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Modernised Portuguese Schools - From IAQ and Thermal Comfort towards Energy Efficiency Plans

PhD Thesis in Sustainable Energy Systems
supervised by Professor Manuel Carlos Gameiro da Silva
and submitted to the Department of Mechanical Engineering, FCTUC

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MODERNISED PORTUGUESE SCHOOLS - FROM IAQ AND THERMAL COMFORT TOWARDS ENERGY EFFICIENCY PLANS

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Since we cannot know all that there is to be known about anything, we ought to know a little about everything.

Blaise Pascal

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Abstract

A major rehabilitation and refurbishment programme of secondary school buildings has been carried out in the last few years in Portugal, led by the state-owned company *Parque Escolar E.P.E.* (*PE*), known as *Secondary School Buildings Modernisation Programme*. This programme took into consideration renewable energy systems, mostly solar panels for domestic hot water (DHW) production. Nevertheless, 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 phase of new and refurbished buildings, energy and indoor climate quality (ICQ) audits are important strategies to improve the buildings' energy use. In new buildings, the most common errors are due to poor operation and management.

Schools energy management programmes often result in a list of energy efficiency measures that do not necessarily reflect occupants' conditions or satisfaction. They are more directed to management control and comparison with benchmarks of energy use/m^2 or cost/student to assess energy efficiency. In all cases, monitoring and consumption patterns are mandatory.

In this context, this thesis aims at developing energy efficiency plans (EEP) for modernised Portuguese school buildings.

The framework of the thesis starts with the development of an international overview of the recent research and development in the field of energy consumption in schools [searching for statistical benchmarks that could contribute to an accurate school building indicator (SBI)]. Then, based on a database provided by *Parque Escolar*, an energy consumption assessment of Portuguese school buildings is presented, between the pre and post-intervention phases. Drawing on this procedure, eight representative modernised secondary schools were selected, geographically and climatically distributed.

After, an energy audit and indoor environment quality (IEQ) monitoring is performed in this schools selection. The continuous monitoring period varied between schools, from a minimum of 48h monitoring up to three weeks, during the mid-season [spring – autumn period (excluding summer vacation) in 2013]. Air exchange rates (AER), more specifically infiltration rates, are quantified aiming at determining the current airtightness condition of the refurbished schools. A subjective IEQ assessment is also performed, focusing on occupants' feedback, providing insight on the potential linkages between energy use and occupants' satisfaction and comfort.

The thesis builds on the current EEP panorama and practice, which is based only on cost/energy control, extending it to address the equilibrium between IEQ evaluation and occupants' perceived conditions/preferences. This approach is applied in two schools – selected based on the previous study on energy and IEQ conditions of the eight schools.

The EEP methodology starts by deepening the knowledge of each school, mostly focusing on crossing the schools occupancy schedule with systems operation [(mainly those controlled by the building management system (BMS)]. An analysis on recently updated legislation is also performed (in particular fresh air flow rates requirements). It is shown that some potential energy savings can be achieved and that IEQ conditions can be improved at very low or even negligible costs. Other considerations, namely addressing the thermal energy production systems of the schools (e.g., boilers scheduling), the lighting systems (e.g., lighting circuits) and non-controlled plug loads, are also mentioned.

Based upon all these findings, a handbook of good practice is drafted for secondary school buildings in Portugal. This EEP is accompanied by a list of Energy Efficiency Measures (EEM). It is proposed that this document is headed by a School – Energy Performance Certificate (S–EPC) based on the billed energy consumption. This document suggests the establishment of the figure of the Energy Manager.

Keywords: Refurbished secondary schools; Energy audit; Indoor environmental quality; Indoor carbon dioxide; Energy efficiency plans.

Resumo

Durante os últimos anos, tem vindo a decorrer em Portugal um importante programa de reabilitação de escolas secundárias, coordenado pela empresa pública *Parque Escolar E.P.E.* (*PE*), denominado *Programa de Modernização do Parque Escolar Destinado ao Ensino Secundário.* Este programa teve em consideração sistemas de energia renováveis (SER), nomeadamente a integração de painéis solares para a produção de águas quentes sanitárias (AQS). Não obstante, com a introdução de sistemas de aquecimento, ventilação e ar condicionado (AVAC), em edifícios que anteriormente eram dotados apenas de ventilação natural, verificou-se um aumento do consumo energético dos mesmos.

Durante os períodos iniciais de ocupação de edifícios novos e reabilitados, as auditorias energéticas e de qualidade de climatização interior são estratégias importantes para melhorar o consumo de energia nesses edifícios. Nos edifícios novos, os erros mais comuns devem-se a má gestão e manutenção.

Os programas de gestão de energia em escolas resultam frequentemente numa lista de medidas de eficiência energética, que não reflete necessariamente as condições ou satisfação dos seus ocupantes. Tendem a ser mais direcionados para o controlo de gestão e comparação de indicadores de consumo de energia/m^2 ou custo/estudante como meio de avaliação de eficiência energética. Em qualquer um dos casos, a monitorização e padrões de consumo são imperativos.

Neste contexto, esta tese tem por objetivo desenvolver Planos de Eficiência Energética (PEE) para edifícios escolares reabilitados em Portugal.

A estrutura da tese inicia com o desenvolvimento de uma contextualização internacional dos recentes estudos desenvolvidos no campo dos consumos energéticos de escolas [procurando indicadores estatísticos que possam contribuir para a definição de um rigoroso indicador de edifícios escolares (IEE)]. Seguidamente, a partir de uma base de dados fornecida pela *Parque Escolar*, realiza-se uma avaliação do consumo energético de edifícios escolares em Portugal, entre as fases de pré e pós-intervenção. Este processo permitiu selecionar um grupo representativo de oito escolas secundárias, distribuídas geográfica e climaticamente.

Posteriormente, desenvolveu-se uma auditoria energética e de qualidade ambiental interior (QAI) nas escolas selecionadas. O período de monitorização contínua variou entre escolas, desde um mínimo de 48h até três semanas, no período de meia-estação [primavera – outono de 2013 (excluindo o período de férias de verão)]. As taxas de renovação horária, mais

especificamente as taxas de infiltração, medidas durante os períodos de desocupação, foram também quantificadas, revelando a condição atual de hermeticidade destas escolas. Desenvolveu-se ainda uma avaliação subjetiva de QAI, centrada nas respostas dos ocupantes, o que permitiu explorar a relação entre o consumo energético e o conforto e satisfação dos ocupantes destas escolas.

A tese desenvolve o panorama geral dos atuais PEE, baseados unicamente no controlo de energia/custos, estendendo-os, com vista a alcançar o equilíbrio entre a avaliação de QAI e as condições/preferências percecionadas pelos ocupantes. Esta abordagem global foi realizada em dois casos de estudo do grupo de oito escolas, cuja seleção foi baseada no anterior estudo das condições de QAI e consumo energético.

A metodologia dos PEE inicia com um aprofundamento da informação de cada uma das escolas, principalmente focado no cruzamento de informação do horário de ocupação da escolas com os horários dos sistemas [(nomeadamente, dos controlados pelo sistema de gestão técnica centralizada (GTC]. Realizou-se ainda uma análise dos requisitos de ar novo à luz da legislação recentemente atualizada. Os resultados demonstram que potenciais poupanças energéticas poderão ser atingidas e que as condição de QAI podem ser melhoradas, a custos reduzidos ou mesmo negligenciáveis. Outras considerações, nomeadamente as direcionadas aos sistemas de produção de energia térmica (e.g. horário de funcionamento de caldeiras), aos sistemas de iluminação (e.g. circuitos de iluminação) ou cargas de tomada não controladas são também apresentadas.

Com base em todos os resultados obtidos, elaborou-se um manual de boas práticas para as escolas secundárias em Portugal. Este PEE é acompanhado de uma lista de Medidas de Eficiência Energética (MEE). Propõe-se que este documento seja encabeçado por um Certificado de Desempenho Energético de Escolas (CDE–E) baseado nos consumos energéticos evidenciados pelas faturas. A criação da figura do Gestor de Energia é também sugerida neste documento.

Palavras-chave: Escolas secundárias reabilitadas; Auditoria Energética; Qualidade ambiental interior; Dióxido de carbono no interior; Planos de eficiência energética.

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Nomenclature

Abbreviation	Denomination
AEB	All-electrical building
AER	Air exchange rate
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEAM	Built Environment Analysis Model
BEI	Building Energy Index
BGC	Escola Secundária Abade de Baçal – Bragança
BJA	Escola Secundária D.Manuel I – Beja
BMS	Building Management System(s)
CFA	Conditioned Floor Area
CFD	Central Fire Detection
CLO	Clothing insulation in CLO
CO_2	Carbon Dioxide
CRC	Carbon Reduction Commitment
DCR	Declaration of compliance with regulation, an energy pre-certificate of the building project that is mandatory for the construction license in Portugal
DCV	Demand Control Ventilation
DEC	Display Energy Certificate
DGEE	Direcção-Geral de Equipamentos Escolares
DHW	Domestic Hot Water
DOE	Department of Energy (USA)
EC	European Commission
ECI	Energy Consumption Indicator
EEM	Energy Efficiency Measure
EM	Energy Manager
EMS	Energy Management Systems
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPS	Expanded Polystyrene Insulation
ETICS	External Thermal Insulation Composite Systems
EUI	Energy use intensity
FGRC	Fibreglass Reinforced Concrete
GFA	Gross Floor Area
GHG	Greenhouse Gas
GRD	Escola Secundária Afonso de Albuquerque – Guarda
HDD	Heating Degree Days
HRU	Heat Recovery Unit
IAQ	Indoor Air Quality
ICC	Indoor Climate Conditions
ICQ	Indoor Climate Quality
IEC	Indoor Environmental Conditions
IEQ	Indoor Environmental Quality
IPMA	Instituto Português do Mar e da Atmosfera
IU	Internal Unit
JCETS	Junta das Construções para o Ensino Técnico e Secundário
L/S-P	litres per second per person
LNEC	Laboratório Nacional de Engenharia Civil

LSB	Escola Secundária D.Pedro V – Lisboa
MDF	Medium-Density Fibreboard
MET	Metabolic rate in MET
MM	Mixed-Mode Ventilation
MMFB	Mixed mode fuel building
MMV	Escola Secundária de Montemor-o-Velho
MS	Member States of the European Union
MTS	Escola Secundária Gonçalves Zarco – Matosinhos
MV	Mixed Ventilation
NFA	Net floor area
NV	Natural ventilation
NZE	Nearly Zero Energy
OFA	Occupied floor area
O&M	Operation and Maintenance
OR	Operational rating
OSB	Oriented Strand Board
PBL	Escola Secundária de Pombal
PCM	Phase changing material
PE	Parque Escolar
PMV	Predicted Mean Vote
POE	Post-occupancy evaluation
PPD	Predicted Percentage of Dissatisfied
ppm (unit)	Particles per million [ppm unit = ml/m^3 (REHVA, 2010, p.20)]
PTG	Escola Secundária Mouzinho da Silveira – Portalegre
RCCTE	Regulamento das Características de Comportamento Térmico dos Edifícios
RES	Renewable Energy Sources
RH	Relative Humidity (%)
RSECE	Regulamento dos Sistemas Energéticos de Climatização em Edifícios
SBI	School Benchmarking Indicator
SBS	Sick Building Syndrome
Ta	Air temperature (ºC)
Tmr	Mean radiant temperature (ºC)
TIC	Tecnologias de Informação e Comunicação
TUFA	Total useful floor area
UTC	Universal Time Coordinate = GMT
V_A	Air velocity (ms^{-1})
VAV	Variable Air Volume
VM	Vending Machine
VOC	Volatile Organic Compound
VRF	Variable Refrigerant Flow
VSD	Variable Speed Drive
XPS	Extruded Polystyrene Insulation

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CHAPTER 1. INTRODUCTION

1.1 Context

Children are spending a considerable amount of time in indoor environments, most of the times in schools, where the dissemination of social values and the construction of a sustainable conscience are really important. The physical and non-physical boundaries of such environments have a critical effect on students' health and sense of well-being. School buildings are therefore a fundamental element of society [1].

"Children (…) take in roughly twice as much air by volume compared to their body mass as adults, meaning that they also take in twice the pollutants through respiration" [2] cit. in [1].

In the specific case of school buildings 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 [3] (in comparison to adults they will suffer the consequences of a poor indoor environment earlier [4]) but also, classrooms have a high occupancy rate that may degrade users' health, comfort and performance conditions [5], [6].

Poor indoor air quality (IAQ) in schools is a worldwide problem. In the US, the General Accounting Office found more than 15000 schools with poor IAQ (1995' data) [7]. This problem has also been verified in European countries [8]. Among the consequences of poor IAQ conditions, recent studies have focused on students and teachers performance [5], [6] and verified a notably increased student absenteeism.

To achieve and maintain satisfying IAQ levels, large buildings use mechanical ventilation (MV) systems. The "EE-TC-IAQ" dilemma (energy efficiency - thermal comfort - indoor air quality), as presented by Becker *et al.* (2007) [9], is still a current 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 [10].

Energy consumption and greenhouse gases (GHG) have been given specially attention since 1997. Since the Kyoto Protocol and European Union (EU)'s first commitment period, large efforts towards GHG mitigation have been undertaken globally [11], and specially within the European energetic context.

Within the *EU Climate and Energy Package Effort Sharing targets for 2013-2020* [12], the Portuguese commitment was to reduce GHG emissions by 1% , with reference to the 2005 level, i.e., the *Effort Sharing Decision* set national emission targets for 2020, expressed as percentage changes from 2005 levels.

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 [13] and its 2010 recast [14], assumed special relevance in this context. In the Portuguese legislation, the EPBD was ensured in the form of three decree-laws, in 2006 [15]–[17].

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) – comprising, at that time, 205 schools [18]. It was envisaged by PE the intervention in 332 schools by 2015 (i.e., 70% of the total building stock of secondary schools in the country) [19]. Recent school energy managements programmes (EMP) strongly take into consideration renewable energy systems. The PE's school rehabilitation programme[1] also took these into account.

Most existing school buildings, which were naturally ventilated (NV) at their origin, were refurbished in accordance to the new legislation [15]–[17], integrating HVAC systems to comply with the new requirements of thermal comfort (TC) and indoor air quality (IAQ).

This PhD research aimed to comprehensively assess these interventions in terms of the overall energy efficiency of the buildings and their equipment with the scope of optimizing the energy consumption and the indoor environmental quality (IEQ) in their exploitation phase. By focusing on the relationships between energy performance and occupants' feedback, it identifies measures to improve energy efficiency, considering occupants' satisfaction and comfort [20].

1.2 Problem statement

"Over short time scales (hours), poor IAQ causes discomfort problems (perception, odors and temperature), loss of attention and learning ability of pupils as well as health effects (e.g. headache). On the other hand, sufficient ventilation rates in classrooms have been shown to improve performances of students, e.g. results of maths and reading tests." [21]

Except for the work done in California (USA) and North European countries, research on IEQ related specifically to new or refurbished school construction was scarce until the end of last century. Today worldwide studies are being performed on this field.

[1] National Portuguese programme similar to *The Building Schools for the Future Programme* in the UK.

The first known studies on students' performance were performed in Sweden. In the late 60's, Holmberg and Wyon (1969) [22] "announced" *"the dependence of performance in school on classroom temperature"*. Later, Johansson studied *"mental and perceptual performance in heat"* [23]. In the USA, Allen and Fischer published *"Ambient temperature effect on paired associated learning"* [24] – a reference document for several years among several research areas: from psychology to engineering.

Recent studies on IEQ, productivity and fatigue have been developed in offices and call centres, as those of Seppanen, Fisk and Lei [25]–[27], or the ones of Tanabe *et al.* [28]–[33]. Based on experimental methods (e.g., monitoring the effect of high temperature on task performance and fatigue or the effect of the difficulty level of tasks and high temperature on cerebral blood flow), these studies reflected upon a balance between environment concerns and office productivity.

The European Project ThermCo (2009) [34], developed by the Technical University of Denmark, explored the linkage between thermal discomfort sensation and the reduced concentration or decreased motivation to work. Occupants' perception of performance was researched by Kamaruzzaman *et al.* in 2011 [35] and, later, the relationship between IEQ factors and overall workspace satisfaction was addressed by Kim and De Dear in 2012 [36]. The linkages between IEQ and workspace satisfaction has been addressed by several other authors [37]–[40].

In [41], 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.

Myhrvold *et al.*(1996) [42] preceded Wargocki and Wyon's extensive work on students' schoolwork performance, that has been continuously published since 1999 [5], [43]–[46]. The study of Shendell *et al.* (2004) [47] relating CO_2 concentrations to student attendance also included a relevant literature review on the topic. Other authors have developed similar studies, including Shaughnessy *et al.* (2006) [48], Bakó-biró *et al.* (2007) [49], Clements-Croome *et al.* (2008) [50], Haverinen-Shaughnessy *et al.* (2011) [51], Lee *et al.* (2012) [52], among others [53], [54].

"The challenge between TC and IAQ also occurs in classrooms in moderate climates: more ventilation means more energy use". [55]

CO_2 control in classrooms and different ventilation strategies [56]–[62] – as the one suggested by the most recent UK legislation (BB101) [63] – have been well thought-out, and the most recent studies on its consequences are being closely followed [64]–[70]. It is noteworthy that changes to the legislation in the UK were preceded by the intensive studies on adaptive comfort by Humphreys and Nicol [71]–[75]. Nowadays, this trend is globally spread and it is supported by several other authors [69], [76], [77].

"The slow changes of the thermal state of the body in cold climatic conditions is due to a reduction of peripheral blood flow as a consequence of vasoconstriction. In hot conditions, however, blood flow between core and skin is increased by vasodilatation. Thermal adaptation of the body temperatures to heat, therefore, is much faster compared to cold." [78]

"(…) field studies are best used for assessing the potential impacts of behavioral or psychological adaptations as they occur in 'real-world' settings" [79].

The study performed by [80], 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 [81]. 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 that rules HVAC requirements for schools (as those expressed in SCE [82], [83] facing the previous one, RSECE [16]). Some studies, based on field measurements (e.g. Santamouris *et al*., 2008 [84]) or simulation (Gameiro da Silva, 2009 in [3]), suggested that the previous requirements of outdoor air flow (30 m^3/h) proposed by the Portuguese legislation, RSECE, might be oversized (significantly higher than those from ASHRAE 62/1:2010 [85]), 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). On the case study in [3], CO_2 concentration levels inside a classroom took into consideration students age difference – this approach is also adopted in [85]. 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.

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

This concern with energy expenses has been clearly stated by Santamouris *et al.* (2007) in [86]. The "increased use of air conditioning creates a serious peak electricity load problem to utilities and increases the cost of electricity". Besides, households "were at risk of having their utility service cut off because of an inability to pay their home energy bills".

This condition is familiar to the Portuguese school building sector. Previously to PE's intervention, most schools were NV 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, the IEQ audit was mandatory to evaluate the current environments inside classrooms. Due to tighter building envelopes, the current IEQ conditions could be worse than before schools' refurbishment – by that time, besides NV promoted by occupants, air flow rates were considerably higher due to higher infiltration rates resulting from older window frames, for example.

The EE-TC-IAQ dilemma [9], previously mentioned, is critical for justifying the establishment of sustainable energy efficiency plans (EEP) in the refurbished schools, more adapted to their reality than those merely based on systems management. However, most existing EEP, also designated energy management programmes (EMP), result in a list of energy and conservation measures that do not necessarily reflect occupants' conditions or satisfaction – more focused on management control and comparison with benchmarks of energy use/m^2 or cost/pupil. In all cases, monitoring and consumption patterns are mandatory.

Changes in energy demand of the school buildings between the pre- and post-intervention measures were characterised based on a PE's database. Based on 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 [19]. Such analysis followed the NEED Project [87] in parallel with *Best Practice Programme/Energy Efficiency* (Energy Consumption Guide 73 - *Saving energy in schools*) [88], IEA-ECBS Annex 36 [89], and [91]–[94].

1.3 Research goals and objectives

The main objective of this doctoral thesis was to develop energy efficient plans (EEPs) that account for an equilibrium balance between IEQ evaluation, occupants' perceived conditions/preferences and energy consumption. Therefore, these EEP were based on monitored energy data, IEQ campaigns and subjective indoor climate evaluations.

More specific goals of the research were formulated in the following research questions:

- Does the energy consumption increase (from NV to Mechanical Ventilated schools) reflect increased students' satisfaction with IEQ?
- Do MV buildings really guarantee better IEQ than NV?
- Is the increase of energy use, in these school buildings (associated with increased mechanization) related to an increase of comfort?
- Does occupant control reduction of the indoor conditions reflect on occupant comfort and satisfaction?
- How are the refurbished school buildings in Portugal responding in terms of IEQ parameters and occupants' comfort legislation (both 2006 [16] and 2013 revision [82])?
- How can monitoring help improving IEQ in retrofitted schools?
- Is it possible to reduce on energy costs? Or is it possible to improve IEQ?

1.4 Methodology

"The post-handover period is the most neglected stage of construction, often looked upon as a nuisance and a distraction. Ironically, this is precisely when much can be fed forward into the completed project, for the benefit of the client and the occupants" [94].

Considering its main goal, the research strategy comprised two main components: *Energy Efficiency Analysis* and *IEQ in classrooms & Student Satisfaction.*

The integrated approach proposed to increase the schools' energy efficiency while providing good indoor environmental conditions to the occupants has been formally presented in September 2014 [20], being recognized as a finalist project in the *Green Brain of the Year Contest 2014* (Middle East Technical University, Northern Cyprus Campus). The methodology aimed at identifying the major energy consumption equipment in schools and potential energy efficiency measures (EEM).

Water consumption and its associated cost could be taken into account for assessing its impact on the global operation costs of the schools. However, this was beyond the scope of the research. Nonetheless, the assessment of IEQ allowed identifying possible corrective measures to problems related to IAQ or TC, also supporting the study of energy efficiency measures (EEM) regarding the assurance of environmental quality.

Energy efficiency in school buildings could only be achieved through an effective energy management methodology as well as an efficient facility management procedure. This was achieved through monitoring and targeting of energy consumption, which mainly consisted of using management techniques to control energy consumption and cost seeking the continuous improvement [95]. Within this study, the energy performance assessment [96] consisted of a detailed examination of the energy usage conditions in the schools installation – this vital tool gives managers the information to support decision making [97].

In parallel to the energy data collection (both from billed energy data and field monitoring campaign) and IEQ analysis of indoor environmental parameters (as air temperature, relative humidity, air velocity and CO_2 concentration values) – measured every minute over a two-week period (on average), a subjective survey has been driven to the school community – that is to say 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. The survey builds on several studies on this subjective analysis (including desired thermal sensation) [68], [73], [98], [99]. It was also referenced in Zagreus *et al* 2004’s study [100]. This type of data collection allowed in 2013, Montazami and Nicol [68] revealing overheating problems in the UK schools – in their case studies, school teachers were asked to rate the level of TC and temperature inside classrooms.

Moreover, Fanger’s TC indices (PPD and PMV) [101] were estimated based on data collection, from both monitored parameters and surveys – accounting for the metabolic rate and clothing insulation. Clothing adjustment can have a significant role on requirements for thermal comfort [102]–[105].

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, like the previous study of authors as Hummelgaard *et al.* (2007) [106]–[108], on differently ventilated office buildings or Han *et al.* (2009) on the residential sector [109]. The TC and IAQ assessment methodology has been reported in 2014 [110], Paper **VII** in **Appendix A**.

Later on, complementary energy use and energy costs simulation was done through the use of computerized tools – one commercially distributed (Designbuilder software [111]) that allowed a total building energy consumption estimation (which gave rise to Nuno Correia’s MSc thesis [112]) and a simplified excel tool focused on HVAC systems energy consumption that accounts on local climate information (developed by Francisco Lamas and submitted for publication to the scientific journal *Applied Energy* [113]).

This methodology enabled objective and transparent estimations and comparisons of scenarios, and it allowed the identification of solutions that can lead to better IEQ conditions at reduced costs. The EE-TC-IAQ dilemma, has therefore been faced in a holistic approach [114], [115].

1.5 Thesis structure

The core of the thesis is divided into four chapters (besides the Introduction and Conclusion chapters), which correspond to the main publications resulting from work hereby reported: two published in conference proceedings, two published in peer reviewed journals and one submitted for publication (papers **II**, **VI**, **VII, IX** and **X** respectively, in **Appendix A** List of publications).

Chapter 2 provides an overview on recent research and developments on energy consumption in schools, as well as the different data categorization. It also highlights the importance of different benchmarking strategies when targeting energy savings in schools. Generally, it provides a state-of-the-art on existing energy data analysis in educational buildings. This section is fully based on the published literature review – paper **VI** [116].

Chapter 3 presents the case studies, including their selection process and characterization. In the first part, the Portuguese secondary schools' context is introduced. Then, the process that conducted to the case studies selection is presented, and lastly, each of the eight case studies is described: constructively and also in terms of the installed systems. The case studies selection subsection is fully based on paper **II** [19].

Chapter 4 presents the data analysis from IEQ monitoring campaigns and IEQ subjective assessment addressed in the eight case study schools using the detailed methodology reported in paper **VII** [110].

In Chapter 5 a proposal for Energy Efficiency Plans in Portuguese secondary schools is presented. Firstly, it presents the initial approach to the school; then, the methodology is applied in one of the schools; again, the methodology is repeated in another school enlarging the validation of some of the proposed measures through simulation tools; and lastly, a proposal for EEP is drafted. The research method first attempt to the EEP is reported in paper **X** [113]; some of the energy savings estimations are drawn from paper **IX** [117].

Lastly, Chapter 6 provides the discussion and summarised conclusions of the energy efficiency plans, and potential improvements for future work. The thesis structure is synthetized in the thesis "road map" presented in **Figure 0**.

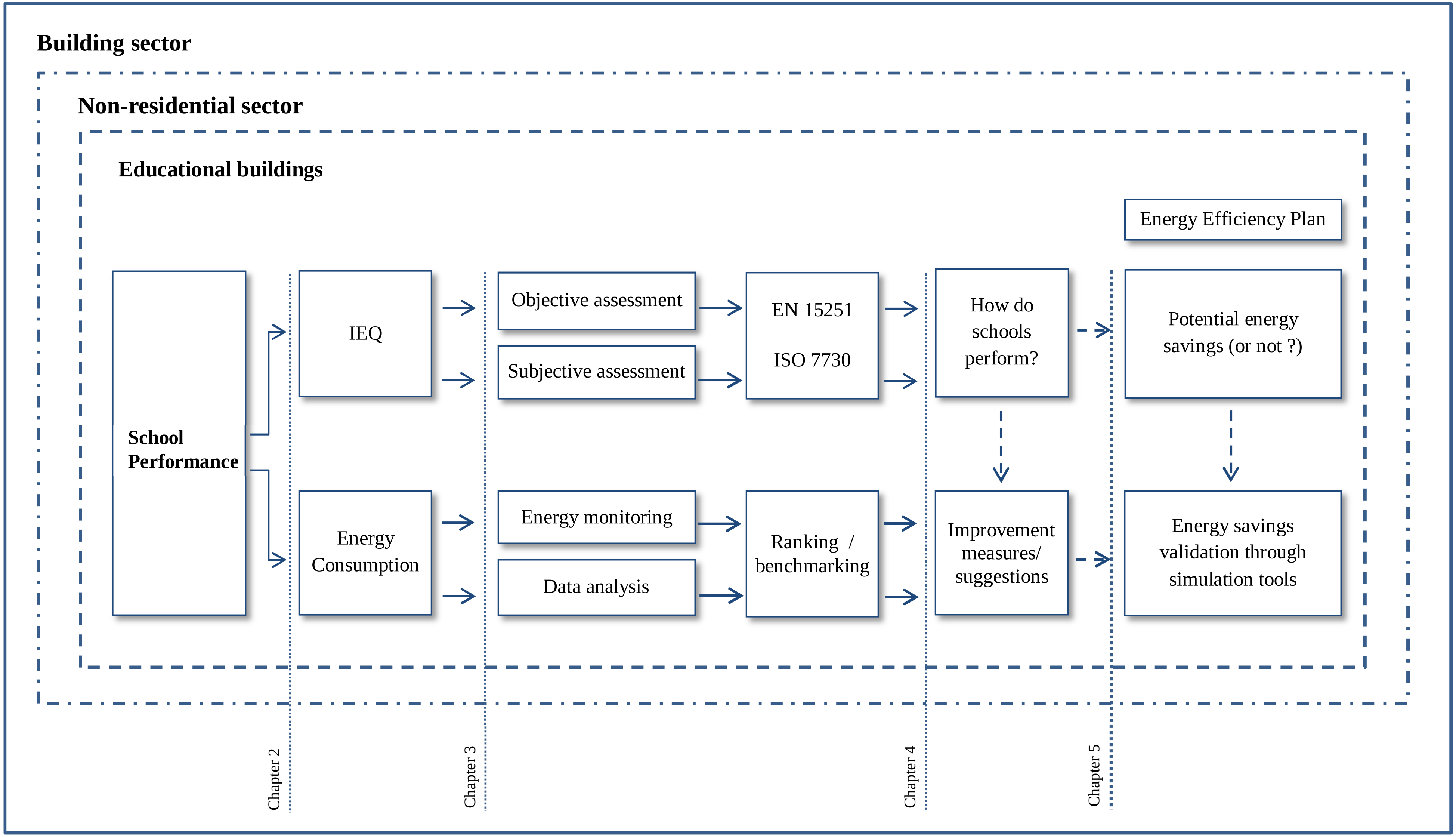


Figure 0 – Thesis “Road map”

CHAPTER 2. STATE-OF-THE-ART ON ENERGY CONSUMPTION IN SCHOOLS

In this chapter, a great quantity of research studies on energy consumption in schools was reviewed, with special focus on those related to energy benchmarks, school sizing and climate, which aimed at contributing to the construction of a school buildings indicator (SBI), one of the new ventures of this dissertation. As previously stated, this chapter is entirely based on paper **VI** [116], **Appendix A**.

2.1 Introduction

In 2002, the Energy Performance of Buildings Directive (EPBD 2002/91/EC) [13] introduced the mandatory energy certification of buildings in the EU from 2006. Within this context, all the Member States (MS) proposed different Energy Performance Certificates (EPC) exhibiting different information expressed into distinct scales. A similar process has been taking place in the US [118]–[122], Canada [123] and Australia [124].

Public buildings with public ownership, like schools, represent an important opportunity towards energy efficiency and suitable Indoor Climate Quality (ICQ) levels representativeness. School buildings “can be used as communication means towards pupils and their families, and can thus reach many different society groups” [125]. Because of their high number in the total state building stock, they contribute to a considerable part of the overall amount of energy consumption, and consequently of the expenses paid by the national budgets [126]. School’s energy use do highly contribute to schools’ running costs – after salaries of teachers and staff, energy costs are the second most significant expense [127].

Worldwide studies and publications present different energy consumption ratios on different descriptors, sometimes with different units and several energy use types. Besides, different approaches/methods lead to barely comparable values. These data characteristics have been summarized in **Table 3**.

Discrepancies between design estimates and actual energy use have been verified which makes the comparison of measured and calculated values substantially difficult. This is verified because a rating based upon real measured consumptions is influenced by the behaviour of the occupants and the calculated values are obtained by computational simulation depending of predetermined load and occupation profiles, which in some cases are very different from the real ones [128]–[130]. Besides that, some simplifications assumed in simulations and the random character of weather conditions may contribute to increase the discrepancies.

Among all public buildings, on account of their educational purpose, school buildings have a major social responsibility. Therefore energy performance in this type of building is of great importance, together with suitable levels of Indoor Environmental Quality (IEQ).

According to [131], circa 30% of the European MS "have experience with measured energy used for national/regional energy performance evaluation". On the other hand, most of EPC procedures are based on simulation/calculation methods and not necessarily on operational rating (OR). This means that, no direct relation can be established between buildings' energy labelling and benchmarking.

Table 1 – Comparison of data characteristics used in energy consumption literature analysis

Location	Energy type	Unit (per annum)	Reference value	Literature	Year Publication
Austria		kWh/m²		[132]	2010
Cyprus	*billed energy*	kWh/m²	typical :average	[133]	2014
Czech Republic	*delivered*			[131]	2011
Denmark	primary	kWh/m²		[131], [134], [135]	2011, 2013
Finland	-	kWh/m²	average	[125], [3]	2010
Flanders	-	kWh/m²		[136] *cit in* [137]	2002, 2008
France	primary	kWh/m²	average	[138]	2012
Germany	primary	kWh/m²		[139], [140], [141]	2013, 2011
Greece		kWh/m²	Average, typical & good practice	[134], [114]	2011
Hungary		kWh/m²		[140]	2011
Italy	primary	kWh/m²	mean	[132], [142], [143], [144], [145]	2002, 2008, 2010, 2013
Northern Ireland	*consumed energy*	kWh/m²	Typical & good practice	[146], [147],	1997, 2000
Poland		kWh/m²		[140]	2011
Portugal	*consumed energy*	kWh/m²	25% percentile median	[148], [134]	2011, 2013
Slovakia		kWh/m²		[125]	2010
Slovenia		kWh/m² kWh/m³		[149]	1999
Spain		kWh/m²		[140]	2011
Sweden	primary	kWh/m²		[134], [140], [150]	2011, 2013
United Kingdom (UK)	*consumed energy*	kWh/m²	good practice: 25% percentile typical: median	[151], [10]	2003, 2004
Argentina	*consumed energy*	kWh/m²	Average = Mean	[152]	2000
Canada	*billed energy*	kWh/m²		[153] *cit in* [114], [154], [155]	2010, 2013
USA		*kBtu/ft²* \$/m² \$/student	Median, 25% percentile	[156], [157], [158]	2010, 2008, 2012
Hong Kong		MJ/m²		[159]	2013
Japan		GJ/m²	average	[160]	2008
Malaysia	*billed energy*	kWh/m²	best practice	[161]	2012
South Korea	*consumed energy*	MJ/m² MJ/student	average	[162]	2012

EPCs in public buildings, particularly in schools, could drive into energy benchmark hypothesis (for heating and electricity needs), based upon reference building types, driven, on their turn, from average/typical consumption values or good practice [88]. Through benchmarking, school facility managers can compare their school to how much energy a typical elementary, middle and high school in a specific geographic region should consume, assuming the same target Indoor Climate Conditions (ICC). Throughout benchmarking, substantial energy cost savings could be generated while improving the ICC of school facilities. In resume, it is a fundamental method to be implemented.

The following sections summarize and explore the peer-reviewed literature on energy consumption in schools. The reviewed existing data emphasizes the challenge of addressing the theme, considering the multiplicity of criteria for data presentation. The information about the different sources that were considered for the literature review is summarized in **Table 3**.

This chapter aims at analysing the school buildings typology (new and existing) in order to achieve a functional benchmarking, based on the real operation conditions of school buildings, by the exploitation of the results made public, through an intensive literature survey on energy consumptions in schools.

2.2 Energy consumption in schools – methodology issues and data

The comprehensive literature review approach has been based on the analysis of papers published in peer-reviewed journals, online publications about the topic and other existing information sources, such as conference proceedings, regulation and standards and European Directives. The survey was made to gather data that is relative to energy consumption in school buildings, documented in the most diverse fields and units: global energy consumption values, electrical energy consumption; fuel consumption for heating, energy data consumption of schools expressed in annual cost per unit of heated/cooled surface area ($\$/m^2$) or per unit of heated/cooled volume ($\$/m^3$) or, finally, as the annual cost per student ($/student).

This research was initiated at the European level, and then followed by American publications and finally Asian substance. Secondly, energy consumption data collection in schools was divided into general energy consumption, thermal energy consumption and electrical energy consumption, **section 2.2.1**. The literature was analysed to determine if a worldwide comparison among the published data could be established.

2.2.1 Energy data analysis

Data on global energy consumption in schools are the most common available in the literature. For global data it goes without saying uncategorized data, e.g. non-specification of energy type (primary or final energy), or data that refers to non-specification of building type (primary school, secondary school, schools with /without pool or canteen, etc.).

Although some authors have been claiming that Display Energy Certificates (DEC) may be used to quantify school's energy consumption, and therefore allowing a fair benchmark, [131], [163], only a minority of the EU countries have this category of buildings fully addressed on their national Energy Performance Certification legislation [131]. **Table 4** refers to this appreciation.

Things are changing [125]. *"Since the 30th of June 2012, public bodies that occupy more than 1000 m² in a building must display an EPC on the front door or in the main lobby of the building"* [125]. The executive came into force in two phases, according to the category of the building being certified. Schools categories: nurseries, schools, colleges and universities fit in phase 2 (a list of the buildings to be certified since the 1st of January 2012, and a list of those with an issued certificate since the 1st of July 2012) [125]. In Belgium, in the Brussels Capital Region, the certificate "is based on consumption data for electricity and fossil fuels used for all purposes, based on meters or invoices", and "the EP indicator is calculated on the basis of the occupied floor area". An index of CO_2 emission is also foreseen. The mean value emissions and energy consumption anticipated for school and college buildings category is 40 $kgCO_2/m^2$ yr and 230 $kgCO_2/m^2$ yr, respectively [125].

In countries like Belgium, e.g., the evolution on the requirements on maximum primary energy demand have been established, greatly based on the evolution of the U values of the construction elements (walls, insulation levels) – either for new or existing buildings [131]. In the Flemish Region, each new or renovated building has to fulfil requirements on EP (E-level): the annual primary energy consumption, divided by reference consumption. Since the 1st of January 2012, the maximum E-level was also set at E70 for schools and office buildings [125]. Moreover, a new requirement on Renewable Energy Sources (RES) was recently added to the EP requirements and is obligatory for all schools from the 1st of January 2014, at least 10 kWh/m² yr of renewable energy will be needed [125].

Different MS have reached different levels of compliance within the EPBD. Starting from a common base, each country has been developing its regulations. In Cyprus, e.g., the Technical Services of the Ministry of Education and Culture are working in order to design and construct the first NZE (Nearly Zero Energy) schools [125].

In Slovakia, besides energy classes' scales for global indicators for schools (from 2013) where the global indicator is expressed in kWh/m^2 yr – primary energy, there is a rating scale for heating energy use. Class D corresponds to the reference value for the existing building stock [125].

In Austria, for instance, the maximum accepted space heating demand and *U*-values for new buildings and for existing buildings in case of major renovation was tightened. In Denmark, a major revision of EPC occurred in 2011. One of the changes is that the energy certification of selected buildings, such as educational buildings, can be based on the calculated or measured energy consumption [125]. In the Finnish situation, the new National Building Code sets maximum values for the energy consumption (*E*-values) calculated with the weight factors – for schools and day care centres the value is 170 kWh/m^2 yr [125]. The values presented in **Table 4** for Czech Republic correspond to Energy Label C – minimum required category for new schools and major renovations [131].

Table 2 – Energy Consumption in schools and EPBD implementation

Location	Type of building	Indicators and Units	Ref. Value
Belgium [131] (Wallon Region)	New schools	*Global* energy performance level (calculated *primary energy* consumption divided by calculated *primary energy* consumption of a reference building)	100
Czech Republic[131]	Education	*Total* annual *delivered energy* consumption (heating, cooling, DHW, lighting, mechanical ventilation): kWh/m^2 per year *Primary energy* and CO_2 are not assessed in EPC	90-130
Denmark [135], [131]	Education	*Primary energy* calculated consumption (heat, electricity, water): kWh/m^2 per year (primary energy conversion factors are being used in the calculation (primary /useful energy).	95
Finland [125]	Schools & day care centres	*E-value* requirements (overall maximum values for energy consumption): kWh/m^2·year primary energy consumption (calculated with weight factor of energy source).	170
Slovakia [125]	Schools	Energy class global indicator: kWh/m^2.year, *primary energy* (and also an energy class for heating energy)	205-272 (85-112)

2.2.1.1 General energy consumption

In Denmark, one of the most experienced MS in EPC [131], the energy frame foreseen in the EPC system for schools provides information on the energy need for cooling, heating, ventilation, DHW and lighting [164].

The values found in the literature for Finnish schools [3], particularly in the Helsinki area, are presented both for *district heating energy use* and the *total electrical energy use*. The values presented in **Figure 1**, correspond to the sum of both.

Butala and Novak [149] presented the results of energy audits performed in 24 old school buildings in Slovenia, built between 1874-1969 and adapted between 1948-1996. Here, the average total energy values (heating, DHW, lighting) are expressed both in *square meter of building area* and *per unit of volume of building*, 192 kWh/m^2 per year and 54 kWh/m^3 per year, respectively. The authors reinforce however that these values fall outside the range of accepted values of the Slovenian codes for energy use. On this paper, the authors provided also another indicator – heating energy per student, whose average value presented is 1646 kWh/pupil a.

The topic of energy relating Hellenic schools has been abundantly published, [114], [134], [165]–[169]. Greek climatic zones definition has been changed. Within the previous regulation (*TIR*) there were three climate zones (A–C). KENAK introduced an additional climate zone (D) within the northern regions of the country (zone C) [169]. In 2011, Dascalaki and Sermpetzoglou [114] developed a comprehensive study aiming at assessing the energy performance of schools on a national level, embracing the three climatic zones (A–C), previously defined in Greece. The collected data was used to define “typical” values, in other words, energy performance benchmarks. From a total selection of 500 schools, the average thermal, electrical and total energy consumption was found equal to 57, 12 and 69 kWh/m^2, respectively. The data were normalized, allowing the authors to provide complementary values for *typical school* and *best practice* (25% percentile). This data is further depicted in **Figure 1**, **Figure 2** and **Figure 3**.

In France, a recent programme on energy renovation of schools is taking place in Paris. In March 2012 in a press-release reported by the city mayor [138], the energetic profile of Parisian schools was revealed – 224 kWh/m^2. The value presented is expressed in terms of primary energy comprising all the energy consumption in the Parisian schools (half of those were constructed between 1880 and 1948).

In the early published Italian literature on the theme, 2002, three “behaviour” categories – *good, sufficient, insufficient,* for different types of schools [142] were found – *nursery schools, elementary schools* and *middle, secondary schools*. A curious aspect on this benchmarking systems is that both the heating and cooling energy needs are presented in terms of volume (non-residential buildings) and not of surface area (residential buildings) [131], which is the most common practice (energy consumption per gross floor area unit) – school height can vary significantly from school to school.

In the Portuguese case, instead, the literature is relatively narrow, fairly unexplored. A first approach to energy consumption in secondary schools, based on 57 case studies data based electric billed, was presented in [148]. Moreover, the legislation is not as precise as in other countries – school buildings are considered as class within the general regulation. The national legislation, recently revised [82], foresees a B- energy efficiency label, at least, for new and major refurbished buildings in the service buildings sector. In this new legislation, the building energy efficiency is determined by comparing the buildings’ simulated energy consumption with a reference building – in other words, with the buildings' simulated energy consumption if it was constructed, lighted and equipped with reference systems in which the building would have a B- label. The B- label corresponds to the median of the energy consumption, for the existing building stock, for the considered type of building.

In the United Kingdom (UK), energy benchmarks in schools are calculated separately for fossil fuel and electricity, so that a school can determine performance against each benchmark for each type of energy use. This presupposition makes it possible that performance may be good for electricity but poor for fossil fuel or vice versa [151]. The values presented in **Figure 1** (determined based on [151]), **Figure 2** and **Figure 3** also highlight the differences between different education levels. The values herein presented do not consider schools with swimming pools. It should be noted that "the median for schools is within 2% of the TM46 Benchmark" [170], (the DEC benchmarks are published as CIBSE Technical Memorandum 46 – a publication offering a complete figure of building energy benchmarks).

Similar to UK data presentation, data exposing benchmark values for Northern Ireland, presented in **Figure 2** and **Figure 3**, do not consider schools with swimming pool. Data revealed by the authors of [147] highlights the importance of sub-categorization building types according to their typology (primary schools vs. secondary schools), but also different energy use, mixed-fuel buildings vs. all-electric. Although the authors of [147] defend that heating and electrical energy values should not be summed, for a general benchmark, this is summarized in **Figure 1**.

The evolution along time in the UK featuring energy benchmarks for DEC and improving energy performance in schools accounting for benchmarking is noteworthy [10], [94], [171], [172]. Currently, more than 15000 school buildings (university campus apart) are *databased* [170], corresponding to the second category (right after Hospital – clinical and research) more carbon intensive.

In North America, Canada, a reference table has already been designed (for different types of buildings) to help balance property's energy use to the national median [155]. Herein, the recommended benchmark metric is the *national median source* – Energy Use Intensity (EUI), expressed in GJ/m^2. The value presented in **Figure 1**, expressed in kWh/m^2, was determined using a web energy converter. The median value corresponds to the middle of the national population of a certain type of building. **Figure 1** presents the median value for *site EUI* (197 kWh/m^2). Since *site EUI* results in a mixture of energy (primary energy plus secondary energy, depending on the type of energy provided to the building, e.g. raw fuel like natural gas vs. a converted product like electricity), *source EUI* use is recommended (in this case, the median value is 283 kWh/m^2).

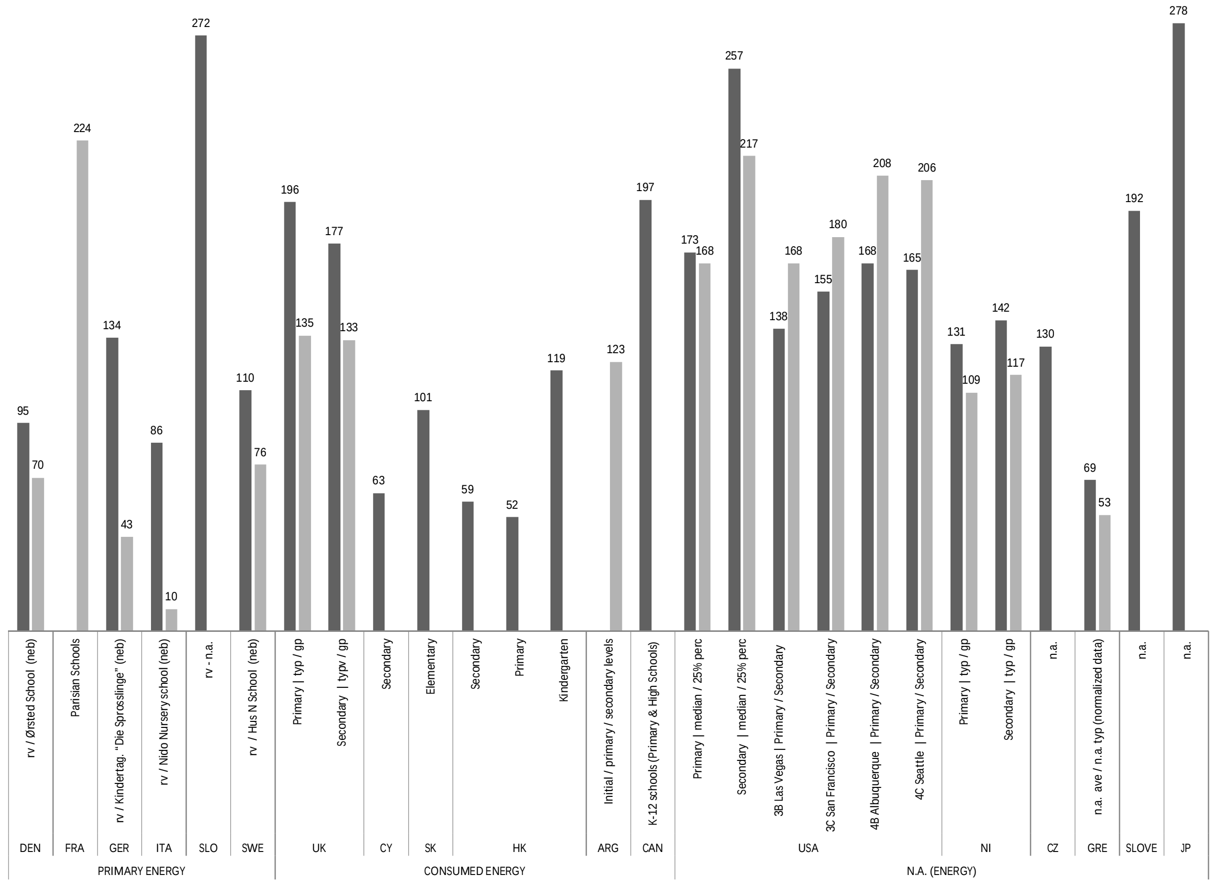
In the USA, a different approach is found in the literature. Normally, energy data consumption of schools are expressed in *annual cost per surface area* ($\$/m^2$) or *annual cost per student* ($/student), [157]. In other situations data is present in *kBtu* (one thousand British thermal units) [158], making a worldwide comparison of the energy values difficult.

The current DOE (Department of Energy) building benchmark models are quite complex and representative of the U.S. housing stock, located in different climatic locations in the U.S. Among the models there are various building types, including primary schools and secondary schools. The climatic zones classification adopts the methodology of the ANSI/ASHRAE/IESNA Standard 90.1-2007 *Normative Appendix B – Building Envelope Climate Criteria*. Herein each climatic zone is classified by a number (1 to 8) representative of air temperature distribution and by a letter (A to C) representing the humidity level, which for North America depends mainly on the longitude. Data processed from the available information [156] for primary and secondary schools in the 8 climatic zones (mean and 25% percentile values) is presented in **Figure 1**. Moreover, general energy consumption values for climatic zones 3B, 3C, 4B and 4C, are presented too.

The values presented in [162], relating the average energy consumption of the elementary schools in South Korean schools are expressed in MJ/m^2 yr in terms of annual energy use (electricity, oil and gas) and per capita, ranging between 2951 MJ/student yr to 3889 MJ/student yr. The values presented in **Figure 1**, correspond to the sum of the three fuel types (energy consumption per unit area) – 365 MJ/ m^2 or 101.4 kWh/ m^2. Almost 72% of this global value corresponds to electric energy use.

In Malaysia (2012), aiming at reaching 2020 more intensive requirements, a study was driven in an university campus [161]. By considering the total annual (electric) bill, it was observed that this university building energy index (BEI) was 116 $kWh/m^2/yr$, lower than *the best BEI practice* and recommended value by the Malaysian Standard 1525 for non-residential buildings: 135 $kWh/m^2/yr$.

The annual average energy consumption value for educational buildings in Japan (from kindergarten until university) presented in [160] is 0.36 GJ/m^2. The value presented in **Figure 1** of 277.8 kWh/m^2 was converted. The influence of the University level on the average value presented is worth mentioning, since all the buildings in this category present a consumption value close to 0.5 GJ/m^2 or higher. The energy use intensity of this educational level might justify the significant differences towards the other Asian countries herein presented.



Notes: DEN = Denmark; FRA = France; GER = Germany; ITA = Italy; SLO = Slovakia; SWE = Sweden; UK = United Kingdom; CY = Cyprus; HK = Hong Kong; ARG = Argentina; CAN = Canada; USA = United States of America; NI = Northern Ireland; CZ = Czech Republic; GRE = Greece; SK = South Korea; SLOVE = Slovenia; JP = Japan; rv = reference value; n.a.= non availabe (type of school building); EB = educational buildings; gp = good practice; typ = typical.

Figure 1 – Schools' annual global energy consumption values per country (kWh/m^2)

The Electrical and Mechanical Services Department (EMSD) of the Government of the Hong Kong SAR Government makes available some Energy Consumption Indicators (ECI) for diverse business operations [159]. Nevertheless, because these are derived from studies on a limited size of samples within the population of respective energy-consuming groups, this entity states they "*should not be construed as representative energy consumption levels of the population, nor as territory-wide standards which businesses in the respective energy-consuming groups should comply with*". Yet, it is interesting coming across ECI for different education services. Values in the literature are presented in MJ/m^2. In **Figure 1**, the values are expressed in kWh/m^2 to allow a better comparison. It should also be added that this entity provides one online benchmarking tool, where one of filling fields is *internal floor area* (IFA), not differentiating whether if it is net floor area (NFA) or conditioned floor area (CFA). The difference towards the commonly variable found in literature – *gross floor area* (GFA) – is noteworthy. In some other cases *total useful floor area* (TUFA) is the considered reference floor space used for benchmark [170]. Many times, the energy reference area is not explicitly defined.

2.2.1.2 Thermal energy consumption

The study on energy consumption on Slovenian schools previously presented [149] introduces an *energy number for heating* in energy-efficient school buildings, varying from less than 112 kWh/ m^2 per year to 196 kWh/ m^2 per year, and referencing a maximum of 1 MWh/pupil per year.

In Finland, Helsinki schools *district heating energy use* is presented in [3] as an average degree-day-adjusted value. A similar approach is also validated in [114]. Herein, stated values for *typical school* and *best practice* correspond to normalized data, taking in account climate variations as well as the operating time among the schools of the sample.

In the UK, schools' benchmark is measured in kilo-watt hour (kWh) per m^2 of *heated floor space* per annum for fossil fuel and electricity. Based on consumption data for 2000 schools in England in 1999-2000, in [151] both *typical* and *good practice* values are presented. The typical value corresponds to the median value of the data. The good practice value matches the lower quartile of the data; this means *"25% of schools sampled performed better than the good practice benchmark"* [151]. The typical value for primary and secondary schools for fossil fuel is 164 kWh/m^2 and 144 kWh/m^2, respectively.

The interval presented as Slovakian reference heating energy use reference values (85-112 kWh/m^2.yr), corresponding to the reference value for the existing building stock [125], class D of the national EPC.

In Italy, for high schools and offices the conventional heating period was fixed at 6h per day [143]. In the study of Corgnati *et al.* 2008, space heating average values vary between 110-115 kWh/m^2 (37-38 kWh/m^3). These values were obtained from a sample of more than 100 schools in the region of Piedmont (northwest Italy, near the Alps). The authors also revealed that the deviation of the profile was quite high, highlighting the heterogeneous profile of Italian school buildings in terms of energy performance. Nevertheless, the specific energy consumption frequency distribution showed a regular profile around its mean value, for which the authors defended the values obtained by the statistical analysis could be taken as benchmarks for building classification purposes within the national energy certification schemes.

