy Rev. 40 (2014) 911–922. doi:10.1016/j.rser.2014.08.010.

[63] US DOE - Energy Efficiency & Renewable Energy, (2010). http://www1.eere.energy.gov/buildings/commercial_initiative/new_construction.html.

[64] H. Yun, I. Nam, J. Kim, J. Yang, K. Lee, J. Sohn, A field study of thermal comfort for kindergarten children in Korea : An assessment of existing models and preferences of children, Build. Environ. 75 (2014) 182–189. doi:10.1016/j.buildenv.2014.02.003.

[65] Department for Education, Facilities output specification for the PSBP PFI projects, (2012).

[66] V. De Giuli, O. Da Pos, M. De Carli, Indoor environmental quality and pupil perception in Italian primary schools, Build. Environ. 56 (2012) 335–345. doi:10.1016/j.buildenv.2012.03.024.

[67] E. PARQUE ESCOLAR, Liceus e Escolas Técnicas, PARQUE ESC, Lisboa, 2010.

[68] PARQUE ESCOLAR EPE, Direcção-Geral de Projecto – Área de, Parque Escolar 2007-2011 Intervenção em 106 escolas, Lisboa, 2011.

[69] E. PARQUE ESCOLAR, Liceus, Escolas Técnicas e Secundárias, Lisboa, 2010.

[70] A. Thumann, W. Younger, Handbook of Energy Audits: Sixth edition, The Fairmont Press, Inc, 2003.