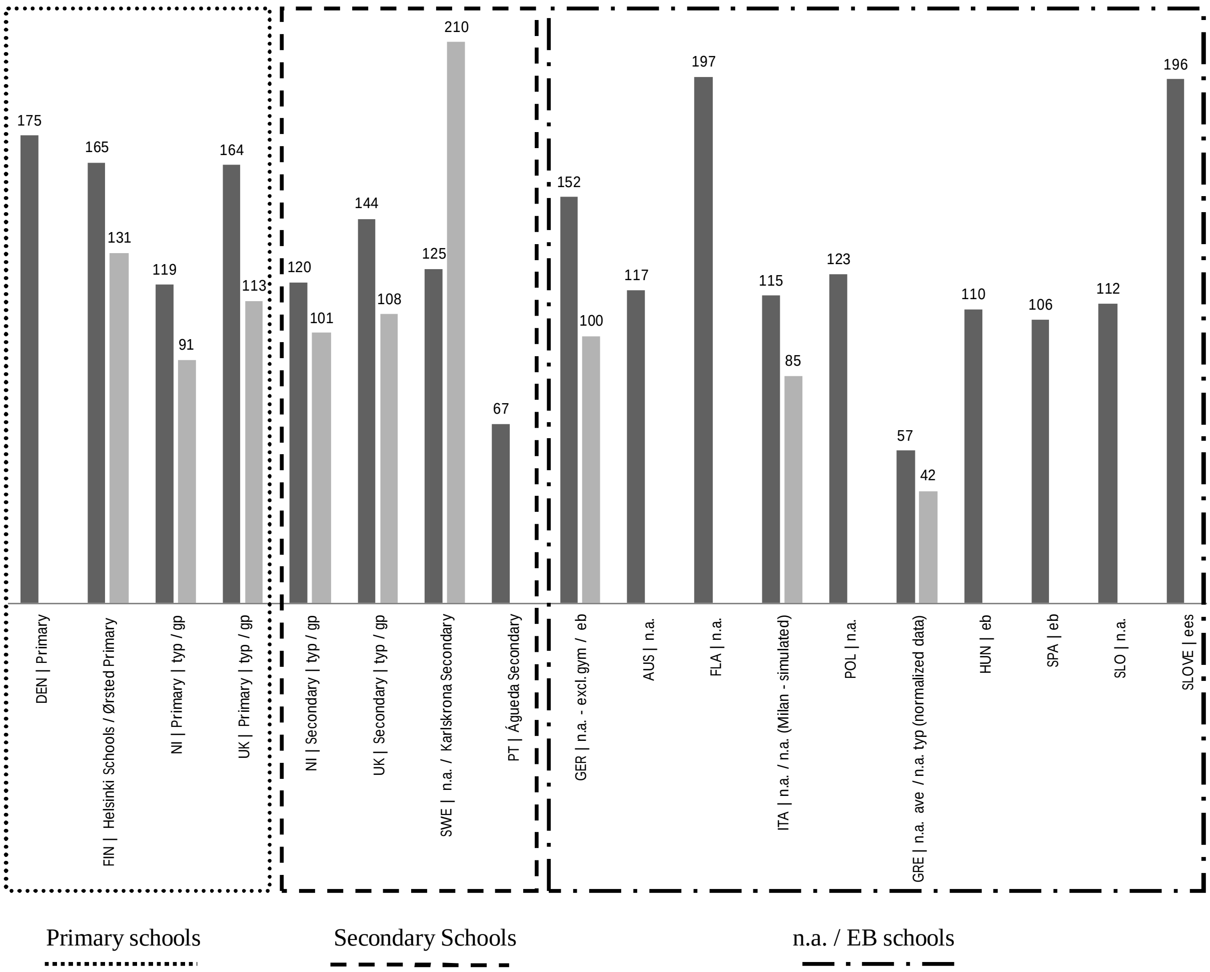
Shortly after, in 2010, ENEA's (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) report RSE/2010/190 [144] reveals complementary information on the period of use of the scholastic buildings. 70% of the school buildings have morning and afternoon courses (9h) and 20% have evening courses, being operational for 14 h/day. It is also noteworthy that more than 30% of these present extra-curricular time use. Complementarily, this report adds that only a fourth of the school buildings adopt a partial heating time table in relation with the hours of use of the building. The average heating energy value herein presented is 27 kWh/m^3 – expressed as specific consumption of *useful energy* (referred to the unit of gross heated volume), lower than the one previously presented in [143]. Interestingly, these Italian values, when compared to the simulated ones under the European project COMMONCENSE (financed by the Intelligent Energy program [173]) are considerably higher. For the scholar buildings in Rome and Milan, the estimated heating energy loads intervals were 24-32 and 73-85 $kWh/m^2 \cdot yr$, respectively [132].

On this same report [132] estimated values are found for heating energy loads and final HVAC energy systems in Austria according to the different comfort and ventilation categories stipulated in EN15251 [174]. The estimated energy intervals were 95-117 $kWh/m^2 \cdot yr$ and 119-146 $kWh/m^2 \cdot yr$, respectively.

The values presented in [140] relating fuel consumption (data presented for Germany, Sweden, Hungary, Poland and Spain) are somehow adjusted, since they correspond to calculated useful heating demands with a BEAM model, that took into account typical national heating system efficiencies (the useful energy demand was transferred to end energy consumption). On the other hand, electricity consumption values (presented in **Figure 3**) are based on Ecofys calculations and metered data from *Rotermund, KG, 2010* – a report that investigates more than 2800 non-residential buildings.

"Mixed Info Schools" in **Figure 3** refers to situations where the information is not structured in the same way and some assumptions or generalizations had to be done during the data analysis.

The study developed by Filippín [152] revealed that in Argentine schools (the sample involved schools from the initial, primary and secondary levels), gas consumption (directly related to heating consumption) accounted for about 90% of total energy consumption. Pitifully, only general values are expressed in kWh/m^2 per year; thermal energy is totally accounted for, but not as an indicator. Curiously, this author also presents energy consumption values in terms of CO_2 emissions 20-60 kg CO_2/m^2 (average 31.4).



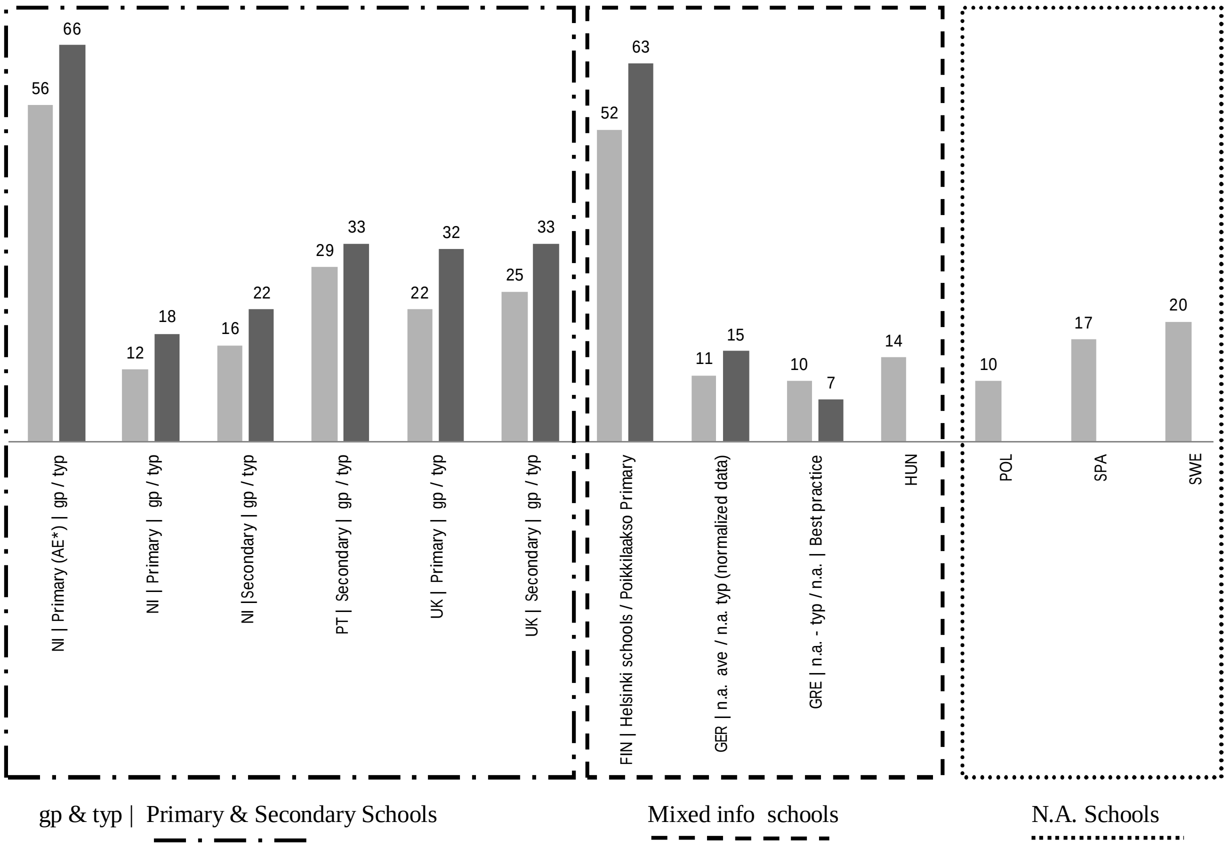
Notes: DEN = Denmark; FIN = Finland; NI = Northern Ireland; UK = United Kingdom; SWE = Sweden; PT = Portugal; GER = Germany; AUS = Austria; FLA = Flanders; ITA = Italy; POL = Poland; GRE = Greece; HUN = Hungary; SPA = Spain; SLO = Slovakia; SLOVE = Slovenia; n.a.= non availabe (type of school building); EB = educational buildings; gp = good practice; typ = typical; ave = average; ees = energy efficient school

Figure 2 – Schools' annual thermal energy consumption values per country (kWh/m^2)

2.2.1.3 Electrical energy consumption

In a Finish case study of a small primary school, presented in [3], the total electrical energy use for lighting, HVAC and equipment is compared with the average electricity use in Helsinki schools – 52 kWh/m^2. It is noteworthy that these values follow UK's [151]. But since no data relating heating energy was presented in [148], it is not possible to affirm whether these schools perform as efficiently as the ones in the UK. They just perform similarly in terms of electrical consumption.

Later in 2013, energy consumption data from refurbished school buildings in Portugal under the *Modernisation of Public Secondary Schools Programme* [175] launched by the Portuguese government in January 2007, were previously presented in [148]. These values relate solely electrical energy consumption. It is noteworthy that the heating system in the modernised Portuguese schools presented in [19], [148] and [175] does not necessarily rely on fossil fuel; hence, the values in [148] might, in fact, reveal a better general energy consumption than those in the UK. This presumption can only be validated if new data related heating energy consumption comes to light.



Notes: AE = All Electrical school buildings; NI = Northern Ireland; PT = Portugal; UK = United Kingdom; FIN = Finland; GER = Germany; GRE = Greece; HUN = Hungary; POL = Poland; SPA = Spain; SWE = Sweden; n.a.= non availabe (type of school building); EB = educational buildings; ave = average; gp = good practice; typ = typical.

Figure 3 – Schools' annual electrical energy consumption values in European countries (kWh/m^2)

2.2.1.4 Normalized energy costs

In the USA K-12 schools represent approximately 8% of the energy use and 10% of the floor area in service buildings nationwide, spending more than $8 billion each year on energy [176]. As previously presented, the USA's approach to energy consumption in schools is more incisive on energy cost per student. One of the most recent studies [157] in the field reveals that in Texas, for example, students' energy cost can vary as much as $75-$200 per year. Moreover, it has been remarked how these values can appear deceiving by misconsidering building space utilization – "variations in space utilization can skew benchmarks for building performance". Almost 70% of the schools in Texas have an actual student density between 75-200 square feet per student, but all the other varied “widely in sq.ft./student, energy cost/student, or both” [157]. Other publications [177], [178] showed "schools spend approximately $75 per student on gas bills and $130 per student on electricity each year" citing U.S. Environmental Protection Agency (EPA) data from 2008.

In 2012 [158], using EPA's data, median energetic cost between 1.3 and 1.38 $/ ft^2 is presented, for different types of school – elementary, middle or high. In another case study, in the Vigo County School Corporation (VCSC) in Terre Haute, Indiana, which is composed of "3 high schools, 2 alternative schools, 6 middle schools, and 18 elementary schools", after a retrofit programme, an Energy Cost Intensity of $0.70/$ft^2$ was found [176] – half of the cost intensity value in ASHRAE 90.1-2004, $1.40/$ft^2$. St.Thomas School new school building in Medina (the first LEED® for Schools Gold Certified project in Washington State) presents an ever more impressive value $0.43/$ft^2$ and EUI of 71.3 kBtu/ ft^2 per year [178].

Authors like [157] recall, nevertheless, the determinant character of the climate adjustment and weather normalization, separating them into more-humid coastal areas and less-humid non-coastal areas. This points out the importance of school location and how this increases energy consumption and costs – normalized energy costs should not be regarded isolated but always in a context.

2.2.2 Benchmarking categories

"Each unit of electricity results in two to three times more CO_2 being emitted as the direct use of fossil fuels in the building. In addition, a unit of electrical energy is more expensive than the equivalent amount of energy obtained through the consumption of fossil fuels in the building's heating system. It is recommended, therefore, that separate indicators be used for electricity and fossil fuel consumption. Where a single indicator is required, the electricity and fossil fuel consumption should each be converted to kg CO_2 and the two numbers added together". [10]

Monitoring and targeting provides mechanisms for the long-term management of energy use and for highlighting potential improvements in the efficiency of energy use [10]. A minimum period of data collection is necessary to provide a useful comparison between a certain building typology.

To allow an understandable comparison between the values from different countries, *final energy consumption*, the value that comes on the monthly energy bills, is used as the unit for benchmark. A School Benchmarking Indicator (SBI) is proposed (previously presented in [148]) based on the metered energy use and is intended to reflect the operational characteristics of a school building: in contradiction to the EPCs that reflect the design characteristics – theoretical energy performance of buildings, based on standardized data and assumptions that do not necessarily reflect true energy performance.

ENEA's report RSE/2010/190 [144] discloses the importance of statistical consistence of data. Using statistical analysis tools, several variables were examined to verify the ability to explain part of the variation of the energy consumption. It was found that the factor that most influences the energy consumption for heating and energy electricity in school buildings, among the analysed sample, was the surface area and/or volume (mostly volume). In some cases, it was also verified to have a significant influence on the heating consumption: the data related to the transmittance of opaque components of the façades, the boiler power and daily period of use (nº hours). As regards the electrical consumption, building surface area was found to be the most significant variable, the one explaining most of the phenomena variation.

The efforts to define coherent figures to be used as benchmarks raises several questions:

- choosing the *building typology* or subcategory;
- defining the *typical energy use* of a certain building;
- establishing appropriate reference values for the definition of *good practice energy use;*
- finding a suitable weather adjustment factor.

2.2.2.1 School Typology

Primary and secondary schools have different energy use, different occupancy density, different hours of use, etc. Therefore, to assure the quality/accuracy of data, like establishing the floor area definitions being used, a primary distinction between scholar degrees should be established. For instances, primary and secondary schools correspond to different educational buildings category. The year of construction should also figure on the final picture. From the reasons already presented and based upon all the literature on the theme, the *typical value* should correspond to the *median value* of the sample, avoiding the disadvantages of choosing the mean, which can be biased by extreme values, and might not be absolutely representative if the data distribution is asymmetric. When *typical* and *good practice* values are addressed, the tendency is that the last one corresponds to the 25% percentile; this means that 25% of sampled buildings have lower energy consumption than these benchmarks.

In [147], the authors draw attention to the different fuel energy use in buildings. Two fuel types have different costs, primary energy use, CO_2 emissions, and hence should be kept separate. Mixed mode fuel buildings (MMFB) have necessarily different energy consumption than all-electric school buildings (AEB). Curiously, some of the most recent buildings running for NZEB, s*elected best-practice buildings*, are *all-electric buildings* (PV and heat pump), for example, the *Enerpos* school in St. Pierre, La Reunion, France [179]. This assumption implies that MMFB and AEB define different SBI categories. Moreover, it is reasonable that electricity and fossil fuels consumption should be kept separate. More information is presented in **section 2.2.2.2**.

2.2.2.2 Data normalization

There are three main topics related to the considerations on data normalization of energy consumption in school buildings: weather adjustment, benchmark unit and different energy uses.

Although some authors do not defend that [147]: “the data analysis did not adjust the raw data in any way, e.g. weather correction, as this kind of normalization can often bring in more inaccuracies than it removes, masking the true trends in consumption”, when attempting an all-in-one benchmarking, climate location should not be disregarded.

Data normalization is a complex issue. For an impartial data comparison, the recalled SBI [148] accounted for metered energy consumption and climate differences adjustments, resulting in a combined unit – kWh/m^2/year/HDD (where HDD stands for Heating Degree Days). This approach is already in practice in some countries’ data presentation, as in the cases presented in [142] and [158].

The possibility of this approach is based upon the fact that “Heating Degree Days (HDD) are a measure of the amount of heat energy which is required to maintain a building at a comfortable temperature (…) and are therefore an estimate of the heating requirements for specific location. HDD are computed as the difference between the base temperature” – that changes between countries – “and the daily mean outdoor air temperature. An accumulation of the daily HDD within a year at a particular location provides an annual HDD value.” [180]. In Portugal the current reference temperature value is now 18ºC [181] but it was 20ºC, e.g. the same as the current reference value in Romania [182].

It is true *billed* energy consumption in school building is influenced by users’ behaviour. It is also true that asset ratings, because they are based on estimated calculations, often do not consider the real period of occupancy of buildings, the accurate efficiency coefficient of the heating plant, the *unregulated energy* (general appliances, computers, non-fixed systems) [183], or *slippage during construction and commissioning* (the building may not be constructed exactly as intended or may not be occupied quite as envisaged) [184].

Benchmark should be withdrawn from *billed* energy consumption, i.e. using an operational rating (OR). Foremost because significant differences between simulation and real use buildings have been found [130], what Bordass *et al.* [184] called the ‘credibility gap’ between predicted and actual energy use. However, this is also because of the trend of some of the MS energy policies [125]. Moreover, assuming a temporal development, this will allow school managers to check their school energy evolution in time – the previous OR should be shown.

The unit kWh/m^2 found in the literature is varied and often imprecise, relating to the type of area under reference, i.e., GFA, NFA, OFA, TUFA, etc. Ideally this unit should refer to the conditioned floor area (CFA).

Most of the times, the available data on buildings' energy consumption corresponds to the type of (primary) energy delivered to the building. Ideally, the total amount of energy consumption in buildings should be disaggregated by final energy end-use (consumptions). Disaggregating energy data helps to know where most energy is used. In the USA, "for schools in general, lighting, ventilation, heating, and cooling account for 80% of energy consumption": **Figure 4**, based on data available at [176], illustrates this scenario.

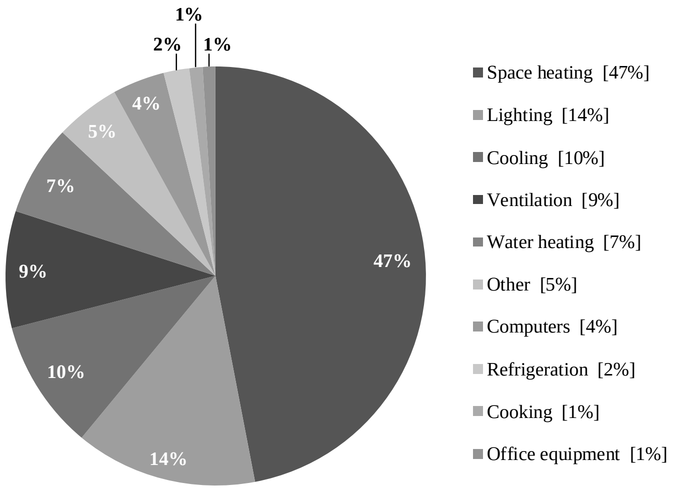


Figure 4 – Average energy use profile of schools in the USA

Unfortunately, this information is not always available and also, gas and electricity consumption is not always used for the same purpose – for example, heating in schools is not always assured from gas; it is proposed that the breakdown of the total amount of energy is by final energy end-use, according to **Figure 4,** or at least, that electricity and gas consumption should be kept separately, resulting into two different indicators, imbued with the Finish approach [131]:

a) *Gas consumption: for space heating & domestic hot water (DHW);*
b) *Electricity consumption: for lighting, HVAC systems & electrical equipment.*

Very often only billed data is available. Within this approach, it is possible to allocate consumptions even if the final energy end-use is unknown. Although not ideal, this policy allows a higher level of detail compared to the one more often presented in the literature.

One of the potential benefits of the SBI is encouraging the generation of a national database of building energy performance to assist in better informing policies, a mean of promoting better standards for energy management, and a continuous evaluation. The comprehensive review of Perez-Lombard *et al.* [185] describes how building energy certification schemes for existing buildings should be implemented by the use of operational ratings with reference values (benchmarks) taken from the building stock.

2.3 Discussion

This study should be considered as a contribution to the issue of energy consumption of school buildings' benchmarking, for which there should be further developments, checks and additions. Therefore, the obtained results are an assessment of the magnitude of the problem and potential of its solution.

The breadth of the term *education buildings* embraces different-sized schools (elementary, primary, secondary school buildings) that offer different education levels, which entail a wide gap in the energy needs even among buildings with the same general use classification. Different school levels anticipate different occupation densities and time-table occupation and therefore different energy consumption. The same reasoning can be applied to the difference between high schools and university buildings. In the context of USA, for instance, the difference between primary and secondary schools can correspond to almost 50% increase in terms of the global energy consumption (173 vs. 257 kWh/ m^2). This value is quite contrasting the UK's – in this case, secondary schools' global energy consumption is 10% lower than primary schools' (196 vs. 177 kWh/ m^2).

Moreover, it is defended that besides the building standard use – teaching, other specific facilities such as swimming pools should be analysed separately. Gymnasiums night occupation should also be accounted.

Statistical benchmarks based on buildings' *billed energy consumption*, databased on a national level, are to be developed – this is already in practice in the UK (DCLG - Department for Communities and Local Government) [183], in Germany (GEFMA - *Rotermund Ingenieure and the German facility Management Association*) [140] and in the USA (DOE-Department of Energy), [186]. In the UK, for example, it has been verified that typical global energy consumption values vary between 177 and 196 kWh/m^2, in primary and secondary schools, which is very similar to Canadian k-12 schools (both primary and secondary), 197 kWh/m^2.

Comparisons of the presented values are difficult and might be fallacious. By looking at data in **Figure 1**, for example, it would be unfair or even incorrect to state that schools in a certain country spend more energy than in the UK, since we do not know the energy resources combination of the consumed energy that would allow us to convert it into primary energy. Typical thermal energy consumption values are 14% higher in primary (164 kWh/m^2) UK schools than in the secondary level (144 kWh/m^2), but we also observe that in Northern Ireland typical values are practically the same in both educational levels – 119 and 120 kWh/m^2. These parallelisms, recalling **Figure 2**, cannot be so strongly established between Northern Ireland and Hungary, for example. Data presented for Hungarian educational buildings does not refer to the educational level.

Moreover, it has been verified that different energy "feed" buildings have different energy performances, for which mix-mode buildings and all-electrical buildings should be approached differently.

Under any circumstances, energy benchmark of the school buildings is to be achieved by compromising indoor thermal conditions or indoor air quality of the school buildings.

CHAPTER 3. CASE STUDIES PRESENTATION

The case studies selection process and their characterization are described in the current chapter. As formerly stated, the case studies selection, section **3.1** is grounded on paper **II** [19]**, Appendix A**. The database on the Portuguese secondary schools under study was provided by Parque Escolar E.P.E.

3.1 Public Portuguese secondary schools context

In 2007, a state-owned company, Parque Escolar E.P.E. (PE), was created (by Decree-Law n. 41/2007) for planning, managing, developing and implementing the *Modernisation of Public Secondary Schools Programme*, launched by the Portuguese government in January 2007 [175].

At the time, the Portuguese network of public secondary schools included 477 schools, predominantly built since 1968 [187]. With the endeavour of raising the standards of educational facilities, PE had envisaged the intervention in 332 schools by 2015 (i.e., 70% of the total building stock of secondary schools in the country). By the end of 2009 the programme involved 205 schools, and 4 consecutive phases: the pilot phase (Phase 0) involved only 4 schools; Phase 1 started in June 2007 and covered 26 additional schools; Phase 2 was initiated in March 2008 encompassing further 75 schools, and interventions started in June 2009; finally, Phase 3 was initiated in April 2009 and was supposed to cover 100 other schools [18]. Early in the second half of 2011, a reassessment of the Modernisation Programme was initiated by PE, in order to adapt the company's investment programme to the economic and financial international environment. In this context, a cost reduction plan was proposed, leading to the suspension of 34 schools in Phase 3 and all of Phase 4.

The large scale of this programme and the multiple typology of spaces of its operational interventions have been subject to various criticisms, namely concerning: labs were determined to have permanent, versatile and continued use (combining exhibition and laboratory practices, with guaranteed security conditions); it was PE’s choice that the sport venues were covered (but not enclosed) and workshop spaces should ensure versatility, flexibility and functional adaption (PE, 2010). Beyond the ambition of the considerable scale at stake, this programme was also characterized by the diversity of educational provision of the schools and by their geographic dispersion on the Portuguese continental territory. The Modernisation of Public Secondary Schools Programme also intended to integrate and implement a whole new set of legislation relating to accessibility, environmental comfort, safety, etc. The main difficulties early anticipated were the short period for completion and the need to perform the interventions while schools were working.

This initiative was launched in circumstances of strong public investment and was part of an economic stimulus strategy aimed at boosting economic growth throughout the country. Nowadays, the context has dramatically changed, and the situation of economic crisis and severe financial constraints, both for institutions (public and private) and families, might be invoked to reinforce the value of carefully analysing the possibilities to reduce the maintenance and operating costs of these refurbished school buildings and their equipment.

In the framework of a research and development (R&D) project involving a partnership between University of Coimbra's R&D Units (ADAI, INESC-C and GEMF) and TDGI (a facility management company specialized in global management of buildings, technical and industrial facilities) - *Escolas Energeticamente Eficientes* (3Es) [188], an assessment of the Modernisation of Public Secondary Schools Programme was proposed focused on energy consumption. The work being carried out in the initial months of this project as well as the main R&D future developments were early presented in 2013 [19].

3.1.1 Case studies

Starting from a database of the schools that were, or were expected to be in the future, subject to refurbishment interventions under the *Modernisation of Public Secondary Schools Programme*, a pre-selection of 57 schools was narrowed towards a final selection of 8 school buildings. The methodology was divided into three main stages – data collection, data analysis and development of energy use indicators.

Stage 1. The process was initiated by establishing a single Climatic Map of Portugal, combining the different climatic zones (winter and summer), based on *Regulamento das Características de Comportamento Térmico de Edifícios* [17], as presented in **Figure 5**. Besides the geographical distribution on the territory, the main criterion for the selection was the development phase of the refurbishment interventions. The buildings that no longer had refurbishment works in 2011 have been considered as "completed/concluded". As the aim of the project was the optimization of the energy consumption in the exploitation phase of refurbished school buildings, it was important to focus on buildings where the retrofit intervention was already finished and records of pre and post-intervention energy demand were available.

Stage 2. Having verified the absence of refurbished schools in some municipalities and their corresponding climatic zones, some other schools – with interesting properties for the characterization appraisal – were selected, although having been completed just in 2012. This contributed to increase the geographical diversity and representativeness of the sample. At the end of this stage, 57 schools were pre-selected for further analysis.

Stage 3. In order to support the selection of the final group of 8 schools to be analysed, a number of energy use indicators (EUI) were calculated [19].These indicators enable the examination of energy consumption of very different buildings, in terms of typology, size or the number of students [189]. **Table 3** lists some of the key EUI computed. These calculations were performed on an annual basis for each one of the 57 school buildings included in the preliminary sample.

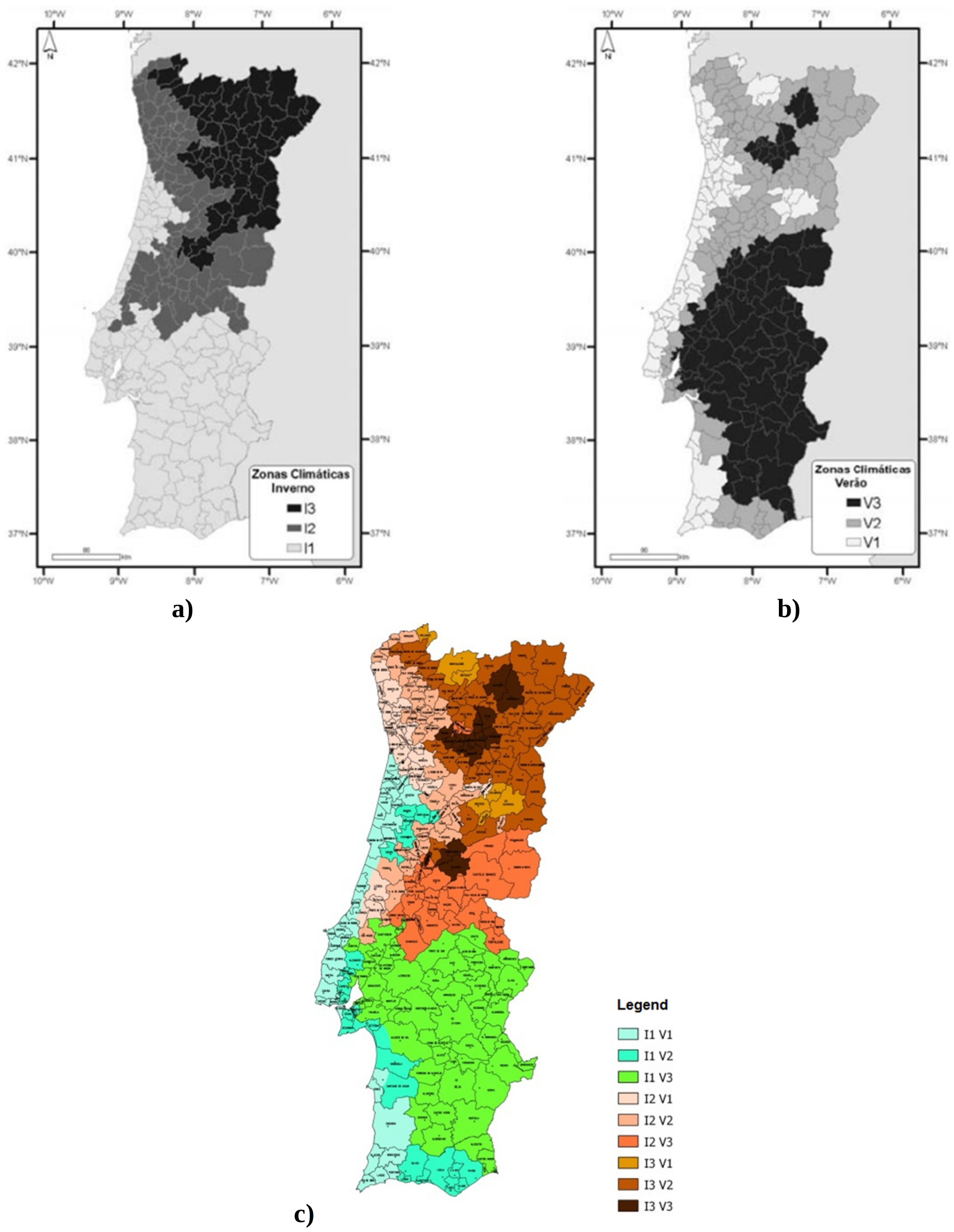


Figure 5 – Portuguese Climate zones, a) Winter & b) Summer [RCCTE, DL 79/2006 - Implementation of EPBD (2003) in Portugal]; c) Map of Portugal combining climatic zones for the heating and cooling seasons

Table 3 – Energy use indicators

Indicator	**Acronym** [units]	**Definition**
Specific Energy Consumption of Electricity	**SEC_{GFA}** [kWh/m^2]	Ratio between the annual Energy Consumption of electricity and the total Gross Floor Area (GFA) of the building.
Specific Energy Consumption of Electricity per student	**SEC_S** [kWh/student]	Ratio between the annual Energy Consumption of electricity and the number of enrolled students.
Variation of Specific Energy Consumption of Electricity	**ΔSEC_{GFA}** [kWh/m^2]	Variation of annual Specific Energy Consumption of electricity with the refurbishment (after *vs.* before intervention)
Proportional change of Specific Energy Consumption of Electricity and Gross Floor Area	**ΔSEC_{GFA} / ΔGFA**	Ratio between the pre- to post-refurbishment variations of SEC and of GFA.

3.1.1.1 The case study schools selection

Based on the data analysis, a final selection of 8 schools was done for further screening, including *in-situ* audits. The criteria for this selection were (sequentially applied):

- Balanced distribution by different climatic zones;
- Higher value of SEC_{GFA} after the refurbishment;
- Higher ratio between the increases of SEC_{GFA} of electricity and of GFA;
- Availability of the building's DCR (Declaration of compliance with regulation, an energy pre-certificate of the building project that is mandatory for the construction license).

Table 4 presents the main characteristics of the 8 selected schools.

Table 4 – Main characteristics of the 8 schools selected

School / Climatic Zone	**PE construction phase**	**SEC_{GFA}** [kWh/m^2]			**$\Delta SEC_{GFA, 08-11}$ [%]**	**ΔGFA_{08-11} [%]**	**$\Delta SEC_{GFA, 08-11}$ / ΔGFA_{08-11}**
		2008	**2010**	**2011**			
W1 S1	2	12.54	44.37	51.67	312	73	4.27
W1 S2	1	9.89	74.19	49.05	396	26	15.23
W1 S3	1	14.47	37.91	45.06	211	64	3.29
W2 S1	1	13.41	52.93	47.19	252	104	2.42
W2 S2	2	11.87	17.15	31.67	167	47	3.55
W2 S3	1	18.72	19.95	54.19	189	45	4.20
W3 S1	2	11.88	18.04	51.76	336	34	9.88
W3 S2	2	13.27	15.68	18.11	36	38	0.95
Average for the 57 schools		16.18	28.01	34.53	231	165	1.45

The selected criteria for energy performance were based on data of electricity consumption, the only one available at that stage. The most consuming buildings were identified and significant increases of SEC_{GFA} were found.

Note: It is noteworthy that by the end of 2013 the national legislation regarding the regulation for the Energy Certification of Buildings was updated [82] *and this school selection would probably have changed, since some of the climatic zones of the buildings were also revised.*

3.1.1.2 The schools climate condition

From 8 case studies selection, the work approach started by framing and characterizing the external conditions of the case studies. The eight schools buildings are located in the continental Portuguese territory, according to the next map – **Figure 6**. A summary of the reference climate data of each school is presented in **Table 5**.

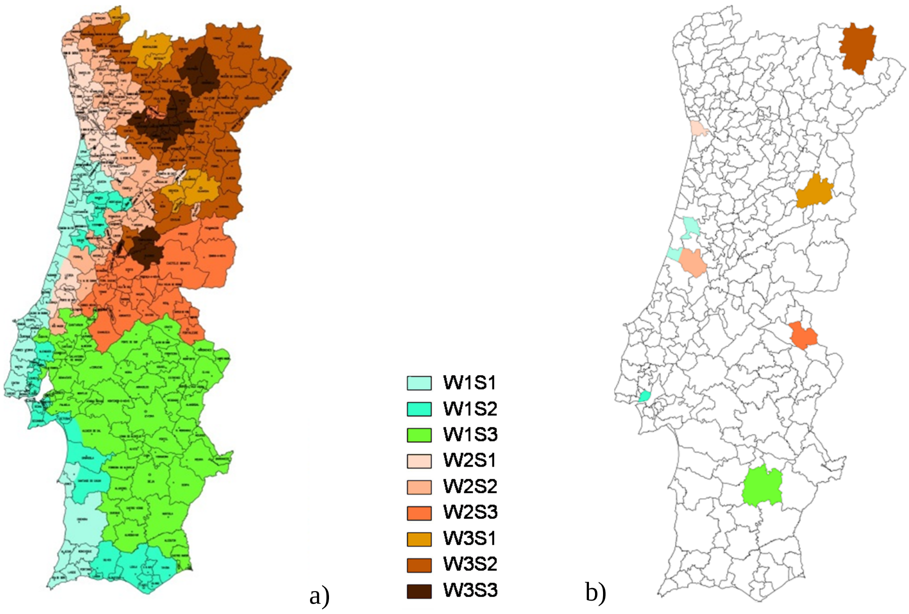


Figure 6 – Map of Portugal with climatic zones for the heating and cooling seasons a); Map highlighting the 8 schools' selection CCD[2] b)

Table 5 – 8 schools' selection – CCD distribution and reference climate data

CCD	**Climatic Zone [selection phase / new SCE]**	**Heating Degrees Days (HDD) [selection phase / new SCE]***	**Distance to the oceanic coast (km)**	**CCD's Altitude (m)**	**Schools' Altitude (m)**
Montemor-o-Velho	W_1S_1 W_1S_2	1410 1265	17,5	67	28
Lisboa	W_1S_2 W_1S_2	1190 1022	13,5	109	80
Beja	W_1S_3 W_1S_3	1290 1145	85	178	255
Matosinhos	W_2S_1 W_1S_2	1580 1140	1,5	94	25
Pombal	W_2S_2 W_2S_2	1580 1226	28	126	75
Portalegre	W_2S_3 W_1S_3	1740 1496	165	246	475
Guarda	W_3S_1 W_3S_2	2500 2235	126	717	1028
Bragança	W_3S_2 W_3S_2	2580 2036	175	680	695

Note: The new HDD presented in grey account the schools altitude.*

From the data previously presented and in accordance with the climatological normal for the interval 1971-2000, next presented, it is clear that the schools with higher heating requirements are the schools located in Guarda and Bragança. **Figure 7** shows the annual evolution of the mean, minimum and maximum monthly temperatures in the cities of Bragança (BGC), Beja (BJA), Coimbra (CMB), Guarda (GRD), Lisboa (LSB),

[2] *CCD - Census County Divison*

Portalegre (PTG), Porto (PRT) and Santarém (STR) – the climate in Pombal varies between Santarém's and Lisboa's.

The school in Guarda is located in the city presenting the lowest mean monthly temperature. The school in Bragança is positioned in the city with the lowest average of minimum temperatures. On the other hand, the school in Beja is located in the city which has the highest average of maximum temperatures.

The school in Lisboa is situated in the city with lower rigorous climate during the heating season, followed by the school in Portalegre and Beja. Regarding the cooling period, the school subjected to lower maximum temperatures is the one located in Guarda.

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 and Bragança have greater needs for heating than for cooling, contrarily to the schools in Beja, Portalegre and Pombal, where the greatest cooling needs are expected.

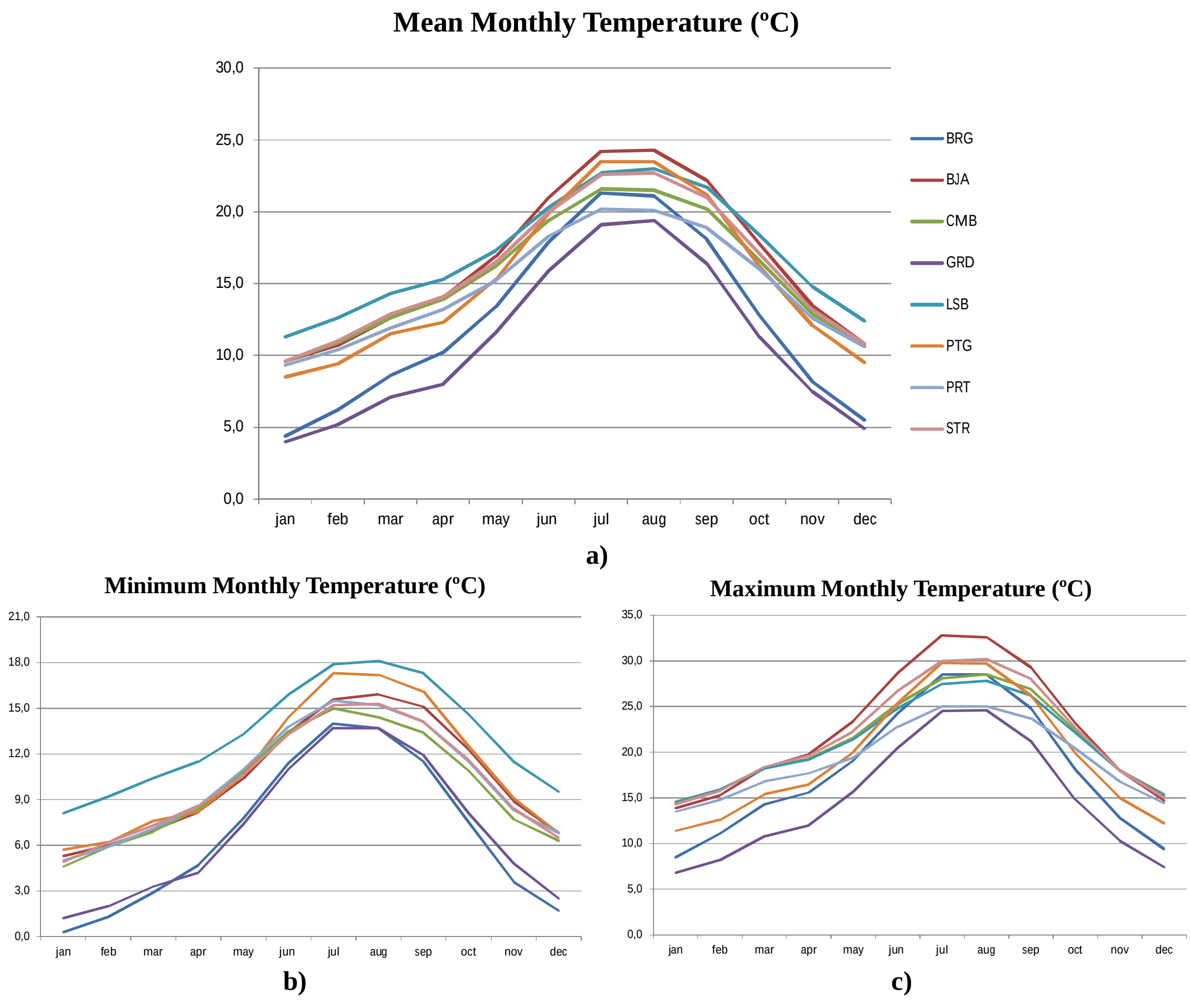


Figure 7 – Mean Monthly Temperature a), Minimum Monthly Temperature b), and Maximum Monthly temperature c) for the cities corresponding to the 8 schools' CCD selection
[Temperature values were obtained from www.ipma.pt]

3.2 The school buildings and their systems

3.2.1 Case study I – Escola Secundária de Montemor-o-Velho (MMV)

MMV is located in Largo da Nossa Srª do Desterro, county of Montemor-o-Velho. It is part of a wider scholar complex, including *Escola Básica 2/3 Jorge de Montemor* and a kindergarten. Geographically it can be identified by its coordinates 40º10'N 8º40'W.

Formerly inaugurated in the 70's, the school was subject to rehabilitation works from July 2009 until November 2010. This intervention, that in a preliminary stage only foresaw major refurbishing works in the existing buildings (block A1, A2, A3 and S), has evolved to the demolition of these and the construction of new ones. It also included a new Gymnasium (Gym), a new Library (Lib) and the Canteen (C). **Figure 8** and **Figure 9** illustrate the space and corresponding organisation of the current deployment.

Figure 8 – Escola Secundária de Montemor-o-Velho | Aerial view
[Source: *Google Maps*, 2013 (GPS: 40.1813240000000, -8.6745430000000)]

Figure 9 – Escola Secundária de Montemor-o-Velho | Layout plan (post-intervention)
[Source: *Parque Escolar*, EPE (2012)]

The school is composed of four main buildings:

- Central Building (buildings A1, A2, A3 & S), a two floor construction composed of classrooms, laboratories, staff room, students association, offices, toilets and storages;
- Library (Lib), one floor high, composed of lounge, reading room, direction room, circulation areas, toilets and archive, sitting 13.5m from the central building;
- Gymnasium (Gym), a two floor construction composed of a multipurpose room / gymnasium, locker rooms, bathrooms and circulation areas, at a distance of 33.5m from the central building (including an outdoor covered sports area);
- Canteen (C), one floor high, composed of cafeteria, social area, kitchen, toilets, changing rooms and storerooms.

From the construction perspective, the interior walls are composed of perforated brick coated with plaster on both sides measuring 150 mm and 220 mm (U value from 1.33 $W/m^2\,°C$ according to the DCR, in 150 mm walls). In A1-A3 blocks, the walls between the classrooms are composed of two masonry layers of 110 mm perforated brick with soundproofing layer in-between, plastered on both of the external sides of the bricks (290 mm in total). The external walls present three types of generic solutions, namely:

- Central Building: double masonry layer of 150 mm perforated bricks separated through a ventilated cavity, partially insulated with 40 mm layer of XPS, plastered on both sides (classrooms façade);
- Central Building: double masonry layer of 150 mm perforated bricks separated through a ventilated cavity, partially insulated with 40 mm layer of XPS, internal layer of 110 mm brick and thermal insulation with Viroc board 50mm (patio façade, with variable ventilated cavity dimensions);
- Library, Gymnasium and Canteen walls consist of an exposed concrete layer (250 mm), internally coated with a thermal insulation layer (60 mm) and an inner brick plastered wall (110 mm + 20-30 mm).

Generally, the intervention was characterized by the application of a thermal insulation layer between the inner and outer facade panes, in concrete or brick.

The fenestrations are mainly composed of double glazing elements in aluminium frames with thermal cut. One of the main fenestration elements in the Central Building is VE01 – double casement window, provided of an internal roller blind (solar factor equivalent to 0.56 or 0.60). A façade section is present in **Figure 10**.

Vertical section

1. Roof construction:
   Round gravel roofing (100 mm)
   Thermal insulation XPS
   Bituminous sheeting over floor screed (20 mm)
   Levelling layer (pitch=2%)

2. Wall construction:
   External painted plaster (20 mm)
   Brick layer (150 mm)
   Ventilated cavity (20 mm)
   Thermal insulation XPS (40 mm)
   Brick layer (150 mm)
   Painted plaster (20 mm)

3. Floor construction:
   Interlayer in rock wool fibres (40 mm)
   False ceiling: plasterboard (125 mm)

4. Thermal cut aluminium frame w/ double glazing
   (tempered glass 8mm + Air 8mm + Laminated glass 44.1)
   Grey *Ataíja* windowsill stone (40 mm)

5. Contact w/ ground
   Grey *Ataíja* stone (20mm)
   Glue cement
   Plaster (30 mm)
   Double masonry brick wall 110 + 150mm w/ thermal insulation
   (40 mm) & air cavity (20 mm)
   Painted plaster (20 mm)

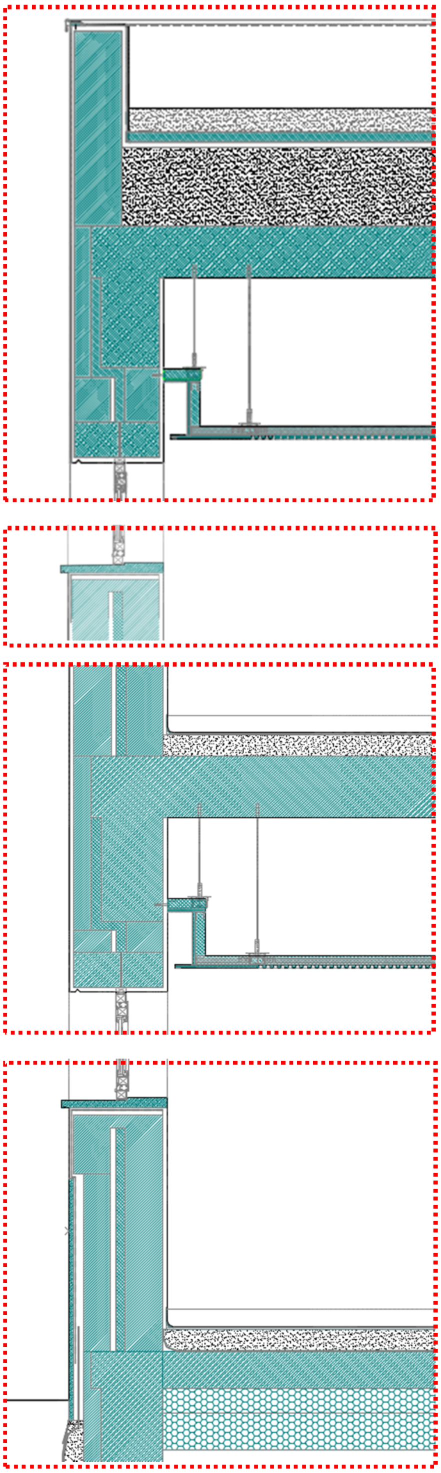


Figure 10 – Escola Secundária de Montemor-o-Velho | Façade section (Central Building)

Roofs present two main construction solutions:

- Central Building: 100 mm finishing layer of washed round gravel over thermal insulation (40 mm of XPS);
- Library, Gymnasium and Canteen: composite system of a waterproofing layer over a thermal insulated coating of rock wool fibres.

The thermal energy production is decentralized – each building has its own independent cooling/heating system. In the Central Building (A1-S) the thermal energy is obtained through VRF units with cooling and heating capacity (heating and cooling power varying between 7.75 – 11.6 kW). The interior units are placed in the ceiling, just before each classroom, while the external units are installed in the roof of each of the buildings. Similarly, HRUs that provide spaces' air renewal (each unit is equipped with heating and cooling coils) are also here located. In the library, canteen and cafeteria the thermal energy production is assured through *rooftop* units with cooling and heating capacity (heating and cooling power varying between 6.79 – 21.9 kW).

DHW is produced in two different locations: two natural gas (NG) boilers provide hot water for baths and environmental conditioning the Gym, another boiler is used for DHW in the cafeteria/canteen (powered 96.5 kW each). There is a solar heating system for pre-heating hot water over the Gym, composed by 32 solar panels ($2m^2$/each), that was not used until January 2015.

3.2.2 Case study II – Escola Secundária D.Pedro V (LSB)

LSB school is located in Estrada das Laranjeiras, nº 122, Lisboa. Inaugurated in 1969, the school was subjected to refurbishing works from September 2008 until June 2010.

In addition to the renewal of the existing facilities (buildings A1, A2, A3, Central Building - CB and the Gymnasium – Gym), these works included the construction of a new building (NB). **Figure 11** and **Figure 12** illustrate the schools' site plan and spatial organisation, corresponding to the pre-intervention period and current deployment.

Figure 11 – Escola Secundária D.Pedro V | Aerial view (pre-intervention)
[Source: *Google Maps*, 2013 (GPS: 38.7419875700000, -9.1622236250000)]

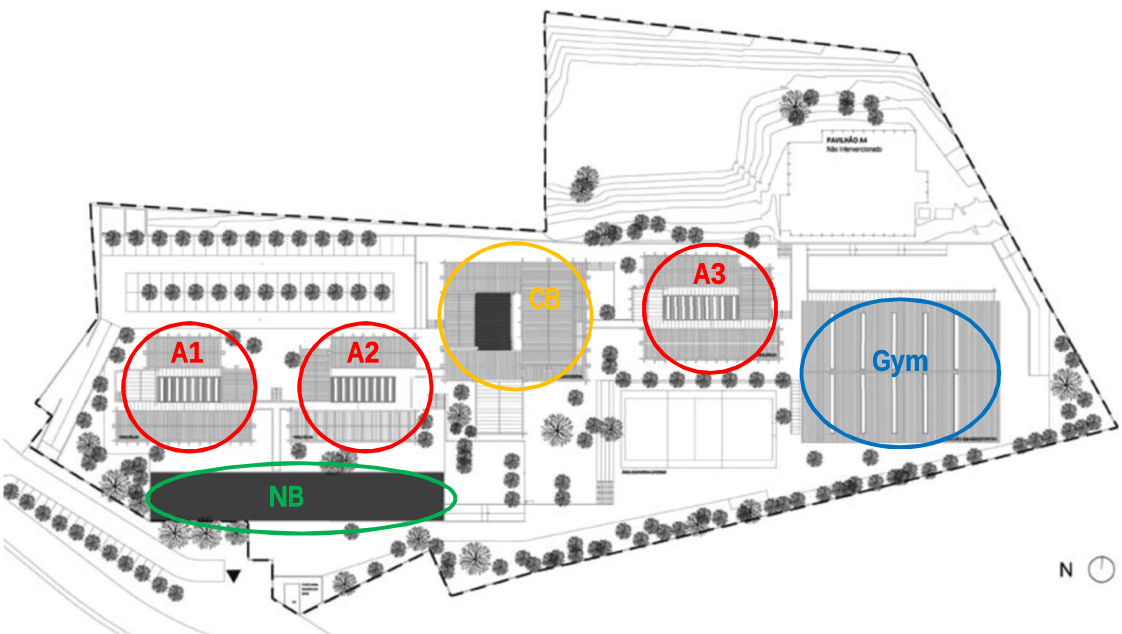


Figure 12 – Escola Secundária D.Pedro V | Layout plan (post-intervention)
[Source: Parque Escolar, EPE (2012)]

School buildings A1, A2 and A3 (pre-existing buildings) are two floors high. A1 is mainly composed of regular classrooms (15); A2 has classrooms (14) and is also provided of locker rooms and a social room for the non-teaching staff; A3 has ITC classrooms (5), drawing classrooms (4) and laboratories (4) for scientific subjects besides a multimedia studio.

The central building (CB) works as a support area for teachers and school management. Herein, the administrative area, the direction board, the secretariat and storage spaces are located. The kitchen, cafeteria and canteen are also located in the CB.

The new building (NB) is also a two floor high construction. Here, the library, the auditorium/multipurpose room, the students association and some technical areas are located. The sports pavilion (Gym) holds the gymnasium and the corresponding support spaces.

Vertical section

1. Roof construction:
   Painting w/ bitumen emulsion
   Thermal insulation w/ double layer of "styro foam" roofmate plates – 100 mm (50+50)
   Geotextile felt + layer of lightweight concrete + floor screed
   Polymer bitumen membrane

2. Walls | finishing:
   Bus over plastered masonry (existing wall)
   Interior coating: plastered board w/ 50 mm rock wool insulation panels

3. Existing walls:
   Concrete (enamel painting or ink epoxy)
   Brick masonry (painted w/ ink epoxy)

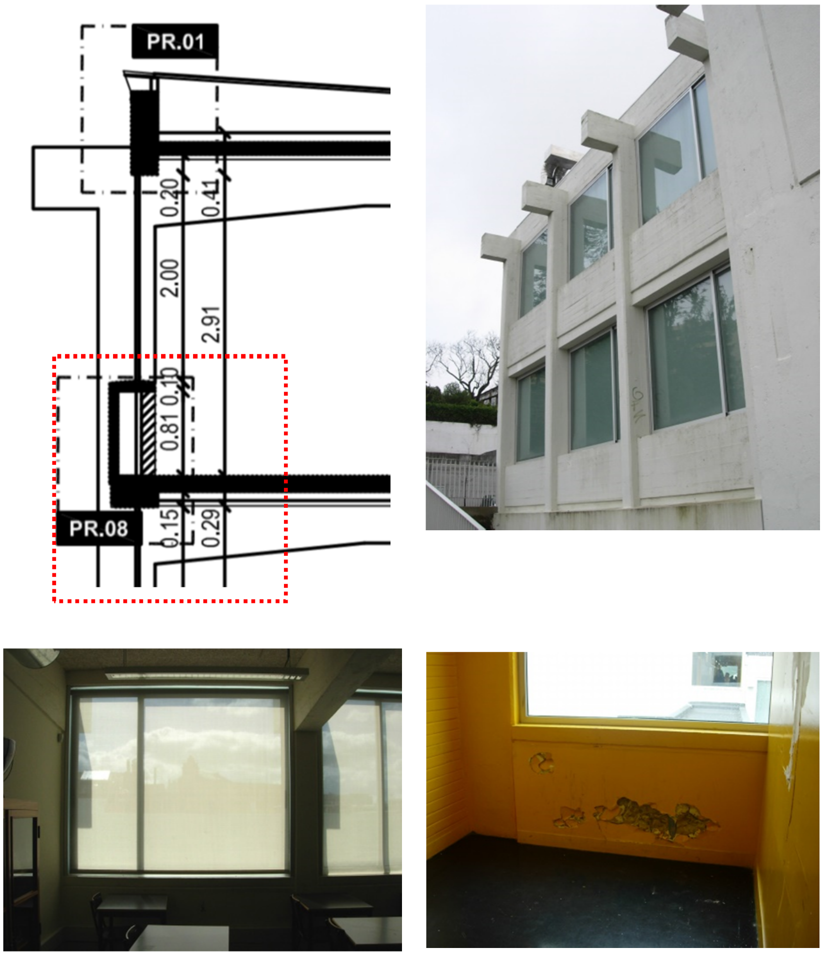


Figure 13 – Escola Secundária D.Pedro V | Façade section and images from inside (Building A2)

The external walls present two types of generic solutions, namely:

I. Pre-existing buildings – thermal insulation applied from the inside (linear thermal bridges' problem was not solved): 50 mm rock wool panels coated with plasterboard were placed over existing brick or concrete walls;

II. New building (NB) – thermal insulation also placed from the inside, either between two layers of brick (200 mm + 110 mm) with 40 mm width (+ 30 mm air cavity) or attached to one brick layer (300 mm width) plastered on the outside.

The main glazing surfaces, namely in classrooms, are composed of two sliding double glazed aluminium window frames.

The thermal energy production lays on a centralized production system of heating and cooling, whose primary distribution system composed by six substations (one per building). Cooling is assured through a 195.6 kW powered chiller. DHW production and environmental heating are assured by two boilers, 350 kW and 400 kW each.

There are also two independent solar panel systems for DHWs pre-heating; one at the gym (20 panels with $2m^2$/each) and another one in the CB (3 solar collectors equally dimensioned).

Thermal diffusion into different spaces is provided by mural fan coil units and ventilation grids. Air renewal is ensured by AHUs equipped with cooling and heating coils.

3.2.3 Case study III – Escola Secundária D.Manuel I (BJA)

BJA is located in Rua S. João de Deus, in Beja. Initially inaugurated in 1960, the school was intervened from October 2008 until November 2009. The refurbishment included works on the existing facilities (buildings A,B,C) – as well as the connecting galleries between these, the construction of a new building for laboratories (G) and a new sheltered sports area (F). **Figure 14** and **Figure 15** illustrate the school space and respective organisation.

Figure 14 – Escola Secundária D. Manuel I | Aerial view
[Source: *Google Maps*, 2013 (GPS: 38.0077219000000, -7.8657759720000)]

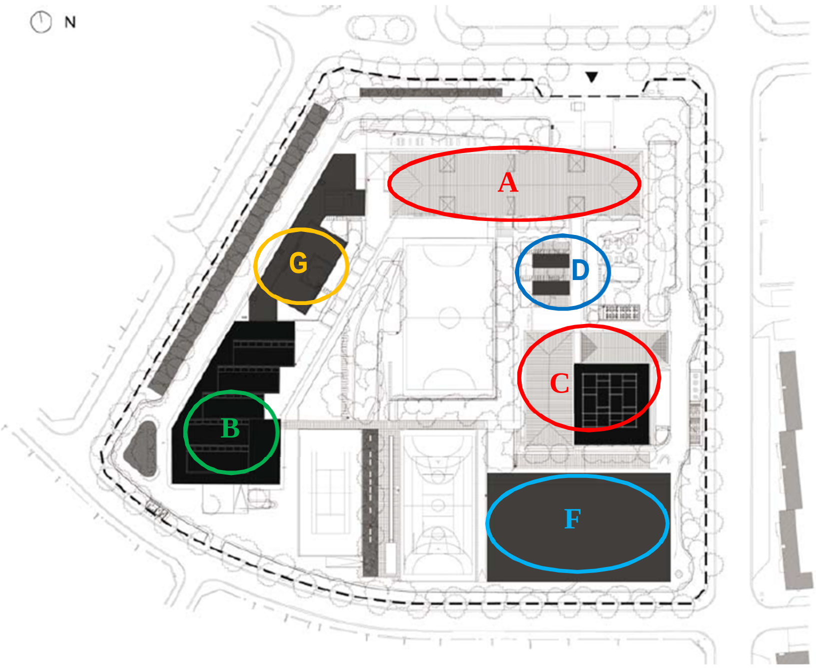


Figure 15 – Escola Secundária de D.Manuel I | Layout plan (post-intervention)
[Source: *Parque Escolar*, EPE (2012)]

Building A is the main administrative and teaching (21 classrooms) building. It is three floors high (level 0, 1 and 2). Besides regular classrooms, the building has 5 ITC rooms and other support spaces for students and teachers. The workshops and the mechanical and electrotechnical labs are located in B, another pre-existing building. Building C is also three floors high (levels 1, 2 and 3). Mainly addressed to recreation and social activities, the library, the refectory and the cafeteria are located here, besides a multipurpose room (where some indoor gymnastic classes take place) and the students' association.

In the new sector D, a convenience store and reprography are located in the gallery connecting A and C.

The new sports activity building – F has locker rooms and an outdoor covered sports area. The new laboratorial building – G is two floors high (level -1 and 0). Here 5 laboratories and other support rooms for scientific subjects are located.

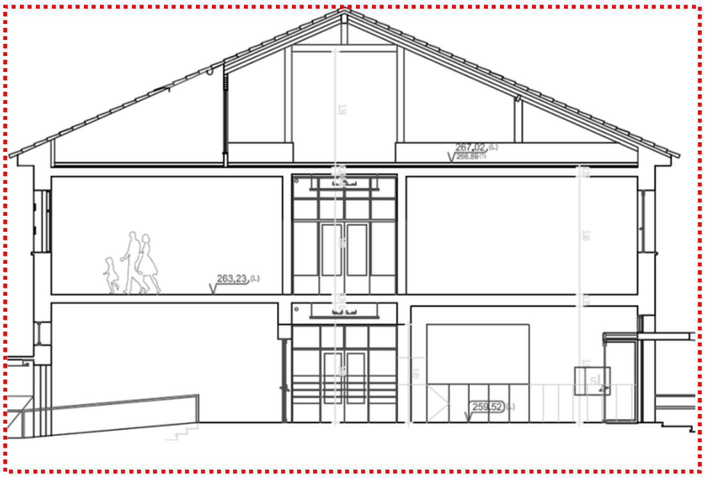
External walls are either in stone masonry or perforated brick, covered with painted plaster. The façades present three types of generic construction solutions, namely:

- Simple paned walls without insulation;
- Double layered walls with or without thermal insulation in the air cavity;
- Simple paned walls with insulated system placed on the outside (60 mm EPS).

In terms of glazing very different solutions can be found in this school. The pre-existing sliding aluminium windows (with a superior hopper) in classrooms were refurbished. In building A, other fenestration solutions can be found: new double glazed aluminium frames (mainly doors and double casement windows) or simply non-framed double glazed surfaces (fixed glazing surfaces acting as walls). Some indoor glazed spaces were provided stainless steel frames with 12 mm tempered glass. There is also a wooden glazed surface – the atrium main door, pre-existing element. Here, the initial glass was substituted by a laminated glass. In classrooms and labs, internal shading devices complement the glazed solution.

The thermal energy production lays on a centralized production system of heating and cooling. Thermal production is achieved through a heat pump with vapor compression cycle (powered 110 kW/ 106 kW for heating and cooling, respectively). DHW production and environmental heating is provided by a 100 kW condensing boiler. On the roof of building F there are 30 solar panels ($2m^2$/each) for DHW provision. Thermal diffusion into spaces is ensured by fan coil units, radiators and ventilation grids (served by AHUs equipped with cooling and heating coils, which provide air renewal into spaces).

Vertical section



1. Wall construction:
   20 mm external plaster (restored layer)
   Granite window sill (restored)
   460 mm masonry wall
   20 mm painted plaster on the inside
   JE 06 – Pre-existing aluminium window
   Internal rolled curtain, black-out type

2. Roof construction:
   Tiled roof (pre-existing wood structure)
   Ventilated technical area under the roof
   Thermal slab coating consisting of:
   60 mm polystyrene base w/ a top layer of
   reinforced screed w/ fibre additive

Figure 16 – Escola Secundária de D.Manuel I (pre-existing building A) | Façade section

3.2.4 Case study IV – Escola Secundária Gonçalves Zarco (MTS)

MTS is located in Av. Villagarcia d'Arosa, in Matosinhos. Formerly inaugurated in 1969, the school was subjected to rehabilitation works from September 2008 until June 2010. This school is located on a site with 23800 m^2. It is organized into independent bodies, articulated by an external gallery. Besides the refurbishment of the existing facilities (buildings A, B, C), the intervention included the construction of two new buildings: one for social/recreation area (Soc) and a new building of laboratories, integrating the existing workshops (C). The library (Lib) was not subjected to any construction intervention. **Figure 17** and **Figure 18** illustrate the schools' area and corresponding organisation of the current deployment.

Figure 17 – Escola Secundária João Gonçalves Zarco | Aerial view
[Source: *Google Maps*, 2015 (GPS: 41.1784266900000, -8.6767338250000)]

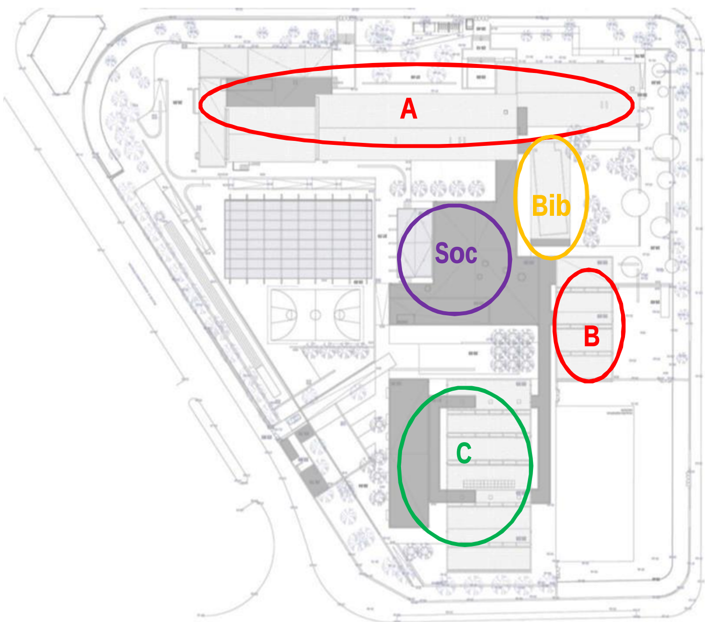


Figure 18 – Escola Secundária João Gonçalves Zarco | Layout plan (post-intervention)
[Source: *Parque Escolar*, EPE (2012)]

The school is organized in three main sectors:

- Building A, a five floor construction (organized in a system of stacked split-level plan with seven (staggered) levels, from -2 to 4), mainly composed of 34 classrooms, a gymnasium, teachers' rooms, administrative areas and the school direction board;
- Building B, a pre-existing building (like A) that was expanded, mainly addressed to social activities. Connected to the library, it is composed by: the canteen and cafeteria, a multipurpose space, the stationary and reprography and the students' association. Some technical areas (as the "boilers' room") are also located here. It is organized in level -1 and -2.
- Building C was also refurbished and expanded. All spaces are distributed along level -1. It includes technical subjects, such as 1 mechanical and 2 electricity workshops; 9 ITC rooms and other laboratories affected to scientific subjects, besides 2 regular classrooms.

Constructively, interior walls are either composed of perforated brick plastered on both sides, or composed of plasterboard elements (single or doubled boards) with a metallic structure (sometimes with a mineral wood panel inside). External walls present one generic solution: continuous external thermal insulation coating in ETICS (External Thermal Insulation Composite System) with varying dimension – 30 mm over the refurbished pre-existing plaster of the "old" buildings or, 50 mm dimension when coating new walls (support elements are mainly perforated bricks 200, 300 or 500 mm width).

The new glazed surfaces are now composed of double glasses (at least one laminated), mostly supported in thermolacquered aluminium with thermal cut frames. Some iron frames can also be found, but mostly in internal glazed elements. Ceilings are mostly suspended plasterboard structure, but some painted tinned plaster can also be found.

In terms of roofing, the ceramic tiled roof was kept in building A. The indoor ventilated garret, used as HVAC system equipment storage is insulated through high density rock wool panels (50 mm) and in terms of pavement, reinforced screed with 80 mm was used. In B and C, buildings and connection galleries, the roof is of the horizontal type, either with a substract layer, waterproofing and thermal insulation (*roofmate* 40 mm), geotextile and finishing in rounded gravel or finishing in protection sandwich panel made of high density rock wool insulating core and metal coatings in steel plate.

Vertical section

1. Roof construction:
   Round gravel roofing
   Geotextile sheeting
   Thermal insulation
   Waterproofing layer
   Levelling layer

2. Wall construction:
   ETICS (External Thermal Insulation Composite System) – also designated as “thermal plaster”, composed of an expanded polystyrene layer covered with a reinforced plaster sheeting
   Perforated brick
   Painted plaster

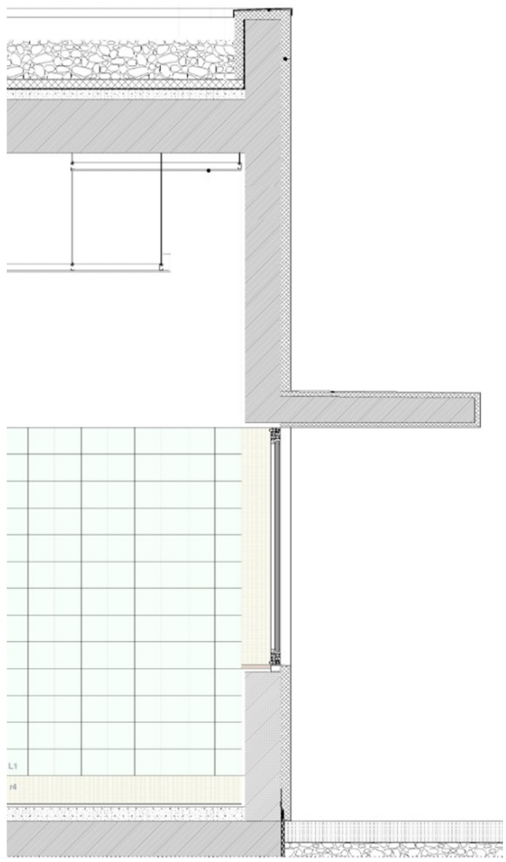


Figure 19 – Escola Secundária João Gonçalves Zarco | Façade section

The thermal energy production lays on a heating and cooling centralized system. Cooling is achieved through a 140 kW chiller; while heating is mostly ensured through two 400 kW boilers also used for DHW production. There is also a solar panel system with 15 units (2m^2/each) on top of building C.

Thermal energy diffusion into spaces is ensured by fan coil units, radiators and diffusion grids (served by AHUs equipped with cooling and heating coils that provide air renewal into spaces).

3.2.5 Case study V – Escola Secundária de Pombal (PBL)

PBL is located in Rua da Escola Técnica, in Pombal. Inaugurated in 1963/64, the school was subjected to rehabilitation works between July 2009 and October 2010. The intervention was mainly focused on the envelope level in the existing buildings (A+A1, B+B1, E+E1, D+D1), comprising also the construction of two new buildings – buildings F and G. **Figure 20** and **Figure 21** illustrate the schools' site plan and spatial organisation, corresponding to the pre-intervention period and current deployment, respectively.

Figure 20 – Escola Secundária de Pombal | Aerial view (pre-intervention)
[Source: *Google Maps*, 2013 (GPS: 39.9191091500000, -8.6245388030000)]

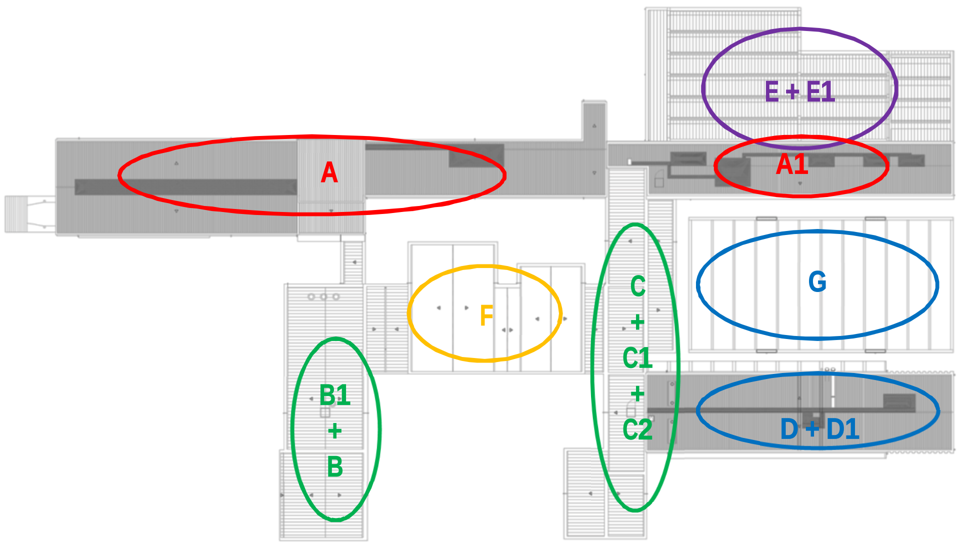


Figure 21 – Escola Secundária de Pombal | Layout plan (post-intervention)
[Source: *Parque Escolar*, EPE (2012)]

Building A is a pre-existing building, three floors high (level 0, 1 and 2). It is the main teaching building with more than 25 classrooms, some addressing artistic domains. Here the direction board and several teachers' offices are also located. Spaces are distributed along a central corridor (with rooms facing north and south). Sanitary facilities are present in all levels. Alike A, A1 is an existing building that only had two floors. After the intervention it gained one more floor, housing several scientific laboratories, five ITC classrooms and technical areas, besides staff room.

B and B1 buildings are only one floor high (level 0). Here the secretariat/reception area and some support offices are situated, besides rooms designed for special education programmes/adults training. C, C1 and C2 hold mostly the school social areas: the students' association, one area dedicated to school clubs, one room supporting sports and health education, besides the medical office and cafeteria.

D and D1 are also pre-existing buildings, with 3 floors distributed from level 0 to 2. Level 0 comprises the canteen and technical areas, and also one classroom and locker rooms supporting sports activities; in level 1 the multipurpose room and the indoor gymnastic room; in level 2 some rooms supporting physical education teaching staff. In E and E1, workshops for technical subjects such as metrology, automation and mechanic are located.

F and G are two new buildings. F holds the school main lobby, the library and the auditorium. It is the school space main 'hinge', connecting school areas B to C. Similarly to the other schools, G corresponds to the outdoor gym: an outdoor covered sports area.

Constructively, interior walls are mainly composed of 110 mm perforated brick, plastered on both sides. External walls present two main solutions, namely:

- Pre-existing buildings: a "coating system" ─ ETICS[3] (50 mm layer of expanded polystyrene) on the upper levels and FGRC[4] on the ground floor (over 50 mm layer of thermal insulation rigid foam);
- All the new constructions were encased with FGRC.

Regarding glazed surfaces, all the single glass windows have been replaced by double glass with thermal cut aluminium frames. The majority of the glazed areas, especially in classrooms, were provided with light curtain devices on the inside.

[3] External Thermal Insulation Composite System.
[4] Fibreglass Reinforced Concrete.

Vertical section

1. Roof finishing:
   Existing gutter covered with zinc sheeting
   Fixed drip edge and fascia cover in zinc

2. Wall construction:
   ETICS (External Thermal Insulation Composite System)
   - 60mm
   External plaster (20 – 35mm)
   Perforated brick masonry (110 - 150 mm)
   Air cavity
   Perforated brick masonry (110 mm)
   Plaster (20 – 35mm)

3. Contact w/ ground:
   FGRC panel (min 15 mm)
   Extruded polystyrene (60 mm)
   External plaster (20 – 35mm)
   Perforated brick masonry (110 - 150 mm)
   Air cavity
   Perforated brick masonry (110 mm)
   Plaster (20 – 35mm)
   Pre-fabricated reinforced concrete sill

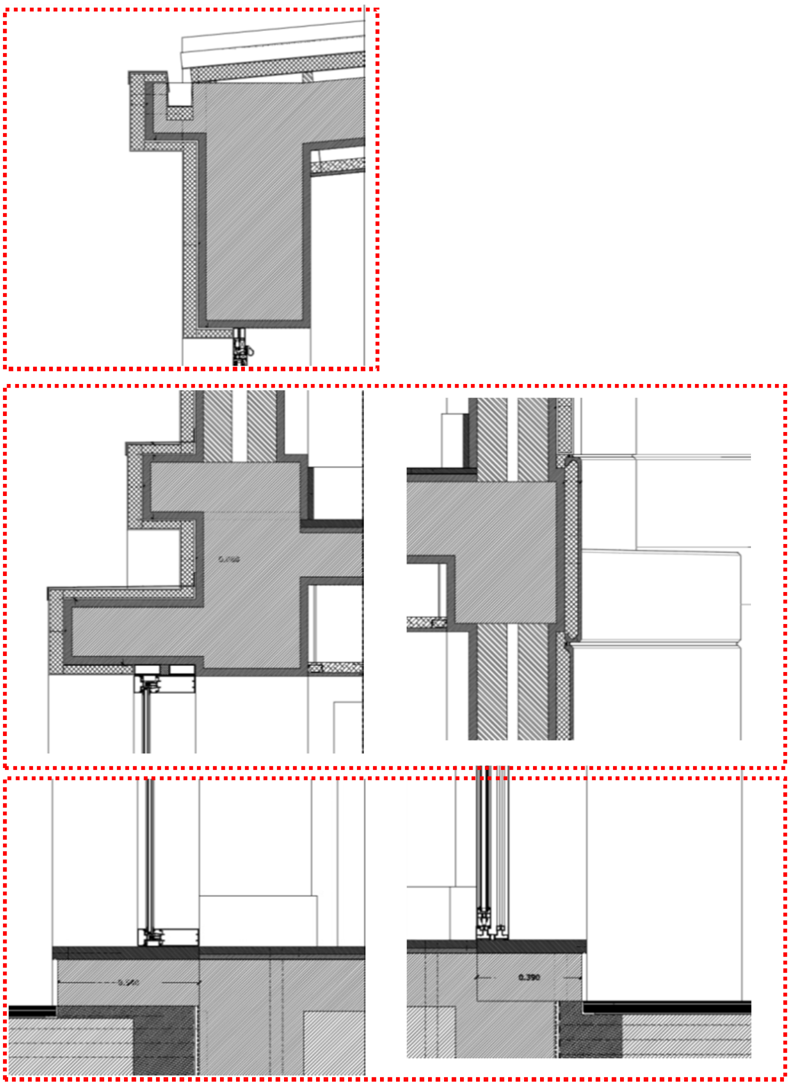


Figure 22 – Escola Secundária de Pombal | Façade section

Herein, the thermal energy production solutions are quite diverse, depending on the school spaces' typology. Administrative areas are acclimatized with individual units, split and *multisplit* type or modular systems with variable refrigerant flow (VRFs). Larger areas with lasting occupation, such as classrooms are provided of centralized systems of thermal energy production (heating and cooling). In these cases, thermal production is assured through two vapour compression cycle heat pumps (HP1 powered 274 kW/ 255 kW for heating and cooling, and HP2 87.7 kW/ 77 kW, respectively).

High volume spaces, such as the canteen and the auditorium, with non-permanent occupancy are acclimatized with *rooftop* units. Thermal diffusion indoors is provided by mural fan coil units and ventilation grids. Spaces air renewal is mostly ensured through AHUs with heating and/or cooling coils. DHW and some environmental heating are supported through two condensation boilers (powered 85 kW each). There is also a solar heating system for pre-heating hot water with 16 solar panels.

3.2.6 Case study VI – Escola Secundária Mouzinho da Silveira (PTG)

PTG is located in Avenida do Bonfim (EN 359), in Portalegre. Inaugurated in 1976/77, the school was subjected to rehabilitation works from September 2008 to June 2010. Besides the refurbishment of the existing facilities (buildings A, B, C, D and F), this intervention also included the construction of two new buildings: G (library and museum space) and E (the gymnasium supports area). **Figure 23** and **Figure 24** illustrate the schools' space and location of the pre-intervention period and current deployment, respectively.

Figure 23 – Escola Secundária Mouzinho da Silveira | Aerial view (pre-intervention)
[Source: *Google Maps*, 2015 (GPS: 39.3033155800000, -7.4327144030000)]

Figure 24 – Escola Secundária Mouzinho da Silveira | Layout plan (post-intervention)
[Source: *Parque Escolar*, EPE (2012)]

Building A is a two floor high building (level 0 and 1) mainly composed of ITC classrooms, scientific laboratories and design classrooms. There is also the teachers' room and the auditorium. Alike A, B is also a pre-existing building whose 11 regular teaching classrooms and meeting room are distributed in levels 0 and 1 (just like C and F). D is the only pre-existing building developed in a single floor/level. It supports school activities and school management. Herein the secretariat and the direction board are located, besides the canteen and school cafeteria. It also holds the reprography and school material shop, besides the main students' social area.

The main sports area, E, is also a pre-existing structure with two floors. The new building G connects A and D. Besides library it also embraces the school archive.

The external walls present two types of generic solutions, namely:

- On the pre-existing buildings (A, B, C, and F), thermal insulation was applied from the inside – EPS panels covered by plasterboard (10 + 40 mm) placed over the existing concrete walls;
- On the new building (G), the exposed concrete layer is provided of a thermal insulation (50 mm XPS) and water repellent layer over internal thermal masonry brick.

The new glazing areas are double glass windows in anodized aluminium frames. Classrooms are provided with internal shading devices: opaque over the first window near the drawing board and translucent in the remaining.

In this school the thermal energy production system follows a decentralized strategy – each building has its own independent cooling/heating system. These units are normally placed on the buildings' roof. Buildings A, B, C, D and F are provided with heat pump systems for the production of thermal fluid for heating and cooling controlled by AHUs (HPs power varying between 23.0 – 47.6 kW / 23.0 – 56.0 kW for heating and cooling respectively). In the gym (building E), there is a 162 kW boiler for DHW production and environmental heating and a chiller for pre-cooling environment. On this roof there is also a solar panel system composed of 18 units (2 m^2/each). In G (where the library is located, for example) there is an air condition central unit *rooftop* type, powered 31 kW both for heating and cooling.

Air renewal is warranted through AHUs with heating and/or cooling coils. Thermal diffusion indoors is carried by AHUs, mural fan coil units, fan heaters and ventilation grids.

Vertical section

1. Wall construction PeA2:
   Exposed concrete
   Thermal insulation – type Pladur-Term N (10 + 40 mm) – on the inside face of the wall
   Acrylic enamel painting

2. Window type:
   VeA01 – Anodized aluminium window frames

3. Wall construction PeA6:
   Reinforced concrete/lightweight
   Concrete masonry
   Rock wool (40mm)
   Plasterboard

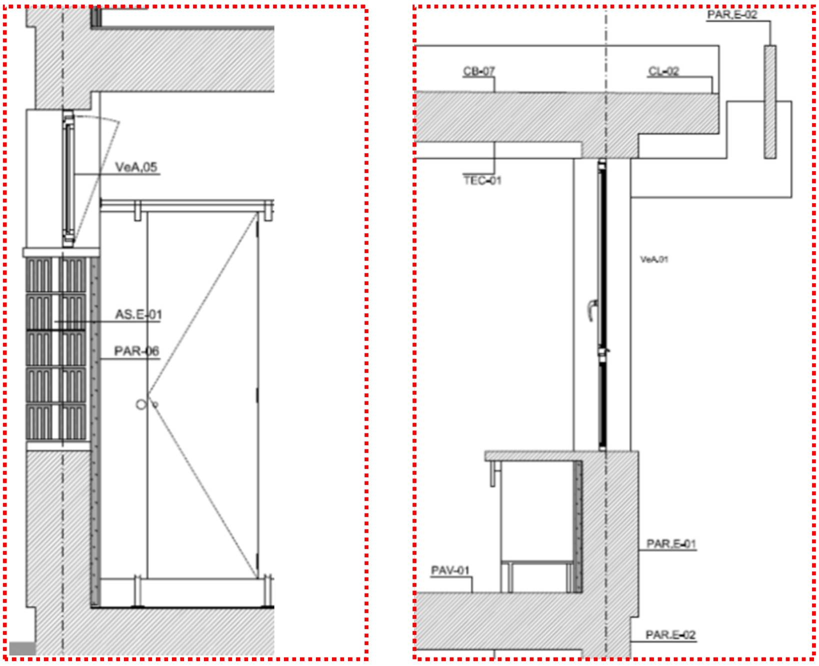


Figure 25 – Façade section | Escola Secundária Mouzinho da Silveira (pre-existing build. e.g. C)

3.2.7 Case study VII – Escola Secundária Afonso de Albuquerque (GRD)

GRD is located in Avenida Dr. Afonso Costa in the city of Guarda. Originally designated as *Liceu Nacional da Guarda* it was inaugurated in 1969. Recently the school was subjected to rehabilitation works from July 2009 to December 2011. Besides the refurbishment of existing facilities (sectors A, B, C, D, E and F), this intervention also included the construction of three new sectors - A1, A2 and the Gymnasium pavilion (Gym). **Figure 26** and **Figure 27** illustrate the schools' space and location of the current deployment.

Figure 26 – Escola Secundária de Afonso de Albuquerque | Aerial view
[Source: *Google Maps*, 2013 (GPS: 40.5366830000000, -7.2749070000000)]

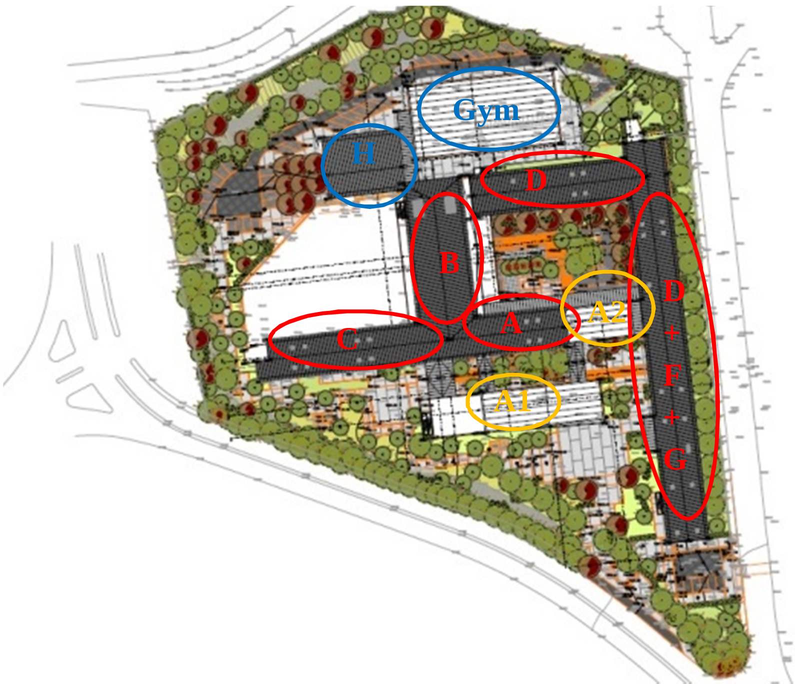


Figure 27 – Escola Secundária de Afonso de Albuquerque | Layout plan (post-intervention)
[Source: *Parque Escolar*, EPE (2012)]

After the refurbishment, the school's organisation comprises 11 sectors in total. Sectors A, A1 and A2 are composed by a pre-existing cell (A). Three floors high, here the administrative area (direction board and secretariat), the amphitheatre, the library, the auditorium and exhibition areas are located, besides work spaces for the teaching staff.

B is also an existing and refurbished building. Mainly containing social areas, such as a multipurpose room, the cafeteria and the canteen, besides the students' association and the reprography, spread through four levels (-2 to 1).

C is three floors high (level -1 to 1). It holds visual arts classrooms (visual education, drawing and geometry rooms), a room for technical education, the school archive and the staff room.

Sectors D, E, F and G are composed of three floors (level -1 to 1 or 0 to 2) mainly containing regular teaching classrooms, ITC rooms and laboratories for scientific subjects.

H compromises one of the gyms, the locker rooms and other spaces supporting sports practices. The main sports activities take place in the new gymnasium-sports pavilion (Gym).

Constructively, the interior walls are mostly composed of 150 mm perforated brick coated with plaster on both sides. The external walls present two types of generic solutions:

- Pre-existing walls (w/ variable thickness) – coated in expanded polystyrene 60 mm (finishing system type *cappotto*).
- New walls are constituted of double masonry layers of 150 mm perforated bricks separated through a ventilated cavity (min 50 mm), added 30 mm layer of XPS thermal insulation covered with 0.65 mm zinc plated layer.

The intervention was mainly characterized by continuous thermal insulation coating from the outside. In terms of glazed surfaces, the new doors and windows are mainly composed of Nordic pine wood frames with double glazing. In some cases the external glass is internally coated with vinyl opal film. The school's roofs present very different solutions: "heavy" existing roofing above non-ventilated attic (180 mm) with an interior finishing of chipboard panel or acoustic painted plasterboard panels; "heavy" existing terrace with coated floor sheet metal panels on inverted beams and interior finish with suspended ceiling / acoustic painted plasterboard panels or OSB[5] panels; etc.

[5] OSB – Oriented Strand Board

Vertical section

1. Geotextile
2. Viroc board (32 mm)
3. Iron profile
4. Iron profile
5. Gutter in zinc plate
6. PVC drain
7. Drip edge in zinc

8. Wood frame with double glazing (6 + 18mm argon+ 4 mm)

9. Window sill finished in white aluminium lacquer
10. ETICS type *"capoto-viero"* painted in white

11. Pre-existing concrete element

12. Window sill finished in white aluminium lacquer
13. ETICS type *"capoto-viero"* painted in white

14. Waterproofing layer

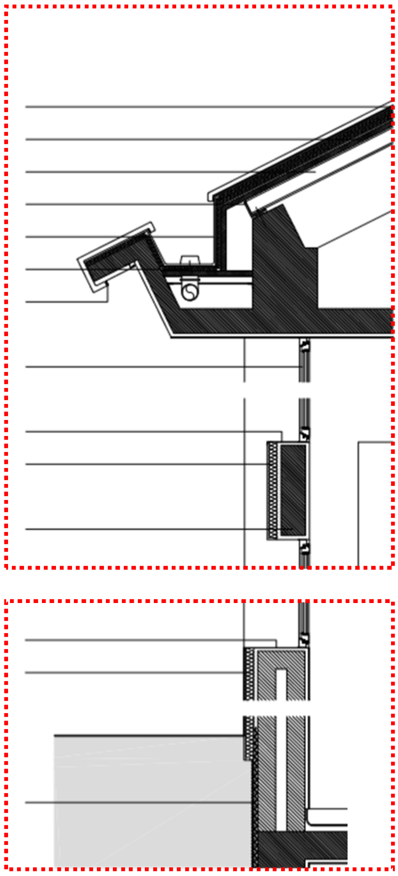


Figure 28 – Escola Secundária de Afonso de Albuquerque | Façade section

Thermal energy production in this school is assured through two vapour compression cycle heat pumps (HP1 powered 10 kW/ 10.1 kW for heating and cooling, and HP2 180 kW/ 165 kW, respectively).

The auditorium, the amphitheatre, the canteen, the library and some other spaces, such as ITC classrooms, are provided with independent acclimatization systems, composed of rooftop and VRV units. The kitchen area has an autonomous supply and air extraction system. All the other areas, including classrooms are served by the HPs. Thermal diffusion indoors is carried out by mural fan coil units, radiators and ventilation grids (served by AHUs equipped with cooling and heating coils, which provide air renewal into spaces).

For heating compensation and DHW, there is one condensation boiler (powered 45.4 kW) and a solar heating system for pre-heating hot water with 18 solar panels.

3.2.8 Case study VIII – Escola Secundária Abade de Baçal (BGC)

BGC is located in Av. General Humberto Delgado in Bragança. Inaugurated in 1962 as *Escola Industrial e Comercial de Bragança*, the school was under rehabilitation works between July 2009 and March 2012. This school is constituted by three buildings linked to each other through indoor and outdoor galleries. Besides the intervention on the existing buildings (A + B), it included the construction of a new building (C). **Figure 29** and **Figure 30** illustrate the schools' area and corresponding organisation of the current deployment.

Figure 29 – Escola Secundária Abade de Baçal | **A**erial view

[Source: *Google Maps*, 2013 (GPS: 41.8075335400000, -6.7615519690000)]

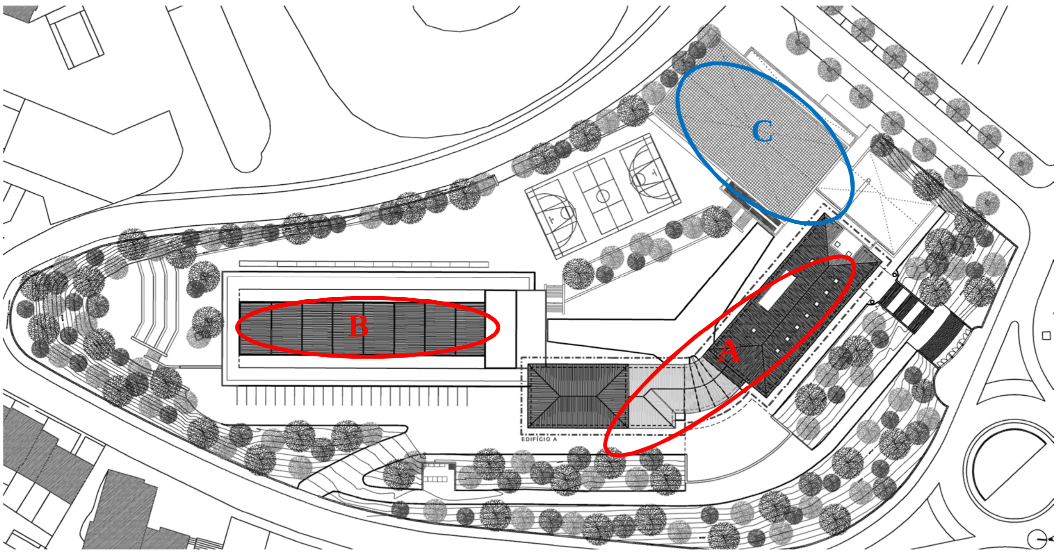


Figure 30 – Escola Secundária Abade de Baçal | Layout plan (post-intervention)

[Source: *Parque Escolar*, EPE (2012)]

The refurbished building A is composed of 21 teaching classrooms, the direction board and teachers' room, one amphitheatre, the library and one exhibition area, as well as the canteen and reprography distributed along four different floors (level 0 to 3). The pre-existing structure (southern part of A) is only two floors high.

B is two floors high (level 0 and 1) and is mainly composed by technical education spaces: herein the mechanical, electrical and carpenter workshops are located. There is also a classroom for drawing lessons and one for arts.

In C (the new building) the administrative spaces (secretariat), laboratories and ITC rooms are located. It also connects A to the new gymnasium and locker rooms. Along the four levels of this building, there are also 4 ITC rooms and 4 laboratories for scientific subjects.

The external walls present two generic solutions, namely:

- Pre-existing walls: 60 mm thermal insulation layer on the inside, type *roofmate*, covered with two layers of plasterboard;
- New walls: painted plaster on the inside over 300 mm cement brick added a 60 mm expanded polystyrene layer (finishing system type *cappotto*).

The glazed surfaces are in many cases constituted of pre-existing refurbished frames, such as JE 02 – white lacquered aluminium frames in which the existing glass was substituted by double laminated glass (33.1 + 6 + 44.1). This double hopper window type is used in most of A building classrooms and in the canteen. The glazed areas are normally accompanied with indoor rolling blinds.

In other cases, such as the school reprography/shop or the teachers' room, the pre-existing wood framed windows were substituted by similar windows to JE 02. In between buildings, such as the connection areas between A and C, or some corridors, there are also some iron framed glazed surfaces. Glass block windows are present in the sports pavilion.

Three main types of roofing were identified:

- Ceramic tiled roofing over wooden structure, internally coated with 100 mm thermal insulation roofmate, finished with MDF[6] boards;
- Roof terrace in granite slabs (600 x 600 mm) over 60 mm thermal insulation;
- Roof terrace in epoxy painted reinforced screed, provided of a double thermal insulation layer of 50 mm/each, separated through double waterproofing layers.

[6] MDF – Medium-Density Fibreboard

Vertical section

1. Plaster
2. Granite windowsill
3. 60 mm thermal insulation (wallmate) covered with two plasterboard panels

5. Electric rail
6. Aluminium exiting windows (JE02)
7. Metal sheet lacquered in white
8. Pine wood furnishing
9. Interior blind

Contact w/ ground:
33. Granite panelling (pre-existing)

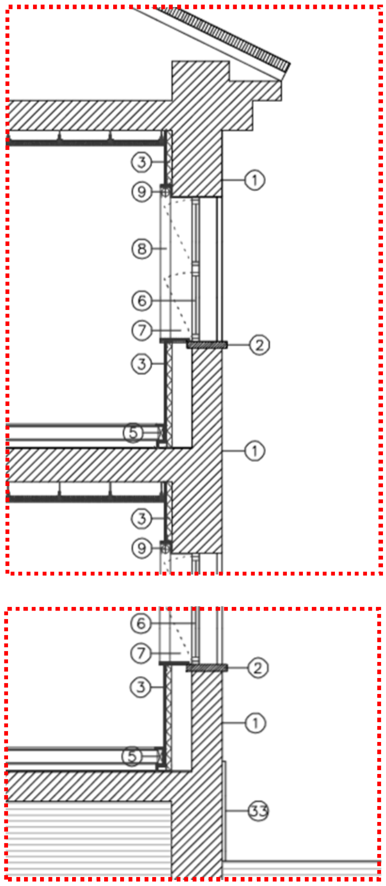


Figure 31 –Escola Secundária Abade de Baçal (Building A) | Façade section

The thermal energy production lays on a heating and cooling centralized system. It is based on heat pumps with vapour compression cycle (powered 51.7 kW for cooling), chiller in B serves only B building while the chiller unit in C serves both A and C building.

For heating and DHW there are two boilers (powered 498.2 kW/each). There is also a solar heating system for pre-heating hot water with 13 solar panels (2 m^2 each) on C roofing.

Thermal diffusion indoors is provided by mural fan coil units, radiators and ventilation grids (served by AHUs equipped with cooling and heating coils, which provide air renewal into spaces).

3.2.9 Schools characterization synthesis

A synthesis of the main construction characteristics of the 8 schools selection is presented in **Table 6**. The schools' data have been organized according to their initial typology and as presented in the literature [190], [191] (Parque Escolar EPE publications).

Table 6 – Construction elements synthesis pre and post- intervention.

School	Typology	Initial building construction characteristics (general notes)	"New" building construction characteristics (short notes)
		Plan of 1958 [191]	
GRD 1969	**Special Design**	**1960 | Ante-Projecto Arch. António Maria Veloso Gomes** 1965 | Projecto Arch. António Maria Veloso Gomes 1969 | Building construction conclusion [190] Special characteristic: winter playground area	**Walls:** Thermal insulation on the outside over existing walls (60mm ETICS) **Ceilings**: OSB panels
LSB 1966	**Lyceum Pavilion Type**	**Author | JCETS – Arch. Augusto Brandão** Special characteristic: adaptability to the site slope Normalized project, general construction references: ▪ structure – modular set of reinforced concrete portal frames spaced 2.66 m ▪ structural elements = 1/3 classrooms length (8m) ▪ exposed concrete elements – both inside & outside the buildings ▪ interior partitions w/ no structural function, built in brickwork & painted white	**Walls:** Thermal insulation on the inside over existing walls (50mm rock wool covered with painted plasterboard) **Roof:** Thermal insulation – 2 layers (50 mm/each) of "Dow Styrofoam Roofmate SL-A" **Shading devices**: Translucent interior blinds
		Standardized studies of 1968 [191]	
PTG 1968	**Lyceum Pavilion Type**	**General author | JCETS – Arch. Augusto Brandão** **School | Arch. Maria do Carmo Matos** *III Plano de Fomento (1968-1973)* | Normalized project Lyceum type [192] 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)	**Walls:** Thermal insulation (40+10mm "PladurTerm-N (xpe)" or 40mm rock wool covered w/ painted plasterboard) applied on the inside over existing walls – brickwork or concrete

		Buildings for technical and vocational education – technical schools [191] **General author | JCETS** Preliminary draft – Technical school type (1950) [192] Special characteristic: workshops area w/ significant dimension	
BJA	**Industrial and Commercial Technical School**	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" classrooms	**Windows:** Aluminium frames + double glazing **Shading devices**: Translucent & opaque interior blinds – classrooms; Exterior blinds – labs
MTS		▪ drawing classrooms 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	**Windows:** Lacquered aluminium frames + double glazing **Walls:** ETICS over existing walls & 50mm rock wool covered w/ painted plasterboard applied from the inside, over existing walls
PBL		▪ general resizing of the buildings – classrooms 4 floors high & physical education 3 floors high (better land use) 4th Normalized project – Technical school type (1960') [192] ▪ building blocks connected through outdoor covered galleries	**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		▪ adaptability to the site slope	**Ceilings**: Suspended microperforated plasterboard (thermal & acoustic) **Walls:** Thermal insulation on the inside over existing walls (60mm XPS covered w/ painted plasterboard)
		Type projects for secondary schools [191]	
MMV	**3x3 Pavilion Type**	**General author | DGEE – Maria do Carmo Matos** Project date: 1985 *(Direcção das Construções Escolares do Centro)* Normalized project, general construction references: ▪ modular classroom sized $50m^2$, set in a regular grid 7.20 x7.20m (structure) ▪ squared building blocks – 21.60 x21. 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	**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

3.2.9.1 Schools' population

As regards the scholar population, there has been an increase in the number of students in 75% of the schools between the pre and the post-intervention period. The exceptions were MMV and PBL. In the second case, this was due to the cut on night special education programmes for adults. Nevertheless, in terms of staff, all schools have verified a decrease on this number, in some cases the teachers' number decreased significantly, in Lisboa circa 12%, even when the number of students increased 13.5%. A summary of these numbers is presented in **Table 7**.

Table 7 – Summary table of the 8 schools' scholar population pre and post-intervention

School	I - MMV		II - LSB		III - BJA		IV - MTS		V - PBL		VI - PTG		VII - GRD		VIII - BGC	
Year	2008/09	2011/12	2007/08	2011/12	2007/08	2011/12	2007/08	2012/13	2008/09	2012/13	2007/08	2011/12	2008/09	2012/13	2008/09	2012/13
Teachers	168	179	180	159	146	97	221	157	137	99	90	72	142	124	96	87
Non-teaching staff	68	66	43	25	38	33	47	45	36	30	31	27	73	63	50	47
Students (nº)	473	309	1241	1408	648	818	1222	1419	1030	955	631	647	892	1065	479	584

3.2.9.2 Schools systems installed power

Concerning fixed installed power needs, such as lighting and ITC technologies serving classrooms and administrative areas, **Table 8** and **Table 9** summarize these data. Moreover, a list on the DHW capacity provided by the new solar panels system installed in each school is also presented. In none of the 8 schools under study PV systems were installed.

Table 8 – Summary table of the 8 schools selection of ITC installed power (W)

School	I - MMV	II - LSB	III - BJA	IV - MTS	V - PBL	VI - PTG	VII - GRD	VIII - GRD
PC + TFT	12540	25190	20020	22770	27390	23980	28600	16830
Video projector	18000	26400	21000	30600	30000	29400	27600	19200

Table 9 – Summary table of the 8 schools selection of lighting installed power (W)

School	I - MMV	II - LSB	III - BJA	IV - MTS	V - PBL	VI - PTG	VII - GRD	VIII - GRD
Total	63664	70313	26846	88481	89031	62305	92504	74339
T5 (%)	69	82	56	83	71	64	78	47

Table 10 – Summary table of the 8 schools selection of solar panel system for DHW**

School	I - MMV	II - LSB	III - BJA	IV - MTS	V - PBL	VI - PTG	VII - GRD	VIII - GRD
No. units	32	23	30	15	16	18	18	13

Note: The system in this school was not being used.*

*** All schools with 2m^2 panels, excluding Pombal and Guarda. Panels' information was not available.*

3.3 Energy performance analysis of schools and systems

Schools consumption characterization: "What gets measured gets done" [193].

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[7] and typical occupancy values, aiming at analysing energy use quantities and patterns, and also to allow comparisons with previous studies. 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 (O&M) 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 EEMs. 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 BMS programing. This subject is further developed in **Chapter 5.**

3.3.1 Schools´ energy consumption

"Heating, ventilation and air conditioning (HVAC) system and lighting system consume up to 60% of the electrical power for buildings", [194]. But it is also true that *"in the Mediterranean region the problem of energy consumption is more complex because the air-conditioning load is as important as the heating load"* [195].

As expected from the schools' installed systems, previously presented, schools in the 3Es project consume both electrical energy (EE) and natural gas (NG). A yearly and seasonal energy consumption synthesis of the 8 schools, expressed both in EE and NG, is presented in **Figure 32**.

[7] As recommended in *Thumann, A., & Younger, W.J.*, 2003 [97], 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.

In **Figure 33** the schools' energy consumption is also presented in monthly values. NG represents on average 24% of the schools' energy consumption [196].

The seasonal billed energy data (**Figure 32**) 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 (LSB and BJA schools, 3 months energy data) and December to April (GRD and BGC schools, 5 months energy data) – for the remaining schools winter energy data was based on 4 months billed data.

In **Figure 32** 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.

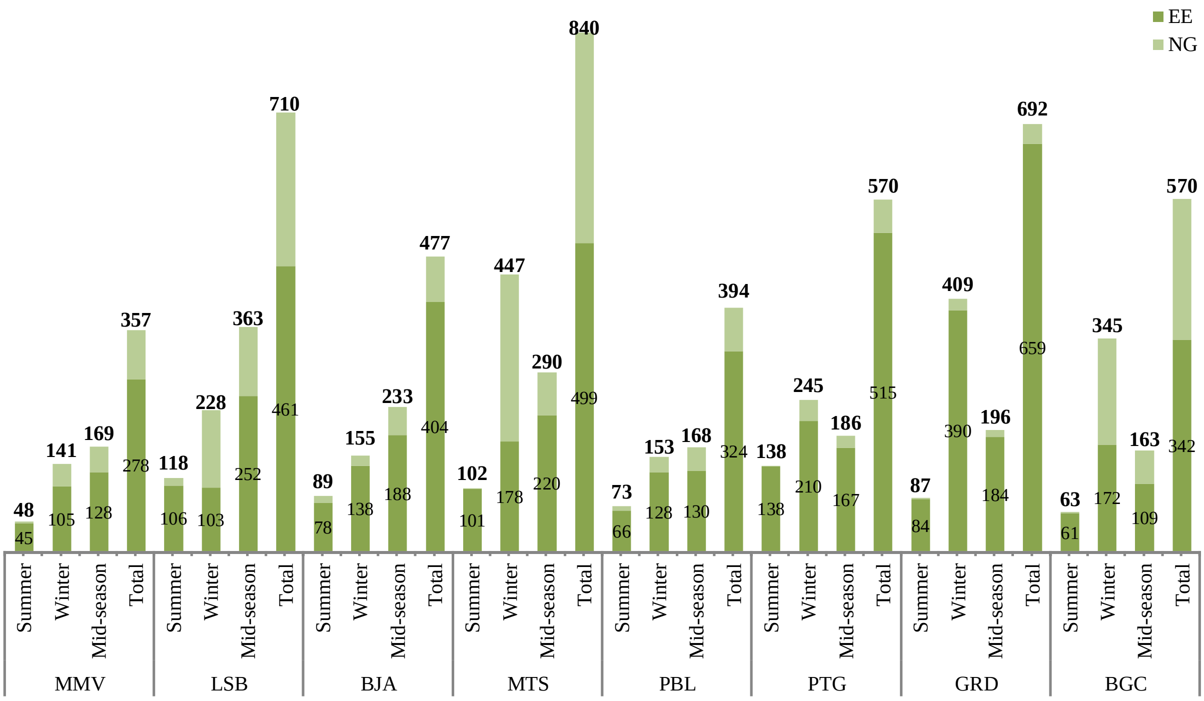


Figure 32 –Syntax table of the 8 schools' energy consumption (data relating one scholar year data e.g. September/2012 – August /2013) [MWh]

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

The contribution of the EE and NG on each school is also depicted in **Figure 33**. The distance between the same coloured lines – Total Energy and Electrical Energy (solid and square dot) – unveils the NG usage in each school.

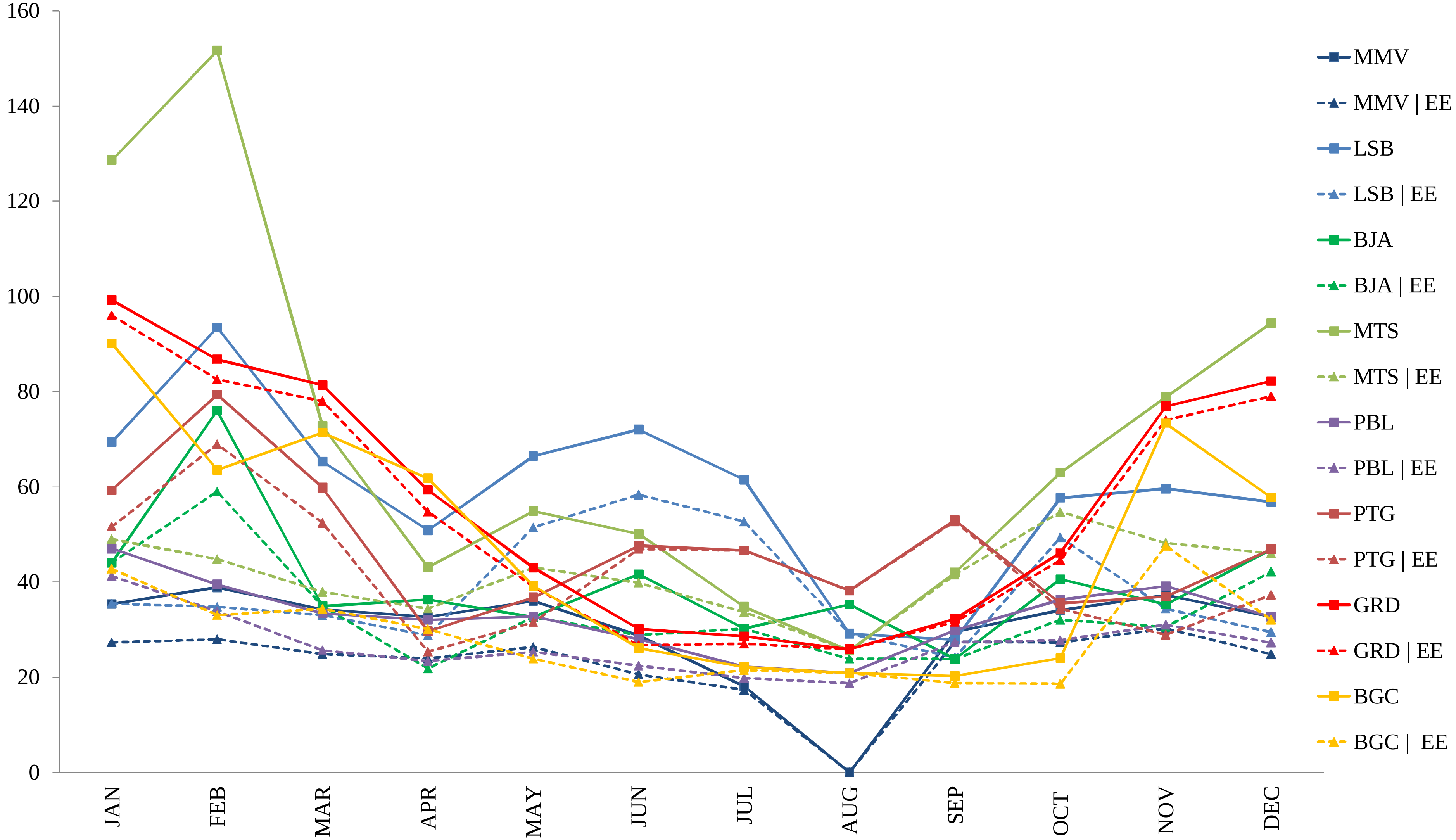


Figure 33 – 3Es schools Total energy and Electrical Energy monthly consumption (data relating one scholar year data e.g. September/2012 – August /2013) [MWh]

In MTS, during the winter (December to March), it is very clear that the heating system is based on NG consumption, due to the greater distance between the lines. One contrasting example is BJA; here, the relatively constant distance between the lines along the year show that the school does not depend so much on NG. Interestingly, LSB shows an increase in both Total and EE energy consumption between April and July, translated in almost parallel lines – this clearly shows the activation of the cooling systems during the pre-cooling season.

Making final judgements based only on these two figures would be misdealing, therefore, some School Benchmarking Indicators (SBI) were established, aiming at better comparison of the schools.

3.3.2 School benchmarking indicators (SBI)

Building up the subject anticipated in **section 2.2.2**, three different SBI are presented in **Figure 34**, along with the median and 25% percentile value of the sample (typical value and good practice value in agreement with **section 2.2**).

Ideally, the schools' energy breakdown should lead to different SBI, aiming at comparing NG (from heated spaces and DHW) and EE consumption (from lighting, HVAC systems and electrical equipment). Since the schools herein presented are Mixed Mode Fuel Buildings (MMFB), this disaggregation is not so simple. Moreover, since it was not possible to disaggregate the amount of energy consumption by end-use in all eight 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 GFA and TUFA. Curiously, GFA's median (GFA typical value) overlaps TUFA's 25th percentile (TUFA good practice).

Figure 34 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 the 3rd to last worse performing, PTG. This figure clearly demonstrates the fragility of overall performance indicators.

The GFA and TUFA lines also reinforce the specificity of such indicators: the school worse performing in terms of GFA is ranked second to last in TUFA, and the schools ranked 3th and 5th, also swap position to the 2nd and 4th position. Objectively, in terms of energy indicator per area, the 3 schools with worst performance are LSB, MTS and PTG, while the 3 least energy consuming are PBL, MMV and GRD.

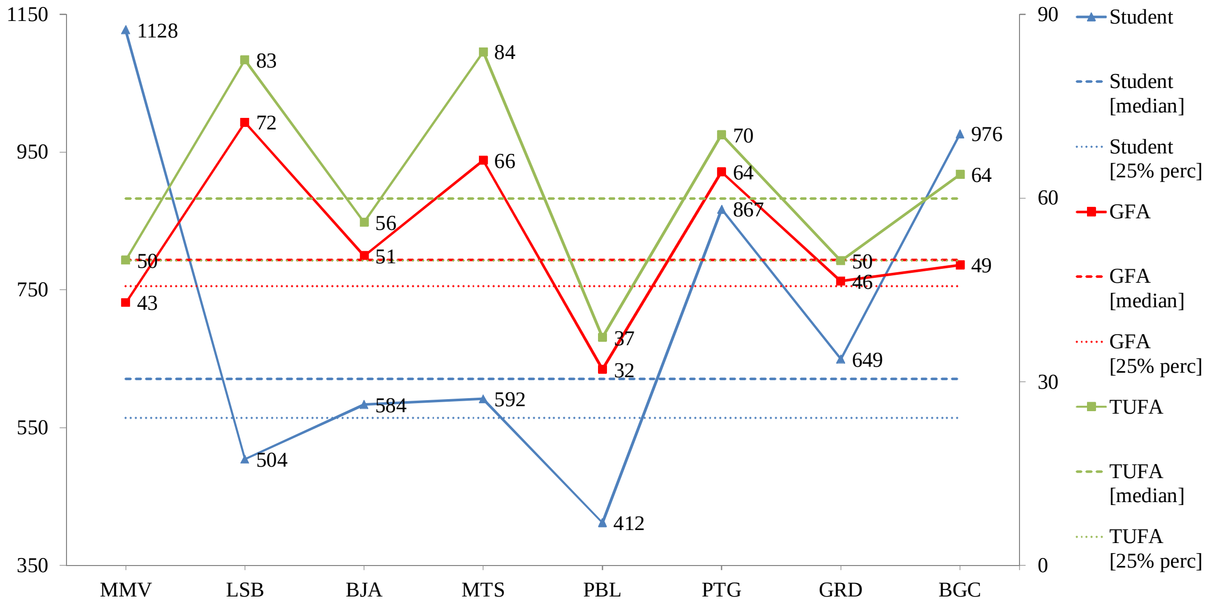


Figure 34 – SBI for the 8 schools selection. GFA and TUFA expressed in kWh/m^2: No. of students expressed in kWh/student

When addressing the SBI expressed in the energy consumption per the number of students, the school with worst performance 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 actually 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. Or, when looking at the opposite situation, MTS and LSB that are apparently worse performing in terms of their surface, are performing relatively well in terms of the quantity of students attending these schools (MTS value fits between the typical value and the good practice, while LSB actually exceeds the good practice value).

"For heating energy consumption a degree-day normalization method (e.g. German standard VDI 2067) is used to average out the influence of varying weather conditions and to allow a better comparison of the heating energy consumption of different years" [197] *in* [198].

Aiming at tuning climate differences, the relation between the 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 35**.

Alike the initial surface normalization, when integrating HDD, differences between GFA and TUFA are 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 three schools with worst performance are LSB, MTS and BJA – LSB and MTS coincide with the "simple" SBI [kWh/m^2].

Figure 35 – Weather data SBI normalization for the 8 schools selection.

From data exposure in **Figure 35**, climate austerity seemed to be quite an excuse for energy consumption. Therefore, it was decided to investigate the relation between the HDD and the energy consumption of each school. The results are presented in **Figure 36**. The image unveils that there is not a strong relation between the two variables – energy consumption and HDD. In fact, the determination coefficient is quite below 0.5. This means that, in this particular set of data, evaluating the schools' energy performance by their climate condition is not a correct judgement.

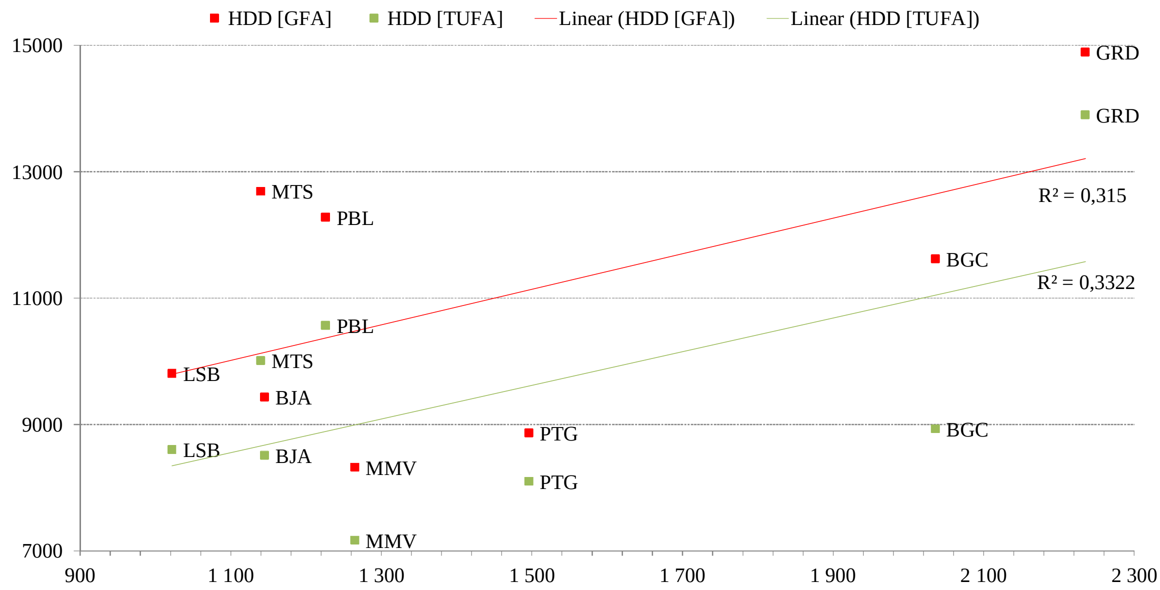


Figure 36 – Energy consumption versus heating degree-days (HDD)

"The overall performance of a building can be crudely expressed as a performance indicator, usually in (kg CO_2/m^2) per year or separately for fossil fuel and electricity in (kWh/m^2) per year. The analysis is normally performed on annual data, allowing comparison with published benchmarks to give an indication of efficiency" [10].

Using CO_2 as an energy performance indicator is common practice in the UK, where carbon intensity is taken quite seriously. Although this is not exactly the Portuguese reality, but since greenhouse gas emissions on an annual basis are also foreseen in the Energy Performance Certificate (EPC) – expressed in kgCO_2e, this possible SBI was also explored.

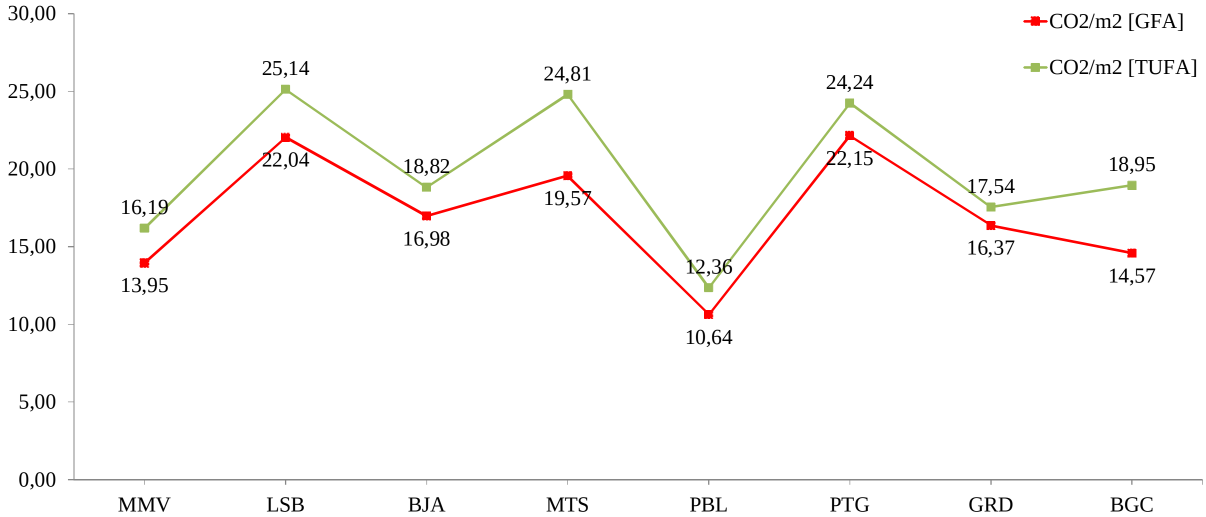


Figure 37 – CO_2 data SBI normalization for the 8 schools selection expressed in kgCO_2e/m^2.

Similarly to the first SBI (expressed in kWh/m^2), when normalizing data in terms of CO_2e, some differences were found between the indicator expressed in function of the GFA and TUFA. The common ranked position is in fact PBL, the best positioned school. MMV is in both SBI ranked second (in the first SBI analysis it swapped position). The school positioned at the bottom is PTG that, when analysed in terms of the TUFA comes 3rd to last.

Besides GFA and TUFA differences, that were already expected, the most relevant factor of this SBI is related to the ranking positioning itself. Due to the different energy conversion factors applied to electricity and natural gas, SBI expressed in kWh/m^2 and kgCO_2e/m^2 does necessarily lead to a different ranking of the schools.

3.4 Results and discussion

Within this chapter, the 8 secondary schools integrating the 3Es Project, which constitute the 8 case studies of this study, were presented. Besides their particular construction and systems characteristics, the schools were also presented in terms of their climatic context.

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 [116], [148], [196]. In fact, the approach suggested in [116], 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 sample allowed establishing a typical (typ) and a good practice (gp) value. In **Figure 38**, TUFA values (the less favourable values) are compared with the ones presented in the literature relating to consumed energy values in secondary schools.

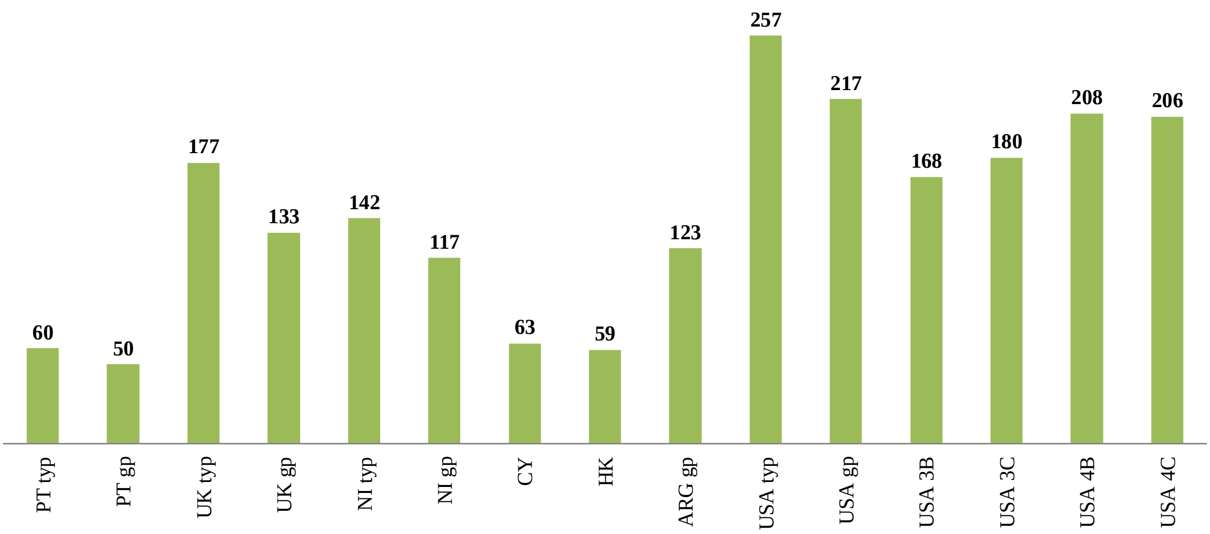


Figure 38 – Secondary schools' annual global energy consumption values per country (kWh/m^2)

The following notes are worth mentioning: (i) Portuguese, UK and Northern Ireland's values correspond to the median (typ) and 25% percentile (gp) values; (ii) CY and HK values are not referred (average values?); (iii) ARG gp values correspond to a mean value; USA's values were determined by the authors of [116], based on data available in [156], 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 60 kWh/m^2 (typ) is in line with the values presented for Hong Kong and Cyprus, but 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).

Within the 3Es Project sample, the school presenting higher SBI – MTS, was in fact, one of the schools that used the HVAC systems the most (information confirmed at the time of the visit and witnessed by the maintenance technician). The implications of this general low HVAC systems operation are further developed in **Chapter 4.**

CHAPTER 4. INDOOR ENVIRONMENTAL QUALITY (IEQ)

The entire methodology developed in this chapter has been previously published in [110], paper **VII**, **Appendix A**, using BJA school as case study, and some early results were also disclosed in [199].

4.1 TC and IAQ monitoring campaigns

Indoor Environmental Comfort results from the combination of four major environmental factors, such as Thermal Comfort (TC), Indoor Air Quality (IAQ), Acoustic Comfort (AC) and Visual Comfort (VC) [3]. Thermal comfort in schools (more specifically in classrooms) has lately been receiving more research attention [8], [62], [103], [200]. Because indoor environmental quality (IEQ) can influence buildings' energy use [62] but also because it might affect students and teachers performance [6], [51]–[53], [201]–[203]. The linkage between IEQ and users' performance has been explored, but most studies are not conclusive, or show limited evidence, recommending further research [201], [203], [204].

HVAC and lighting systems affect the three main factors determining occupants' quality of living as building users: thermal comfort, visual comfort, and indoor air quality [194]. By addressing this theme among schools and educational institutions, the aim was contributing to the growing discussion on the last years on indoor environmental quality (IEQ) [205].

Assessing occupants' satisfaction about the indoor environment has been common practice for evaluating thermal comfort (TC) and indoor air quality (IAQ) perception [68], [69], [206]. In this context, an empirical study has been driven in the eight Portuguese schools focusing on these two factors: TC and IAQ. Monitoring parameters were faced up with perceived TC and IAQ responses.

Field research, or "the analysis of 'real-world'" [62] is important to test the validity of the PMV (Predicted Mean Vote), that provides the basis of the main thermal comfort standards [81], [207]. Several field studies have been investigating the thermal sensation votes (TSV) regarding the indoor thermal environment (ITE). It has been found that people in naturally ventilated indoor environments are comfortable within a larger range of values than in fully conditioned environments. In warm climate it has even been shown that people can achieve comfort at higher temperatures, compared to the recommendations based on PMV calculation [208].

The field campaign was performed in the eight schools during the spring – autumn period (excluding summer vacation) during 2013. Three schools were monitored a second time – MMV and MTS, in June 2013, and PBL, in May 2014. 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). This survey period is coincident with the study by Teli *et al.* from 2011 on UK schools [70].

Additionally, air exchange rates (AER) were measured by the concentration decay method using metabolic CO_2 as the tracer gas.

4.1.1 Monitoring campaign scheduling

The continuous monitoring period varied between schools, from a minimum of 48h to three weeks. Although provided with HVAC systems, namely AHUs and VRFs, 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, similarly to [209]; however, 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 11**. IAQ subjective surveys to the students were generally implemented on the last day of the monitoring period. Twenty-two monitoring campaigns were performed in total (two classrooms per school in the first moment and six classrooms were monitored a second time).

Table 11 – 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*	13/06/2013 – 02/07/2013**	06/06/2013
Lisboa (LSB)	11/03/2013 – 13/03/2013	–	–
Beja (BJA)	29/04/2013 – 13/05/2013	–	13/05/2013
Matosinhos (MTS)	17/04/2013 – 24/04/2013	14/06/2013 – 04/07/2013**	–
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*

*** Schools monitored also during the national examination period 2013.*

4.1.2 Monitored classrooms characterization

Table 12 and **Table 13**, 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. Classrooms' location in each school is further detailed in the correspondent **Appendix B**, B1 – B8.

Table 12 – Summary table of the 8 schools classrooms characteristics' and windows dimension

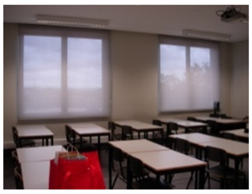
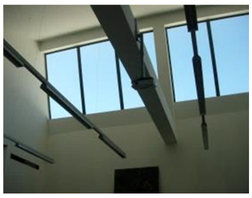
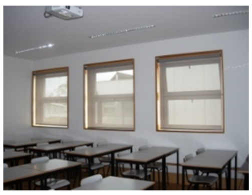
School	Room	Area (m^2)	Ceiling (m)	Volume (m^3)	Number of students (during class period)	Occupancy density (pupil / m^2)	Window to floor Ratio
MMV	**MMV1**	41.75	3.00	125.2	22 (survey)	0.53 (survey)	0.20
	MMV2	47.06	3.00	141.2	24 (surveyed total 24)	0.57 (survey)	0.18
	MMV3	47.40	3.00	142.2	16 (exam)	0.34 (exam)	0.18
	MMV4	48.64	3.00	145.9	16 (exam)	0.33 (exam)	0.17
LSB	**LSB1**	57.72	3.00	173.2	21 (median)	0.36 (median)	0.25
	LSB2	57.28	3.00	171.8	8 (median)	0.14 (median)	0.25
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
MTS	**MTS1**	57.91	variable	304.3	26 (median)	0.45 (median)	0.37
	MTS2	52.10	2.90	151.1	27 (median)	0.52 (median)	0.18
	MTS2	52.10	2.90	151.1	15 (exam)	0.29 (exam)	0.18
	MTS3	52.40	2.90	152.0	15 (exam)	0.29 (exam)	0.18
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; LSB = Lisboa; BJA = Beja; MTS = Matosinhos; 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.

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 13**, refer to the "key classrooms" in each school – mostly because MMV3, MMV4 and MTS3 windows/classroom characteristics, do not differ from their peers.

Table 13 – Syntax table of the 8 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.						
LSB 1 & LSB2	**Window**	2.00	2.40	4.80	14.40 (3)	
	Window (opening)	2.00	0.65	1.30	3.90 (3)	
LSB1 and LSB2 are located in two different buildings, A2 and A3. Both rooms are S oriented. Windows are also equal in both rooms: sliding windows (maximum opening corresponds to the smallest sliding glazed area).						
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.						
MTS1	**Window**	1.25	1.70	2.13	(hopper) 6.38 (3)	
		2.02	3.70	7.47	(skylights) 14.95 (2)	
	Window (opening)	–	–	–	(hopper) 1.87 (3)	
MTS1 is located in building B. There are windows type hopper windows, S oriented and skylights facing N. Window opening was roughly estimated as ¼ area of the hopper windows area.						
MTS2	**Window**	0.60 + 1.1	1.50	2.55	9.30 (4)	
	Window (opening)	–	–	–	1.65 (4)	
MTS2 is located in building A, windows are S oriented. One of the fixed glazed areas above the hopper window is a ventilation grid instead of a glass. This piece was not accounted in the glazed areas. Window opening area was roughly estimated as ¼ area of the hopper window.						
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.						

4.2 IEQ analysis – Monitored data

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). The recorded values of these parameters are presented in sections **4.2.1** and **4.2.2**. Data were registered every 60 sec for the total monitoring periods. The only attempt to place the equipment in the middle of the room (and according to ISO 7726 [210]) was done in the first visited school, D. Pedro V in Lisboa. The impracticability of this procedure conditioned the future monitoring campaigns. Because of regular class action, and considering students behaviour, the measurements were not registered totally in accordance with this ISO – the equipment were integrated in the room furniture, at a height of circa 0.6 m above the floor (near the breathing height for seated people) or over the suspended ceiling.

The occupancy periods in both classrooms were further analysed: for each of the monitored class days, an occupancy period was defined according to the classroom schedule, which varied daily. The results of the percentage of compliance of each of the parameters evaluated, according with the reference values ([81] – Cat. B, [16] , [174] – Cat. II), are presented for each school in **Appendix C** (C1 – C8), for both monitored classrooms. It is noteworthy that the temperature reference values used to compute the compliance of this parameter refer to operative temperature (20 **-** 24 ºC), while the monitored temperature in the classrooms was air temperature (T_a). The comparison herein presented was possible because the monitoring campaigns were driven during the mid-season, when temperature differences between air and mean radiant temperatures are not so significant.

Data analysis within this section can be accompanied with **Appendix D**, D1 – D8.

4.2.1 Classroom indoor air temperature

"The thermal comfort sensation of building occupants is determined by the climatic parameters (room temperature, humidity, air speed and radiation levels) and by personal factors such as the activity and clothing level of the occupants", [211] cited in [104].

The indoor air temperatures (Ta) distribution in both monitored classrooms in each school is presented in **Figure 39**. It can be observed that 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 the only two schools that did not follow the trend were PBL and MTS, revealing lower temperatures in the classroom facing south, PBL2 and MTS2.

One of the issues that might contribute to the results in PBL and MTS are 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. In MTS2 instead, the results are, mostly probably, due to the higher metabolic level achieved in the technical courses that are taught in this classroom. Another reason might be the percentage of glazed surfaces (higher solar gains). As previously presented in **Table 12**, although MTS1 presents a lower occupancy density, it also presents a much higher window to floor ratio than MTS2 (0.37 vs. 0.18); this is primarily due to the 15 m^2 skylights (**Table 13**).

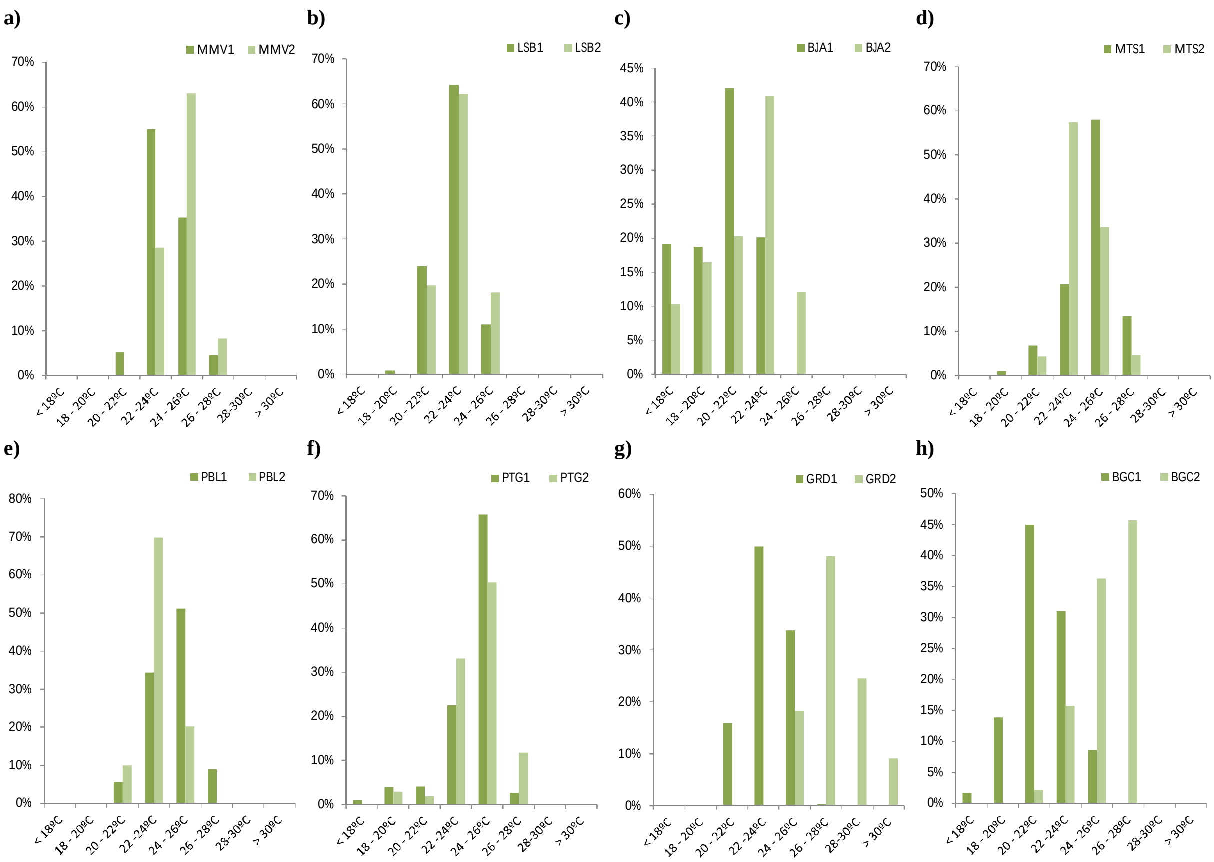


Figure 39 – Air temperature distribution intervals in the monitored rooms. (a) MMV; (b) LSB; (c) BJA; (d) MTS; (e) PBL (2014 monitoring); (f) PTG; (h) GRD and (i) BGC

Indoor Ta values higher than 26ºC were registered in MMV, MTS, 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 14**). 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 developed in this chapter 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, while in MTS it varied between 79 and 91% in MTS1 and MTS2, respectively, and surpassed 80%, either in PBL or PTG; in LSB, Ta varied between 20–24ºC more than 80% of the occupancy periods and more than 60% in BJA.

It is also 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 14**, 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 14 – Summarizing table of the Ta statistic data during the occupancy periods in the monitored classrooms (as defined in **Appendix C**, C1 – C8)

Statistic data	**MMV1**	**MMV2**	**LBS1**	**LSB2**	**BJA1**	**BJA2**	**MTS1**	**MTS2**	**PBL1**	**PBL2**	**PTG1**	**PTG2**	**GRD1**	**GRD2**	**BGC1**	**BGC2**
Highest	26.9	26.2	24.5	25.9	23.0	25.9	27.7	27.2	27.4	25.5	26.3	27.3	26.2	30.7	25.5	27.5
lowest	20.7	22.7	19.9	20.5	16.1	17.4	20.8	19.3	21.2	20.8	17.4	19.6	20.4	24.8	16.4	21.3
average	**23.8**	**24.8**	**22.7**	**23.0**	**20.3**	**21.6**	**23.8**	**24.5**	**24.4**	**23.3**	**24.1**	**24.3**	**23.4**	**27.5**	**21.6**	**25.6**
St dev	1.2	1.0	1.0	1.0	1.8	2.1	1.2	1.5	1.3	0.9	1.7	1.5	1.2	1.6	1.7	1.4

Note: PBL = 2nd monitoring campaign, 2014

4.2.2 Classrooms IAQ and CO_2 concentration values

"Air quality of building can be evaluated in buildings where people are the main pollution source by measuring the average CO_2 concentration in the building, when building is fully occupied" [174], since carbon dioxide in the indoor air results mostly from the human metabolism. Like indoor particulate matter [59], [212], CO_2 concentration values are related to occupancy. The continuous monitoring of the CO_2 concentration is generally a faithful indicator of human occupancy and of ventilation effectiveness. The threshold limits specified by the current national legislation for CO_2 in the indoor air are 2250 mg/m^3 (1250 ppm), average concentration value during the various occupancy periods (as defined in **Appendix C**, C1 – C8).

The results of the percentage of compliance with CO_2 parameters (presented in **Appendix C**) are not fully satisfying, because they are analysed using 1250 ppm as the upper limit (and not as an average threshold as suggested in the current legislation [213]). This was intentionally done towards contrasting the precedent legislation [16] – 1000 ppm upper concentration limit. When investigated in light of the current legislation [213], the results obtained in some of the schools, even under the absence of MV systems in action, are not so bad.

In terms of CO_2 concentrations, along the various occupancy periods the values varied between 387–3526 ppm in the eight monitored schools. CO_2 values recorded during the national exam periods were not accounted because they are not representative of the school regular operating conditions: reduced room occupancy comparing with the regular school operating period (e.g., 15 students and 1 or 2 teachers per classroom); classrooms' doors are kept open during the exams, contributing to air mixing and decreasing CO_2 concentration values indoors.

As shown in **Table 15**, in terms of the current national regulation [213], the CO_2 reference value is fulfilled only 50% of the time (average $\leq$ 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). By plotting the average indoor CO_2 concentration values in the expression PD (%) = 395*EXP (-15.15*C_{CO2}^-0.25) [214], [110] where the PD is expressed in terms of CO_2 concentration values in excess to outside air (ppm), the PD values, presented in **Table 15**, were obtained. Since outdoor CO_2 concentration values were not measured, a value of 380 ppm was estimated.

Table 15 – Summary table of the average and maximum CO_2 concentration average values during the occupancy periods (as defined in **Appendix C**, C1 – C8)

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
LSB1	818 – 2731	975	33.3	4904	29.0 ± 15.3
LSB2	635 – 896	146	100	2809	13.8 ± 4.2
BJA1	387 – 2235	686	50.0	6223	23.6 ± 14.5
BJA2	458 - 3103	830	40.0	7645	26.3 ± 15.2
MTS1	615 - 975	150	100	1890	14.2 ± 4.2
MTS2	991 - 1655	293	60.0	2449	24.4 ± 5.4
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.*

The school with the best results was MTS. These are justified by the fact that HVAC systems were operating, at least during part of the day. Additionally, room MTS1 has a workshop profile (i.e., for practical/experimental classes), and it has a larger height/volume than usual; consequently, CO_2 due to human occupancy is more diluted. In contrast, room GRD1 is one of the rooms with worst performance in terms of IAQ because it has very low ceiling (< 2.50 m) and volume (<133 m^3).

The values presented for MMV2 (**Table 15**) 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 [174], 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 eight schools under study should fit between categories II and III (new buildings and major renovations; existing buildings). These results, summarized in **Figure 40**, revealed that there was significant improvement potential of IAQ, since schools unveil great IAQ levels in the worst performing category.

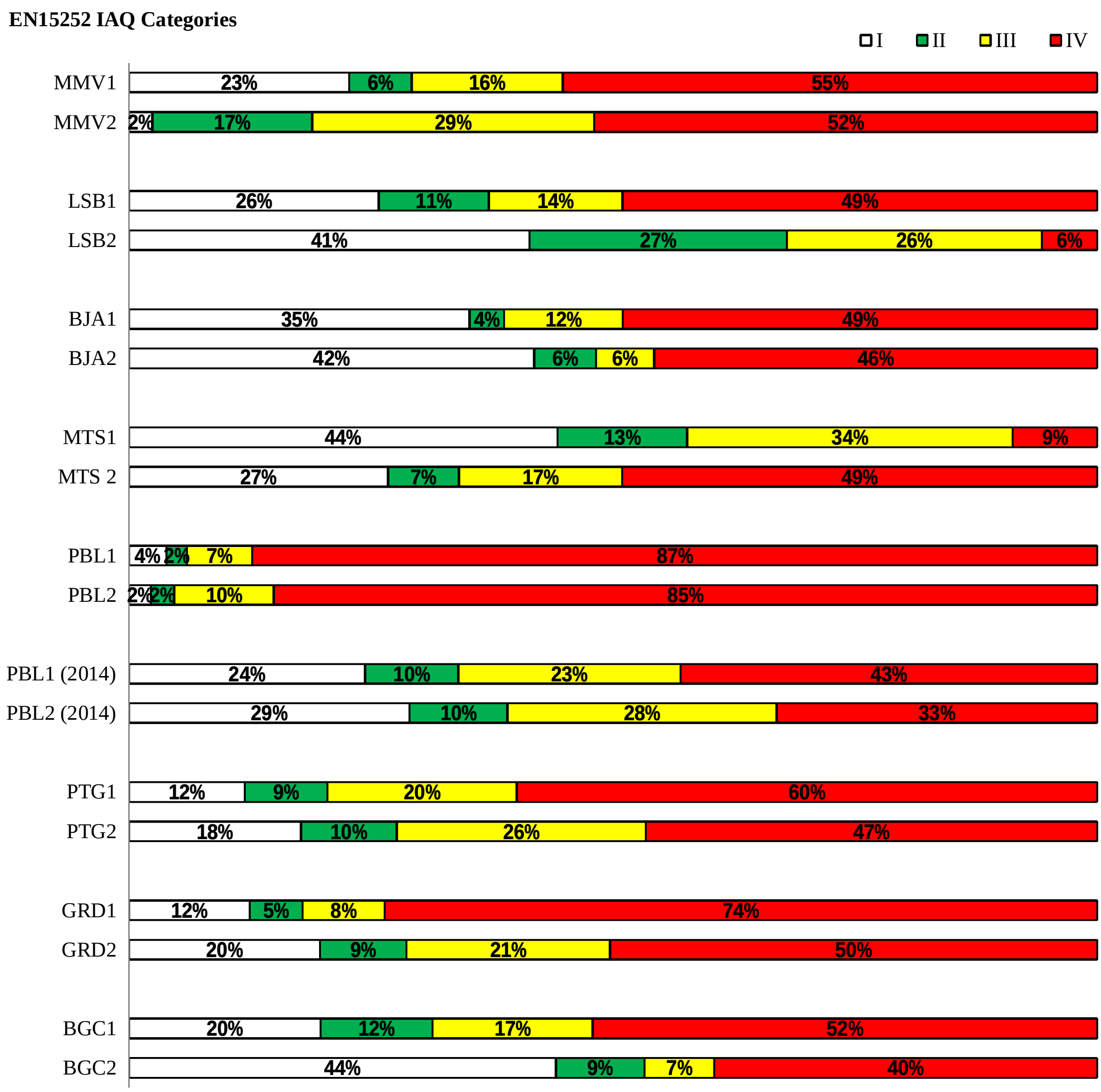


Figure 40 – Concentration evaluation expressed in percentage of time during occupancy periods in IAQ categories, according to the values of Table B4 in EN15251, expressed in concentration above outdoor concentration (considered 380 ppm)

4.2.3 Relative Humidity

As presented in **Appendix C** (C1 – C8), relative humidity (RH) in schools 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.

4.2.4 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" [215].

In [65], the authors ventilation measurements aimed at: *"assessing the CO_2 levels and to estimate time-varying ventilation rates in newly built schools without altering the normal performance of the ventilation system and carrying out a number of small intervention studies in each classroom (windows opened/closed, etc.) to test the capabilities of the design to adequately ventilate the room"*; and in [216], *"CO_2 generated by the occupants was then used as a tracer gas for the determination of ventilation rates"*.

Within the current Portuguese panorama, ventilation rates in secondary schools were measured within the *Net Zero Energy School* project [*Escola Secundária de Vergílio Ferreira* (Lisboa) at the pre-refurbishment phase (Winter [217] and Mid-season [218])] and within Cardoso's [219] internship to the Portuguese *Ordem dos Engenheiros – "Evaluation of the potential use of Natural ventilation in school buildings"* ("Avaliação do Potencial de Utilização da Ventilação Natural em Edifícios Escolares", in Portuguese), where air exchange rates (AER) were estimated in three refurbished schools located in Aveiro and Coimbra.

In this research, this issue was deepened by approaching CO_2 metabolic decay values as a method to determine 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 [216], [92], [220], 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 [221], after the occupants have left the room, the CO_2 concentration decays exponentially (in NV 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 [222]), 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" [223].

Figure 41 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)***.

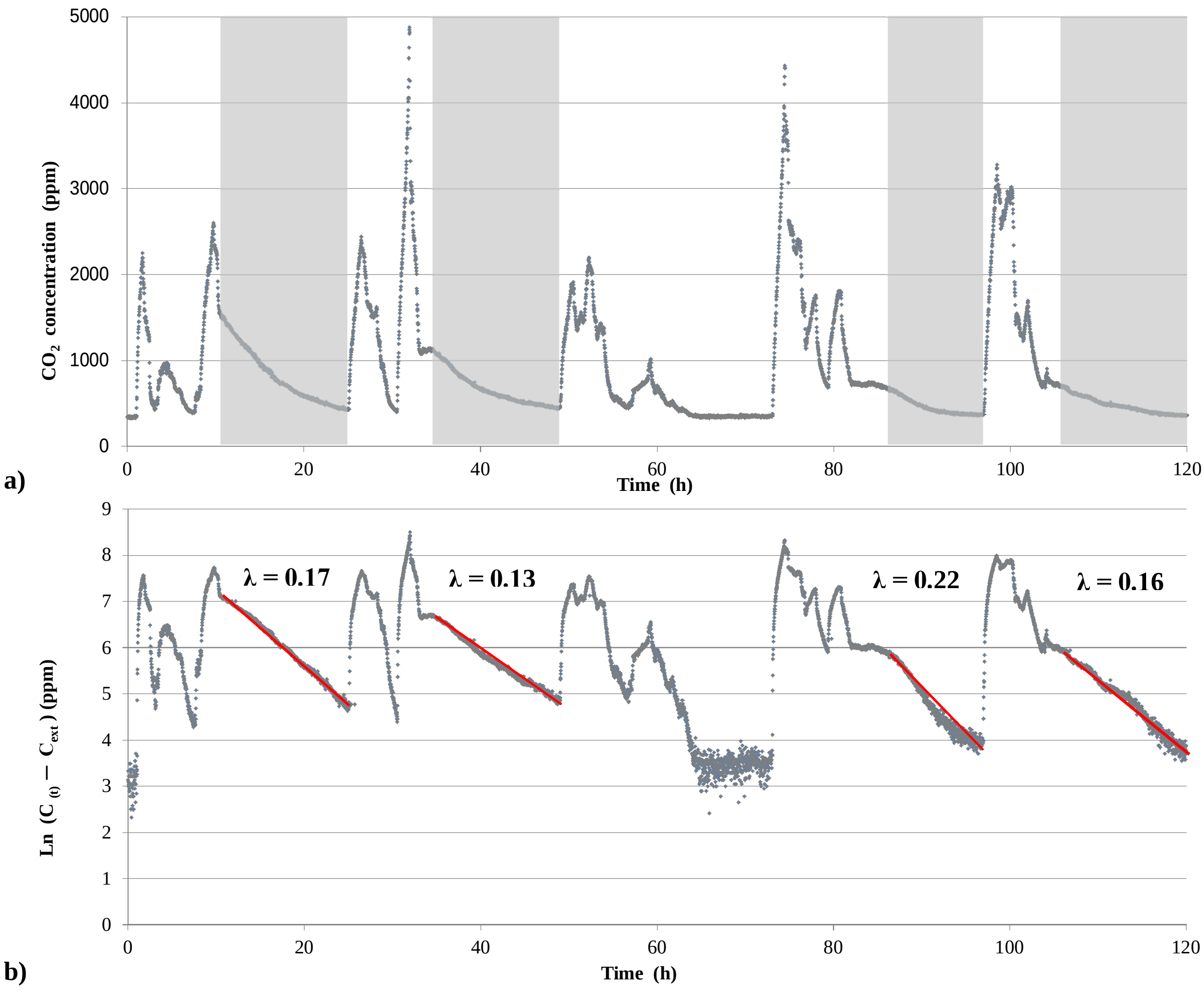


Figure 41 – Five-day CO_2 concentration in GRD1 (30 Sep – 04 Oct 2013), a); Linear regression during the same CO_2 monitoring period (4 concentration-decay validated), b); Shadowed areas identify non occupancy periods

In **Table 16**, the obtained values for AER and fresh air rates (Q) for all the monitored schools are presented. Only robust AER estimations were considered (regressions achieving high R^2), like the example illustrated in **Figure 41**. For this reason no value is presented for MTS – R^2 was in some cases lower than 0.70. Moreover, the obtained λ values were always significantly higher (significantly pronounced decays) than those from the remaining schools, meaning that these did not correspond to infiltration rates but to ventilation rates obtained through mechanical systems.

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., LSB2, 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 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 school (**Figure 27** and **Figure 63**), 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 [222] 0.6 ± 0.3 per hour. This shows the current airtightness condition of the refurbished schools.

Table 16 – 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
LSB1	1	-	-	**0.05**	-	-	8.48
LSB2	2	0.05	0.28	**0.17**	0.16	100	28.4
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}).

4.3 IEQ questionnaire - subjective assessment

Auditing indoor climate quality (ICQ) in buildings, during the occupation period, is an important procedure [224]. Foreseeing a more complete TC study, a subjective assessment was driven for each of the two monitored classrooms in each school. The assessment was based on a questionnaire specially set-up for the evaluation of environmental quality in schools and guaranteed the respondents' anonymity. A previous version of the final outline of the questionnaire was formerly applied in an academic campus [225] and presented in [103].

Besides the general characterization of the students (age, gender, height, weight), they were asked to mark what they were wearing by means of a clothing check–list, so that the actual clothing level could be calculated [81]. This information was used to calculate the PPD and PMV indices presented in **section 4.3.3**. Students were also asked on their position inside the classroom (relative position to windows/door/interior walls). The other questions concerned Thermal Comfort (TC), Indoor Air Quality (IAQ), Acoustic Comfort (AC) and Visual Comfort (VC). The questionnaire was previously explained by the research team members, before being applied to the students. Research team members were present during the survey and answered promptly when any information was questioned. At this point, only TC and IAQ questions are studied. The questionnaire ended with a question on global evaluation of the room's environment conditions.

Students provided a judgment on thermal acceptability, thermal sensation and thermal preference, answering questions such as:

a) Do you consider the thermal environment condition acceptable?

b) How do you feel in this moment?

c) How would you like to feel?

Question *a)* was answered on a discrete two-point scale (acceptable/not acceptable; yes/no); *b)* and *c)* were answered using a continuous scale with qualitative indications, latter converted to quantitative votes, as previously explained by de Carvalho *et al.* 2013, [103].

They were also questioned about draughts and air dryness, and about their preference on indoor air temperature: "If you could control indoor air temperature, would you prefer: a) It varied in accordance with the external climate conditions; b) It was almost the same all year despite the external climate". For the indoor air quality vote, the adopted parameters were the *Air stiffness* and the *Air smell* votes followed by *Air quality* (Global assessment).

The full layout of this individual questionnaire on indoor environment quality in schools is presented in **Appendix E**.

4.3.1 Classrooms conditions

In school buildings different types of lessons may occur in the same room. As such, different levels of activity can be undertaken, which are normally accompanied by different types of clothing insulation.

In [104], a Netherlands' case study is presented, where three main rooms were considered, corresponding to three different educational activities: theory rooms, practical rooms (designed for practical classes as physical education, arts, etc.) and combined theory-practical rooms (mixed use classrooms). As such, a study on clothing insulation is carried out [104]. Assuming that the tables of insulation in ISO 9920 [226] were not accurate (since the values were all for adult sizes), the author performed a detailed analysis using an equation for the intrinsic insulation calculation, followed by a scale of the clothing weight based on body surface area (AD, Dubois and Dubois 1916), taking a 1.8 m^2 person as reference. Interestingly, the absolute insulation values obtained were similar to those expected for adults during the same time of the year (winter time). It is notable that there is no school uniform in the Netherlands' schools, contrary to the UK example; nevertheless, children's outfit was rather similar, comprising jeans, polo shirt or blouse, and a sweater. This is also the case in the public school buildings in Portugal.

The survey addressed only students (thus excluding other school users, e.g., teachers) in order to assess how each school was performing from the viewpoint of its main and dominant occupants. **Table 17** and **Table 18** present a summary of the occupants' characterization and classrooms' conditions.

Table 17 – 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* [81]*. The wooden chair insulation (0.01 clo according to Table C.3) was not considered.*

Table 18 – 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	03/06/ 2014 @ 10:30	24.7	55.2	1159	17.2	Survey after the beginning of the class at 10:30 (after the morning interval between 10:10 - 10:25).
PBL2		24.1	58.7	1647		
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.

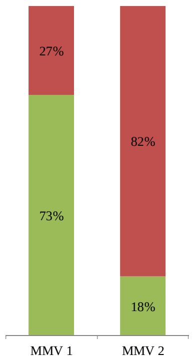
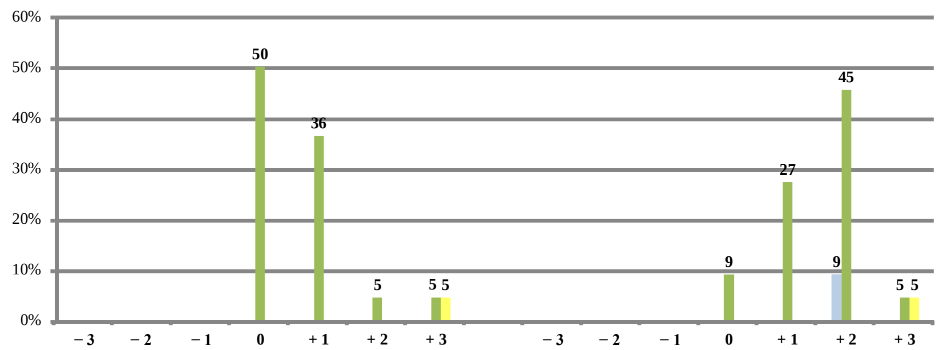
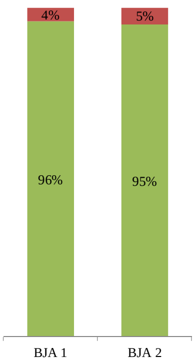
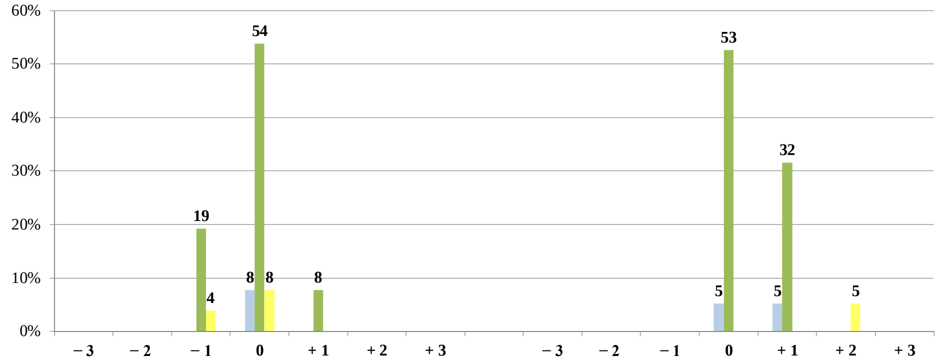
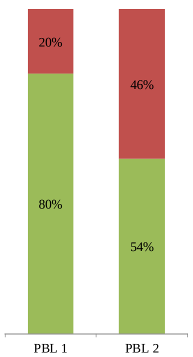
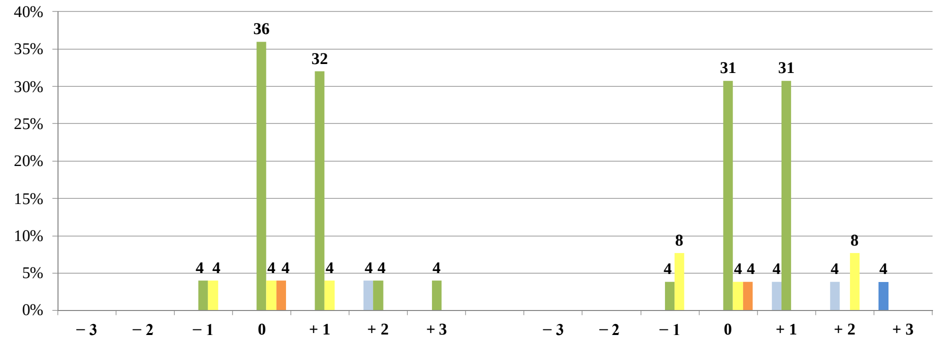
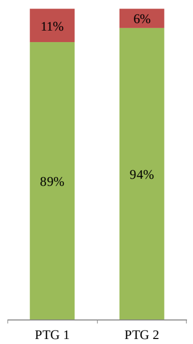
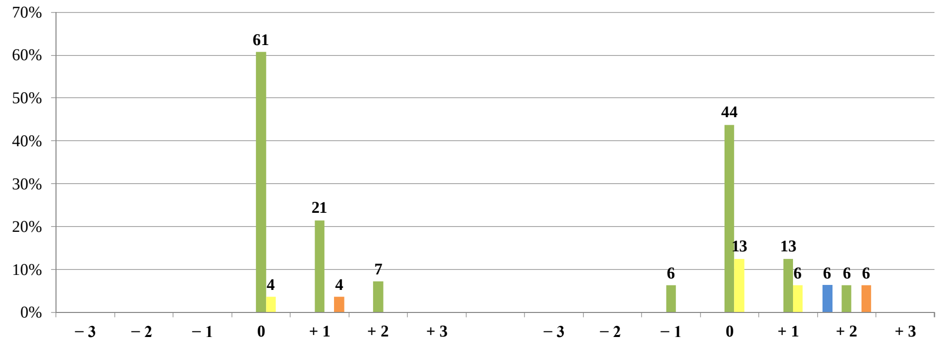
Notes: MMV2. Since monitoring in MMV2 was earlier interrupted in 17/05/2013, Ta herein presented has been estimated based on temperature differences between Ta in the room and external temperature in 07/06/2013.RH was estimated as 50%.

4.3.2 Answers from the questionnaires

"the human perception of air quality is affected by air temperature [227].*The acceptability of inhaled air decreases with both increasing air temperature and humidity"* [225]

Table 19**Table 19** and **Table 20** 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.*

Table 19 – Summary table of the 12 classrooms' conditions (average) during the questionnaire

School / Question	Thermal Acceptability	Thermal sensation vote and Thermal preference
	Do you consider the thermal environment condition acceptable?	*How do you feel at this moment? & How would you like to feel?*
	Yes No	Much cooler A bit cooler No change A bit warmer Much warmer
MMV		
		MMV 1 **MMV 2**
BJA		
		BJA 1 **BJA 2**
PBL		
		PBL 1 **PBL 2**
PTG		
		PTG 1 **PTG 2**

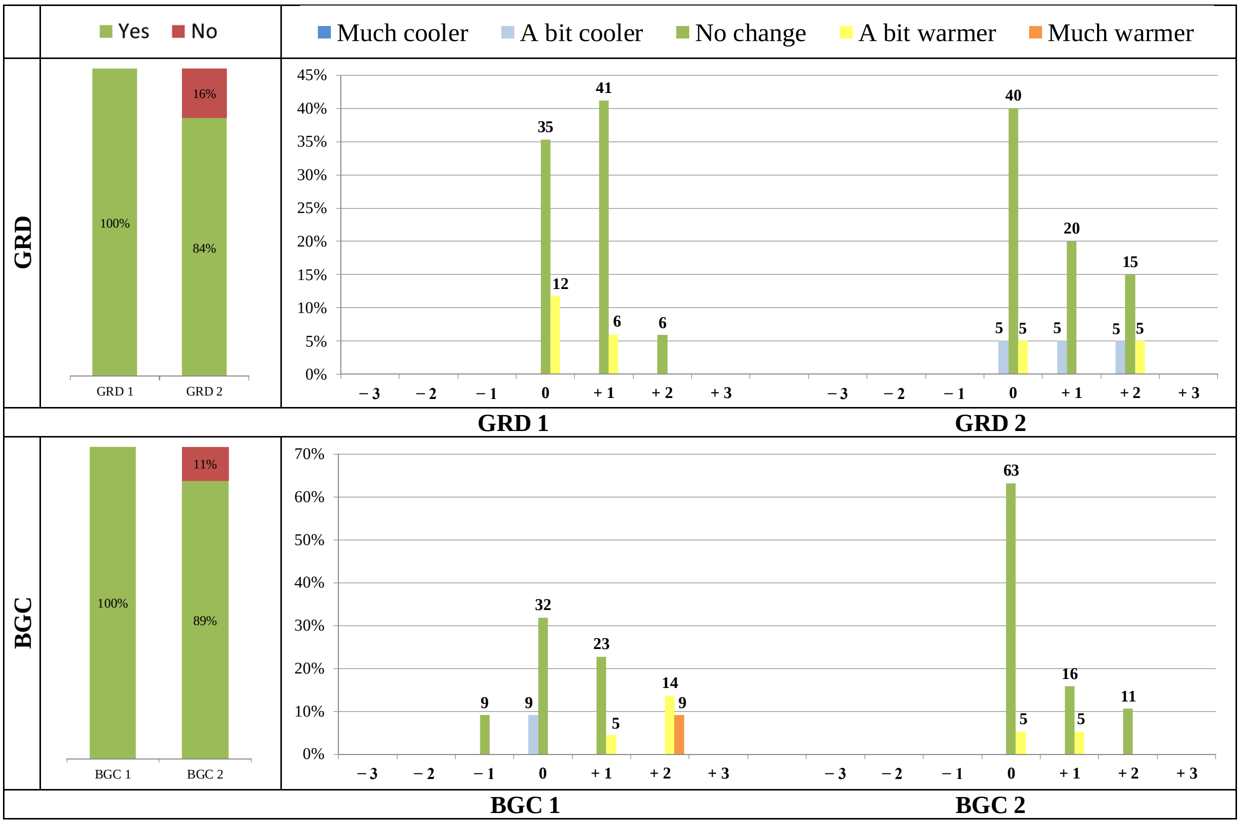
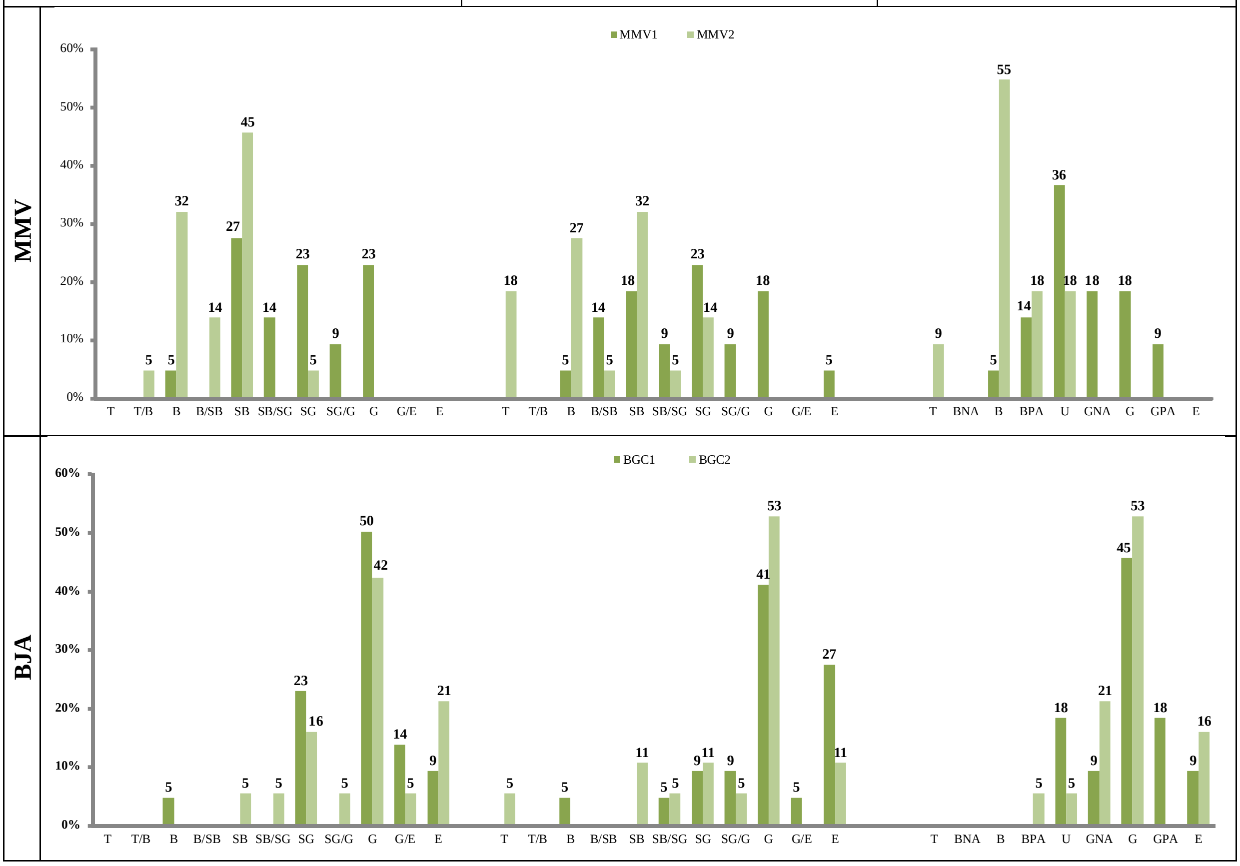


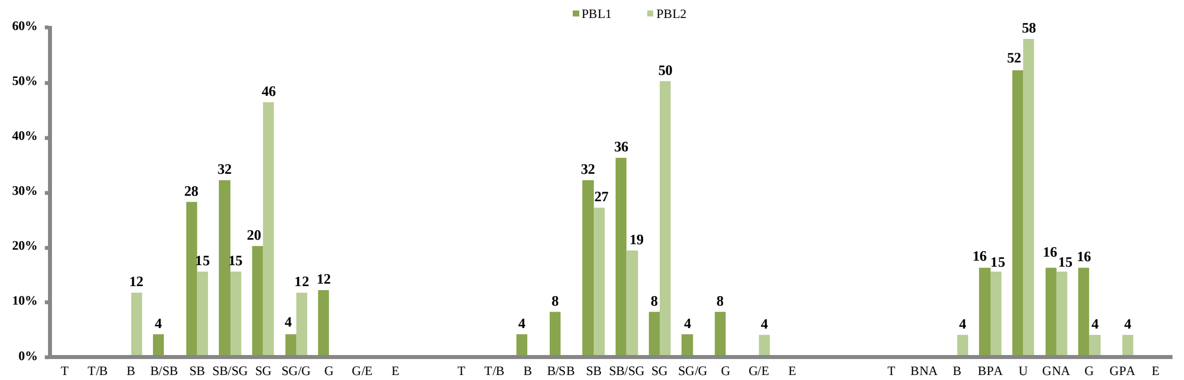
Table 20 – Answers from the IAQ questions. Summary table of the 12 classrooms

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

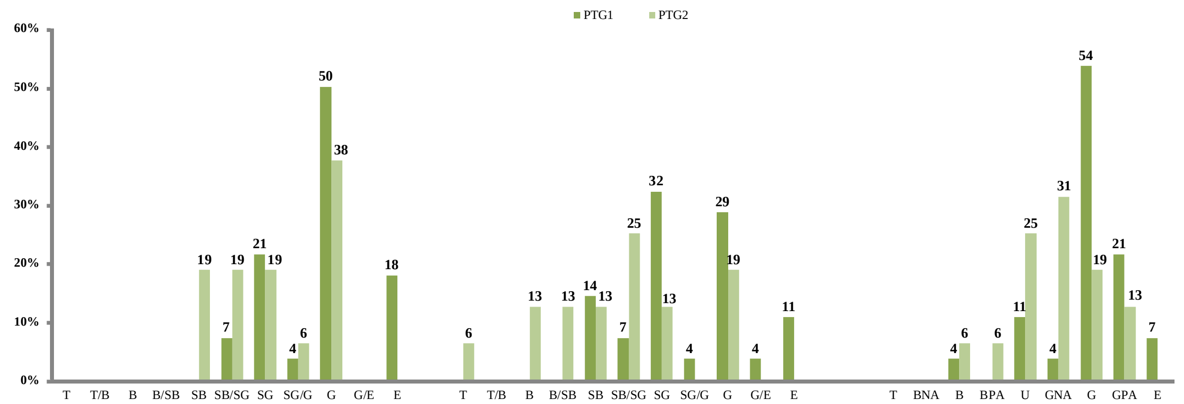


	Air stiffness votes (*Clean Air/Polluted Air)*	*Air smells* votes	General air quality votes

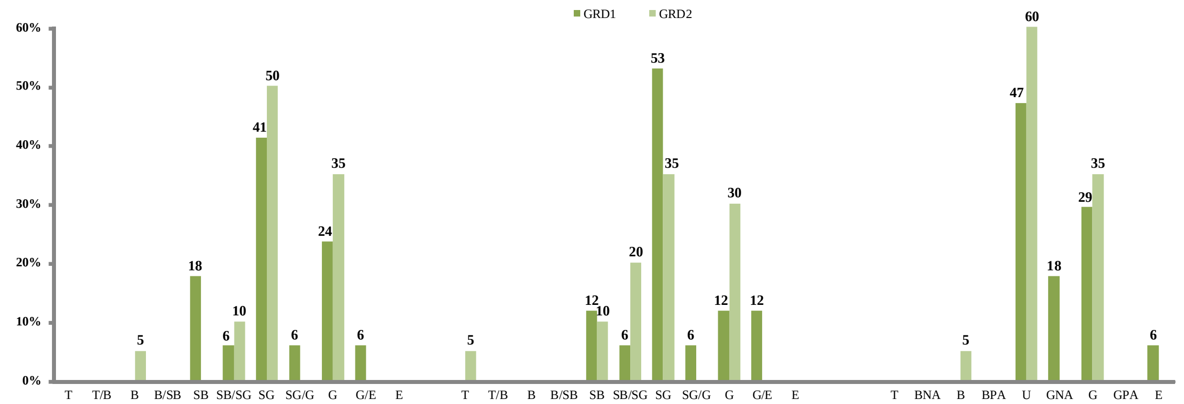
PBL



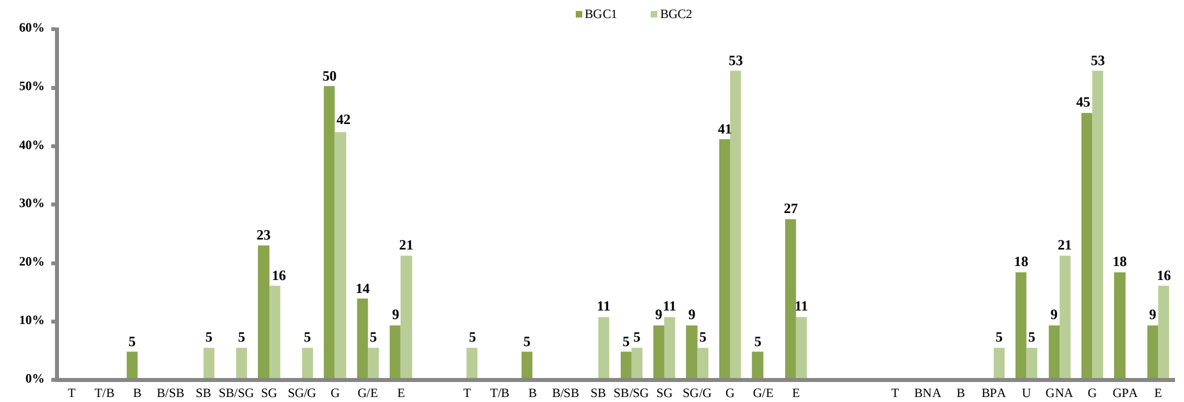
PTG



GRD



BGC



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.

4.3.3 Estimation on comfort indices based on schools' data collection

The recorded data were elaborated in order to evaluate Fanger's thermal comfort indices, PMV and PPD, according to ISO 7730 [81]. The procedure has been previously exposed in [8]. Based on a simulation tool developed by Gameiro da Silva [228], [229], TC indices were calculated. In the present case studies, data input relating to environmental conditions were: air temperature (monitored value), mean radiant temperature (estimated: based on Ta ± 1ºC), air velocity (estimated in accordance to [81]) and RH (monitored value) – instead of partial vapour pressure. The other parameters are clothing insulation (which were obtained from the questionnaires and calculated based on [81]), the metabolic rate (that was considered 1.2 met - sedentary activity**)** and mechanical power.

Aiming at comparing PMV and PPD indices, with the results obtained from the questionnaires, the considered values for each of the varied parameters are presented in **Appendix F**, from which three results for each classroom were obtained. **Figure 42** presents a synthesis of the simulated results in six schools. No simulation was performed for LSB or MTS, since no questionnaire was driven in these 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.

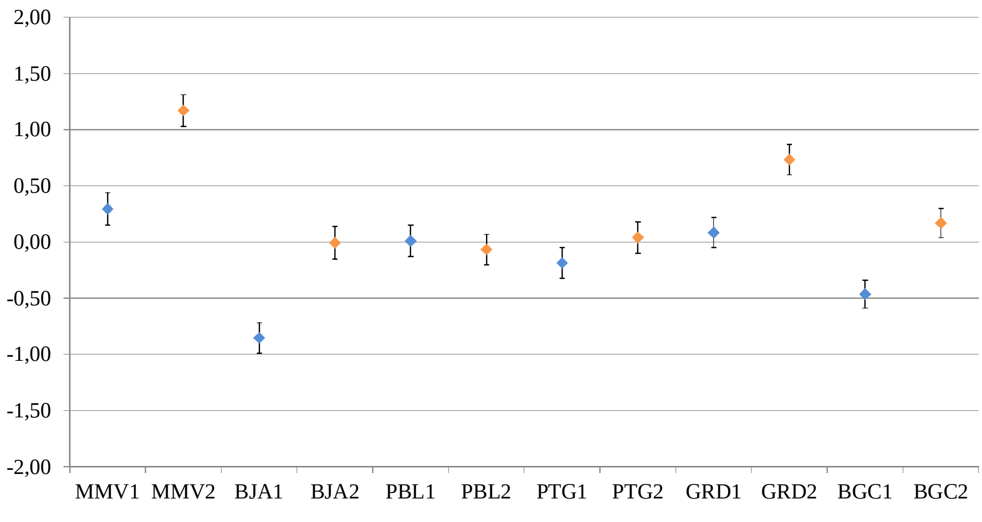


Figure 42 – PMV calculated votes (mean and standard deviation) based on simulation

4.3.4 Indoor air quality analysis based on CO_2 concentration values

Following the reasoning previously presented in **section 4.2.2** (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)"*, it was determined the percentage of dissatisfied (PD).

In **Figure 43**, PD with IAQ in classrooms during the questionnaires (CR 1752-1998 [230]) is plotted together with PD derived from the questionnaires. It is noteworthy that PD votes, driven from the global assessment question on *Air Quality*, just like TC votes (previously presented), were given in a continuous scale with qualitative indications, latter converted to quantitative votes (-500 to 500), [103]. The PD values corresponded to negatives votes with an absolute value higher than 100.

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 [219].

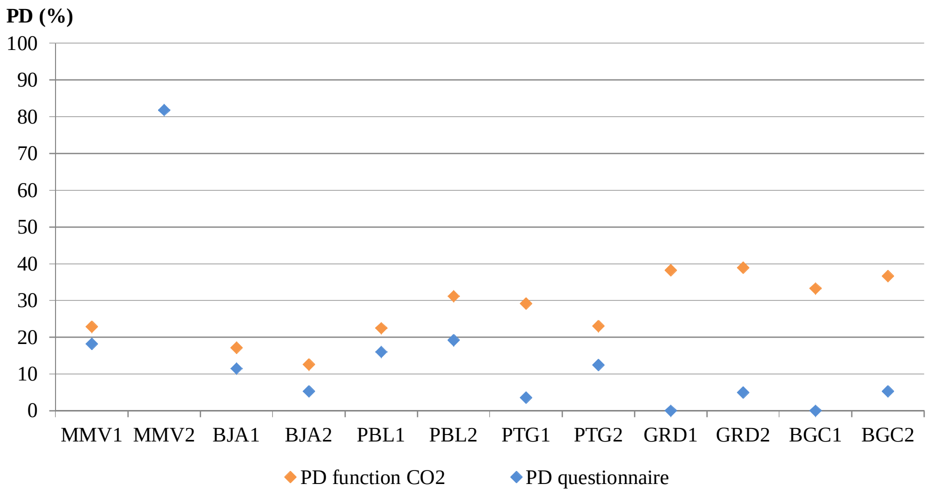


Figure 43 – Percentage of dissatisfied estimated on CO_2 concentration excess in relation to outside air (CR 1752-1998) plotted together with PD values from the questionnaire

4.3.5 Results

According to EN 15251:2007 [174] (Table 1: Description of the applicability of the categories used), when analysing these case studies, we should be looking at Category II (Normal level of expectation and should be used for new buildings and renovations). Based on this same EN 15251:2007, for Category II the recommended values for PPD should be <10 and PMV should vary between ± 0.5 (table A.1, Annex A). The reference values presented for this thermal environment category are the same in ISO 7730 [81]. Not all the values presented in **section 4.3.3**, **Figure 42,** respect the conditions recommended by the standards. 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%.

Figure 44 presents a summary of the thermal conditions (indoor Ta, ºC) of the classrooms during the questionnaires' period, plotted with PMV simulations (in green) and TSV (in grey), mean and standard deviation votes (previously estimated in **section 4.3.3**). 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. Additionally, in **Figure 44**, TSV of boys (in blue) and girls (in pink) are also distinguished.

"It should be noted however that the definition of the people dissatisfied as those who vote beyond the central three categories is questionable, as other research has found that some subjects may actually find the thermal environment acceptable even if they voted outside these categories" [231], [232] cited in [69].

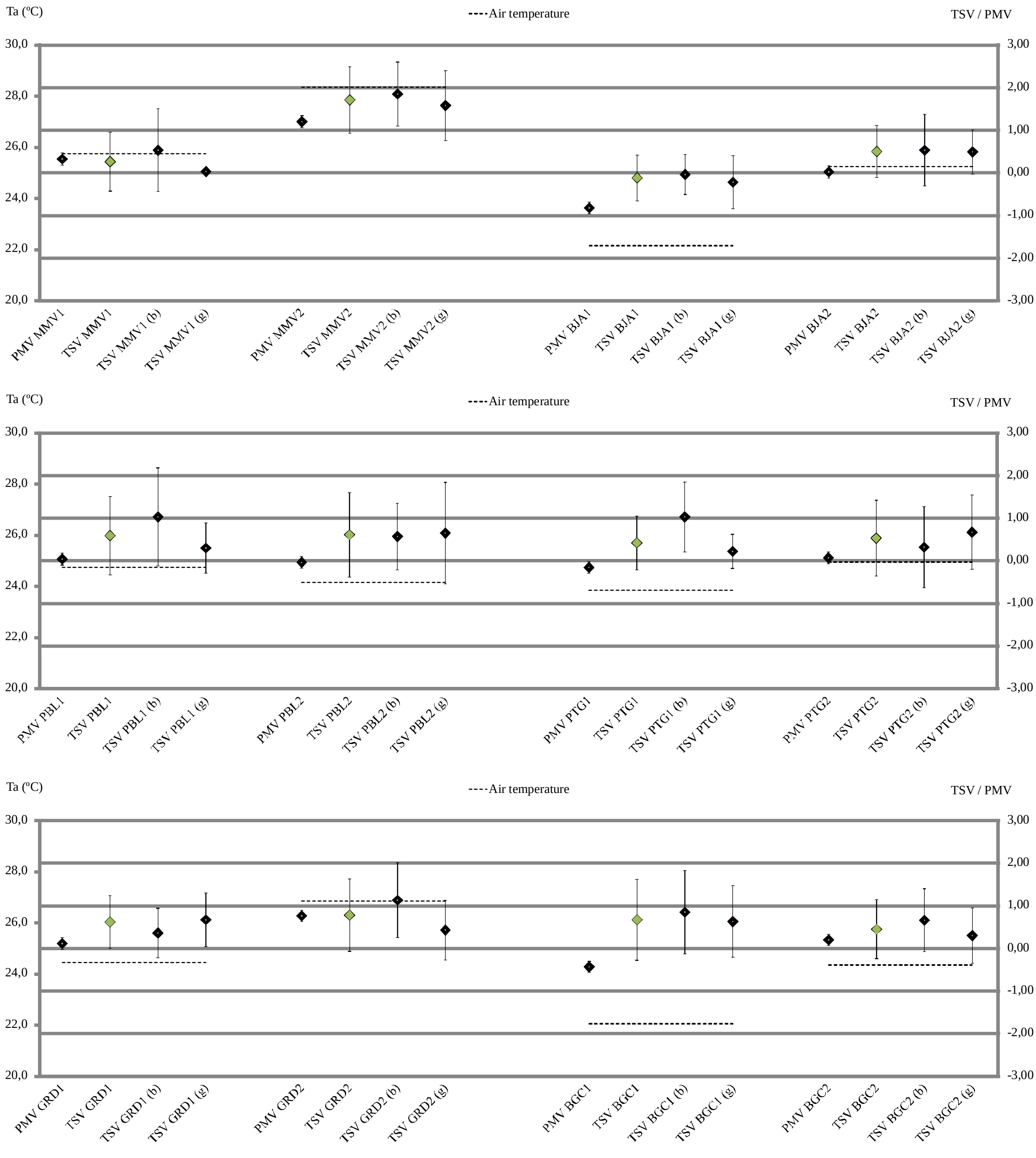


Figure 44 – Air temperature values plotted against TSV and PMV (mean and standard deviation)

Although TSV overestimates PMV in all cases except for MMV1, in 75% of the cases thermal acceptability (TA) 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*.

In **Figure 44**, 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 42**). Generally, TSV are always 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).

The results confirm that people may feel comfortable under a wider range of temperature than those recommended by the standards and also reinforce that *"people living in warm climates can more easily accept and work longer in hot environment than people from colder climates"* [224]. Other studies in classrooms have confirmed that people in naturally ventilated indoor environments are comfortable within a range of microclimate values that is wider than in fully conditioned environments [231], *"occupants seem capable of adapting to a broader range of conditions (…) than predicted by ISO7730"* [233] *cit in* [234].

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), [235] – which may be explained by the smaller Ta difference in our case studies (< 3ºC) in comparison to a higher Operative Temperature difference in [235] (~ 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 $TSV_{BGC2} = 0.42 \pm 0.69$ ($Ta_{BGC2} > Ta_{BGC1}$).

Furthermore, in their study, H. Yun *et al.* (2014) found that *"the distribution of votes was wider for boys than for girls"*. In our study this is a half-truth but not a generalized condition in all the schools: although this was verified in 67% of the classrooms, in PBL1, for example, $TSV_{PBL1}girls = 0.27 \pm 0.59$ and $TSV_{PBL1}boys = 1.00 \pm 1.15$, but the contrary was verified in room PBL2, where $TSV_{PBL2}girls = 0.62 \pm 1.19$ and $TSV_{PBL2}boys = 0.54 \pm 0.78$. In other situations, the existing difference is really small to be assumed as substantial, e.g. classroom PTG2, $TSV_{PTG2}boys = 0.29 \pm 0.95$ and $TSV_{PTG2}girls = 0.64 \pm 0.87$.

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, $Ta \geq 28.3$ 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 again 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 partially explored in **section 4.3.4**. 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 43**; 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.

4.4 Discussion

"It is logical to study thermal comfort by conducting surveys of real occupants in real buildings since the whole purpose of HVAC systems in buildings is to satisfy the requirements of the occupants" [236].

The work presented aimed at evaluating TC and IAQ in recently refurbished Portuguese secondary classrooms running in free running conditions / natural ventilation mode or mechanically ventilated, mostly during mid-season. The environmental parameters influencing TC and IAQ were measured (Ta, RH and CO2 concentrations), while parallel subjective assessments of the occupants were collected. In this study, the comparison between the subjective votes (TSV) and predicted votes, deriving from the objective monitoring of some environmental parameters allowed the test in field both in the "traditional" approach and in the adaptive one.

This study reinforced findings of previous studies conducted in classrooms – students in secondary schools in Mediterranean climate under free running conditions in mid-season:

- 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. From **Figure 44** it can be withdrawn that girls' mean TSV was generally lower than boys' (in 67%). Although a consciously analysis should be withdrawn of such sample (due to the limited sample of 262 individuals, who answered the survey), some factors might explain this trend: such as the girls' basal metabolic level, which is generally slightly lower than boys' and the clothing insulation layer, which might be lower in girls. Further investigation on this subject is suggested to explore this gender hint.

*"Achieving optimum **indoor air quality** relies on an integrated approach to the removal and control of pollutants using engineering judgment based on source control, filtration, and ventilation"* [237].

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 [85]). In the UK, the recent version “Facilities Output Specification for School Buildings” [238] and BB101 [63] “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’[239]. 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.

CHAPTER 5. ENERGY EFFICIENCY PLANS FOR SCHOOLS

This chapter research method, aiming at defining EEP, is reported in paper **X** [113]**, Appendix A**, in which **sections 5.1** and **5.2** are based on. Section **5.3** is partially based on paper **IX** [117].

5.1 EEPs approach

Apparently extreme, the situation of the Portuguese schools studied within 3Es Project face, in fact, a comparable problem to the households described by Santamouris *et al.* [86], i.e. "at risk of having their utility service cut off because of an inability to pay their home energy bills" – energy costs represent a significant effort for school managers.

Besides enforcing buildings' refurbishment, EPBD's revision aimed at promoting BMS enhancement. In fact, by pointing at EU's 2020 targets, the project *SMART Portugal 2020* foresaw "reducing Emissions and Increasing Energy Efficiency through ICT" [240], where *Buildings*, *Power management* and *Transportation* were defined as priority areas.

Building use, energy and IEQ performance analysis during the first years of occupation (as those presented in **Chapter 3**) are important to identify opportunities for fine tuning of the systems operation or even future projects. This action has been designated by some authors as POE – post-occupancy evaluation [94].

Within this context and in the 3Es Project, as seen in **Chapter 4**, the IEQ in the Portuguese secondary schools has been compromised due to the non-operation of the HVAC systems. This proposal aims at optimizing schools' indoor environmental conditions unveiling that it is possible to improve the HVAC systems' operation and optimizing energy use and costs, while maintaining good environmental conditions. Part of this challenge goes through focusing on the Building Management Systems' (BMS) operation, following the recommendations from *The Climate Change Bill* and the EPBD, as recalled in [90] – "specific improvements *(are)* to be made both in design and operation ". These have also been reinforced by EN15232:2012 [241]. Moreover, as presented in [242] referring to [243], "careless behaviour can add one third to a building's designed energy performance, while conservation behaviour can save a third".

Another part of the energy demand addresses ventilation and temperature indoors: "ventilation of schools in warm climates have a dilemma between the energy efficiency (EE) on one side and IAQ and TC on the other [9]. The challenge between TC and IAQ also occurs in classrooms in moderate climates: more ventilation means more energy use" [55].

Energy consumption in school buildings has been achieving a higher level of concern in many parts of the globe. In Japan, for instance, due to the 2011 tsunami and succeeding energy accessibility limited conditions, indoor air temperature values in classrooms are now kept up to 28ºC [244], [245], much above the reference values [81], [174]. Concerning TC energy use, "higher indoor temperatures in summertime conditions would lead to less prevalence of cooling systems", i.e. "raising summer set point temperature has good energy saving potential" [246].

Generally speaking, in terms of the thermal environment, there have been presented three categories of adaptation: physiological, behavioural and psychological [79], [247]. "Behavioral adaptation is by far the most dominant factor in offering people the opportunity to adjust the body's heat balance to maintain thermal comfort, such as changing the activity and clothing levels & opening/closing windows and switching on fans" [246].

Since in the Portuguese public schools (from primary school until university), there is no mandatory dress code, adaptive opportunities regarding clothing insulation are made easier. In two studies on IAQ and TC in Portuguese secondary classrooms [110], [199], the authors concluded that students in secondary schools in Mediterranean climate, under free running conditions in mid-season, accepted indoor temperatures (Ta) higher than 25ºC, reinforcing findings from previous researches conducted in classrooms – these studies were undertaken in the schools of BJA and PTG during the present research.

Additionally, it was identified a trend where slightly warm environments gather the thermal preference during the mid-season. It is remarkable that within the survey driven to the students in the 3Es project schools (**section 4.3**), the answers to the question relating their preference on indoor air temperature (Ta) were unequivocally: *"If you could control indoor air temperature, would you prefer: a) It varied in accordance with the external climate conditions; b) It was almost the same all year despite the external climate"* [110]: more than 75% (77% ± 9%) expressed their preference on Ta related to the external conditions. This allows foreseeing the possibility of driving Ta to the extreme ranges of comfort in the standards – 19 ºC in winter and 25 ºC in summer (especially, since there are not classes during summer (after June 21 until mid-July there are only examinations, and during these days, the schools' direction boards tend to turn on the HVAC systems).

This methodology has been submitted for publication to the scientific journal *Applied Energy* [113].

5.1.1 Knowledge of the object of the study

"For both residential and office buildings, the electricity demand remains one of the crucial elements to meet sustainability requirements. (…)The heating or cooling of a space to maintain thermal comfort is a highly energy intensive process accounting for as much as 60–70% of total energy use in non-industrial buildings. Of this, approximately 30–50% is lost through ventilation and air infiltration" [237].

In addition to the spatial distribution of the school areas (as presented in **section 3.2**) and acquaintance of the school climate condition and building physics, major focus is addressed to other schools' data, namely schools' population, schools spaces' occupancy schedule and advanced acquaintance of the schools' systems installation and operation – therefore, **sections 3.2.9.1** and **3.2.9.2** were improved.

These requisites presupposed following visits to the schools, in order to better understand the BMS operation, gauging lighting and HVAC systems manoeuvring (checking eventual doubts not previously clarified), etc. **Table 21** presents the calendar of the main visits promoted to the two schools chosen as primary challenges: MTS and MMV.

Table 21 – Scheduling of the main visits promoted to the MTS and MMV secondary schools

School	I - Walkthrough	II - Monitoring campaign (Energy + IAQ)	III - Monitoring campaign (IAQ) & HVAC widening	IV - BMS control and management
MTS	04/03/2013	17/04/2013 – 24/04/2013	14/06/2013 – 04/07/2013	06, 13 & 14/10/2014
MMV	23/01/2013	16/05/2013 – 11/06/2013	13/06/2013 – 02/07/2013	09/06/2015

5.1.2 BMS control

"Systems linked to a BMS typically represent 40% of a building's energy usage and if lighting is included, this number approaches 70% […]. An improperly configured BMS with control errors can easily increase the energy consumption of buildings in the region of 5% – 30% – in some cases even more." [198]

Traditionally, three BMS control features influence energy performance [248]:

- Time schedules (matching systems operation with occupancy periods);
- Occupancy (adjusting lighting and ventilation to match actual occupation patterns);
- Condition (controlling by desired temperature, lighting level or ventilation demand).

"The general objective of a BECM system is to fulfill the occupants' requirements for comfort while reducing energy consumption during building operations". [243]

Energy management systems (EMS) [249], Building Energy and Comfort Management (BECM) systems or simply Building Management Systems (BMS) allow the supervision of the different systems running in a building. In some cases they even permit controlling and registering data. In the eight school' case studies, the systems vary significantly, but generally, it can be indicated that these mainly allow managing HVAC systems (even if the system is not "truly a system" – in BJA, the AHUs are controlled electronically, but individually). In PBL the BMS is a bit more complex, allowing also lighting control and the solar panels' system, besides fire alarms visualization.

5.1.3 Ventilation requirements

"The purpose of ventilating a building is to provide clean outdoor air to the occupants and to remove excessive heat from inside the building. Therefore, the ventilation loads of a building are both thermal and pollution». Moreover, *"ventilation is needed to meet the metabolic requirements of occupants and to dilute and remove pollutants emitted within a space. Usually, ventilation air must be conditioned by heating or cooling in order to maintain thermal comfort and, hence, becomes an energy liability"* [237].

The secondary schools under the modernisation programme led by PE, have been designed in compliance with 2006's law ventilation requirements [16], based upon the European Directive 2002/91/CE [13]. The group of secondary schools of 3Es Project is no exception. For classrooms, for instance, at least heating and ventilation systems are mandatory. In [16], the maximum concentration limits of the pollutants were tabled, set per occupant and per unit area of space [117]. This regulation, imposed for a room of 25 pupils, minimum air renewals of 750 m^3/h and CO_2 concentration lower than 1000 ppm – these values were more demanding than in many other European countries [250]. In Germany, for example, the "air volume requirement of each occupant" is 20 m^3/h [251].

Broadly, the projects developed after 2006 and before 2014 present total air flow rate values between 750 – 1000 m^3/h. Recently, this legislation has been under revision and a new one is mandatory since December 2013 [82]. The new mechanical ventilation requirements allow two different methods for the calculation of the fresh air flow rates: a prescriptive one (based on fixed values as the previous legislation) and an analytical method (that takes into account the real or predicted occupancy profile and the corresponding emission rates of bioefluents). Both methods take into account the age and activity level of the occupants [117], [252].

A comparison between the former and present requirement values from both legislations is presented in **Table 22** [117]. Additionally, another difference is found in the current legislation: instead of a fixed value for CO_2 concentration (previously 1000 ppm), the current law foresees a protection threshold i.e. maximum average of 1250 ppm (2250 mg/m^3). The new value of 24 m^3/h per person (6.67 L/s), obtained from the prescriptive method, is just slightly lower than EN 15251 ventilation rates' reference value 7.0 L/s/person [174].

Table 22 – Summary table of the old and new fresh air flow rates [117]

Space	Design conditions (2006 legislation [16])		Prescriptive method (2013 legislation [82])		Analytical method (2013 legislation [82])	
	$m^3/(h.occ)$	h^{-1}	$m^3/(h.occ)$	h^{-1}	$m^3/(h.occ)$	h^{-1}
Classroom	30	4.30	24	3.44	19	2.72
Corridors	5	1.68	2	0.67	2	0.67

5.2 Application of the proposed methodology in MTS

Besides the information already presented relating the school in Matosinhos (MTS) – section **3.2.1**, some other data was later investigated.

Concerning the school population, between 2008/09 and 2011/12, it was verified a decrease in the teaching personnel of about 30%, while it was verified an increase in the number of students (16%), corresponding to 1419 students in the scholar year 2011/12.

Pursuing the energy and IEQ audit and, as presented in [196], within the 8 school selection, in terms of the energy use indicator (EUI) gross floor area (GFA), 12695 m^2, EUI = 66 kWh/m^2. If only the *total useful floor area* (TUFA) - 10013 m^2 - is considered, EUI = 84 kWh/m^2. Considering 2011/12 number of students, the EUI (kWh/student) corresponds to 592.

This school consumes both electrical energy (EE) and natural gas (NG). The EE contracted power of 292.95 kVA supplies electricity according to a Medium Voltage tariff, with four different daily periods, with different energy prices, as presented in **Table 23**. In 2011/12 NG accounted for 40% of the total energy consumed. This is particularly significant if considered the average values: 76% EE vs. 24 NG [196].

Table 23 – The supplier schedule for active energy prices in winter and summer

	Winter time	**Summer** time	**Active Energy Quarterly Period (EUR/kWh)**	
			I | IV	II | III
Peak	09:30 – 11:30 19:00 – 21:00	10:30 – 12:30 20:00 – 22:00	0.1287	0.1316
Half-peak	08:00 – 09:30 11:30 – 19:00 21:00 – 22:00	09:00 – 10:30 12:30 – 20:00 22:00 – 23:00	0.1004	0.1030
Normal off-peak	22:00 – 02:00 06:00 – 08:00	23:00 – 02:00 06:00 – 09:00	0.0708	0.0735
Super off-peak	02:00 – 06:00	02:00 – 06:00	0.0604	0.0677

Relating renewables, only domestic hot water (DHW) production was provided, covering part of the DHW needs (15 panels of 2m^2/each on top of building C). Hence, NG is used for DHW production in the thermal power plant, heating of several rooms and in the meal production in the industrial kitchen – during the scholar year 2011/12 over 36200 meals were prepared.

Regarding thermal energy production, the school has a central heating and cooling system. Cooling is ensured through an air-to-water chiller whose main characteristics are given in **Table 24**, along with the characteristics of the equipment for DHW production and environmental heating – two NG boilers. Thermal diffusion indoors is provided by fan coil units, radiators and ventilation grids. Spaces air renewal is ensured through air handling units (AHU) equipped with heating and cooling coils – presented in **Figure 45**. Typically, indoor climate control in a school building is divided into zones. Herein, because a zone includes several rooms, the zones are designated "under-actuated" [253], e.g. each classroom climate cannot be independently controlled, since they share the same AHU.

Table 24 – Main characteristics of the thermal energy equipments

Equipment	**Brand**	**Model**	**Power [kW]**
Chiller	Carrier	AquaSnap 30RB0302--0428-PEE	140*
Boilers 1 and 2	Buderus	Logano GE515	400 kW**

*Note: *COP = 2.8; ** Efficiency 92%.*

In **section 3.2.9.2** the main installed power systems were described, namely ITC equipment. In order to reduce the energy consumption of unused computers, a computer network management system is programmed to send two types of shutdowns to the computers when they stay connected but without use. The first order is at 19:00 (by the end of the daytime classes); the second order is at 00:00 and is coincident with the end of the night classes. As regards the video projectors, according to the information received, programed shutdown is not possible due to lack of network points.

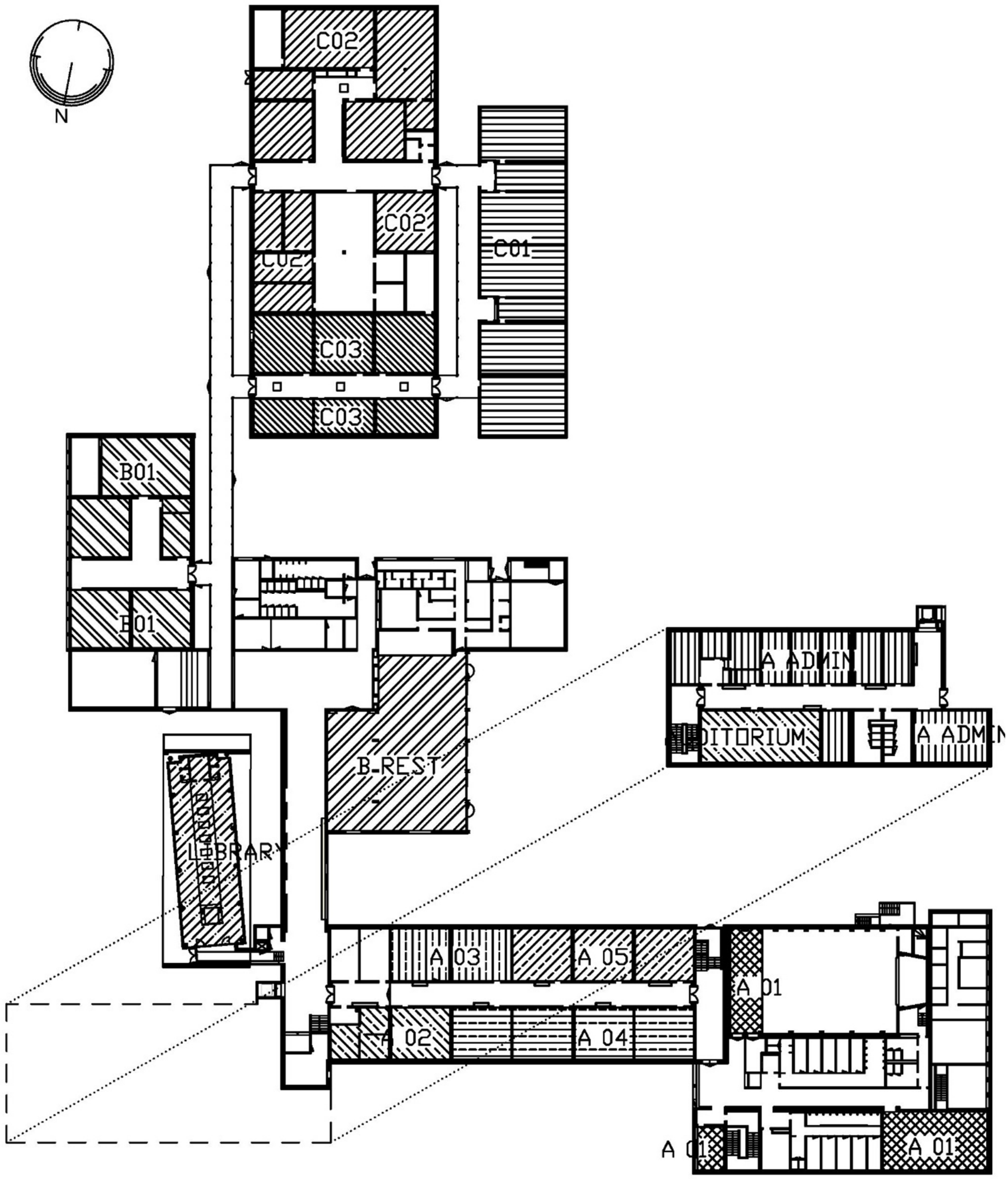


Figure 45 – Simplified floor plan of the school buildings (level -1: A, B, C and level 2: A) and main thermal zoning (AHUs plan distribution)

5.2.1 BMS architecture and control

Theoretically, building management systems (BMS) allow controlling different systems in buildings and assuring the accurate management of the energy demand, improving comfort levels and IAQ [254]. The BMS interface of this school is user friendly. In contrast to other cases under the same *Modernisation Programme* [255] or within the 3Es project [256], this

BMS does not allow lighting control. It allows controlling and managing numerous HVAC equipments of the school, time scheduling of the various equipments, besides set point temperature definition of the acclimatized areas, and commanding supplying and extraction fans.

Beginning with the assumption proposed in **section 5.1.2**, the first step was the analyses of the EE contract and the BMS configuration, immediately finding some gaps (incoherencies). At present only the first two points (*Time schedules* and *Occupancy*) are focused.

5.2.1.1 BMS operation and functionality

In a first analysis of the BMS interface, some inconsistencies between the plans in the BMS and the signalled spaces and naming in the classrooms were found, probably due to changes in the course of the construction works.

Naturally, this circumstance makes correct programming of the BMS harder. The central heating and cooling equipments operate under a stand-alone configuration. BMS (**Table 25**) they are just turned on/off. In terms of the AHUs, the temperature control is done through sensors placed in the supply and return air ducts (5 out of 14 AHUs, **Table 26**).

5.2.1.2 Time scheduling

Firstly, it was assumed classrooms occupancy corresponded to the time-table occupancy defined at the beginning of the scholar year (8:15 - 18:00 + 19:00 - 22:50[8] – maximum classroom occupancy). Secondly, administrative and service areas occupancy was expected to correspond to the working personnel schedule.

By crossing the information presented in **Table 23** (relating the EE contract) with the AHUs scheduling in the BMS (which synthetized the information of **Table 25**), it was verified that there was not a grounded reason for AHUs' switch-on 5:00. Avoiding a peak-load at 8:00, which could raise the contracted power, is a sensible strategy. Nevertheless, a 3 hour anticipation for the start operation of AHUs before the beginning of classes is not so understandable (once the heating system is not based in an all-air configuration).

In terms of IEQ, for example, the results obtained from the IAQ monitoring carried out in classrooms (visits II and III in **Table 21**), revealed the classrooms' capacity of CO_2 removal during night time. The IAQ analysis, based on the measured CO_2 concentration

[8] Only very few classrooms are occupied between 22:55 – 23:45.

average during the occupancy periods above the outdoor concentration (PD(%) = 395*EXP (-15,15*C_{CO2}^-0,25) [214], also revealed that PD varied between 8.3%–31.3%. The extreme noncompliance values were obtained in the classrooms where occupancy load was higher than projected.

Due to the occupancy of the library starting at 9:00, it is possible to activate this AHU only at 8:30, for instance, instead of the programmed 6:00 schedule. Additionally, since this space is not daily open until 17:00, considering the anticipation of turning off this AHU, could be a fine strategy for energy saving. The AHU serving the secretariat was also unadjusted to this space occupancy period (9:00 – 17:30).

Table 25 – MTS | Main automatic systems operational time

System	Naming	Start	Finish	Space	Building
AHU	A1, A ADMIN	06:00	20:00	Administrative/staff	A
AHUs	A2, A3, A4, A5	05:00	20:00	Classrooms	A
AHU	Library	06:00	17:00	Library	B
AHU	B REST	06:00	00:00	Restaurant / Dining area	B
AHU	B1	06:00	17:00	Classrooms/workshops	B
AHUs	C1, C2, C3	06:00	17:00	Workshops, ITC rooms, labs	C
Extraction Fan	-	Various schedules		Bathrooms / Kitchen area	Various

As regards bathrooms air extraction fans, three different schedules were found: "All-day", 7:00–16:00 and 8:00–17:00. Since classes start at 8:15 and there are only a few night classes (special education programmes), it was verified an inappropriate BMS scheduling – there could be a reduction of the operation in the non-occupancy period.

A proper AHU scheduling also optimizes the running time of the heating and cooling systems (here, classrooms are only provided a heating system).

5.2.1.3 Room occupancy and the ventilation system sizing

As stated in **section 5.1.3**, although the school's recent intervention, the ventilation parameters were out-dated. The influence of using the requirements of the current regulation has been formerly studied [117] and it was concluded that these could lead up to 5% decrease in the final energy consumption of the studied school.

In **Table 26**, it is displayed a list of the AHUs of this school and corresponding fresh air flow rates – existing and proposed values. The new Q values were estimated accounting the same expected number of people considered at the design phase.

Adapting the existing AHUs to the current requirements seems like a good opportunity for energy savings. In other words, if less air is supplied into the spaces, besides decreasing fresh air flow rates, less air needs to be heated or cooled. Potential energy savings of this energy efficiency measure (EEM) are further presented in **section 5.2.4**. Since the canteen area, served by *AHU CB REST*, is over pressured, it is not suggested any change to this equipment. In this particular case, the amount of fresh air is not determined by the ventilation needs, but by the thermal load of the room.

Table 26 – Summary of the schools' AHUs and corresponding fresh air flow rates (Q)

Equipment Designation	Fans nº Velocities	Project/Existing Q (m^3/h)	New Q (m^3/h) Prescriptive method	Ratio (%) new Q / Project Q
AHU A1*	Variable	3000	2700	90
AHU A2*	Variable	5850	4450	**76**
AHU A3*	Variable	5520	4450	**81**
AHU A4*	Variable	7500	6000	**80**
AHU A5*	Variable	7500	6000	**80**
AHU A REST*	1/-- (Fix)	1650	1300	78
AHU A ADMIN**	1/1 (Fix)	5940	4750	80
AHU Auditorium**	1/1 (Fix)	3000	2000	67
AHU Library**	1/1 (Fix)	1800	1200	67
AHU B1*	1/-- (Fix)	3700	2950	**80**
AHU B REST**	1/1 (Fix)	10000	-	0
AHU C1**	Variable	5100	4100	79
AHU C2*	1/-- (Fix)	6450	5300	**80**
AHU C3*	1/-- (Fix)	4950	4350	**88**

*Note: * = 100% Fresh Air; ** Mixed air.*

5.2.2 Lighting systems

As previously stated, this school BMS does not control the lighting systems. Nevertheless, some control was design predicted: presence sensors were considered both in bathrooms and cloakrooms serving the shower rooms.

In MTS there is a widespread use of luminaires equipped with fluorescent lamps. The majority of the spaces is equipped with T5 fluorescent lamps powered 49W with electronic ballasts (83% of the lighting installed power). More data is present in **Table 27**.

Table 27 – Summary of two types of classrooms (based on two IAQ monitored classrooms). Main characteristics and power loads

Classroom	Area (m^2)	Ceiling (m)	Volume (m^3)	No. of occupants (during class period)	Occu. density (pupil / m^2)	Window to floor ratio
Typical	52.1	2.90	151.1	27 (average)	0.51 (average)	0.18
Workshop	57.9	3.85 (min)	304.3	26 (average)	0.44 (average)	0.37
	Loads	**Quantity (nº)**	**Power (W)**	**Subtotal (W)**	**Total power (W)**	**Power to floor ratio (W/m^2)**
Typical	Luminaires	9	45	441		
	PC + TFT	1	100	100	1141	**21.9**
	Video projector	1	600	600		
Workshop	Luminaires	12	45	588		
	PC + TFT	1	100	100	1288	**22.2**
	Video projector	1	600	600		

Note: Lighting load estimation neglects ballasts contribution, only T5 lamps were considered.

5.2.2.1 Lighting control in classrooms

During the scholar year 2013/14, the school direction board adopted an occupancy control system (card reader) in the classrooms (buildings A, B and C), which has several features:

- Registration of the entry (teacher and students) and exit time (teacher) in the classroom;
- Automatically turns off the lights after 1–2 min the end of classes: the activation (ON) depends on the teacher (at the entry), the closing does not. If one class extends besides the schedule, as in the case of an examination or if the break period is suppressed between classes (45+45 min), luminaires operation can be restarted by manual switching;
- It ensures that no light will be left on during unoccupied periods. Thus, it aims at avoiding human distraction – the exception might run on the few classrooms occupied in the last period of the scheduled (23:10 – 23:55). This situation is expected to occur rarely: i) only very few classrooms have teaching activity during that period; ii) it is not expected that the teacher extends the last class.

5.2.2.2 Lighting in corridors

Generally, in circulation areas as corridors, the control is carried out area by area, in the correspondent electrical switchboard. Presently, roughly only 25% of the luminaires are left on. This information is consistent with the designation of the emergency lighting.

At the same time, it was verified that the connection between buildings A and B, through the hallway floor -1, was already "calibrated" – the maintenance personnel has already proceed to some *delamping* of the luminaires on the non-emergency lighting circuit. Nevertheless, not all the lighting circuits are optimized.

Commonly, the fixtures in the circulation areas are organized in two circuits. In some cases, it was observed that although there was enough daylighting, some lamps were ON because they were connected to the remaining circuits, representing unnecessary energy consumption. An effort to disaggregate lighting circuits was driven and, a few suggestions were done, in the sense of controlling some of these situations by external lighting levels that could be obtained by daylight sensors.

One of these examples is the main atrium/reception area of the school, whose lighting circuit is connected to the interior corridor of building A. **Figure 46** clearly shows one of the moments in which the these luminaires could be OFF (nine luminaires of 49W/each), i.e. 441Wh of EE consumption could be avoided. This same reasoning was addressed in buildings B and C.

Figure 46 – Foyer / Reception school area

In B, space b-102, designated as *indoor playground* is also equipped with two circuits (corresponding to three parallel rows of luminaires). Assuming that the central line of fixtures (8 lamps T5 49W) does not hold any emergency luminaire, the adoption of a light sensor here is also suggested; since it has good natural lighting conditions – due to circular skylights in this space, 400Wh could be avoided.

In C, a similar situation was found in the corridors: two circuits (one regular and other "security") serve all the 31 fixtures (22 + 9 "security"), **Figure 47**. The lighting circuit begins on the upper limit of space C-104 and ends on the left side of C-102. In the middle is located C-105 circulation area which has natural lighting conditions totally unequal from other spaces (glazed corridor, both on the left side and at the headers). Herein, it is suggested that the non-emergency lighting circuit is disassociated into three circuits, namely:

- C-104 and C-103 (7 luminaires);
- C-105, C-106 and C-107 (9 luminaires);
- C-102 (5 luminaires).

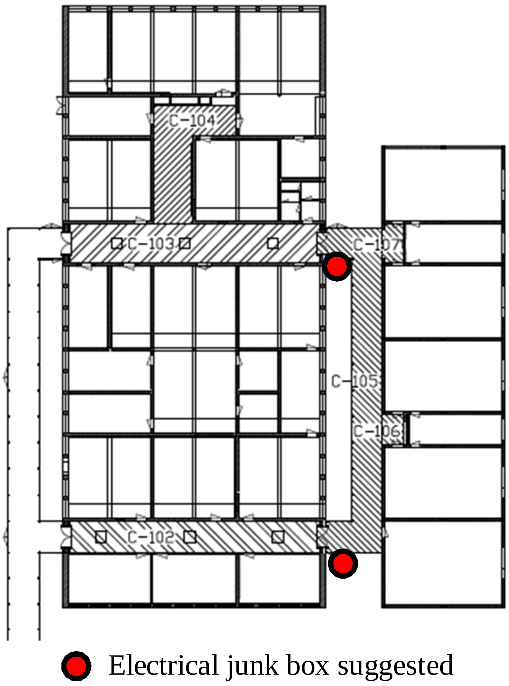


Figure 47 – Building C, Plan -1 floor. Shadowed areas correspond to circulation areas.

In the corridor leading to the Library, some "dysfunctional" situations were found, namely an excessive number of fixtures. In one corridor (a-106), four T5 49W units serve a 10 m path (that has a glazed emergency exit door at the end); by conducting a simple estimation on the illuminance values of this space, it was found a range of 305-326 lux, facing the project benchmark for circulation spaces of 200 lux (in EN 12464 the reference value for traffic areas is even lower [257]). Therefore, delamping in this corridor can also be one possible way of reducing lighting energy consumption.

5.2.3 Human factors

Since building occupants' behaviour can greatly contribute to a buildings' energy use performance. In [258], it is proposed the installation of an interactive poster in an office building, encouraging occupants' behaviours to save energy.

A study on Swiss office buildings, equipped with Integrated Room Automation (IRA) investigates the potential of using occupancy information to implement a more energy efficient building climate control [259]. In [260], the authors investigate through simulation the occupancy based indoor climate control contribution towards energy-efficiency in commercial buildings.

Behavioural issues are not limited to the thermal adaptation indoors. Here, it is defended that human occupancy – based on the classrooms occupancy schedule/time-table, should be integrated in the HVAC system operation/BMS programing.

Besides space occupancy, human behaviour strongly influences energy consumption. One of the examples is the school library. Architecturally, it works as an independent rectangular glass box, developed according to the N-S axis. The lighting installed power is almost 1700W (lighting density of approximately 8.9 W/m^2). This operation system is locally controlled by the responsible of this space. Strongly illuminated with natural light from E and W, lights are frequently turned ON because curtains are down to prevent glaring. Because sun does not face East and West simultaneously, more careful behaviours should be implemented, since different lighting circuits allow turning E and W luminaires at different times. Moreover, since this space is not always full occupied, conducing students to a smart action suggesting their seating positions could also be a simple gesture.

5.2.3.1 Technological illiteracy or simple sins of omission

In [261], the authors explore through simulation the impact of a special proactive strategy in order to reduce energy consumption in a three-storey university building. Besides lighting and temperature adjustment to "predicted occupancy and occupant preferences based on occupant schedules", e.g. the coordination of meetings, "originally scheduled in 3 different thermal zones, were investigated for relocation". This control strategy revealed improvements both in terms of occupant comfort and reduced energy consumption during times of peak occupancy.

Herein, the suggestion is that classes lectured in building A, e.g., could be grouped accordingly to their corresponding AHU. This approach would be greatly effective especially during night-time classes; since these correspond to special education programmes and have a reduced number of students (fewer classrooms are occupied). This zoning opportunity could also take advantage on the fact that AHUs zones are north and south distributed, therefore solar gains and consequent heating/cooling benefits might emerge.

Relating IAQ and given the current SCE [82], previously presented, it is suggested an occupancy break approximately at half of the daily period (8:00–18:00). Promoting a room vacancy contributes to the dilution of the pollutants load, either through the space exfiltration due to windows cracks or opening operation. In a simplified mode, it is expected a natural decay of the CO_2 concentration due to the non-occupancy, thereby reducing the CO_2 peak concentration and AHUs use during this interval. If this strategy is applied, significant improvements of the IAQ in the classrooms are expected by “simply” increasing the air exchange rate (in a non-mechanical way). This action is particularly more effective during the mid-seasons: pre-heating and pre-cooling. This should be considered whenever the outdoor climate conditions are favourable to interior spaces, e.g. if the outdoor temperature is high, hot air infiltration will contribute to the students’ discomfort after this interval – in this case windows should not be opened.

From the EE monitoring some other conclusions were driven. From both main low-voltage (LV) and the power plant electrical boards it was possible to check that the BMS ignored holidays (**Figure 48**). During the Christmas holidays season (December 17th 2014–January 2nd 2015), the register showed that some of the AHUs serving classrooms were running.

a)

b)

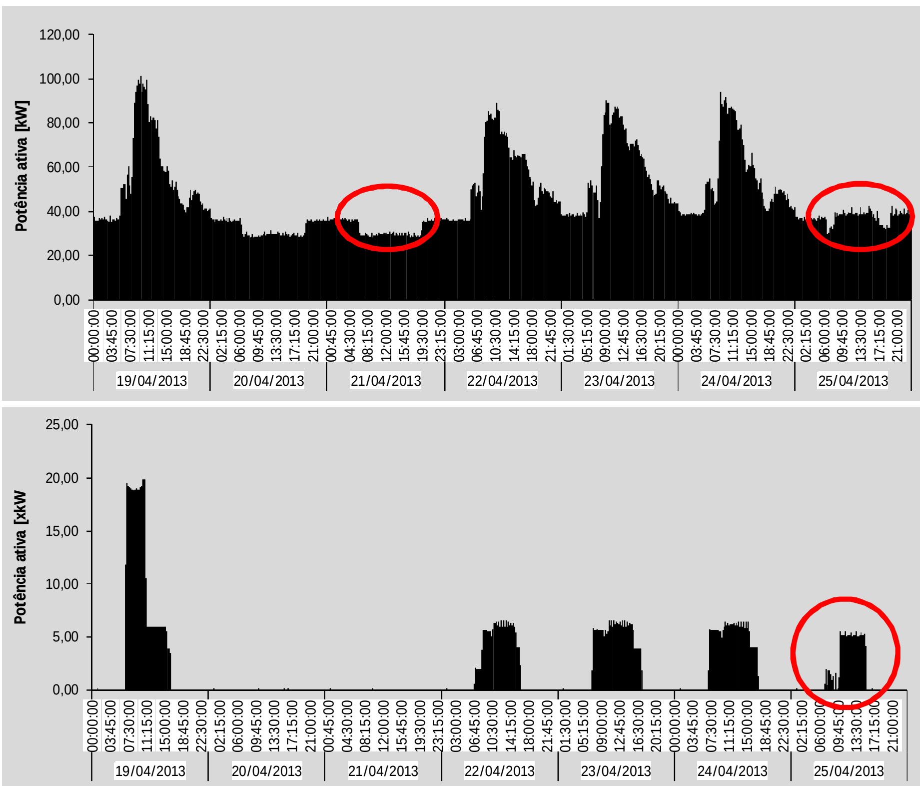


Figure 48 – Load diagrams obtained during EE monitoring, 19th April – 25th April 2013; a) Main LV Board; b) Thermal power plant electrical board.

5.2.4 Potential energy savings

In terms of HVAC systems, immediate and quantifiable energy savings are expected due to two premises:

1. Adjusting AHUs fresh air flows to the current legislation requirements.
2. Readjusting AHUs schedule to the classrooms/spaces real occupancy (also attending the EE supply contract);

Other savings might also be expected if attention is driven towards lighting.

5.2.4.1 Ventilation requirements readjustment

Indoor air quality is guaranteed, in this school, by mechanical ventilation. AHUs are used to supply fresh air, at the room conditions (temperature and eventually humidity), or at certain conditions that will provide the desired temperature and humidity set points. In the first case, as it happens in the classrooms, thermal loads are suppressed by terminal units, such as hot water radiators (only used, of course, for heating conditions, at 20ºC). Nevertheless, some heating capacity is due from a temperature difference between the outdoor air entering the AHU and the supply air into the room.

Based upon these considerations, an excel tool has been developed [113], aiming at estimating the heating energy demands of the AHUs serving classrooms during an entire scholar year, *i.e.* the integration of the computed heating transfer rate over the considered period of time – this tool was mostly rooted on *The 2013 ASHRAE Handbook of Fundamentals* [262]. This working file includes the integration of an energy plus weather file that may vary according to the building site. Therefore, the energy estimations account on the supplied air temperature difference, between the outside air temperature and the 20ºC supplied air during the occupancy period. Some results obtained from this simulation tool are presented in **Table 28**. School breaks, holidays and the three vacation periods (Christmas, Easter and summer holidays) were taken into account in the simulation time-schedule.

Table 28 – Energy consumption of the AHUs serving classrooms and the library (thermal heating energy)

AHU ID	Area served by AHU (m^2)	BMS present schedule	annual operation time (h/yr)	Energy consumption (kWh)		Energy Ratio
				Q existing	Q proposed	Qp / Qe (%)
AHU A2	411.5	05:00 – 20:00	2250	28053	21340	76.1
AHU A3	364.6	05:00 – 20:00	2250	26471	21340	80.6
AHU A4	524.3	05:00 – 20:00	2250	35965	28772	80.0
AHU A5	521.5	05:00 – 20:00	2250	35965	28772	80.0
AHU B1	292.9	06:00 – 20:00	2068	15605	12442	79.7
AHU C2	514.1	06:00 – 17:00	1689	23676	19455	82.2
AHU C3	281.6	06:00 – 17:00	1689	18170	15967	87.9

Note: for the present calculation pumps' electrical energy consumption was not considered. In CAV systems their contribution is very small when compared with the fan component.

From this simple estimation, the adjustment of the fresh airflow rates of these AHUs to the current legislation requirements might lead to decrease of 35817 kWh /yr of the useful energy in the thermal heating energy of the air supplied into the classrooms (38932 kWh /yr in terms of final energy if considered the 92% efficiency of the boilers – that work alternately). In practice, as the fan power is a cubic function of Q [117], a Q reduction of 20% in the air volume (in the scenery of the prescriptive method – **Table 26**) results in an approximate 50% decrease of the needed fan power. Leading to a remarkable reduction of the installed electrical power and consequently an extension of the energy consumption decrease.

Since AHUs serving classrooms in building A, namely A2, A3, A3 and A4 have electronic variable-speed (EVS) drive that can be controlled by the BMS, adjusting the airflow rate in this AHUs can be immediate and at negligible cost.

On the other hand, AHUs B1, C2 and C3 have constant velocity fans, for which some changes in the equipment have to be done, namely fixed pulleys need to be replaced for fan speed regulation. In this case some investment is required – a budget of 320€/each (price without VAT) has been proposed by a HVAC installer. From the energy estimation presented in **Table 28**, through a rough approximation on the energy cost savings, assuming an average price 0.12 kWh, it is expected an annual saving of more than 4600€, that in terms of a simple payback period estimation, would mean that these changes may pay for themselves in less than four months, this without accounting the monthly decrease on the electric energy bill.

5.2.4.2 BMS rescheduling

Improving energy efficiency in buildings does not necessarily mean reducing energy costs. For the present simulation it is suggested an improvement on the BMS scheduling. i.e. changing AHUs operation time in accordance with the rooms occupancy and the EE contract. The initial difference is the morning kick-off; instead of 6:00, it is suggested delaying this moment to 7:00 and 7:30, differing AHUs start in buildings A, B and C. The other variation, deals with the night-time operation of the AHUs serving classrooms with late occupancy, aiming at improving IAQ in those rooms.

Table 29 unveils the crucial role of the BMS, strengthening our suppositions in **section 5.1.2 BMS control**. By simply adjusting the BMS schedule, the thermal heating energy consumption of the AHUs might decrease up to 67.4%.

The total amount of energy potentially saved, just within these 7 AHUs, exceeds 37000 kWh annually (41128 kWh /yr final energy, 14.1 kWh/m^2) – 20% less facing the current state. If this strategy is operated in conjunction with the new fresh air requirements, in some AHUs the energy might fall almost 50% of the current energy consumption. Herein more than 66000 kWh (71864 kWh/yr final energy, 24.7 kWh/m^2) could be saved annually, representing a decrease of 36% facing the actual energy consumption of these 7 AHUs.

Table 29 – Energy consumption of the AHUs serving teaching rooms (thermal heating energy)

AHU ID	**BMS suggested schedule**	**Annual operation time (h/yr)**		**Energy consumption (kWh)**			**Energy Ratio (%)**	
		Existing schedule	Suggested schedule	Existing schedule	Suggested schedule	Suggested Sched + Proposed Q	Between schedules	Between existing sched & new sched + proposed Q
AHU A2	07:00 – 18:00	2250	1626	28053	18913	14387	67.4	51.3
AHU A3	07:00 – 23:00	2250	2352	26471	24845	20029	93.9	75.7
AHU A4	07:00 – 18:00	2250	1626	35965	24248	19398	67.4	53.9
AHU A5	07:00 – 23:00	2250	2352	35965	33757	27006	93.9	75.1
AHU B1	07:30 – 18:00	2068	1535	15605	10856	8656	69.6	55.5
AHU C2	07:30 – 18:00	1689	1535	23676	18925	15551	79.9	65.7
AHU C3	07:30 – 18:00	1689	1535	18170	14524	12764	79.9	70.2

Note: for the present calculation pumps' electrical energy consumption was not considered. In CAV systems their contribution is very small when compared with the fan component. The existing schedule is presented in ***Table 28****.*

5.2.4.3 Lighting

The current lighting control solution in classrooms is a saving energy strategy. From the simplest energy consumption point of view, since they are turned off by the end of each class period (45 min), it potentially results in a daily 130 min spare of energy consumption, regarding the daily maximum occupation of these spaces, **Table 30**.

The question arising from this option, is the exponential increase number of cycles of the luminaire – thirteen (13) for both lamps and ballasts; in contrast, for example to only two or three cycles, with the system being turned off during the lunch break, and by the end of the daily and nigh classes, 13:00, 18:00 and 23:45, for example. The current option affects both the lifetime of the lamps as well as their luminous flux.

Table 30 – Summary of class breaks

Class schedule	**Break time between classes (min)**
8:15 – 9:05	5
9:10 – 10:00	15
10:15 – 11:05	10
11:15 – 12:05	5
12:10 – 13:00	15
13:15 – 14:05	5
14:10 - 15:00	10
15:10 - 16:00	15
16:15 – 17:05	5
17:10 – 18:00	0
Subtotal	**85 (1h25min)**
19:00 – 19:50	15
20:05 – 20:55	10
21:05 – 21:55	5
22:00 – 22:50	5
22:55 – 23:45	0
Subtotal	**45**
Total	**130 (2h10min)**

This concern is further illustrated through the technical product information of the *T5 Ecosaver Aura Long Life* (in theory 10% more efficient than standard T5). The product brochure presents its own comparison: 3h-switching cycle[9] (2h45min ON and 15min OFF)

[9] Service life of the lamp failure rate and the lumen depreciation is calculated based on a 3-hour operation switching cycle according to IEC/EN 60081.

with 12h-switching cycle (11h ON and 1h off). Between the two options, the lamp in the first situation faces a decrease of almost 19% of the operation/life-time.

In the current situation of the school a higher operation/life-time decrease might be expected due to the greater number of cycles (9 cycles just between 8:15 and 18:00).

Given this information, and considering that it has not been carried out a quantitative study facing the lighting system in these classrooms, it is suggested that special attention is given to these, e.g. keeping a register of the frequency of lamps' replacement. In case it is verified a shortened period of time, it would be suggested, increasing the number of switching cycles, helping to increase the lamps' lifetime and reduce equipment and maintenance costs.

5.3 Replication of the proposed approach in MMV

The secondary school building located in Montemor-o-Velho has been previously presented in section **3.2.1**, as well as its physics and main systems. In section **3.2.9.2** its main power systems have also been described (ITC, lighting and solar panels for DHW). Complementary information is presented in the following sections.

Concerning the school population, between 2008/09 and 2011/12, it was verified an increase in the teaching personnel of about 6.6%, while it was verified a decrease in the number of students (34.7%), corresponding to 317 students in the scholar year 2011/12. As regards the energy and IEQ audit and, as presented in [196], in terms of the energy use indicator (EUI) considering a gross floor area GFA = 8326 m^2, EUI = 43 kWh/m^2. If only the TUFA (7172 m^2) is considered, EUI increases to 50 kWh/m^2. Considering the number of students of academic year 2011/12, the EUI (kWh/student) corresponds to 1128, almost MTS's double.

Alike MTS, this school consumes both EE and NG. The EE contracted power of 372 kVA supplies electricity according to the same tariff – Medium Voltage. In 2011/12 NG accounted for 22.2% of the total energy consumed. This value is quite close to the 3Es group of schools' average values: 76% EE vs. 24% NG [196], but significantly lower than MTS's were thermal energy production in classrooms is assured through warm watered radiators.

Renewables in this school cannot be considered in this analysis since the 32 panels' system on top of the Gym (more than the double of MTS's DHW capacity) was not operating during the period of this study (they were only "reactivated" in January 2015 when the school was attributed a new maintenance technician). Hence, NG consumption numbers relate DHW production and meals' production in the industrial kitchen (during the scholar year 2011/12 over 9900 meals were prepared). DHW is consequently prepared in two different locations: in the canteen and in the gym (1+2 boilers, 96.5 kW/each). In the latest, warm water production serves both DHW and heating of indoor environment.

As previously stated, this school thermal energy production follows a decentralized heating/cooling strategy – each building has its own acclimatization system (type VRF with internal and external units) and ventilation unit (HRU). The main characteristics of the units serving the school, controlled by the BMS, are next presented in **Table 31** and **Figure 49**.

Contrarily to MTS, in MMV there is not a computer network management system programed to shut down the computers or projectors (30.5 kW installed power in total).

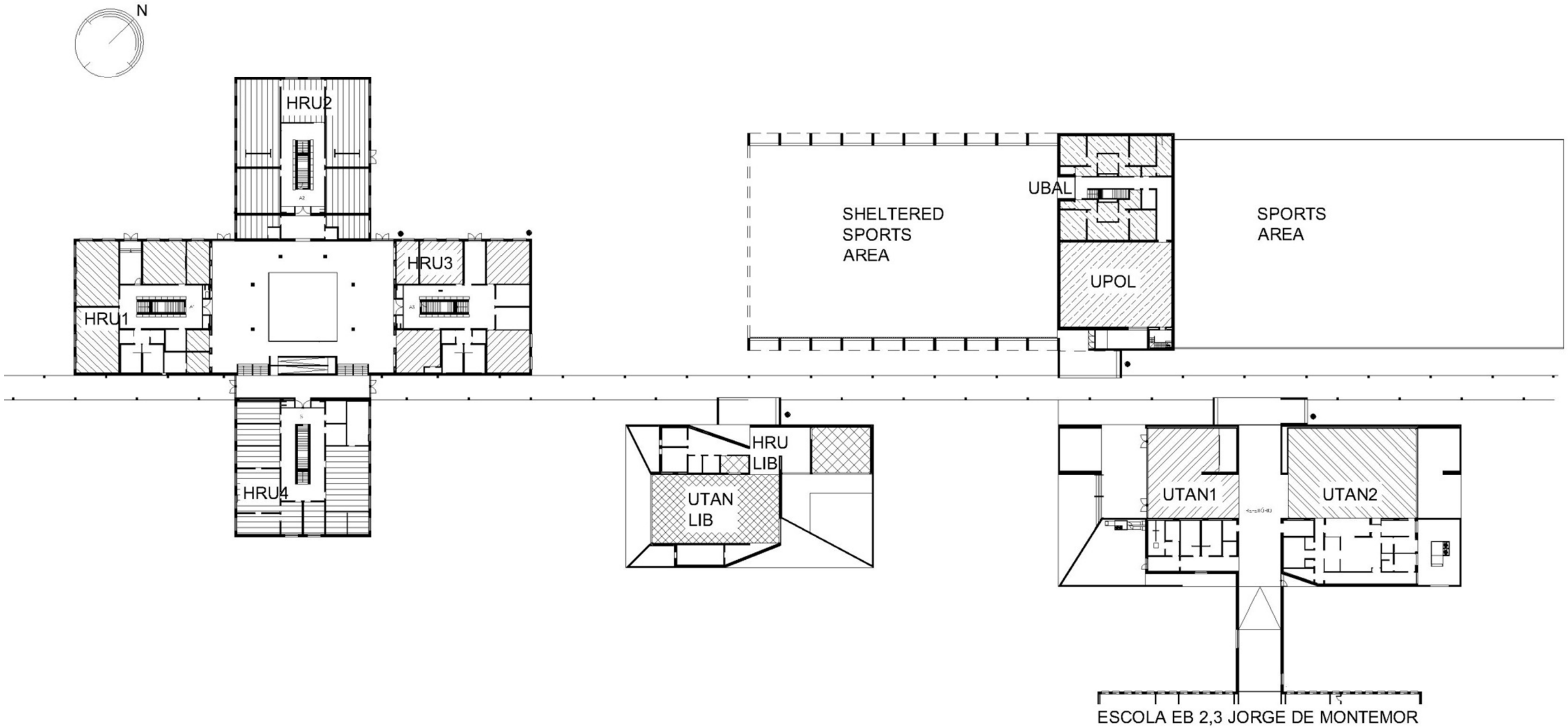


Figure 49 – Simplified floor plan (level -1) of the various school buildings in MMV (A1 – S, Lib, Gym & Canteen) and main thermal zoning

Table 31 – Main characteristics of the VRF and *rooftop* units in MMV

HVAC system	VRF			Rooftop		
Building	**S**	**A1 & A2**	**A3**	**Canteen**	**Bar / Cafeteria**	**Library**
Power (Heat./Cool)*	9.60kW / 9.58kW	11.6kW / 7.75kW	11.6 kW /11.6kW	19.94kW / 21.9kW	8.45kW / 9.2kW	6.79kW / 7.2kW
Quantity	2	4	2	1	1	1

Note: Absorbed electric power*

5.3.1 BMS operation and scheduling – HVAC and lighting

In contrast with MTS, the indoor climate of each classroom in MMV can be controlled independently – each zone consists of a single room, therefore designated as "fully activated" [253].

From the BMS, mainly designed to control the HVAC systems and lighting, it is possible to check the main HVAC systems status, but not "manoeuvring" all of them. Relating the main teaching and administrative buildings (A1 – S), only the HRUs, and some extraction fans, may be enabled/disabled through their operation time. For this reason the BMS is complemented with a software package from the manufacturer (Sanyo). In this, each classroom's Ta might be individually controlled – by setting Ta set points at each internal unit of the VRF system that is serving the classroom (nevertheless, the school has opted by blocking each building classrooms' Ta). Building S – that holds the main administrative areas – is given total fan velocity and Ta autonomy.

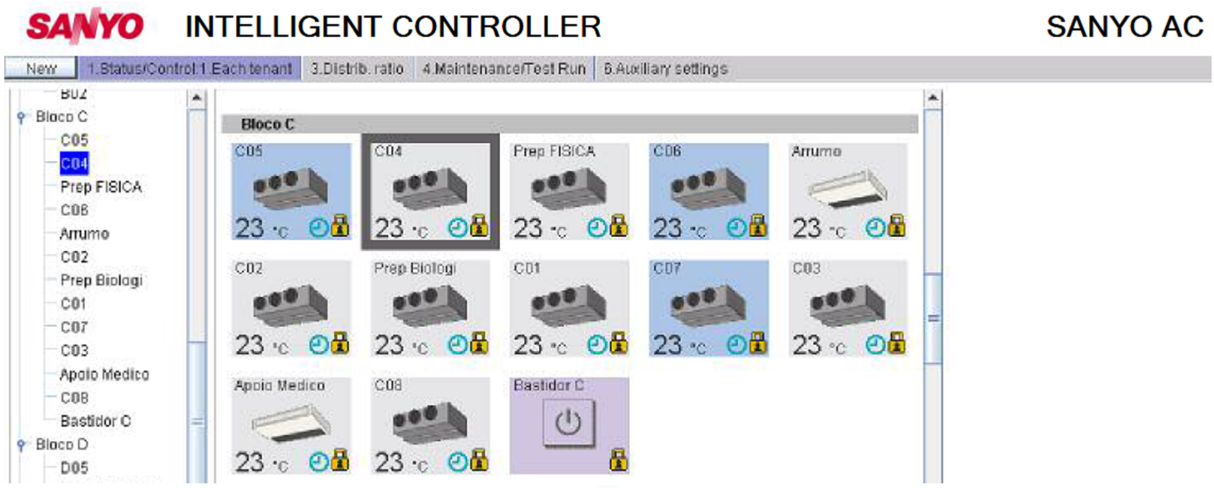
Table 32 presents a synthesis of the school's main HVAC systems scheduling. This BMS only allows a weekly agenda. It is not possible a monthly scheduling or holiday data integration. Lighting scheduling is presented in the coming sections.

Table 32 – MMV | Main automatic systems operational time (Monday – Friday)

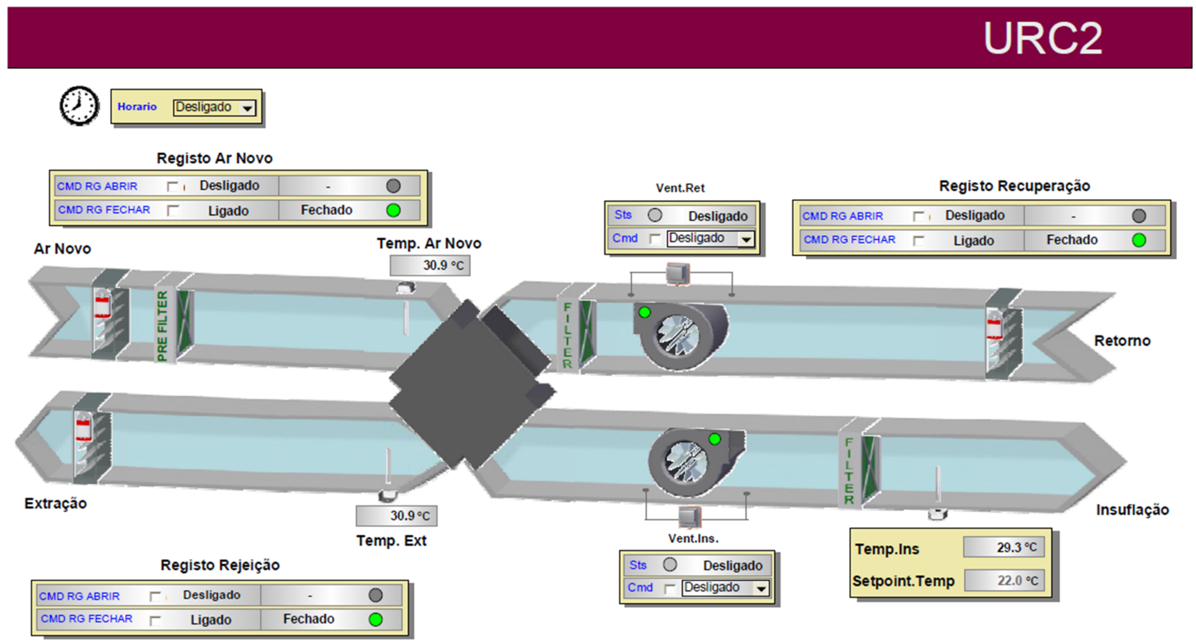
System	Naming	Start (am)	Finish (pm)	Space	Building
HRU	URC1, URC 2, URC 3	07:00	08:00	Classrooms/laboratories, ITC rooms	A1, A2, A3
		10:00	10:30		
		13:00	13:30		
		17:00	17:30		
HRU	URC 4	Data unavailable		Administrative / staff	S
AHU	UPOL	10:30	11:00	Multipurpose room	Gym
		15:00	16:00		
AHU	UBAL	09:00	12:00	Locker rooms	Gym
		14:00	16:00		
Extraction Fan	-	Various schedules		Bathrooms / Kitchen area/ Technical rooms	Various
Boiler	G_CLD	06:00	20:00	Multipurpose room / Locker rooms	Gym
Boiler	R_CLD	Always active		Restaurant / Dining area	C
Chiller	R_Chiller	08:00	16:00	Restaurant / Dining area	C
AHU / Rooftop	UTAN 1 *	12:00	13:00	Bar	C
AHU / Rooftop	UTAN 2 *	12:00	13:00	Restaurant / Dining area	C

Note: Not directly controlled from the BMS, locally controlled in the nearest technical area. All the remaining equipments are controlled from the BMS and complementary software program.*

As stated before, in some internal units' (IU) – part of the VRF system, air temperature (Ta) is blocked on the software package complementary to the BMS. One of these situations is presented in **Figure 50**, corresponding to building C (also designated as A2). In this figure, besides being shown the graphical interface software package of the manufacturer, it is also displayed a detailed view module of the HRU, serving the same building, controlled from the BMS.



a)



b)

Figure 50 – Space investigator of the graphical interface provided by the manufacturer. Detailed information on Building C (A2), a); Detailed view module of the HRU 2 (the unit serving building C) on the BMS, b).

5.3.2 Fresh air flow rates readjustment

Alike MTS, also MMV's HVAC systems were designed in accordance with the precedent legislation. For this reason they are equally oversized. Besides *rooftop* units serving the bar/canteen and library, all the other spaces are oversized relating the current legislation requirements. **Table 33** presents a summary of the new fresh air flow rates requirements for each space/equipment, estimated upon the prescriptive method, as referred in **section 5.2.1.3**.

Table 33 – Summary of the schools' equipments and corresponding fresh air flow rates (Q) into various spaces

Space/ Building	Equipament / System Designation	Existing Q (m^3/h)	New Q (m^3/h)	Ratio (%) new Q / Project Q	Comments (values include 0.8 coefficient – ventilation system efficiency system ε_V, as shown in the descriptive document of the project, new Q values prescribed in [213])
Multipurpose room (Gym)	AHU	9600	2200	23	Estimation based on 35m³/ occup., nº 50
Reading area (Library)	Rooftop / AHU	2625	1750	67	Estimation based on 20m³/ occup., nº 70
Meeting area & management room (Library)	Mini VRF	1580	1260	80	Estimation based on 24m³/ occup., nº 40
Bar/Cafeteria	Rooftop	3500	2800	80	Estimation based on 28m³/ occup., nº 80
Canteen	Rooftop	10500	8400	80	Estimation based on 28m³/ occup., nº 240
A1/ Classrooms	HRU1	9415	7530	80	Estimation based on 24m³/ occup. [213], nº 26
A2/ Classrooms & laboratories	HRU2	9200	8290	90	Estimation based on 24m³/ occup., nº 26 (classrooms) & 35m³/ occup. [213], nº 17 (labs)
A3/ Classrooms	HRU3	11530	9620	83	Estimation based on 24m³/ occup., nº 26
S	HRU4	7305	4870	67	Estimation based on 24m³/ occup. for offices and 28m³/ occup. for the teachers' room

Generally, total suggested $Q_{MMV} > Q_{MTS}$ in classrooms since at the project phase, in MMV it was defined a ventilation efficiency (ε_V) equal to 0.8; therefore, Q_{MMV} for classrooms is circa 30% higher than Q_{MTS} (Q values estimated for MTS).

More detailed recommendations on how these Q changes might be achieved are presented ahead. Contrarily to MTS, in MMV the *all-air systems* were conceived to simultaneously supply fresh air and acclimatize indoor spaces – for this reason, Q cannot be simply "cut", otherwise, occupants comfort could be compromised.

5.3.3 Lighting systems

As in MTS, motion detectors were considered both in bathrooms and cloakrooms serving the shower rooms. Nevertheless, during our visits, the doors in these spaces were frequently halted, corrupting the sensors control, "activating people presence" even in their absence. This was verified in person at least in two different situations: in the bathrooms serving the

Cafeteria and *Dining area*, and in the cloakrooms in the *Gym*. Naturally, this situation does also compromise the mechanical ventilation system operation.

In MMV, T5 fluorescent lamps represent 69% of the total lighting installed power. In comparison to MTS, MMV classrooms, both "typical" (MMV1 e.g.) and "workshop" (*Sala de oficina de artes* e.g.), present higher power to floor ratios – 26.2 /23.6 W/m^2 vs 21.9/22.2 W/m^2.

Relating the BMS, lighting is only partially controlled. In fact, the information presented in **Table 34**, on buildings A1-S and the Gym, only regards corridors (levels 0 and 1). The time operation is defined as *Always active* since the circulation areas are also provided of twilight sensors. A3 schedule had been temporarily changed because it was verified that some cells were broken and were waiting to be replaced. The Library schedule corresponds to the time occupancy of this space.

Table 34 – MMV | Lighting systems operational time (Monday – Friday)

Naming	Start (am)	Finish (pm)	Building
A1_QP01_ ILUM_hor	Always active		A1
A1_QP11_ ILUM_hor	Always active		A1
A2_QP02_ ILUM_hor	Always active		A2
A2_QP12_ ILUM_hor	Always active		A2
A3_QP03_ ILUM_hor	07:00	21:00	A3
A3_QP13_ ILUM_hor	07:00	21:00	A3
S_QP10_IL_EXT_hor	Data unavailable		S
S_QP10_ILUM_hor	Data unavailable		S
B_QEB_ ILUM_hor	07:59	18:00	Lib
G_ QP01_ ILUM_hor	Always active		Gym

5.3.4 Improving the use of energy

5.3.4.1 In the Gym

Since in the Gym there are only *all-air systems* without recirculation, the suggestion towards the current legislation requirements, i.e. Q reduction, in the *Multipurpose room* is adding a mixing box with data logging and CO_2 probe (return) – the already existence of these accessories, according to the HVAC project descriptive document, must be confirmed. By reducing 75% of the new fresh air into the system, in theory, at least 75% of the required thermal energy might be suppressed.

Relating the *Shower/locker room* areas, since this is a "dirty" extraction circuit, it is not suggested reintroducing/ recirculating the air (as it is not recommend by EN 13779 – "Toilets and wash rooms, saunas" are classified as ETA3, areas of *Extract air with high pollution* *level* [263]). No information relating this equipment was presented in **Table 33**, therefore assuming that the current Q is maintained, equalizing 4580 m^3/h. Nevertheless, by looking at the descriptive document of the HVAC project it was also verified that this space requirements have been designed according to CNQ 23/93. This legislation is frequently applied to swimming pools. Objectively, 23ºC comfort temperature seems relatively exaggerated since in the current case occupants are not facing the same temperature gradient as in pool areas. Therefore, this unit energy saving potential might be achieved through relaxation of Ta set-point.

Using the excel tool previously presented [113], for the current operation period (**Table 32**), lowering Ta to 20ºC, 14.5% thermal energy savings were estimated for this AHU[10]. Nevertheless, this decision-making can only be permanent after a small experiencing period, aiming at not compromising occupants' comfort. In terms of the time operation period of this equipment, it is already quite diminished (**Table 32**), therefore no suggestion is done in this regard.

From the analysis of the current scheduling of the unit serving the *Multipurpose room*, some other remarks can be pointed out. The unit is active solely half an hour in the morning period and one hour again in the afternoon. The presumption is that the school is operating this unit practically only due to ventilation needs, and not space heating. So therefore, suggesting fresh air flow rates reduction, as initially proposed, might not be the best option. Nevertheless, energy heating estimations were simulated considering the same operation schedule as the AHU serving the *Shower/locker room*. Within this figure, considering 75% air recirculation (Q = 2400 m^3/h, slightly above the Q requirements calculation), 14% of thermal energy might be spared[11]. In this case, may the school direction consider longing this unit operation and improve the indoor conditions, especially during winter period.

A more significant energy conservation action might be rescheduling the boiler. According to the BMS, **Table 32**, it is active from 6:00–20:00. If both spaces in the Gym are unoccupied after 18:00, and there are not thermal necessities justifying this equipment operation (either in terms of space heating or DHW), simply adjusting this equipment schedule in the BMS, will necessarily lead to worthy energy savings.

[10] For simulation purposes the following conditions were considered according the HVAC documents and other gathered data: AHU's absorbed power 0.95 + 0.85 kW (supply + extraction fan power); supply Q = 4580 m^3/h and extract Q = 4655 m^3/h, Heat Recovery Efficiency = 50%. Moreover, a 7ºC air temperature difference was considered between indoor air set point and supplied air. Since this unit is only provided of heating battery, no cooling energy was estimated.

[11] The following conditions were considered: AHU's absorbed power 1.9 + 2.0 kW (supply + extraction fan power); supply air equal to extract air – 9600 m^3/h, Heat Recovery Efficiency = 50%. Moreover, 75% of recirculation air was considered, 7200 m^3/h, . i.e. exhaust air equals 2400 m^3/h.

5.3.4.2 In the Library

In the Library it is proposed a reduction of 33% of the new fresh air flow rates for the *Reading area*. Since this space is served by a *rooftop unit* type air condensation heat pump, the adjustment can be done directly in the equipment, promoting the air recirculation of the supplied area.

By the time this study was performed, it was not possible to assess the library's AHU/ *rooftop* operation scheduling. Considering this space occupancy 8:30–17:30, the suggestion would be an operation period from 8:00–17:00, corresponding to an annual operation time of 1820 h/yr (average fan total n. hours considering a typical school year as in [113]). Since this is also an all-air system, during winter time, due to heating needs the morning kick-off could be anticipated if needed.

The *Management room* and the *Meeting room* area both served by a Mini VRF system (composed of an external unit and two direct expansion interior units, **Figure 51**): for the first space it is proposed a 33% Q reduction (90 m^3/h to 60 m^3/h) while for the second a 20% decrease (1490 m^3/h to 1200 m^3/h). The Q reduction can be done directly in the units' fans and the Q regulation should be done in all derivations and grid dampers, in order to set the desired air flow in every duct branch and room, respectively.

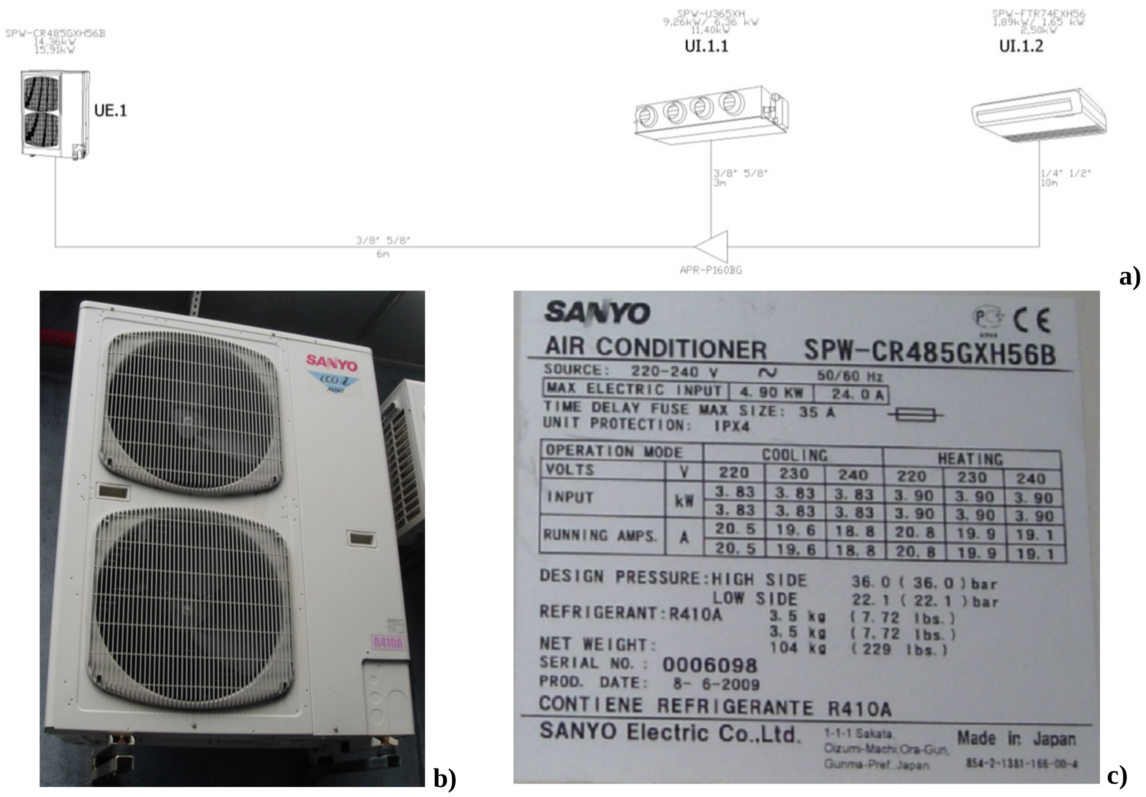


Figure 51 – Library's Mini VRF system. Diagram, a); External Unit – Photo and Technical information, b) & c)

Alike the VRF system in the classrooms' buildings, the Ta of the spaces served by the IUs can be controlled from the BMS. As presented in **Figure 52**, Ta is kept to a lower value than the one considered at the project phase 25 ºC, and below the international thermal comfort standards.

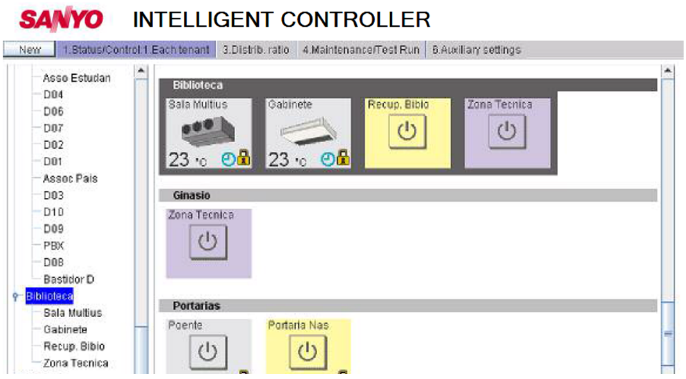


Figure 52 – Graphical interface provided by the manufacturer. Detailed information on the Library' rooms Ta served by the Mini-VRF system.

5.3.4.3 In the Canteen

The Canteen building is composed of two main spaces – the *Cafeteria* and the *Dining area*, provided a *rooftop unit* each (like the *Reading area* in the Library). For both *rooftops* is proposed a 20% Q reduction, **Table 33**. It is worth highlighting that these values would be significantly higher if the ventilation system efficiency (VSE) had been considered 1 and not 0.8 [264] in the project phase (20% vs. 36%).

In fact, due to the temporary occupancy character of each of these spaces, reducing the fresh air flow rates 30% would still probably satisfy IAQ requirements (considering, for example, an operation period 9:00-16:00). Since the *rooftop unit* in the *Dining area* was designed as 100% fresh-air, the volume of air supplied into this space (Q_{supp}) is directly influenced by the fresh air flow rate (Q). Like in the Gym, the reduced operation time of this unit – 1 hour/day (**Table 32**), suggests the unit is operating exclusively for ventilation purposes; once again, under this circumstances, readjusting the fresh air flow rates reduction, as initially proposed, might not be the best decision.

This building HVAC system is complemented with two HRU, serving supplied air both into the bathrooms (by the *Cafeteria*) and the storerooms/cold rooms (by the kitchen area). Therefore, in this case, the attention is addressed to the time operation of these equipments – neither these *rooftop* units, neither the HRU are controlled from the BMS, but from the nearest technical area.

Like in the Gym, an interesting energy conservation action might be rescheduling the boiler, which under the BMS programing, is *Always active*. In terms of DHW necessities, it probably does not need to be operating before 6:00 or 7:00 and might probably be turned off around 16:00, similarly to the chiller. This suggestion, if implemented would reduce this equipment energy consumption by at least 50%, since the operation time is reduced to less than 50% (facing the current 24h daily operation).

5.3.4.4 In the classrooms

The VRFs and HRUs in A1, A2 and A3 serve mostly classrooms and laboratories provided of 100% fresh-air. Each room has its own internal unit.

By applying the new fresh air requirements (Q) in A1, 20% of new fresh air might be suppressed. In A2, Q decrease is only 10% since this building also holds laboratories and for this type of space, the current legislation still prescribes $35m^3/$ (h.occupant). In A3, the new prescribed Q reduction is also not so significant as in A1, 83% of the current value – although this building is mainly occupied with classrooms, there is also a *Cafeteria area* provided of 2000 m^3/h fresh air. As for the *Shower/locker rooms area* in the Gym, air recirculation in this space or Q reduction is not suggested (not recommend in [213]). The attention is driven towards the time operation of this space/internal units. S is the building where major reductions are possible: 33% less fresh air.

Again, it is reminded, the fact that all the Q values now suggested for these four buildings consider ε_V equal to 0.8. If instead of 0.8, ε_V equals 0.9 or 1, the thermal energy savings could possibly increase due to lower Q.

In terms of ventilation requisites, expected energy savings relating these buildings were validated through the simulation tool *Designbuilder* software [111], [265]. The model was developed by Nuno Correia within his MSc Thesis [112]. These four buildings were divided into 40 thermal zones. Alongside the zoning, other input info was added, such as the number of occupants, occupancy density and air change rates. A synthesis of the main input data into the model is presented in **Table 35**. Besides HVAC systems and ventilators, the simulation model also considered the internal loads of electrical equipment and lighting.

For simulations purposes, besides the main vacations periods (summer school holidays, from August 1st until September 14th and Christmas holidays, from December 21st until January 1st), the three day Carnival break and Easter holidays (one week break), were also considered, aiming at approximating to the real needs of the school. The HVAC systems profile was considered equal to the occupancy profile, previously presented (MMV was refurbished aiming at receiving 11-18 year old students, 5 days/week from 8:30–17:55 maximum daily occupancy).

Table 35 – General data input of the school simulation model [117]

Area (m^2)	Ceiling height (m)	Roof	External walls		Glazing	
		U [W/(m^2.°C)]	Insulation Position	U [W/(m^2.°C)]	Solar factor	U [W/(m^2.°C)]
5052	3.74 / 4.04 / 4.74	0.62	Outside	0.48	0.56	2.84

Infiltration rate (h^{-1})	Temperature set point (ºC)		Efficiency		
	Winter	Summer	Ventilation (%)	Heating*	Cooling**
0.5	20	25	80	4.1	3.66

Note: The nominal datasheet COP was used.*
*Note**: The nominal datasheet ERR was used.*

Considering the current legislation, by the prescriptive method, the fresh air flow rates (Q) reduction, resulted into 7% decrease in the annual energy consumption of these buildings. Admitting Q calculation by the analytical method [213], the reduction relating the project values (baseline simulation) was even bigger – 42%; which resulted in a more significant annual energy decrease relating the prescriptive method, since the cooling and heating needs are smaller, and also the fans' power. By using this method, changing Q according to the current legislation requirements, energy savings of 12% could be expected. This is to say that the Q difference between the two calculation methods is translated into 5% energy consumption difference.

In the light of these figures, the suggestion towards Q adjustment is operating directly the HRUs placed on the roof of each building – since they are VSDs provided (by placing pulleys or substituting belts) – the already existence of these accessories, according to the HVAC project descriptive document, must be confirmed. Secondly, attention should be paid to the internal units (IU) serving each room – since most of IU velocity equals 1000 m^3/h, the immediate consequence is that these will "pick the air" somewhere else. Therefore, the resolution might be:

- Limiting the maximum velocity of each IU in line with Q for each room (this action may be taken in the control unit of the outdoor unit or in the local control of the IU) – what might drive some consequences into the thermal power of the IU, and consequent comfort indoors ;
- Ideally, introducing some air recirculation. By looking at the return air and the classroom temperature, it is possible to gauge the ideal supply temperature, avoiding overheating the spaces. The IU temperature globe control is performed by the local controller and not in the return air to the machine.

By looking at **Figure 53**, captured on June 9th 2015, this proposal finds expression very easily: although by the time the *print screen* was captured, the HRU was off (12:00), it is accurately seen that the external temperature 33.1ºC would highly influence the supplied air temperature into the IU (29.1ºC) and therefore the classrooms air temperature. Basically, if less (hot) fresh air gets the IU (considering more air is recirculated) the IUs cooling requirements are reduced. This situation is even more determinant since the IUs are not constantly working (please see the IUs' scheduling in **Table 32**).

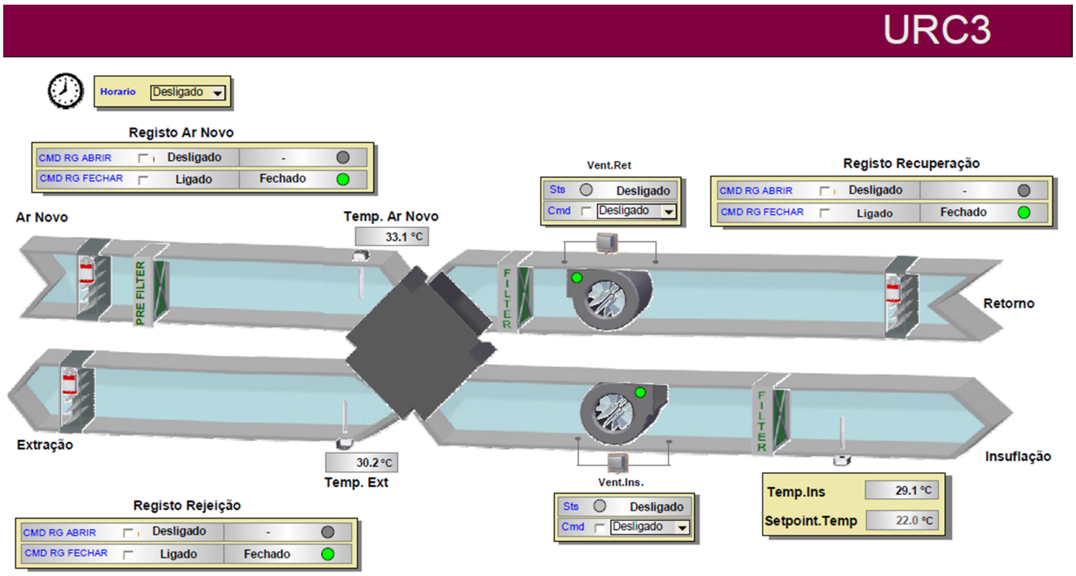


Figure 53 – Detailed view module of the HRU3 in the BMS.

Alongside the potential reduction of the fresh air flow rates, it is important reminding that at no case, IEQ should be compromised. Therefore it is urgent remembering **section 4.2,** were the 3Es schools' IEQ conditions were exposed. Alike the majority of the monitored classrooms, CO_2 concentration values in MMV were significantly high and not complying with the safety and recommended values from the legislation. This was mostly due to the systems non-operation time. In this case, as in the Gym, proposing reducing Q only makes sense if the system's operation time is enlarged.

Looking closer at data, it was observed that the peak concentration values were mostly achieved around 10:00 or between 11:30 and 12:00. This is due to the classroom occupancy scheduling (morning breaks at 10:00–10:20 and 11:50–12:00) and due to the fact that during the morning class occupancy period the HRUs are only turned on between 13:00–13:30. In fact, the current HRU programed scheduling, totally misses the classrooms' occupancy (**Figure 54**).

Since the IEQ monitoring unveiled the classrooms capacity of CO_2 removal during night-time (**Appendix D.1**), the morning kick-off is due to room heating/cooling, more than to ventilation (even if during an unoccupied period). Therefore, the gap arising from the early stop operation at 8:00, before the first morning class at 8:30 is not very understandable. Likewise, there is not a particular benefit for occupants in activating the HRUs between 10:00–10:30: this would be more useful during the last half an hour before the class break at 10:00. Again, during the afternoon, the activation of the equipments between 17:00–17:30 is also not very effective. First, most classes end at 16:15; secondly, since afternoon classes initiate at 14:45, by 17:00 the classroom has been occupied for more than two hours without no air renewal (considering no window is open), being therefore preferable, anticipating this fourth activation moment.

Anoletivo: 2012 - 2013

Tempos	Segunda	Terça	Quarta	Quinta	Sexta	
						07:00 – 08:00
08:30 - 09:15	Mat A / A.11C	Mat A / A.11A	Mat A / A.11A	Mat A / A.11C	Português / A.12A	
09:15 - 10:00						
10:20 - 11:05	BioGeo / A.11C	Português / A.12D	Mat A / A.11C	Português / A.11C	Mat A / A.12A	10:00 - 10:30
11:05 - 11:50						
12:00 - 12:45		Mat B / A.12D	Inglês / A.11C	Mat A / A.11A		
12:45 - 13:30						13:00 - 13:30
13:50 - 14:35						
14:45 - 15:30	EMRC / A.11C		Inglês / A.11A		Inglês / A.11C	
15:30 - 16:15						
16:25 - 17:10						
17:10 - 17:55						17:00 - 17:30

Entrada em vigor: 01/10/2012 Data de Validade: 31 de Agosto de 2013

Figure 54 – MMV1 classroom occupancy time-table (accompanied by HRU 3 operation schedule – in red)

In resume, the current operation time of the HVAC systems (2h30min/day in total) is not enough to comply with IEQ legislation requirements. From the monitored data, previously presented, it was verified that IAQ problems are more significant than TC. Readjusting the HRUs operation as suggested will probably help improving the obtained results. Moreover, in case the school opts by an almost continuing schedule, as 8:00–13:30 and 14:45–17:00 for example, reconfiguring Q values according to the new ventilation requirements might contribute to a better IEQ condition at reduced energy costs than initially foreseen.

5.3.4.5 Lighting systems and other loads

As shown earlier in **Figure 4**, lighting in the USA schools accounts for 14% of the average energy use profile. Besides, according to *Summary of Daylighting In Schools: Reanalysis Report* [266] it is suggested that daylighting improves learning up to 21%. This means that "nonenergy benefits may in fact be dominant project drivers in situations where energy costs are less important to the bottom line" [176].

In the present case study, within the simulation model of this school [112], the lighting energy use represented a more significant share of the energy consumption, more than 30%. Based upon this basis, an energy efficiency measure designated as *Daylighting* was simulated, consisting on the "installation of daylighting sensors in classrooms for control of artificial lighting depending on the availability of natural light, i.e., artificial lighting is only switched on when needed or when sunlight is not enough" [267].

The simulated implementation of 17 illuminance sensors in the classrooms suggested a 5% reduction of the annual energy consumption, being more noticed from March to October, when the daily number of sun insulation hours is higher. Estimating a "simple payback method, by averaging the kWh price in different daytime tariffs, it was obtained a payback period of two years and seven months" [267]. The energy savings are in line with those in [176]. In the *Advanced Energy Retrofit Guide*, the authors encourage the installation of photo sensors and ballasts with dimming system to maximize the potential of natural lighting. This simulation exercise, in spaces such as classrooms, suggests energy saving of 2.5–4.5%; nevertheless, a much longer pay-back period is suggested, nearly 40 years. The difference might be due to the opted system and its costs. In [112], no dimming solution was considering, just illuminance sensors, ON/OFF.

Hence, since the school was recently refurbished and no additional expenditures are foreseen, maybe the efforts should be drawn towards reducing artificial light and use behaviour. Naturally, this campaign should be specially driven towards the teaching personnel, the decision making inside classrooms. Triggering mechanisms as training or awareness campaigns among teachers for the maximum use of natural lighting is fundamental to promote behaviour patterns change.

As previously stated, in MMV unlike MTS, there is not a computer network management system programed to shut down the computers or projectors. Hence, some improvements could also be addressed to this issue, minimizing the human negligence impact factor on energy consumption.

Relating the bathrooms extraction fans, different schedules were found, but not differing much between them. Most are activated at 8:00 and end functioning around 17:00. More unusual and not so understandable is the variation on the technical rooms extractors' schedule: in A1 it operates from 08:00–18:00, in A2 from 09:00–17:30 and in the Canteen area from 08:00–20:00.

5.4 EEP draft document

The understanding of an EEP for a school building is that this handbook of good practice relates to energy management as an emergency plan to fire safety in buildings. Likewise, this EEP should be the buildings' operator responsibility.

Making the analysis of a school building as an energy system, six main components are found: building envelope; HVAC systems; lighting, electrical equipment and installations; local energy production; occupants. Therefore, an EEP for a scholar building is based on two main drivers: physical/monitoring conditions/parameters and a formation/educational component. It can be defined as the systematization of a set of proceeding rules, aimed at controlling energy expenditures and limiting the consequences of uncontrolled/abnormal consumption, optimally managing the resources, both material and human. It is thus an important preventive and operational management tool, since it establishes the means to deal with energy related data, when to set-up the maintenance plans[12], monitor/register energy consumption and assign missions/activities.

This document is supposed to be dynamic and should be adjusted to every school at the beginning of a scholar year, particularly when there are changes in the school functioning – e.g. the provision or cancellation of night classes. In a simplified way, these changes will require the HVAC systems and lighting rescheduling, O&M practices, etc. from the previous scholar year.

Related to the EEP there is the S–EPC (School – Energy Performance Certificate) to be fixed in appropriate location (in the school main entrance for example) – section **5.4.3**. Although the EEP is especially driven towards the school community, this S–EPC, which is part of the EEP, makes possible the transmission of information in the energy field, not only to the people that regularly attend the school, but also for any visitor or person outside the school community.

Finally, this EEP should be headed by an energy manager (EM) **– section 5.4.2**.

[12] These maintenance plans have already been defined at the consignment/construction phase. The warranty of the equipment actually depends on the compliance of these plans.

5.4.1 The EEP outline

The contents of this handbook should have several sections, as follows:

- School overview

  E.g. general information on the school spatial distribution, school population, types of energy consumed, energy contracts and characterization of the main systems and equipments that consume energy;
- Energy Manager functions (**section 5.4.2**)

  E.g. promoting EE monitoring campaigns and analysing load diagrams (e.g. checking if there are unnecessary loads during unoccupied periods, such as weekends or holidays);
- Energy Auditing

  E.g. school systems operation & maintenance procedures /frequency & registration;
- Energy efficiency measures (EEM) addressing:
  - Systems operation (e.g. changing set points, routines/scheduling, control methods)
  - Behaviour (e.g. promoting behavioural change of students, teachers and staff)
  - Potential Investment (e.g. introducing changes in the buildings/systems or purchasing new equipment).

Table 36 presents more detailed recommendations and actions for potential follow up. The measures based on [176], namely their payback period, refer to two of the cities in USA's located in the climate zones[13] 3B and 4C, the closest to the Portuguese climate condition (3B, 3C, 4B and 4C).

Regarding the EEMs, a few notes should be pointed out: no suggestion was driven towards CFLs or T12/T8 fluorescent lamps replacement since it was assumed this measure was already taken in the recent refurbishment Program intervention. The same reasoning was driven towards single glazing substitution by double glazed surfaces, wall and roof insulation, etc., since these are targeted to modernised/refurbished schools. Moreover, no architecture design change is proposed since the schools are already functioning; some other EEM could be suggested if this was a pre-construction phase, and the objective a design guide [268]. The EEMs signalled in bold in **Table 36** correspond to suggestions withdrawn from the case studies developed in the current section of the thesis.

Besides cleaning and regular maintenance expenses, all the EEM that foresee capital investment deserve a case-by-case study. In MMV, for example, the implementation of

[13] In the USA, the classification of climate zones adopts the methodology proposed by the ANSI / ASHRAE / IESNA Standard 90.1-2007 Normative Appendix B - Building Climate Criteria envelope, wherein a zone is defined by a numeric value from 1 to 8, representative of the annual air temperature distribution and, by a letter from A to C, which is a function of the location in terms of humidity.

exterior shading devices in windows facing south (*louvres*), was explored and, in fact, the simulated results obtained from four different simulations (different *louvres* size and distance between axes) unveiled the inefficiency of this measure [112] – although cooling requirements are reduced, the thermal heating energy consumption increased due to lower solar gains in the heating season. This is mostly due to the school functioning period – in Portugal, secondary schools classes end in the mid of June; classrooms are occasionally occupied in July due to examinations, and have no occupation in August.

Another situation relates NZEBs targeting. On-site energy production should be explored by the EM. One way of achieving this goal with no capital investment, would be an agreement with a private Energy Service company (ESCO). These companies develop, install, and manage the project from start to finish and can work with the school to identify sources of financing.

Table 36 – Energy Efficiency Measures

Item	EEM Description	Potential energy savings | Improvements of the current conditions	Literature
Systems			
Air conditioning Ta set points	Changing temperature settings for different times or situations in the BMS	Adjusting Ta from 22,2ºC to 20ºC means about 12% energy savings (for every degree (ºF) of change in temperature, energy costs change 2%–3%)	[269] in [176]
	Adjust the temperature of inlet air;	N.e	[270]
AHU/HRU rescheduling	**Adjusting the BMS operation time**	**Up to 30% reduction of the thermal heating energy, e.g. 14.1 kWh/m² per year**	**[113]**
	Changing the operational time of ventilation units	N.e	[270]
Artificial lighting	**Adjust light levels for the tasks conduced in each area by delamping or/relamping**	**400Wh energy savings in circulation areas**	**[113]**
	Clean lamps, fixtures and diffusers	N.e	[176]
Boilers adjusted scheduling	**Adjusting the BMS operation time**	**N.e**	**[113]**
Building envelope	Cleaning and sealing the building envelope | Repair broken exterior doors	N.e.	[176]
	Remove weed growth in roof terraces, avoiding waterproofs layers damaging	**Increase the water layers lifespan. N.e**	**–**
DHW system	Repair any damaged pipe and tank insulation Lowering boilers' temperature to the real needs (minimum 55-60ºC due to *legionella*)	N.e	[176]
	Adjusting the BMS equipment operation time to the real needs of the schools (e.g. adjusting the boiler to the gym schedule)	**N.e**	**–**
Heating system	During the non-use period some air may infiltrate into the radiators, reducing the system efficiency since it blocks the water circulation. Bleeding out the air annually	N.e	[176]
HVAC equipments	Verify or establish a comprehensive maintenance protocol Optimize equipments start/stop procedures Turn off unneeded heating/cooling equipment during off-seasons	N.e	[176]

IAQ maintenance	**Keeping a register of the BMS received information (e.g.CO_2 values in spaces served by the *rooftops* units in MMV)** **Increase or reduce the ventilation operation of the equipments according to the register & legislation requirements (e.g. increasing the operation time or adjusting Q)** Cleaning & Inspection; Keeping coils from the refrigerators clean; changing filters "Dirty condenser and evaporator coils reduce airflow and cooling capabilities" Filters changing/cleaning varies between 1–6 months	**–** **Potential investment depends only on the HVAC system currently present in the school.** **7% - 12% annual energy savings (e.g. MMV)** "Cleaning fan blades annually can extend the life of the fan and gives O&M staff the chance to inspect for chips or cracks" N.e.	**[113]** **[112]** [176]
Kitchen	Verify or establish an effective maintenance protocol for cooking equipment in kitchen areas and break rooms, including cleaning exhaust vents, heating coils, and burners Reducing the operating time of cooking equipment | schedule cooking activities to use equipment at full capacity Inspect oven door seals and hinges and repair if necessary Calibrate cooking equipment temperature settings, repair broken knobs, ensure pilot light is not overlit Adjust the temperature of inlet air;	"Ensuring that condenser coils are clean and unobstructed can keep refrigerators and freezers operating at maximum efficiency." Up to 60% energy can be reduced N.e N.e N.e	[176] [271] in [176] [270]
Lighting systems maintenance	Cleaning & inspection; ensure lights are off when spaces are unoccupied (e.g. motion sensor blocking)	Lighting levels can decrease by as much as 15% without proper cleaning	[176]
Nigh cooling (MV)	Increasing the operation time of fans of the ventilation system	Improving occupants comfort during daytime occupancy; primary energy use increase by 2% [simulation in a school without mechanical cooling]	[272]
Plug loads	Manage plug loads. Promote the use of smart plugs that turn off stand by equipments "Can be as much as 25% of a school's electricity use"; In MMV main classroom buildings, these represent as much as 30%.	N.e	[176] & [112]
Presence sensors maintenance	Regular cleaning	N.e	[176]
Solar panels maintenance	Check pipe insulation Cleaning	Pipe insulation deteriorates over time. Minimize uncontrolled heat losses.	[176]
All	Update and maintain a systems manual with O&M requirements	–	[176]
Behavioural			
Air conditioning Ta set points	**Awareness campaign specially driven towards school personnel with independent control e.g. administrative areas**	**N.e**	**–**
Artificial lighting	**Ensure that motion sensors are not halted – awareness raising campaign driven to school staff**	**N.e**	**–**
Blind use promotion	Keeping blinds closed at night	Heating energy savings: 32€/window e.g 1600€/yr [in a school with 50 windows (4 m^2/each), climate zone 6.4 heating months]	[273]
Classroom schedule	**Rescheduling and zoning opportunity; regrouping classrooms according to the HVAC system serving them, , also accounting on their solar orientation** **Promoting 1h break room vacancy in the middle of the day - increasing the air exchange rate (in a non-mechanical way)**	**N.e** Up to 5% improvement in energy consumption meeting relocating **N.e**	**[113]** [261] **[113]** & [82]
Daylighting promotion	Keeping blinds open during the day in winter time, i.e. empower solar gains	88€/window e.g.4400€/yr [in a school with 50 windows (4 m^2/each), climate zone 6.4 heating months]	[273]
Individual electrical heater (e.g. found in MTS)	**Ensure it does not stay active during unoccupied periods. Advising users to turn it off or keeping it to the minimum during lunch break for example.**	**N.e** Adding a timer (approx.. cost 15€) . N.e.	**–** [273]

Kitchen	Efficient practice – engaging kitchen staff	E.g. after bringing water to boil, boil water at minimum setting possible. N.e	[176]
Night cooling (NV)	Leaving windows open at night during summer time, Enabling cumulative heat release	N.e	[273]
Office equipment Printers	Printing draft option	Increasing tonners lifetime	[176]
Office equipment Computers & printers	**Programming self-shutdown, avoiding human distraction**	**N.e**	–
Potential investment			
AHUs rescheduling & fresh air flow rates (Q) adjustment	**Adjusting the BMS and Q to the current legislation requirements through replacement of fixed pulleys for fan speed regulation** Airflow rates for each system should be stated in the O&M documents. Test and adjust ventilation flow rates as needed to meet the requirements	**Up to 49% reduction of the thermal heating energy, e.g. 24.7 kWh/m^2 per year; 320€/AHU investment liquidated in less than 4 months**	**[113]** [176]
	Install variable speed drives (VSD) on chilled-water and hot water pumps	-0.2% Site energy savings 1st year. Payback time 1.3–4.1yrs	[176]
	Upgrade to demand control ventilation (DCV) to reduce outside air flow during partial occupancy	10.7–22.7% Site energy savings 1st year. Payback time 6.7–7.7 yrs	[176]
Artificial lighting	Replace incandescent exit signs with LEDs (these work 24/7) LED signs typically use less than 44 kWh/yr. It represents 5% annual energy for an exit sign using incandescent lamps.	Rated illumination levels for 10–25 yrs, what reduces associated relamping cost. 0.5–0.8% Site energy savings 1st year. Payback time 2.6–3.2 yrs	[176]
	Install wireless motion sensors for lighting in rooms that are used intermittently	1.2–2.0% Site energy savings 1st year. Payback time 0.9–1.6yrs	[176]
	Replace HID lights with T5 high-out fluorescent in gymnasiums	0.4–0.7% Site energy savings 1st year. Payback time 2.5–5.6yrs	[176]
	Install more efficient exterior lighting for façades and parking lot	0.87% Site energy savings 1st year. Payback time 4.5–11.7yrs	[176]
Daylighting promotion	**Installation of daylighting sensors in classrooms**	**Illuminance sensors: 5% annual energy reduction, payback period 2yrs & 7months**	**[112]**
	Install photo sensors and dimming ballasts to dim lights when daylighting is sufficient	2.5–4.5% Site energy savings 1st year. Payback time 28.8–39.9 yrs	[176]
DHW system / Service water heating	Install low flow showerheads in shower rooms	0.3–0.4% Site energy savings 1st year. Payback time 7.9–10.5 yrs [study assuming the installation in 40 showers]	[176]
Office equipment Computers	**Conduct an economic viability study on acquiring/installing a computer network management system as in MTS**	**Avoiding human distraction / promoting programmed computer shutdown**	–
Plug loads	Timing OR adding occupancy sensors to vending machines (VM) [14] VM might consume more than 3000 kWh/yr. Some timers might be provided by the suppliers under request Deactivating the fluorescent lamps in VM	"typical energy savings from occupancy-sensor based systems run about 20%–40% at a cost of about $90 per machine"; 990 kWh/yr can be spared	[176] & [268]
	Institute a "green purchasing" policy, e.g., replace cafeteria appliances with more efficient models	0.9% Site energy savings 1st year. Payback time 11.6–19.0 yrs	[176] & [268]

Note: EEF in bold are outcomes of the two case studies in this section. N.e *stands for non-estimated.*

5.4.2 The EM functions

The Energy Manager (EM) should be responsible for monitoring and evaluating the school energy consumption and associated costs. Assessing the energy consumption evolution is a key action to throw light on any anomalies and/or potential improvements. Naturally, this person must have some knowledge on the subject, predisposition to the position and being

[14] "A passive infrared occupancy sensor to turn off the compressor and fluorescent lights (…) when no one is around; a temperature sensor will power up the machine only as needed to keep products cool [176]."

able to face the key areas that determine the energy performance of the school, such as heating/cooling, ventilation, lighting, etc.

Bearing in mind that the energy performance of an energy system requires knowing where, how and when there is energy consumption, the EM should among other functions:

- Analyse the various energy bills (electrical energy and gas), gathering this information and exploring other energy contract options available in the market;
- Assess long-term energy consumption, in particular identifying gaps and possible causes;
- Contribute to the development of energy consumption indicators, such as those of presented in the S–EPC – section **5.4.3** ;
- "Eliminate or minimize costs associated to abnormal situations driven from broken equipments, unawareness or misuse" and incident reporting [273];
- Increase the HVAC systems energy efficiency, particularly through the proper parameterization of the temperature set point on the BMS, especially when discomfort situations are reported, either by excessive heat or cooling;
- In times of the non-operation of the HVAC systems, inform the school so that other ventilation forms are promoted (e.g. window/door opening, crossed ventilation);
- Test/balance the mechanical ventilation seasonally in order to check the flow rate and adjust it if needed[15];
- Ensure that the Maintenance Plans are fulfilled, guaranteeing good IAQ conditions, namely through a register of filters cleaning/replacement, coils, grids, and /or check and repair ducts, dampers, valves, etc.;
- Create a registration system of O&M activities, following the commissioned Maintenance Plans;
- Conduct analysis on lighting[16], office or other equipment replacement for more efficient systems; e.g. printers[17] and outdoor luminaires/lamps – mainly façades and sheltered sports areas (in the next five years);
- Work directly with ESCOs, aiming at studying the possibility of on-site energy production;
- Promote actions towards the school performance improvement (e.g. awareness/good practices campaigns).

[15] A field test was performed in MTS in November 2014. It was found that the air supplied by AHU CA3 into the several classrooms was balanced.

[16] Lighting technology has been suffering significant progresses. By now, the schools outdoor lighting systems were implemented five years ago.

[17] Brands such as EPSON, have now available equipment models with, supposedly, 88% lower energy consumption when compared to standard equipments, allowing an ECO mode among other features, (http://global.epson.com/SR/environment/new_perspective/office_2.html).

Good practice campaigns proposed by the EM engaging the school community might include activities such as:

- Follow an initiative with origin in the University of Leeds, called *Energy Saving Days* or *One Hour Switch Off Days*, the EM might propose the challenge of one day/class in a singular way, i.e. without the use of energy consumption, e.g. computers, lighting, etc. This event is similar to the *Earth hour*. Next year event is scheduled for May 19th 2016 (http://www.earthhour.org/);
- Use the school building as a teaching tool. The EM might promote an activity in which the school community (or just the students) is shown the good practice procedures, e.g. showing the evolution of the energy consumption (explaining the S–EPC, the school position in relation to the other schools nationwide); explaining the solar panels functioning, etc.;
- Encourage the participation in event competitions related to energy (e.g the *KidWind Project* [274]), playing as a form of motivation. These might be done in coordination with science teachers, bringing science of energy into the curriculum (e.g. using the *Secondary Energy Infobook* [275]).

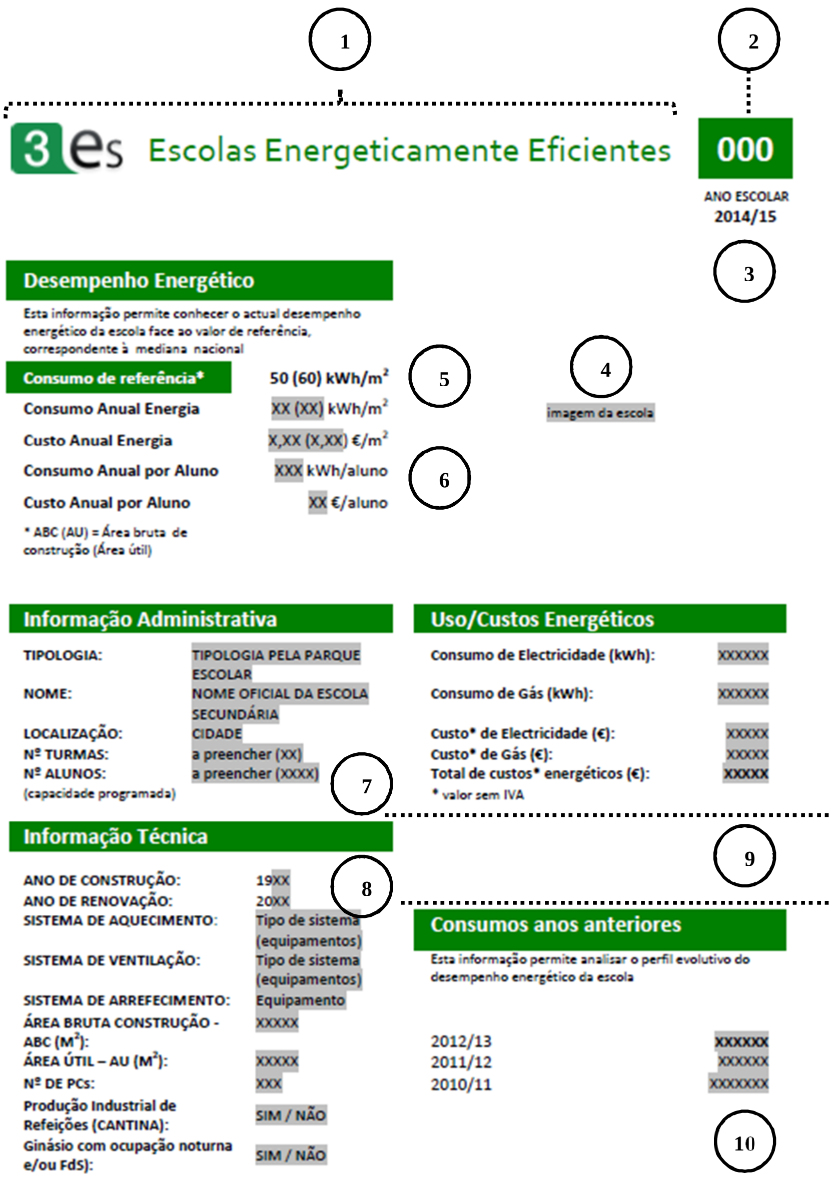
These types of activities permit the students' integration and discussion of the school reality, that is, a project-based learning experience. Students may, for example, read a book on how energy is produced through observation of the energy performance of school-based bills, applying statistical analysis, mathematical or research methods. Intra-class energy competitions can also be proposed, helping to promote awareness and developing leadership skills.

5.4.3 The school energy ID | S-EPC

Aiming at contributing to the development of a nationwide SBI – an official and precise rating – it is proposed a school energy performance ID document, based on the billed energy consumption, “incorporating national-scale statistical data, covering bottom-up details of individual buildings” [163].

The following pages unveil the front page of this S–EPC (School – Energy Performance Certificate) and the proposal of its filling with data from MTS and MMV. The document is written in Portuguese as it targets Portuguese Schools.

Similarly to the policy implemented in the UK – since October 2008, it is mandatory for public buildings over 1000 m^2 to obtain a DEC each year [163], the recommendation is that this S–EPC is available in a public area of each school.



1. ID of the 3Es Project
This logo can be replaced by the one of the entity responsible for national-scale statistical data

2. School numbering according to PE database

3. Scholar year

4. Site plan of the school

5. Reference value (kW/m^2)
Value corresponding to the national median value, expressed in GFA and TUFA. The presented value corresponds to the 8 schools’ selection. Preferably, this benchmark should have a bigger sample (> 50 buildings) to provide a useful analysis

Note: DECs are expressed in TUFA and not GFA. Since PE database was not provided in TUFA, presenting this single indicator would limit the replication of this documents in other schools outside the 3Es Project

6. Energy consumption per student
Student indicator is shown to accentuate the differences between school buildings

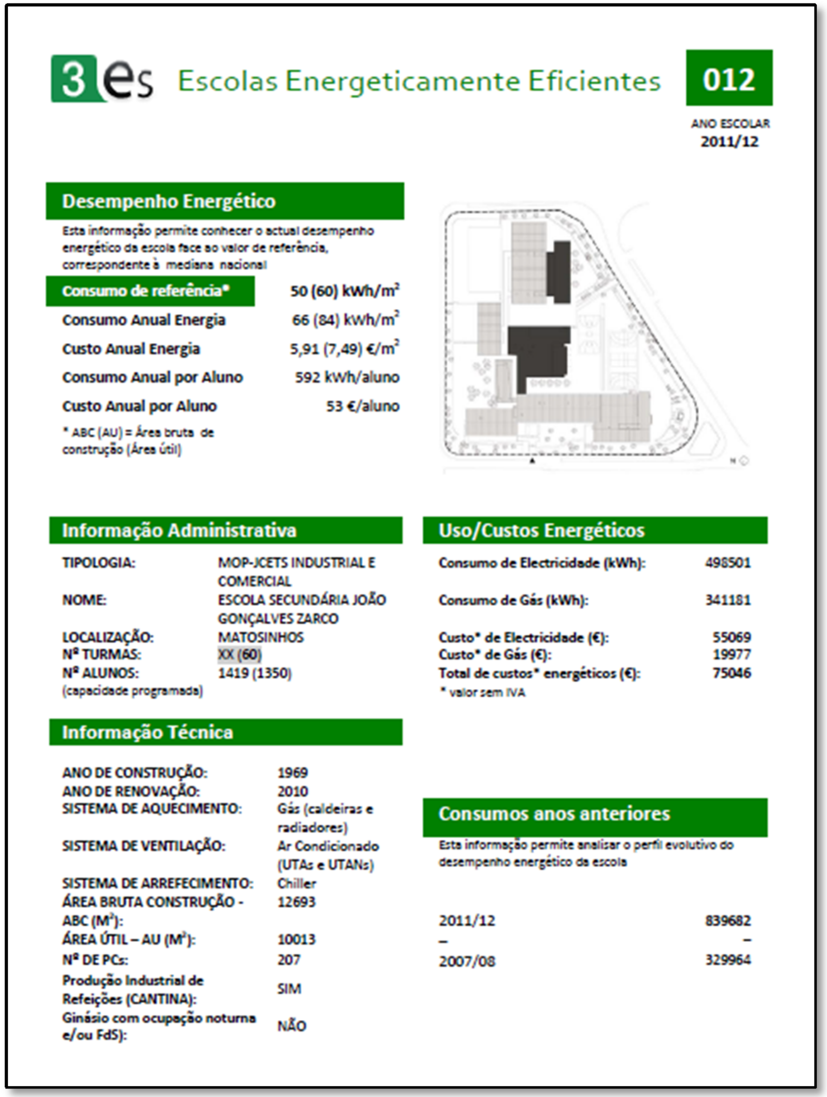
7. Administrative information
To be completed in accordance with PE’s glossary

8. Technical information
Namely year of construction, type of HVAC systems that contribute to influence the school performance, Gym night occupancy, etc.

9. Energy consumption data
Gas, electricity consumption expressed both in kWh and costs (€)

10. Comparison of the current school performance against past data

Figure 55 – School – Energy Performance Certificate layout.



3es Escolas Energeticamente Eficientes **012**

ANO ESCOLAR 2011/12

Desempenho Energético

Esta informação permite conhecer o actual desempenho energético da escola face ao valor de referência, correspondente à mediana nacional

Consumo de referência*	50 (60) kWh/m²
Consumo Anual Energia	66 (84) kWh/m²
Custo Anual Energia	5,91 (7,49) €/m²
Consumo Anual por Aluno	592 kWh/aluno
Custo Anual por Aluno	53 €/aluno

* ABC (AU) = Área bruta de construção (Área útil)

Informação Administrativa

TIPOLOGIA:	MOP-JCETS INDUSTRIAL E COMERCIAL
NOME:	ESCOLA SECUNDÁRIA JOÃO GONÇALVES ZARCO
LOCALIZAÇÃO:	MATOSINHOS
Nº TURMAS:	XX (60)
Nº ALUNOS: (capacidade programada)	1419 (1350)

Uso/Custos Energéticos

Consumo de Electricidade (kWh):	498501
Consumo de Gás (kWh):	341181
Custo* de Electricidade (€):	55069
Custo* de Gás (€):	19977
Total de custos* energéticos (€):	75046

* valor sem IVA

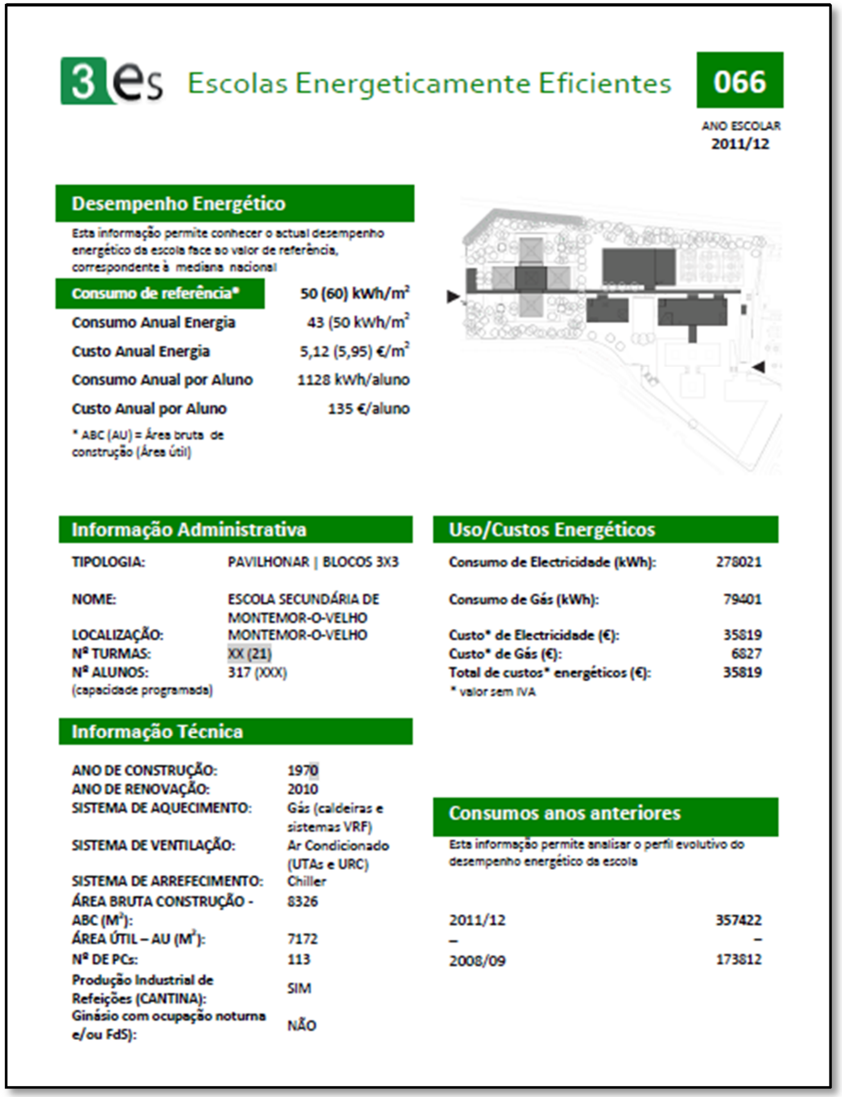
Informação Técnica

ANO DE CONSTRUÇÃO:	1969
ANO DE RENOVAÇÃO:	2010
SISTEMA DE AQUECIMENTO:	Gás (caldeiras e radiadores)
SISTEMA DE VENTILAÇÃO:	Ar Condicionado (UTAs e UTANs)
SISTEMA DE ARREFECIMENTO:	Chiller
ÁREA BRUTA CONSTRUÇÃO - ABC (M²):	12693
ÁREA ÚTIL – AU (M²):	10013
Nº DE PCs:	207
Produção Industrial de Refeições (CANTINA):	SIM
Ginásio com ocupação noturna e/ou FdS):	NÃO

Consumos anos anteriores

Esta informação permite analisar o perfil evolutivo do desempenho energético da escola

2011/12	839682
–	–
2007/08	329964



3es Escolas Energeticamente Eficientes **066**

ANO ESCOLAR 2011/12

Desempenho Energético

Esta informação permite conhecer o actual desempenho energético da escola face ao valor de referência, correspondente à mediana nacional

Consumo de referência*	50 (60) kWh/m²
Consumo Anual Energia	43 (50 kWh/m²
Custo Anual Energia	5,12 (5,95) €/m²
Consumo Anual por Aluno	1128 kWh/aluno
Custo Anual por Aluno	135 €/aluno

* ABC (AU) = Área bruta de construção (Área útil)

Informação Administrativa

TIPOLOGIA:	PAVILHONAR | BLOCOS 3X3
NOME:	ESCOLA SECUNDÁRIA DE MONTEMOR-O-VELHO
LOCALIZAÇÃO:	MONTEMOR-O-VELHO
Nº TURMAS:	XX (21)
Nº ALUNOS: (capacidade programada)	317 (XXX)

Uso/Custos Energéticos

Consumo de Electricidade (kWh):	278021
Consumo de Gás (kWh):	79401
Custo* de Electricidade (€):	35819
Custo* de Gás (€):	6827
Total de custos* energéticos (€):	35819

* valor sem IVA

Informação Técnica

ANO DE CONSTRUÇÃO:	1970
ANO DE RENOVAÇÃO:	2010
SISTEMA DE AQUECIMENTO:	Gás (caldeiras e sistemas VRF)
SISTEMA DE VENTILAÇÃO:	Ar Condicionado (UTAs e URC)
SISTEMA DE ARREFECIMENTO:	Chiller
ÁREA BRUTA CONSTRUÇÃO - ABC (M²):	8326
ÁREA ÚTIL – AU (M²):	7172
Nº DE PCs:	113
Produção Industrial de Refeições (CANTINA):	SIM
Ginásio com ocupação noturna e/ou FdS):	NÃO

Consumos anos anteriores

Esta informação permite analisar o perfil evolutivo do desempenho energético da escola

2011/12	357422
–	–
2008/09	173812

Figure 56 – MTS and MMV S–EPC fulfilled according to the layout previously exposed.

5.5 Results and discussion

"An energy efficient strategy in school buildings has a dual target: energy conservation and improved indoor conditions in classrooms". [126]

Aiming at developing Energy Efficiency Plans for the secondary schools under study, a strategy was outlined. The approach was developed within two schools of the 3Es Project, *Escola Sec. de Gonçalves Zarco* (MTS) and *Escola Sec. de Montemor-o-Velho* (MMV). MTS was one of the schools with the worse performance in terms of the EUI expressed in kWh/m^2 and MMV performed the worst in $student/m^2$ (**section 3.3**). The first step was improving the knowledge of each school (building physics, systems, occupancy schedules, etc.); the second step was getting to know the school BMS and its operation. An analysis on the recently updated legislation (in particular fresh air flow rates requirements) and, its repercussions on energy consumption were performed.

One of the major sources' of electrical consumption in schools is the pre-set heating/cooling systems of the building operated by the BMS which, in both schools, did not take into account the contracted energy tariff or occupancy status [248].

Identifying gaps in terms of day to day operation of the BMS undoubtedly has the potential to reduce energy consumption. In this way, the energy performance of a HVAC system and EEMs were readily identified and can be implemented at very low or even negligible costs – in order to achieve energy efficiency in buildings, the energy optimization of HVAC systems is very important, since the energy performance of these is affected by operating conditions and, constrains the building users' IEQ.

In terms of IEQ, the results obtained from the IAQ monitoring carried out in classrooms, revealed the classrooms' capacity of CO_2 removal during night time, both MTS and MMV. The IAQ analysis, based on the measured CO_2 concentration average during the occupancy periods above the outdoor concentration, $PD(\%) = 395*EXP(-15,15*C_{CO2}\hat{}-0,25)$ [214], revealed that in MTS, PD varied between 8.3 % – 31.5 % and, in MMV, it varied between 11.3 % – 50.3 % . If in MTS the extreme noncompliance values were obtained in the classrooms where occupancy load was higher than projected; in MMV the values are explained due to the lack of (mechanical) ventilation, corresponding to a peak occupancy period where the average CO_2 equalized 3303 ppm and the maximum surpassed 7000 ppm. As previously demonstrated, "simple" infiltration is not enough to remove indoor pollutants.

The potential energy savings presented in section **5.2.4** are therefore encouraging towards MV promotion among the schools' decision makers. By simply adjusting the BMS and corresponding AHUs schedule a decrease up to 32.6 % of the useful thermal energy consumption of these equipments might be achieved, corresponding to 14.1–24.7 kWh/m^2. Additionally, considering the new fresh air requirements of the current legislation, fan units energy consumption of the AHUs shall also decrease around 50%, since a reduction of at least 20% in the supplied air volume is expected.

Moreover, by looking at the obtained results from the simulation in MMV (buildings A1–S) [112], other results were obtained, that may be expected in other schools, namely: (i) the HVAC systems represented a significant part of the final energy consumption; (ii) the revision of the ventilation requirements showed the decisive nature of the fresh air flow rate (Q) parameter in the HVAC energy aspect; (iii) the analytical method used to calculate Q has shown a saving potential over the prescriptive methodology of about 5%.

Some other considerations, namely addressing the lighting systems, can be pointed out:

- The absence of lighting control in classrooms puts on occupants' behaviour a major responsibility. In MMV these systems represent 30% of the energy consumption. In MTS the school solved this problem by adopting an occupancy control that automatically turns off the lights by the end of classes;
- Natural lighting promotion in classrooms, through the installation of sensors suggested up to 5% reduction of the annual energy consumption in the main group of buildings in MMV;
- Circulation areas lighting circuits should be paid more attention. In some situations, the installation of illuminance sensors might improve energy expenditures in this field, even if some works, such as circuits' disaggregation is needed.

In the main group of buildings in MMV, plug loads represent 30% of the electrical energy consumption. Therefore major attention is worthy draw to these, namely the "new loads", such as the presence of at least one computer and one video projector per classroom and the recent spread presence of vending machines, for example. Most schools have now fully dedicated ITC classrooms which represent significant energy consumption loads. In MTS it has already been implemented a computer network management system programed to shut down the computers. This action might be implemented in other schools, if possible, also including projectors. Another option is programming computer with self-shutdown.

Mostly based on these findings, in **section 5.4**, an EEP for secondary school buildings in Portugal is drafted. Its structure is accompanied by a list of EEM. Within this document, leaded by an S–EPC (School – Energy Performance Certificate) to be fixed in appropriate location in the school, the creation of the figure of the Energy Manager is proposed.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

"The energy consumption of school buildings, due to their high number in the country, contribute to a considerable overall amount of energy consumption in public buildings, that results in an increase of the expenses paid by the national budget" [126].

Based upon this scenario, common to the Portuguese reality, this thesis presents a set of energy efficiency measures for Portuguese secondary schools, based upon an analysis of energy consumption and indoor environmental conditions of a selected group of eight schools, distributed through different climate zones in mainland Portugal.

The observations and conclusions of each chapter can be summarized as follows.

6.1 State-of-the art on energy consumption in schools

This chapter aimed at providing an overview of the recent research and development in the field of energy consumption in schools. It was entirely based on paper VI [116], Appendix A.

The outcomes suggest that when attempting to determine an energy benchmark some considerations should not be forgotten: standard indoor environmental conditions (IEC) for classrooms (set-point for indoor operative temperature of 20°C in winter and 26°C in summer as suggested in EN 15251:2007); electrical and heating consumption values should preferably be kept separate; different education levels usually require different energy consumption values. Comparisons between the presented values in the literature were difficult and might have been fallacious, due to the unknown energy sources combination of the consumed energy. Moreover, different energy "feed" buildings showed to have different energy performances, for which mix-mode buildings and all-electrical buildings be differently approached.

A climatic adjustment based on Heating Degree Days (HDD) was introduced as a possible strategy to normalize heating energy consumption. For an impartial data comparison, either based on an operational rating or a simulation carried out for reference conditions, benchmark reference values should be expressed in terms of billed energy data. Statistical benchmarks based upon a national database were suggested.

6.2 Case studies presentation

The eight secondary schools that constitute the case studies of this thesis were presented in Chapter 3. Their selection is grounded on paper II [19], Appendix A. A characterization of these was also performed, both from an energy and construction point of view. Energy disaggregation by end-use was not achieved. Both electrical and gas billed energy data, expressed in kWh were summed to calculate the schools' annual global energy consumption.

Aiming at addressing the subject of data normalization, namely achieving an accurate school building indicator (SBI), different variables were explored. The climate adjustment based on HDD, previously suggested, showed to be deceptive.

An indicator based on the total useful floor area (TUFA) was generated for the eight schools sample. The median corresponded to the typical value (typ) and the upper quartile to the good practice (gp). The estimated values for the Portuguese secondary schools were significantly lower than most of the literature. This finding rose some questioning about the HVAC systems running operation and the indoor environmental conditions inside classrooms. The results on this investigation were presented in the following chapter.

6.3 Indoor environmental quality (IEQ) analysis

In Chapter 4 an IEQ analysis of the eight schools was performed. The detailed methodology followed on this chapter has been previously reported in paper VII [110], Appendix A, using BJA school as case study.

The continuous monitoring period varied between schools, from a minimum of 48 h monitoring up to three weeks, during the spring – autumn period (excluding summer vacation) in 2013. Both subjective and objective data analysis were carried out in the mid-season in order to investigate the pupil's thermal comfort trends in relation to the environmental conditions. The indoor environmental conditions assessment was made in two classrooms per school, preferably classrooms with different solar orientation. Twenty-two classrooms were analysed in total. The classrooms' spatial characterization is described. Classrooms monitored during the national examination period were excluded since they were not representative of the school regular condition.

Data collection was observed and examined both in the teaching hours and non-teaching periods. Data were registered every 60 sec for the total monitoring periods. Although provided of HVAC systems, namely AHUs and VRFs, it was verified that most of the times, schools classrooms' were in "free running" conditions.

The environmental parameters influencing thermal comfort and indoor air quality were measured (Ta, RH and CO2 concentrations), while parallel subjective assessments of the occupants were collected. This allowed the comparison between the subjective votes (TSV) and the predicted votes (PMV & PPD).

The results reinforced previous findings from researches conducted in classrooms, namely that students in secondary schools in Mediterranean climate under free running conditions in mid-season: (i) accept higher T_a than those determined by the standards – 26.6ºC (TA = 84%); (ii) expressed TSV for *no change*; (iii) confirmed that *thermal neutrality* is not the preferred state. A trend was found for the thermal preference from *Slightly warm* environments in the mid-season: higher temperature ranges are accepted than those presented in the norms. Girls' mean TSV was 67% lower than boys', but due to the restricted sample size (a total of 262 individuals answered the survey), further investigation on this gender subject is suggested to confirm this hint.

Concerning IAQ, it was found that CO_2 concentration requirements of IAQ regulations were not being fulfilled. The concentration of this pollutant frequently exceeded the national and international reference limits. Furthermore, the perceived votes relating IAQ revealed students' adaptation to the environmental CO_2 concentration exposure. The AER values obtained in the schools under-study reveal their airtightness condition; showing that mechanical ventilation is required when windows are closed. This observation helps explaining the high CO_2 concentration found indoors during occupancy periods since in most cases HVAC systems were turned off due to energy costs reduction measures.

Under these conditions, adaptive actions such window(s) and/or door opening, should be promoted to reduce CO_2 concentration levels.

6.4 Energy efficiency plans for schools

Aiming at developing Energy Efficiency Plans for the secondary schools under study, a strategy was developed in Chapter 5, based on two schools of the 3Es Project. This chapter research method was reported in paper X [113] and is also partially based on paper IX [117], Appendix A.

Firstly, the knowledge of each school was deepened, mostly focused on crossing the schools occupancy schedule with systems operation, principally those controlled by the BMS. An analysis on the recently updated legislation (in particular fresh air flow rates requirements) was performed as well as its repercussions on energy consumption. It was verified that in none of the schools, the pre-set HVAC systems operated by the BMS took into consideration the contracted energy tariff or occupancy status.

Some gaps relating day to day operation of the BMS were found, and can be implemented at very low or even negligible costs, without compromising the building users' IEQ, which in case of the IAQ (previously assessed in terms of the CO_2

concentration values), has been verified that was compromised (mostly due to the non-operation of the HVAC systems, blocked due to economic constraints).

The potential energy savings achieved through the rescheduling of the BMS and fresh air flow rates adjustment (mostly thermal energy consumption and fans) are encouraging towards the promotion of the actively use of these systems. Some other considerations, namely addressing the thermal energy production systems of the schools (e.g. boilers scheduling), the lighting systems (e.g. lighting circuits) and uncontrolled plug loads, were also pointed out.

Based upon all the findings, a handbook of good practice was drafted for secondary school buildings in Portugal. This EEP was accompanied by a list of EEM. Within this document, leaded by an S–EPC (School–Energy Performance Certificate), was proposed the creation of the figure of the Energy Manager.

6.5 Future work

"All knowledge which ends in words will die as quickly as it came to life". Leonardo da Vinci

Although the conclusions of this thesis are limited to the cases from which they have been derived, the main objective of the EEP definition was that it could be replicated to other case studies. Facing the presented facts, it can be stated that adjusting the ventilation systems of the schools to its real needs might have a significant contribution to its sustainability. So it is expected that this jointly action with scheduling optimization of automated systems may conduct to significant amounts of energy savings in other schools.

In this section the main unanswered issues and the recommendations for future research are addressed. The proposed methodology driven towards the EEP still has some limitations that should be dealt with, in order to lead to more robust plans that aim at improving energy use in scholar buildings. Therefore, the following subjects should be addressed in the future research:

- **Energy consumption disaggregation**: since this task was only achieved in MMV (empowered by energy building simulation, the model was calibrated with the energy monitoring), it was not presented in the thesis. Ideally, this should be done also for the other seven schools within the 3Es Project, for a fairer comparison. Either through simulation or calculation of energy consumption based on the installed power and operational times of equipment;

- **EEP testing and validation**: It is necessary to test and validate the expected results from the EEP through the implementation of the suggested measures for both schools – MTS and MMV;
- **Replication**: In the present dissertation only two schools' knowledge was proved. The other six schools within the 3Es project, and correspondent EEMs should be tuned.
- **Focus on the kitchen area energy auditing:** energy consumption in schools with industrial energy production is necessarily different from those absent of it. Studies have shown that negligent behaviour can have a significant impact on energy consumption. Kitchens areas are greatly dependent on human action. It would be interesting installing energy meters in the kitchen equipment and potentially displaying data for the kitchen personnel. User behaviour transformation takes time and it might happen that people are just unaware. Moreover major attention towards the mechanical systems of these space is required, e.g. extractors, boilers and chillers operation, etc.;
- **Accounting the (non)studied parameters in the IEQ analysis**: This research did not include important IEQ analysis of noise, lighting, other pollutants besides CO_2, etc. Moreover it would be promising: (i) assessing of the impact of the IEQ conditions on students' performance – this subject has been developed in the literature mostly in offices and call centres – it is rather limited in schools and mostly based on repetitive practices (students' performance cannot be simply evaluated in a matter of time-reducing performing task, but also on results improvement; (ii) varying indoor comfort conditions – the results obtained from this study, suggested that students feel comfort beyond the comfort limits of the applicable legislation. It would be interesting to configure the air conditioning Ta set points to the extreme values of the regulations, e.g. 19ºC in winter time (Cat. III in EN15251[174]) and 26ºC in summer (Cat. II in EN15251[174]) and perform a new subjective evaluation – mainly to check if the lower limits are also accepted just like the upper have been; (iii) exploring the gender hint, relating TSV, e.g. enlarging the sample of the survey.

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APPENDICES

Appendix A. List of publications

This thesis is partially based on the following original publications: Paper **II**, **VI**, **VII** and **X**. The remaining papers are also related to the present PhD study. This list is organized by chronological order.

Paper I [8]	L. Dias Pereira, E. Cardoso, M. Gameiro da Silva. Indoor air quality audit and evaluation on thermal comfort in a school in Portugal. Indoor and Built Environment, 1420326X13508966, first published on October 29, 2013, doi:10.1177/1420326X13508966. http://ibe.sagepub.com/content/early/2013/10/27/1420326X13508966.full.pdf+html
Paper II [19]	M. Gameiro da Silva, C. Henggeler Antunes, H. Bernardo, H. Jorge, L. Cruz, E. Barata, L. Dias Pereira, M. Coimbra, G. Luis, L. Borges, L. Neves, J. Costa. *A preliminary assessment of energy performance in refurbished schools.* 1st International Congress on Energy & Environment: bringing together Economics and Engineering (IEEE Proceedings: pp. 1118 – 1132; ISBN: 978-972-95396-8-8)
Paper III [276]	N.Soares, L. Dias Pereira, J.P. Ferreira, P. Conceição, P. Pereira da Silva. *Energy efficiency of higher education buildings: a case study*. International Journal of Sustainability in Higher Education, doi: 10.1108/IJSHE-11-2013-0147, 2015, http://dx.doi.org/10.1108/IJSHE-11-2013-0147 *Note: Paper resulting from the participation on the* GREEN CAMPUS - Desafio Eficiência Energética no Ensino Superior. *Finalist Selection Project - Watt, we could save!, team Eco2green.*
Paper IV [20]	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 - IPC 2014: Finalist Selection Project.
Paper V [148]	L. Dias Pereira, H.Bernardo, M. Gameiro da Silva. *Energy performance of school buildings: from energy certificates to benchmarking*. VII Mediterranean Congress of Climatization (Climamed'13 proceedings: pp. 511 – 519; ISBN: 978-975-6907-17-7). *Note: Paper invited for submission in REHVA's Journal.*
Paper VI [116]	L. Dias Pereira, D. Raimondo, S. P. Corgnati, M. Gameiro da Silva. *Energy consumption in schools – A review paper*. Renewable and Sustainable Energy Reviews, DOI: 10.1016/j.rser.2014.08.010, 2014. (http://www.sciencedirect.com/science/article/pii/S1364032114006868)
Paper VII [110]	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*. Building and Environment, DOI: 10.1016/j.buildenv.2014.06.008, 2014. (http://www.sciencedirect.com/science/article/pii/S0360132314001942)
Paper VIII [199]	L. Dias Pereira, L. Neto, M. Gameiro da Silva. *Indoor air quality and thermal comfort assessment of two Portuguese secondary schools: main results*. REHVA World Student Congress – HVACRIGA2015 (Proceedings: pp.49-56. ISBN 978-9934-10-685-9).
Paper IX [117]	L. Dias Pereira, N. Correia, A. Gaspar, C. Costa da Silva, M. Gameiro da Silva. *The impact of ventilation requirements on energy consumption in school buildings*. 13rd SCANVAC International Conference on Air Distribution in Rooms – Roomvent 2014 (Proceedings: pp. 736 – 743).
Paper X [113]	L. Dias Pereira, F. Lamas, M. Gameiro da Silva. *Heading for an Energy Efficiency Plan focused on under-actuated HVAC zoned school buildings: A case study***.** Applied Energy, (submitted).

Appendix B. Monitored classrooms' location in each school

B.1 Case study I – MMV

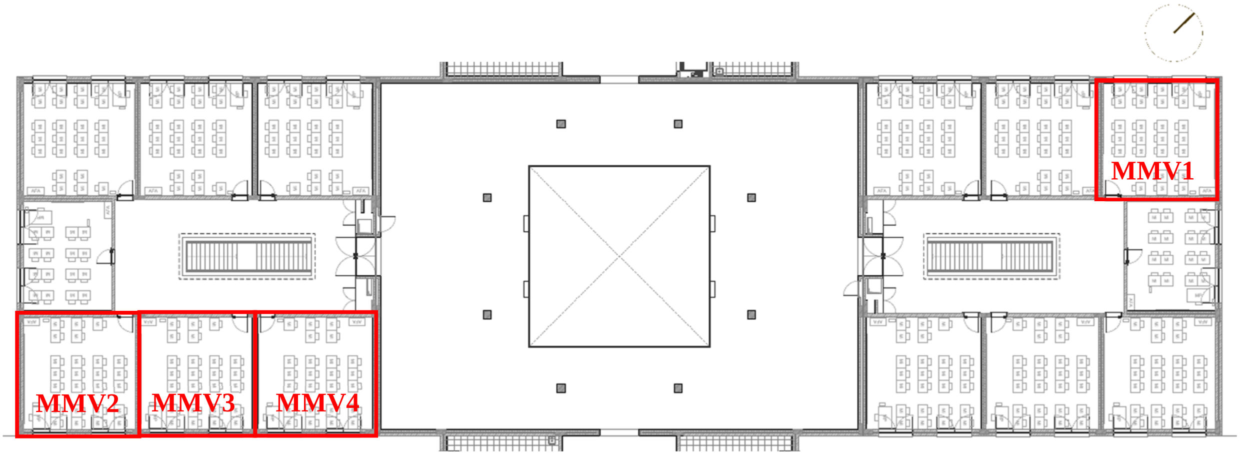
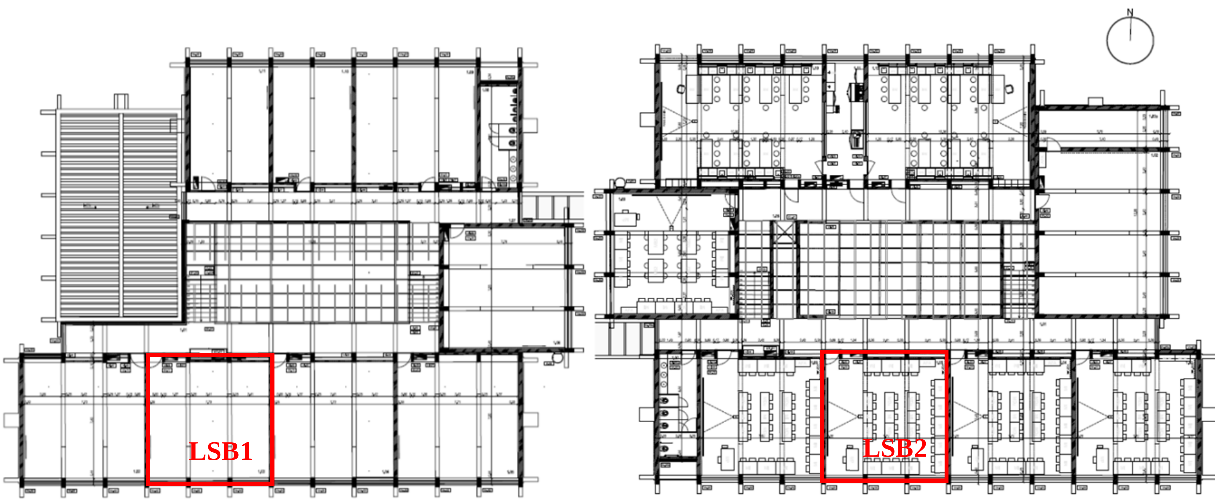


Figure 57 – Escola Secundária de Montemor-o-Velho – Classrooms' location in the school – Level 1 plan, MMV1 (building A3) and MMV2, 3 & 4 (building A1). [Source: Parque Escolar, EPE (2012)]

B.2 Case study II – LSB



a) **b)**

Figure 58 – Escola Secundária de D.Pedro V – Classrooms' location in the school – Level 1 plan. LSB1 (building A2), a); LSB2 (building A3), b). [Source: Parque Escolar, EPE (2012)]

B.3 Case study III – BJA

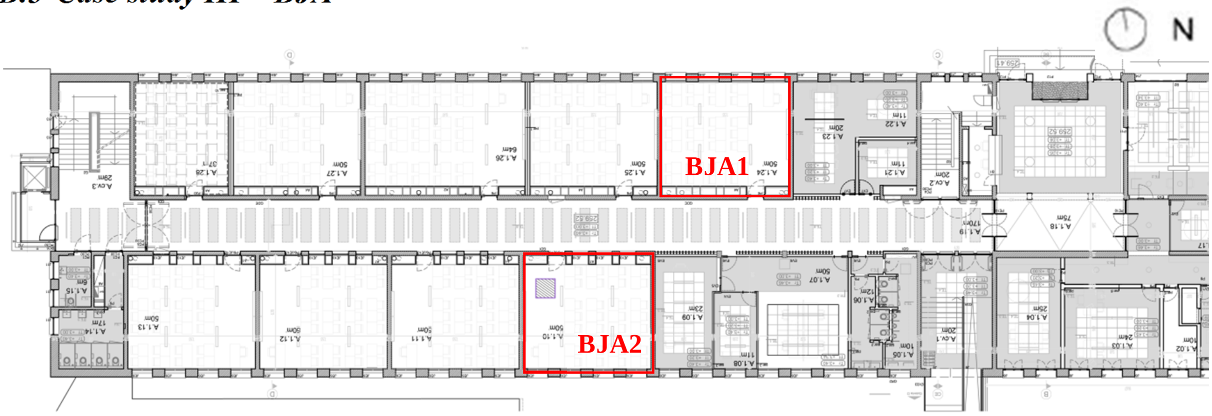


Figure 59 – Escola Secundária de D.Manuel I – Classrooms' BJA1 and BJA2 location in the school – Level 1 plan. [Source: Parque Escolar, EPE (2012)]

B.4 Case study IV – MTS

a)

b)

Figure 60 – Escola Secundária de Gonçalves Zarco – Classrooms' location in the school – Level -1 and 3 plans. MTS1 (building B), a); MTS2 and MTS3 (building A), b). [Source: Parque Escolar, EPE (2012)]

B.5 Case study V – PBL

Figure 61 – Escola Secundária de Pombal – Classrooms' PBL1 and PBL2 location in the school – Level 1 plan (building A). [Source: *Parque Escolar*, EPE (2012)]

B.6 Case study VI – PTG

a) **b)**

Figure 62 – Escola Secundária de Mouzinho da Silveira I – Classrooms' location in the school – Level 1 plan. PTG1 (building C), a); PTG2 (building F), b). [Source: Parque Escolar, EPE (2012)]

B.7 Case study VII – GRD

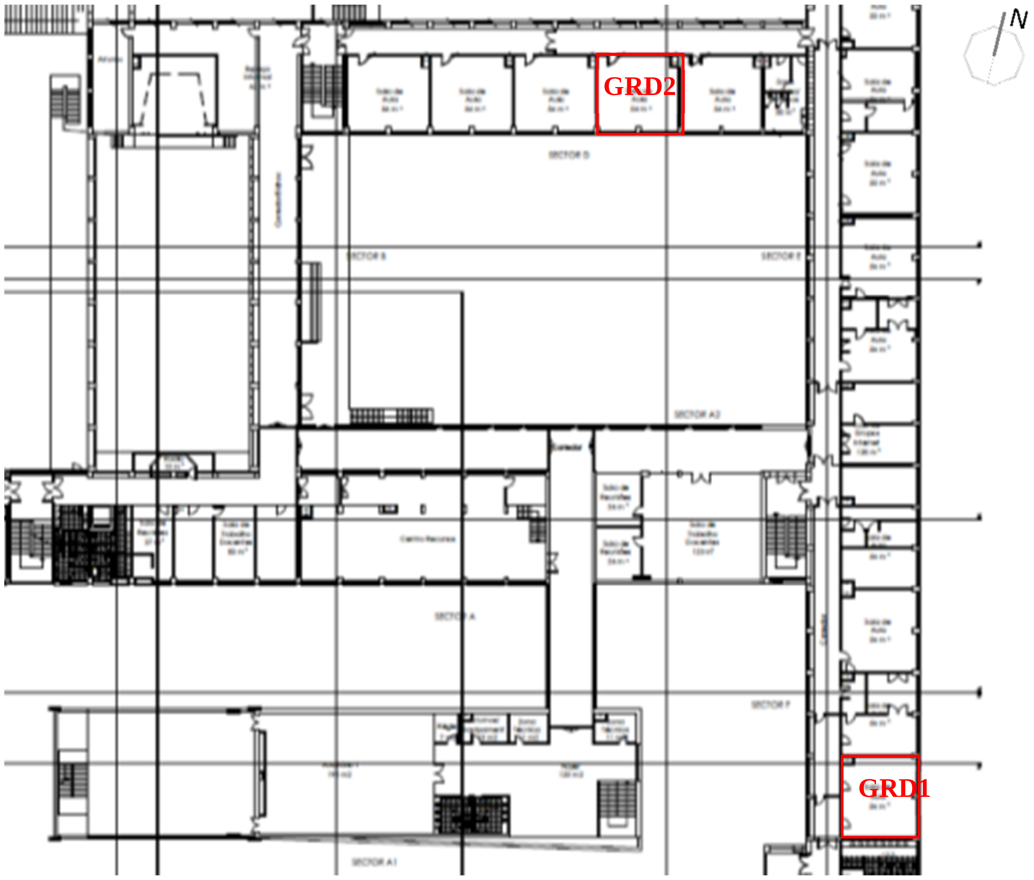


Figure 63 – Escola Secundária Afonso de Albuquqerque – Classrooms' location in the school – Level 1 plan. GRD1 (building G) and GRD2 (building E). [Source: Parque Escolar, EPE (2012)]

B.8 Case study VIII – BGC

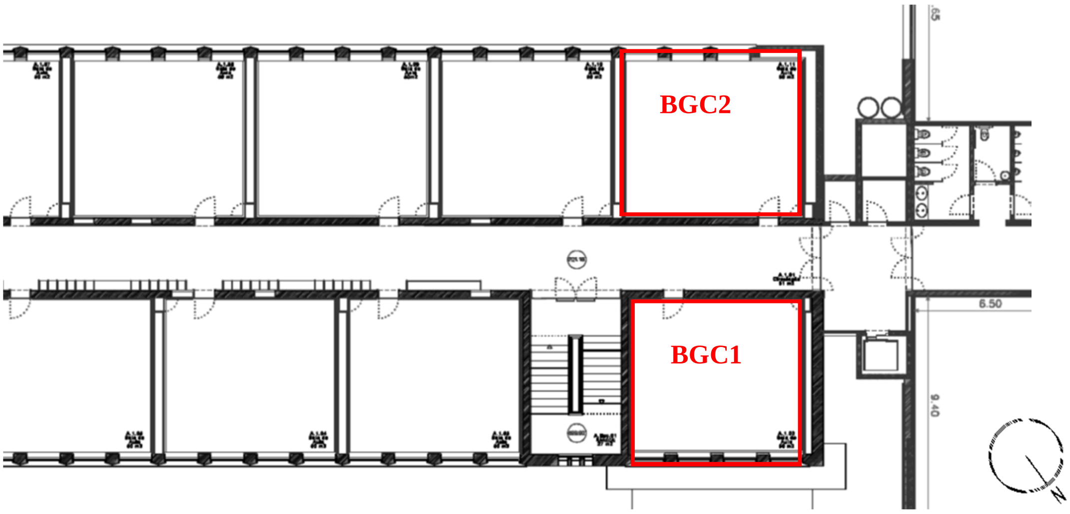


Figure 64 – Escola Secundária Abade de Baçal – Classrooms' BGC1 and BGC2 location in the school – Level 1 plan (building A). [Source: Parque Escolar, EPE (2012)]

Appendix C. Percentage of compliance, average and maximum values during occupancy periods of the indoor air temperature and CO_2 concentration in Classrooms

For each of the monitored schools several occupancy periods were defined according to the classrooms' occupancy schedule, which varied daily. For each of these was determined the percentage of compliance of each of the monitored parameters: air temperature (T_a), air relative humidity (RH) and concentration of carbon dioxide (CO_2).

"Carbon dioxide concentrations are often used as a surrogate of the rate of outside supply air per occupant. Indoor CO_2 concentrations above about 1000 ppm are generally regarded as indicative of ventilation rates that are unacceptable with respect to body odors". [277]

CO_2 percentage of compliance was estimated based upon the new Portuguese legislation [213]. Although the current threshold limits recall an average concentration value during the occupancy period of 2250 mg/m3 (1250 ppm), for the compliance estimation presented on the next tables, this value was considered as an upper limit (against the old legislation superior limit – 1000 ppm). The results previously published relating BJA school [110] were revised, so the information now presented has been updated accordingly. The analysis of this parameter based on the average concentration values is presented in **Chapter 4**.

Two schools were monitored during the national examination period of the scholar year 2012/13. The exams took place at 9:30 in the morning and at 14:00 in the afternoon. The approximation time of each was 120 min + 30 min compensation time. Each exam was considered as a single independent period. Since all the parameters were fulfilled, and as stated before in **Chapter 4**, these are not representative of the school regular condition, data relating these monitoring campaigns is not presented this document.

C.1 Case study I – MMV

Table 37 – Air temperature, Relative humidity and CO_2 percentage of compliance during occupancy periods in classrooms MMV1 & MMV2.

Monitoring Period		**Percentage of compliance MMV1 (%)**				**Percentage of compliance MMV2 (%)**			
		Daily occup.	**Temp**	**RH**	**CO_2**	**Daily occup.**	**Temp**	**RH**	**CO_2**
I	17/05/2013	[08:30 – 16:15]	100	100	6.9	[08:30 – 11:55]	41.8	100	51.5
II	20/05/2013	[08:30 – 16:15]	100	100	4.1	–	–	–	–
III	21/05/2013	[08:30 – 13:30]	100	96.7	11.0	–	–	–	–
IV	22/05/2013	[08:30 – 16:15]	98.5	100	61.4	–	–	–	–
V	23/05/2013	[08:30 – 13:30]	88.7	100	56.5	–	–	–	–
VI	24/05/2013	[08:30 – 16:15]	100	100	84.3	–	–	–	–
VII	27/05/2013	[08:30 – 16:15]	100	100	95.9	–	–	–	–
VIII	28/05/2013	[08:30 – 13:30]	100	100	23.3	–	–	–	–
IX	29/05/2013	[08:30 – 16:15]	93.1	100	54.1	–	–	–	–
X	30/05/2013	[08:30 – 13:30]	100	100	77.1	–	–	–	–
XI	31/05/2013	[08:30 – 16:15]	98.7	100	23.4	–	–	–	–
XII	03/06/2013	[08:30 – 16:15]	62.2	100	63.1	–	–	–	–
XIII	04/06/2013	[08:30 – 13:30]	21.9	100	7.0	–	–	–	–
XIV	05/06/2013	[08:30 – 16:15]	17.6	100	70.4	–	–	–	–
XV	06/06/2013	[08:30 – 13:30]	14.0	100	68.8	–	–	–	–

Table 38 – Average and maximum values over the occupancy periods of the indoor air temperature and CO_2 concentration in classrooms MMV1 & MMV2

Occupancy Period	**Room MMV1**				**Room MMV2**				**Ext***
	Temp (ºC)		**CO_2** (ppm)		**Temp** (ºC)		**CO_2** (ppm)		**Temp** (ºC)
	average	**max**	**average**	**max**	**average**	**max**	**average**	**max**	**mean**
I	**23.1**	23.8	**2093**	4174	**24.8**	26.2	**1380**	2623	12.0
II	**22.6**	23.7	**2742**	6568	–	–	–	–	16.5
III	**23.0**	23.7	**3303**	7142	–	–	–	–	18.4
IV	**23.9**	25.0	**1060**	2030	–	–	–	–	20.8
V	**24.1**	25.3	**1172**	1862	–	–	–	–	22,3
VI	**23.0**	23.5	**718**	1557	–	–	–	–	22.2
VII	**23.2**	24.1	**809**	1407	–	–	–	–	16.7
VIII	**24.0**	24.7	**1784**	3275	–	–	–	–	15.4
IX	**23.3**	25.4	**1525**	3435	–	–	–	–	13.2
X	**22.4**	23.8	**1052**	1408	–	–	–	–	12.6
XI	**24.1**	25.1	**1883**	4891	–	–	–	–	20.7
XII	**24.8**	26.0	**1017**	1689	–	–	–	–	25.9
XIII	**25.2**	25.7	**1983**	2716	–	–	–	–	25.4
XIV	**25.7**	26.9	**1132**	3222	–	–	–	–	20.3
XV	**25.6**	26.5	**1068**	1713	–	–	–	–	16.6

*Note: * Mean external temperatures were calculated during the daily occupational period 8:30 – 17:10. All the meteorological information used in this study, were obtained from www.ipma.pt (Coimbra weather station).*

C.2 Case study II – LSB

Table 39 – Air temperature, Relative humidity and CO_2 percentage of compliance during occupancy periods in classrooms LSB1 & LSB2

Monitoring Period		Percentage of compliance LSB1 (%)				Percentage of compliance LSB2 (%)			
		Daily occup.	**Temp**	**RH**	**CO_2**	**Daily occup.**	**Temp**	**RH**	**CO_2**
I	11/03/2013	[12:10 – 18:00]	100	100	0.0	[13:10 – 23:45]	100	100	100
II	12/03/2013	[08:10 – 18:00]	100	100	91.4	[08:10 – 22:10]	99.4	100	88.7
III	13/03/2013	[08:10 – 15:00]	100	98.5	51.6	[08:10 – 15:00]	90.3	76.9	100

Table 40 – Average and maximum values over the occupancy periods of the indoor air temperature and CO_2 concentration in classrooms LSB1 & LSB2

Occupancy Period	Room LSB1				Room LSB 2				Ext*
	Temp (ºC)		**CO_2** (ppm)		**Temp** (ºC)		**CO_2** (ppm)		**Temp** (ºC)
	average	**max**	**average**	**max**	**average**	**max**	**average**	**max**	**mean**
I	**23.6**	24.5	**2731**	4904	**22.5**	23.5	**879**	1112	13.7
II	**22.3**	23.3	**818**	2183	**23.4**	25.0	**896**	2809	12.5
III	**22.5**	23.6	**1443**	3274	**23.0**	25.9	**635**	1005	9.7

*Note: * Mean external temperatures were calculated during the same daily occupational period as LSB1. All the meteorological information used in this study, were obtained from www.ipma.pt (Lisboa weather station).*

C.3 Case study III – BJA

Table 41 – Air temperature, Relative humidity and CO_2 percentage of compliance during occupancy periods in classrooms BJA1 & BJA2

Monitoring Period		**Percentage of compliance BJA1 (%)**				**Percentage of compliance BJA2**			
		Daily occup.	**Temp**	**RH**	**CO_2**	**Daily occup.**	**Temp**	**RH**	**CO_2**
I	30/04/2013	[08:15 – 17:45]	33.5	100	5.8	[10:00 – 16:15]	89.0	100	0.0
II	01/05/2013	[08:15 – 13:30]	0.0	100	100	[08:15 – 16:15]	0.0	100	100
III	02/05/2013	[08:15 – 17:45]	16.1	100	41.4	[08:15 – 16:15]	63.5	100	7.3
IV	03/05/2013	[08:15 – 16:15]	67.7	100	28.1	[08:15 – 13:30]	76.8	100	34.3
V	06/05/2013	[08:15 – 16:15]	96.3	100	10.4	[08:15 – 17:35]	100	98.6	57.0
VI	07/05/2013	[08:15 – 17:45]	100	100	82.5	[10:00 – 16:15]	100	100	20.8
VII	08/05/2013	[08:15 – 13:30]	100	100	54.0	[08:15 – 16:15]	100	100	75.8
VIII	09/05/2013	[08:15 – 17:45]	100	100	100	[08:15 – 16:15]	100	100	100
IX	10/05/2013	[08:15 – 16:15]	100	100	53.5	[08:15 – 13:30]	100	100	41.6
X	13/05/2013	[08:15 – 16:15]	100	100	74.2	[08:15 – 17:35]	76.3	100	83.3

Table 42 – Average and maximum values over the occupancy periods of the indoor air temperature and CO_2 concentration in classrooms BJA1 & BJA2

Occupancy Period	**Room BJA1**				**Room BJA2**				**Ext***
	Temp (ºC)		**CO_2** (ppm)		**Temp** (ºC)		**CO_2** (ppm)		**Temp** (ºC)
	average	**max**	**average**	**max**	**average**	**max**	**average**	**max**	**mean**
I	**18.5**	19.6	**2222**	3719	**20.4**	22.1	**3103**	7645	14.4
II	**17.0**	17.2	**396**	443	**17.9**	18.1	**463**	502	15.9
III	**18.0**	19.5	**1742**	3301	**19.2**	20.2	**2000**	3008	20.2
IV	**19.4**	21.0	**2016**	5043	**20.1**	21.3	**2119**	4347	22.4
V	**21.2**	22.6	**2235**	6223	**22.6**	23.9	**1376**	5251	23.3
VI	**22.9**	23.0	**917**	2237	**23.5**	24.5	**2222**	4312	25.6
VII	**22.1**	23.0	**1331**	3298	**23.1**	24.5	**1102**	7465	21.5
VIII	**20.8**	20.9	**387**	446	**22.3**	23.0	**458**	488	24.0
IX	**21.5**	23.0	**1248**	2427	**22.8**	24.0	**1346**	2529	22.6
X	**21.9**	23.0	**1116**	2200	**24.0**	25.9	**1136**	5298	25.3

*Note: * Mean external temperatures were calculated during the daily occupational period 8:15 – 17:45. All the meteorological information used in this study, were obtained from www.ipma.pt (Beja weather station).*

C.4 Case study IV – MTS

Table 43 – Air temperature, Relative humidity and CO_2 percentage of compliance during occupancy periods in classrooms MTS1 & MTS2

Monitoring Period		**Percentage of compliance MTS1 (%)**				**Percentage of compliance MTS2**			
		Daily occup.	**Temp**	**RH**	**CO_2**	**Daily occup.**	**Temp**	**RH**	**CO_2**
I	18/04/2013	[08:15 – 17:45]	100	100	70.1	[08:15 – 18:30]	47.9	100	85.6
II	19/04/2013	[08:15 – 13:15]	71.4	100	22.6	[10:00 – 13:15]	35.2	100	100
III	22/04/2013	[08:15 – 16:45]	100	100	59.1	[08:15 – 17:45]	79.7	100	99.8
IV	23/04/2013	[08:15 – 18:30]	74.7	100	67.5	[08:15 – 18:30]	88.1	100	94.6
V	24/04/2013	[08:15 – 13:15]	54.8	100	34.6	[08:15 – 13:15]	75.4	100	97.3

Table 44 – Average and maximum values over the occupancy periods of the indoor air temperature and CO_2 concentration in classrooms MTS1 & MTS2

Occupancy Period	**Room MTS1**				**Room MTS2**				**Ext***
	Temp (ºC)		**CO_2** (ppm)		**Temp** (ºC)		**CO_2** (ppm)		**Temp** (ºC)
	average	**max**	**average**	**max**	**average**	**max**	**average**	**max**	**mean**
I	**23.3**	24.4	**1017**	1814	**25.2**	27.2	**916**	1890	15.4
II	**24.1**	26.1	**1483**	2023	**24.8**	26.3	**975**	1135	19.3
III	**22.7**	23.7	**1176**	2446	**24.0**	25.6	**883**	1267	17.2
IV	**24.3**	26.2	**1040**	1958	**24.3**	25.9	**717**	1406	20.6
V	**25.1**	27.7	**1668**	2413	**25.2**	26.5	**615**	1342	21.3

*Note: * Mean external temperatures were calculated during the daily occupational period 8:15 – 18:30 (except period V, 17:00. All the meteorological information used in this study, were obtained from www.ipma.pt (Porto weather station).*

C.5 Case study V – PBL

Table 45 – Air temperature, Relative humidity and CO_2 percentage of compliance during occupancy periods in classrooms PBL1 & PBL2

Monitoring Period		**Percentage of compliance PBL1 (%)**				**Percentage of compliance PBL2**			
		Daily occup.	**Temp**	**RH**	**CO_2**	**Daily occup.**	**Temp**	**RH**	**CO_2**
I	03/04/2013	—	—	—	—	[14:10 – 16:00]	100	100	96.4
II	04/04/2013	[08:25 – 17:50]	84.1	100	15	[08:25 – 16:00]	96.5	100	4.2
III	05/04/2013	[08:25 – 14:05]	93.3	100	5.6	[08:25 – 16:00]	96.1	100	27.2
IV	08/04/2013	[08:25 – 12:15]	57.6	100	13.9	[08:25 – 16:00]	91.5	100	8.3
V	09/04/2013	[08:25 – 16:55]	93.0	95.9	5.3	[08:25 – 16:55]	96.9	100	22.5
VI	10/04/2013	[09:20 – 13:10]	92.2	100	12.1	[08:25 – 16:00]	97.4	100	6.6
VII	11/04/2013	[08:25 – 17:50]	97.9	100	30.7	[08:25 – 16:00]	100	100	10.1
VIII	12/04/2013	[08:25 – 14:05]	96.2	100	5.6	[08:25 – 16:00]	100	100	12.7
IX	15/04/2013	[08:25 – 12:15]	96.5	100	18.6	[08:25 – 16:00]	100	100	34.0
X	16/04/2013	[08:25 – 11:20]	100	100	27.3	[08:25 – 11:20]	100	100	22.2
XI	22/05/2014	[08:25 – 16:55]	90.6	100	81.2	[08:25 – 16:55]	100	100	95.5
XII	23/05/2014	[08:25 – 16:00]	82.0	100	60.5	[08:25 – 16:00]	100	100	80.3
XIII	26/05/2014	[10:00 – 13:10]	76.4	100	24.1	[08:25 – 17:50]	100	100	75.8
XIV	27/05/2014	[08:25 – 16:00]	48.2	100	34.6	[08:25 – 16:00]	94.5	100	52.0
XV	28/05/2014	[08:25 – 15:00]	60.1	100	63.4	[08:25 – 16:55]	100	100	66.9
XVI	29/05/2014	[08:25 – 16:00]	89.7	100	88.6	[08:25 – 16:55]	100	100	66.7
XVII	30/05/2014	[08:25 – 16:55]	62.2	100	54.0	[08:25 – 16:55]	100	100	78.7
XVIII	02/06/2014	[08:25 – 16:00]	29.4	100	59.4	[08:25 – 17:50]	92.4	100	74.7
XIX	03/06/2014	[08:25 – 12:25]	58.5	100	61.8	[08:25 – 12:25]	100	100	53.9

Table 46 – Average and maximum values over the occupancy periods of the indoor air temperature and CO_2 concentration in classrooms PBL1 & PBL2

Occupancy Period	**Room PBL1**				**Room PBL2**				**Ext***
	Temp (ºC)		**CO_2** (ppm)		**Temp** (ºC)		**CO_2** (ppm)		**Temp** (ºC)
	average	**max**	**average**	**max**	**average**	**max**	**average**	**max**	**mean**
I	—	—	—	—	**21.8**	22.3	**1081**	1286	14.0
II	**19.8**	20.8	**1733**	2300	**21.6**	23.6	**2629**	3859	11.9
III	**20.1**	21.7	**1663**	2333	**21.6**	23.4	**1909**	3817	10.5
IV	**19.2**	20.9	**2133**	3389	**20.8**	23.4	**3029**	7190	11.6
V	**20.9**	22.6	**3255**	8076	**21.5**	23.0	**2284**	7747	12.3
VI	**21.1**	23.3	**2933**	7986	**21.4**	23.1	**2091**	3381	14.2
VII	**20.7**	22.3	**1389**	2166	**22.1**	23.2	**2048**	3587	12.6
VIII	**21.2**	23.7	**2420**	7247	**22.4**	23.8	**2347**	4036	14.6
IX	**20.7**	22.6	**1819**	2950	**23.2**	24.7	**1886**	3956	17.3
X	**20.4**	22.0	**1447**	2536	**21.8**	23.0	**1530**	2213	13.6
XI	**23.7**	25.4	**792**	1564	**22.5**	24.2	**736**	1390	17.0
XII	**22.9**	25.6	**1242**	2130	**23.3**	24.5	**995**	1533	16.3
XIII	**24.0**	26.2	**1771**	3218	**22.8**	23.9	**1028**	1725	16.7
XIV	**24.9**	27.2	**1876**	4598	**23.6**	25.2	**1311**	2316	17.8
XV	**24.5**	27.2	**1122**	2822	**23.2**	24.7	**1112**	2484	17.7
XVI	**23.2**	26.1	**743**	1482	**23.3**	24.4	**1142**	2765	17.4
XVII	**24.4**	26.2	**1202**	2458	**23.7**	24.8	**995**	1630	18.3
XVIII	**25.3**	27.3	**1230**	2339	**23.9**	25.5	**1028**	2284	18.1
XIX	**25.1**	27.4	**1271**	2414	**23.9**	24.8	**1299**	2025	17.0

*Note: * Mean external temperatures were calculated during the daily occupational period 8:25 – 17:50 (except periods X, 11:20 and XIX, 12:25). All the meteorological information used in this study, were obtained from www.ipma.pt (Ansião weather station).*

C.6 Case study VI – PTG

Table 47 – Air temperature, Relative humidity and CO_2 percentage of compliance during occupancy periods in classrooms PTG1 & PTG2

Monitoring Period		**Percentage of compliance PTG1 (%)**				**Percentage of compliance PTG2**			
		Daily occup.	**Temp**	**RH**	**CO_2**	**Daily occup.**	**Temp**	**RH**	**CO_2**
I	03/05/2013	[09:15 – 13:30]	62.1	100	12.1	[08:25 – 16:05]	100	100	41.2
II	06/05/2013	[08:25 – 16:05]	93.6	100	9.4	[08:25 – 16:05]	100	100	22.4
III	07/05/2013	[08:25 – 16:05]	82.0	100	38.8	[08:25 – 16:05]	100	100	73.7
IV	08/05/2013	[08:25 – 13:30]	67.4	100	48.5	[08:25 – 13:30]	100	100	36.9
V	09/05/2013	[08:25 – 16:05]	40.8	96.9	39.5	[08:25 – 16:05]	100	100	38.6
VI	10/05/2013	[09:15 – 13:30]	100	100	49.6	[08:25 – 16:05]	100	100	100
VII	13/05/2013	[08:25 – 16:05]	63.4	100	76.5	[08:25 – 16:05]	29.0	61.2	80.0
VIII	14/05/2013	[08:25 – 11:50]	1.0	100	83.1	[08:25 – 11:50]	26.7	100	67.2

Table 48 – Average and maximum values over the occupancy periods of the indoor air temperature and CO_2 concentration in classrooms PTG1 & PTG2

Occupancy Period	**Room PTG1**				**Room PTG2**				**Ext***
	Temp (ºC)		**CO_2** (ppm)		**Temp** (ºC)		**CO_2** (ppm)		**Temp** (ºC)
	average	**max**	**average**	**max**	**average**	**max**	**average**	**max**	**mean**
I	**19.4**	20.5	**2112**	3020	**20.8**	21.9	**1757**	4615	22.6
II	**23.9**	25.4	**2078**	3768	**23.6**	24.2	**1554**	2139	21.7
III	**24.5**	25.7	**1753**	3775	**23.4**	23.9	**1049**	1627	24.3
IV	**24.3**	25.9	**1450**	2995	**23.5**	24.0	**1511**	2312	19.4
V	**24.9**	25.5	**1497**	2420	**23.7**	24.3	**1270**	1807	19.2
VI	**24.1**	24.8	**1235**	2066	**23.2**	24.0	**856**	1234	22.1
VII	**24.9**	26.1	**1108**	2192	**25.1**	25.3	**1012**	1772	28.1
VIII	**25.5**	26.3	**976**	1317	**25.3**	26.5	**1141**	1760	21.7

*Note: * Mean external temperatures were calculated during the daily occupational period 8:30 – 16:05 (except periods IV, 13:30 and VIII, 11:50). All the meteorological information used in this study, were obtained from www.ipma.pt (Portalegre weather station).*

C.7 Case study VII – GRD

Table 49 – Air temperature, Relative humidity and CO_2 percentage of compliance during occupancy periods in classrooms GRD1 & GRD2

Monitoring Period		Percentage of compliance GRD1 (%)				Percentage of compliance GRD2			
		Daily occup.	**Temp**	**RH**	**CO_2**	**Daily occup.**	**Temp**	**RH**	**CO_2**
I	27/09/2013	[14:00 – 17:20]	100	100	100	[14:00 – 17:20]	**0**	100	18.4
II	30/09/2013	[08:30 – 17:20]	100	100	70.8	[08:30 – 16:30]	**0**	100	72.1
III	01/10/2013	[08:30 – 15:35]	96.0	82.2	35.9	[08:30 – 17:20]	**0**	100	47.6
IV	02/10/2013	[08:30 – 13:35]	100	100	9.2	[08:30 – 16:30]	**2.5**	100	73.8
V	03/10/2013	[08:30 – 16:30]	100	99.0	22.7	[08:30 – 17:20]	**8.5**	100	55.2
VI	04/10/2013	[08:30 – 15:35]	88.3	100	30.3	[09:20 – 17:20]	**5.1**	100	40.3
VII	07/10/2013	[08:30 – 17:20]	100	100	31.3	[08:30 – 16:30]	**0**	100	41.8
VIII	08/10/2013	[08:30 – 17:20]	92.5	100	26.0	[08:30 – 17:20]	**0**	100	58.9
IX	09/10/2013	[08:30 – 13:35]	100	100	5.6	[08:30 – 16:30]	**0**	100	52.4
X	10/10/2013	[08:30 – 15:35]	62.6	100	23.5	[08:30 – 17:20]	**0**	100	57.4
XI	11/10/2014	[08:30 – 13:35]	62.4	100	5.2	[09:20 – 17:20]	**0**	100	59.1
XII	14/10/2014	[08:30 – 17:20]	100	100	24.3	[08:30 – 16:30]	**82.0**	100	77.1
XIII	15/10/2014	[08:30 – 15:35]	100	100	3.1	[08:30 – 17:20]	**76.4**	100	35.6
XIV	16/10/2014	[08:30 – 15:35]	100	100	3.3	[08:30 – 16:30]	**0**	99.6	62.0
XV	17/10/2014	[08:30 – 13:35]	78.1	100	3.6	[08:30 – 10:10]	**0**	100	37.4

Table 50 – Average and maximum values over the occupancy periods of the indoor air temperature and CO_2 concentration in classrooms GRD1 & GRD2

Occupancy Period	Room GRD1				Room GRD2				Ext*
	Temp (ºC)		**CO_2** (ppm)		**Temp** (ºC)		**CO_2** (ppm)		**Temp** (ºC)
	average	**max**	**average**	**max**	**average**	**max**	**average**	**max**	**mean**
I	**24.2**	24.4	**626**	871	**26.8**	27.3	**1372**	1653	12.3
II	**22.7**	24.2	**1065**	2708	**26.3**	27.2	**1013**	1925	14.9
III	**23.5**	25.2	**1654**	5385	**26.5**	27.7	**1453**	3336	15.2
IV	**24.0**	24.9	**1601**	2296	**25.9**	26.7	**996**	2342	15.8
V	**23.8**	24.8	**1891**	4576	**26.3**	27.7	**1545**	3133	14.9
VI	**24.0**	25.3	**1781**	3279	**27.3**	28.2	**1335**	2039	15.1
VII	**22.2**	24.9	**1417**	4146	**28.1**	29.4	**1294**	1949	17.6
VIII	**23.5**	25.2	**1645**	2729	**29.0**	30.4	**1180**	1483	19.6
IX	**23.4**	24.2	**2440**	3847	**28.8**	30.2	**1208**	2185	15.9
X	**24.4**	25.7	**2107**	6136	**29.2**	30.3	**1340**	2838	19.1
XI	**24.6**	26.2	**3636**	6804	**29.6**	30.7	**1069**	1602	18.2
XII	**22.0**	24.3	**1889**	5666	**25.9**	27.0	**975**	2075	14.0
XIII	**23.3**	24.5	**2591**	4618	**27.0**	28.8	**2195**	3953	15.2
XIV	**23.1**	23.6	**2276**	5447	**27.4**	28.6	**1129**	1992	16.8
XV	**24.2**	25.1	**2904**	6817	**26.2**	26.8	**1467**	2276	17.9

*Note: * Mean external temperatures were calculated during the daily occupational period 8:30– 17:20 (except periods I, 14:00 and XV, 13:35). All the meteorological information used in this study, were obtained from www.ipma.pt (Guarda weather station).*

C.8 Case study VIII – BGC

Table 51 – Air temperature, Relative humidity and CO_2 percentage of compliance during occupancy periods in classrooms BGC1 & BGC2

Monitoring Period		**Percentage of compliance BGC1 (%)**				**Percentage of compliance BGC2 (%)**			
		Daily occup.	**Temp**	**RH**	**CO_2**	**Daily occup.**	**Temp**	**RH**	**CO_2**
I	25/09/2013	[08:30 – 13:30]	100	100	53.8	[08:30 – 13:30]	0	100	80.7
II	26/09/2013	[08:30 – 16:15]	42.5	100	94.8	[08:30 – 16:15]	0	100	100
III	27/09/2013	[08:30 – 15:15]	100	100	84.2	[08:30 – 13:30]	0	100	31.9
IV	30/09/2013	[08:30 – 17:50]	100	100	70.9	—	—	—	—
V	01/10/2013	[08:30 – 17:50]	100	100	79.3	—	—	—	—
VI	02/10/2013	[08:30 – 13:30]	100	100	8.3	—	—	—	—
VII	03/10/2013	[08:30 – 16:15]	100	100	62.9	—	—	—	—
VIII	04/10/2013	[08:30 – 13:30]	100	100	26.9	—	—	—	—
IX	07/10/2013	[08:30 – 17:50]	95-0	100	49.0	—	—	—	—
X	08/10/2013	[08:30 – 17:50]	94.8	100	29.2	—	—	—	—
XI	09/10/2013	[08:30 – 13:30]	100	100	34.2	—	—	—	—
XII	10/10/2013	[08:30 – 16:15]	81.1	100	34.5	—	—	—	—
XIII	11/10/2014	[08:30 – 15:15]	95.1	100	39.7	—	—	—	—
XIV	14/10/2014	[08:30 – 17:50]	85.6	72.5	22.3	—	—	—	—
XV	15/10/2014	[08:30 – 17:50]	84.8	100	52.8	—	—	—	—
XVI	16/10/2014	[08:30 – 13:30]	72.4	94.4	70.1	—	—	—	—
XVII	17/10/2014	[08:30 – 16:15]	93.3	36.7	57.1	—	—	—	—
XVIII	18/10/2014	[08:30 – 13:30]	100	100	25.9	[08:30 – 13:30]	100	99.7	5.6

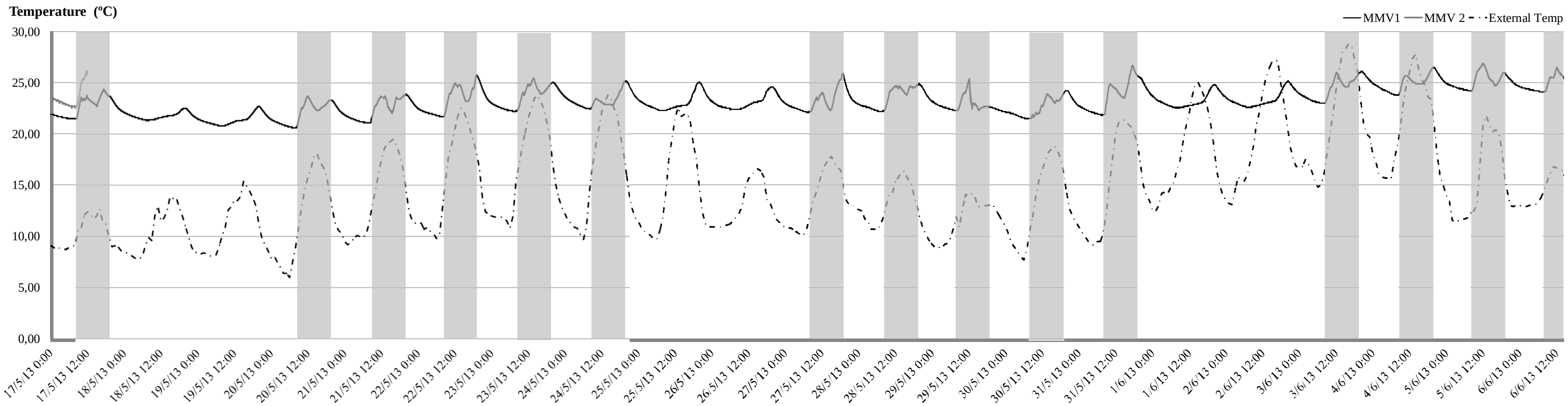
Table 52 – Average and maximum values over the occupancy periods of the indoor air temperature and CO_2 concentration in classrooms BGC1 & BGC2

Occupancy Period	**Room BGC1**				**Room BGC2**				**Ext***
	Temp (ºC)		**CO_2** (ppm)		**Temp** (ºC)		**CO_2** (ppm)		**Temp** (ºC)
	average	**max**	**average**	**max**	**average**	**max**	**average**	**max**	**mean**
I	**23.5**	24.6	**1228**	2073	**26.7**	27.5	**902**	1495	23.6
II	**24.6**	25.5	**850**	1423	**26.1**	26.8	**552**	998	22.9
III	**23.9**	24.5	**908**	1572	**26.3**	27.0	**1510**	2278	16.3
IV	**22.7**	23.6	**721**	3285	—	—	—	—	17.9
V	**22.2**	22.8	**865**	2023	—	—	—	—	17.1
VI	**21.9**	23.0	**2684**	3804	—	—	—	—	18.0
VII	**22.6**	23.7	**1246**	3160	—	—	—	—	18.8
VIII	**22.3**	23.4	**1901**	3368	—	—	—	—	17.3
IX	**21.0**	21.9	**1832**	3871	—	—	—	—	18.4
X	**21.1**	22.2	**1422**	2496	—	—	—	—	20.1
XI	**20.6**	21.6	**1919**	3546	—	—	—	—	18.3
XII	**20.2**	21.7	**1506**	2126	—	—	—	—	18.6
XIII	**20.9**	21.7	**1825**	3327	—	—	—	—	16.6
XIV	**19.6**	20.9	**2051**	3592	—	—	—	—	14.1
XV	**20.2**	21.5	**1376**	2592	—	—	—	—	16.5
XVI	**19.5**	20.4	**1006**	1611	—	—	—	—	18.3
XVII	**20.9**	21.9	**1144**	2526	—	—	—	—	19.2
XVIII	**22.0**	23.5	**1550**	2187	**23.2**	24.0	**1938**	2922	14.7

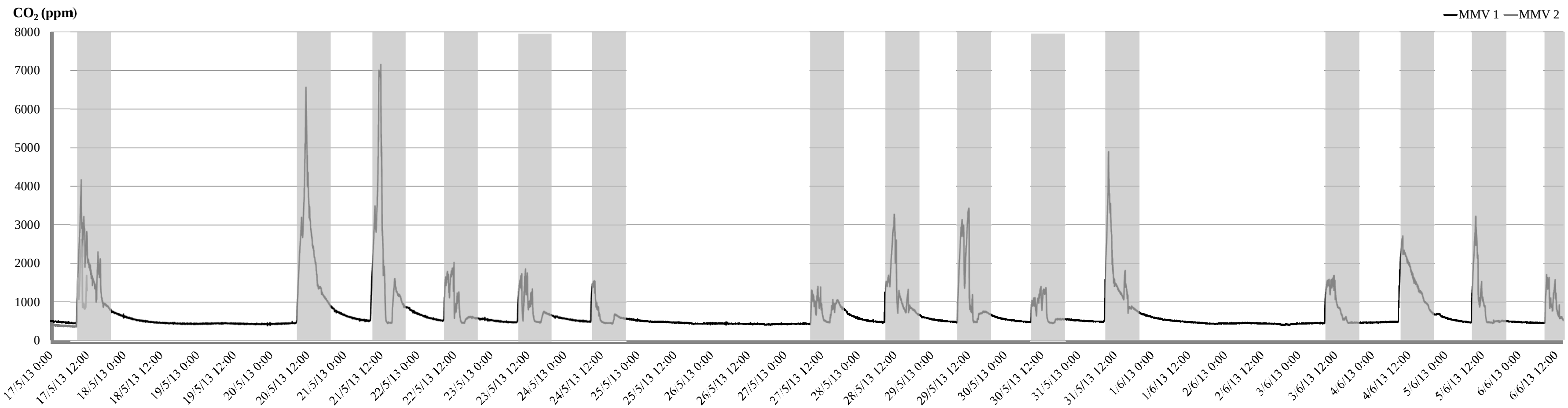
*Note: * Mean external temperatures were calculated during the daily occupational period 8:30 – 17:50 (except period XVIII, 13:30). All the meteorological information used in this study, were obtained from www.ipma.pt (Bragança weather station).*

Appendix D. Classrooms' graphical representation of the recorded values

D.1 Case study I – MMV



a)

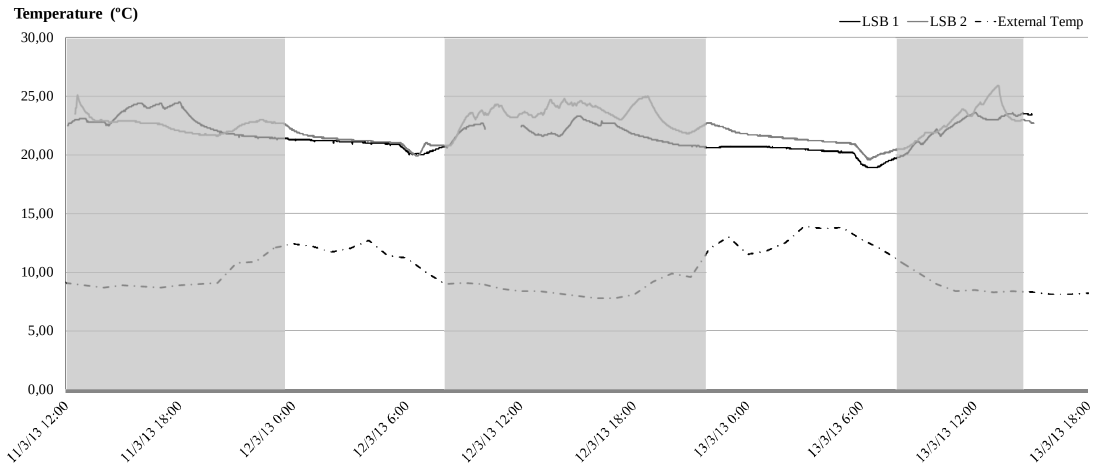


b)

Figure 65 – a) Temperature values in classroom MMV1 and MMV2 between 17th – 6th June 2013; b) CO_2 concentration values (the shadowed areas correspond to the occupancy periods, as defined in Appendix C1).

D.2 Case study II – LSB

a)



b)

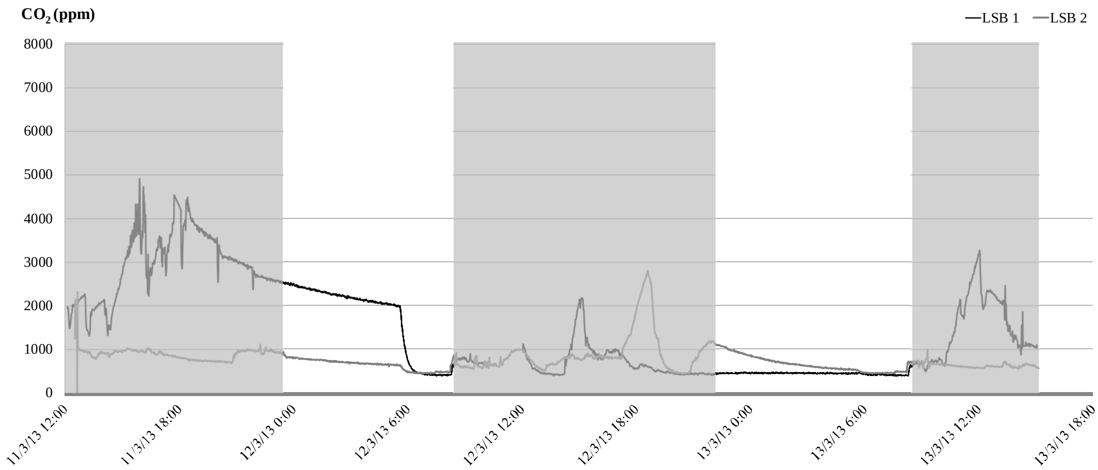
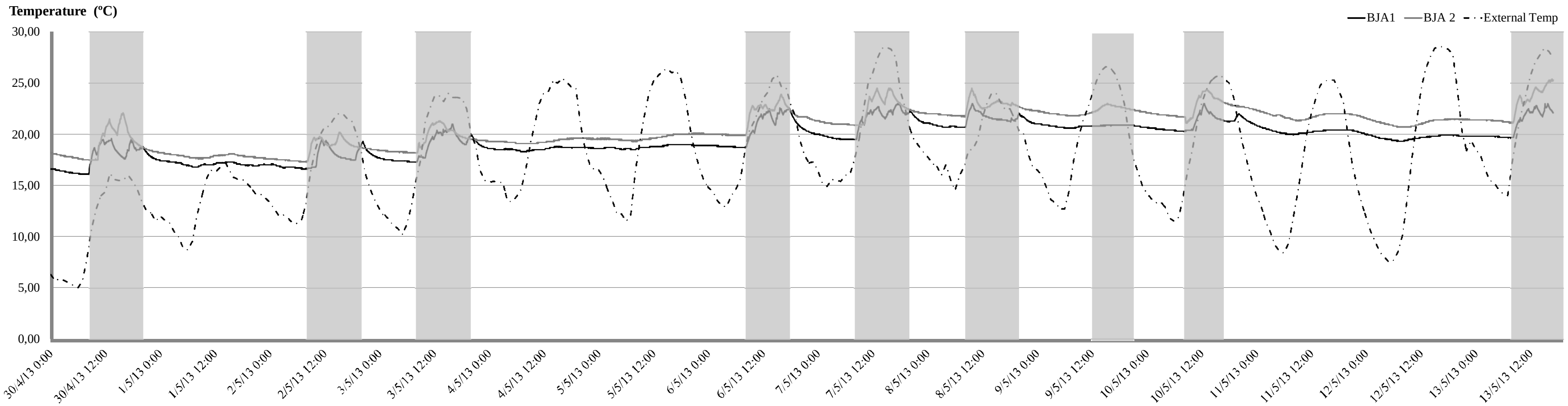
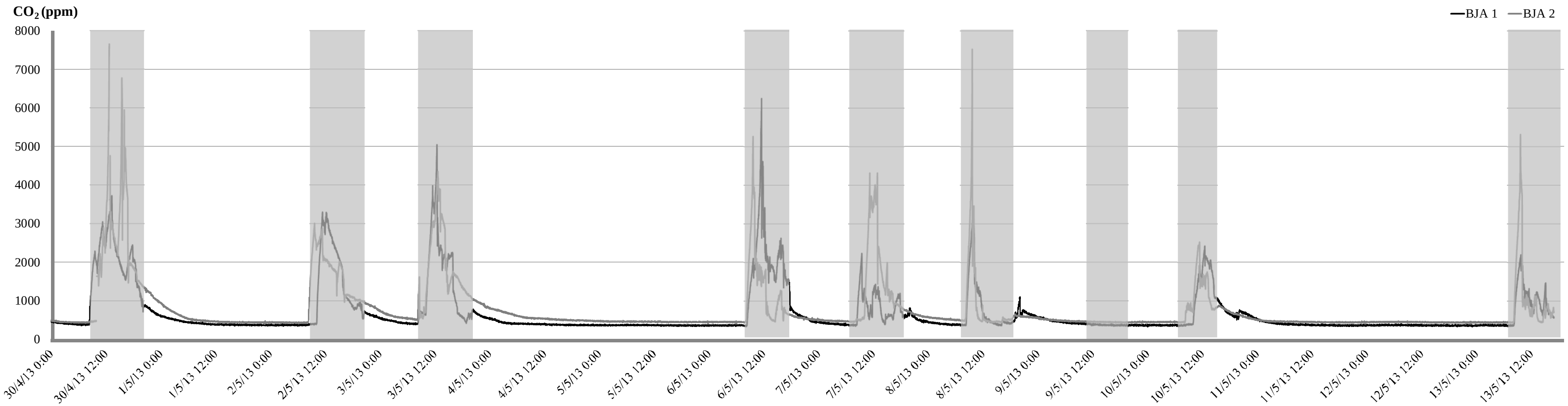


Figure 66 – a) Temperature values in classroom LSB1 and LSB2 between 11th March – 13th March 2013; b) CO_2 concentration values (the shadowed areas correspond to the occupancy periods, as defined in the Appendix C2).

D.3 Case study III – BJA



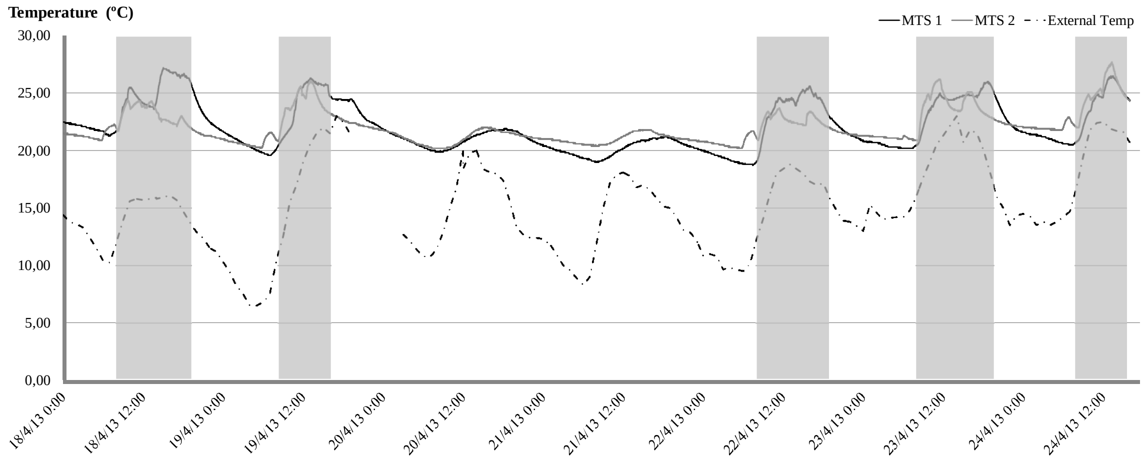
a)



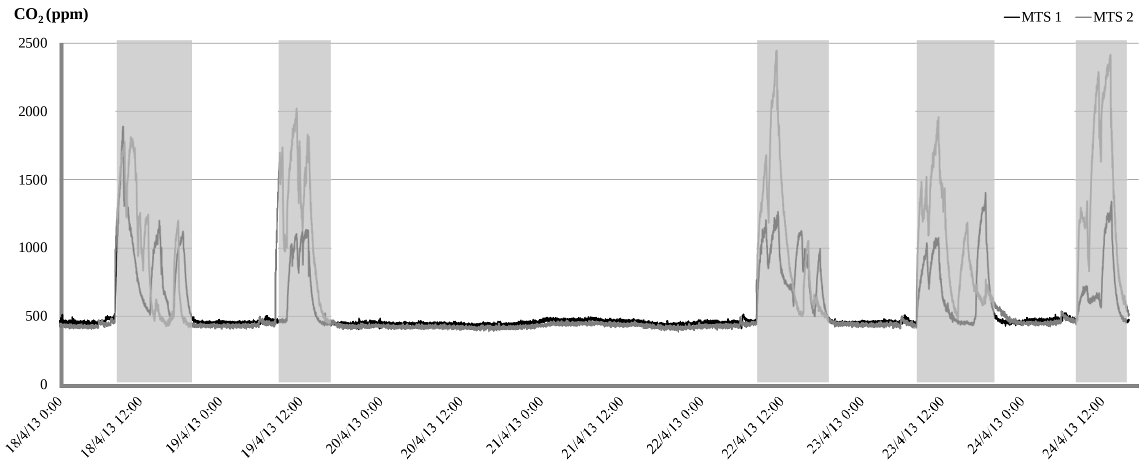
b)

Figure 67 – BJA recorded values in classroom BJA1 and BJA2 between 30th April – 13th May 2013; a) Temperature values; b) CO_2 concentration values (the shadowed areas correspond to the occupancy periods, as defined in the Appendix C3).

D.4 Case study IV – MTS



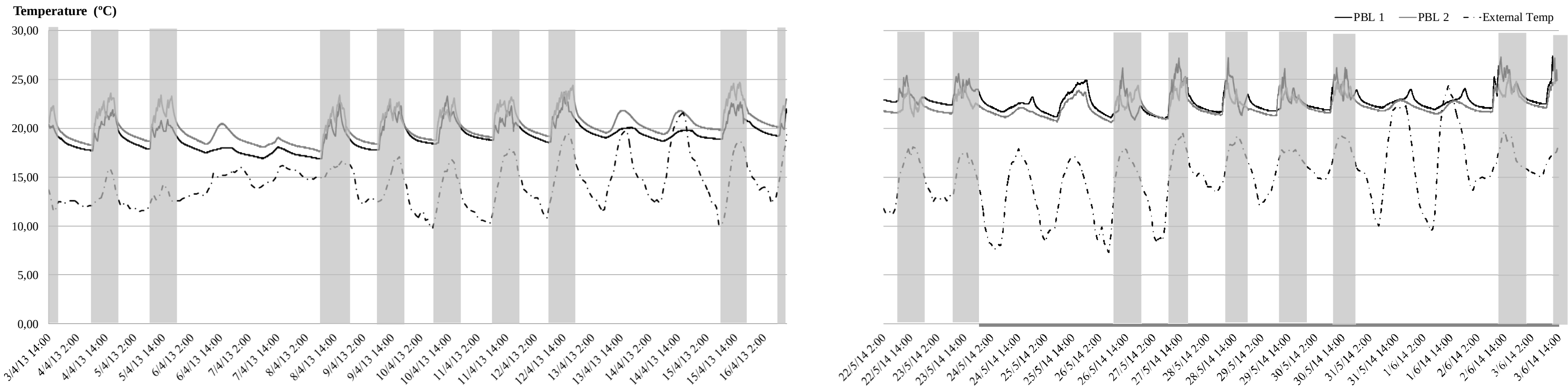
a)



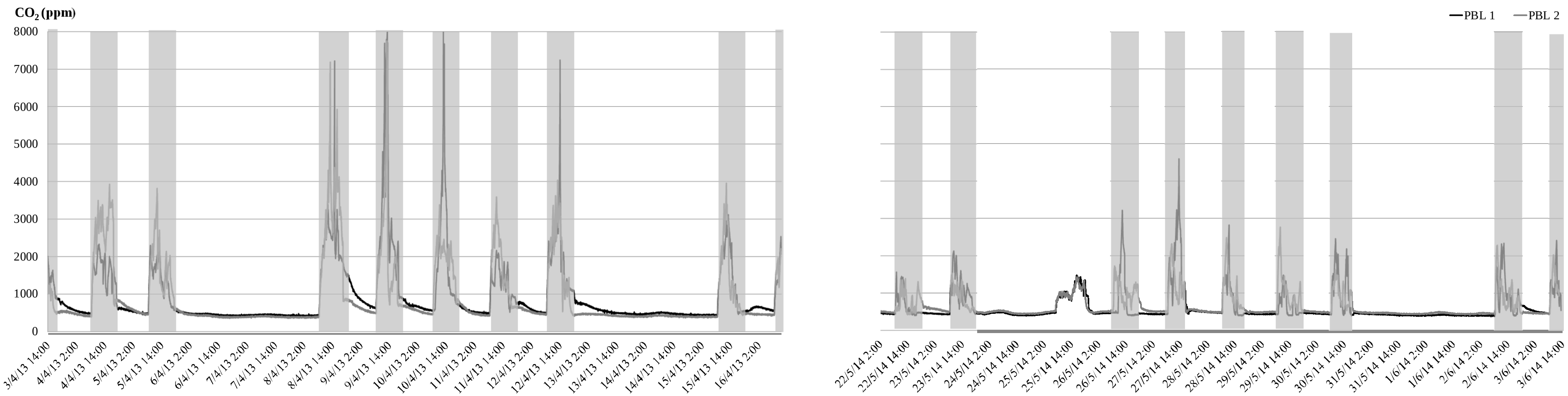
b)

Figure 68 – a) Temperature values in classroom MTS1 and MTS2 between 18th April – 24th April 2013; b) CO_2 Concentration values (the shadowed areas correspond to the occupancy periods, as defined in the Appendix C4).

D.5 Case study V – PBL



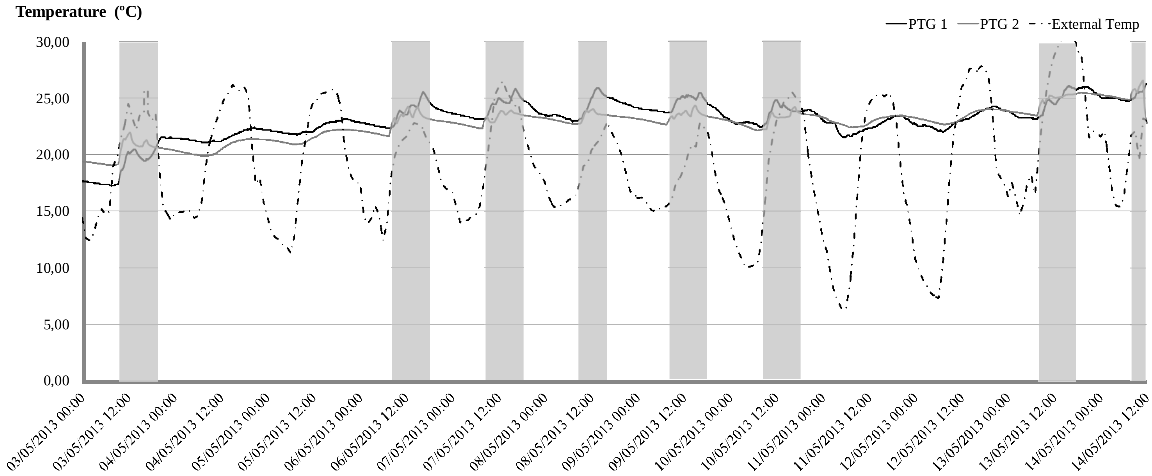
a)



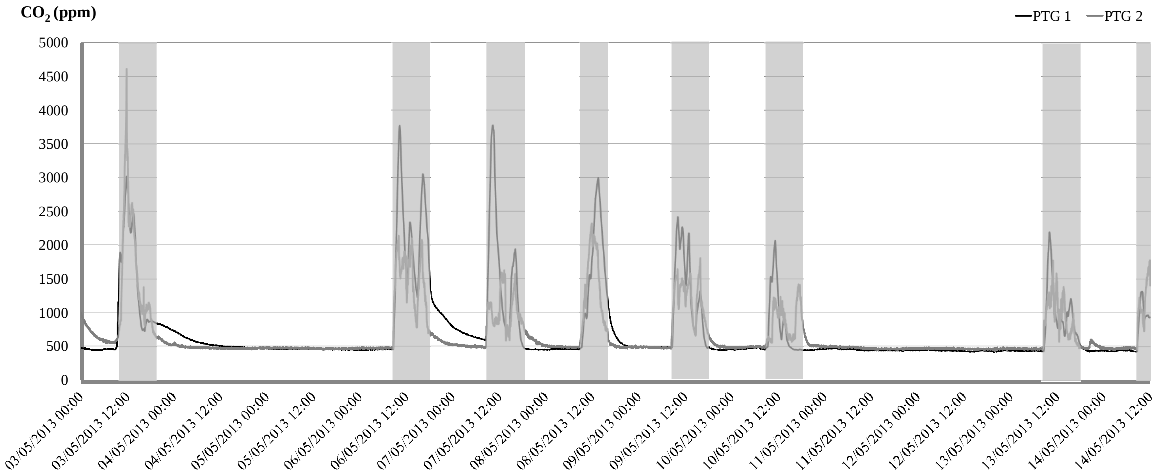
b)

Figure 69 – a) Temperature values in classroom PBL1 and PBLA2 between 30th April – 13th May 2013; b) CO_2 concentration values (the shadowed areas correspond to the occupancy periods, as defined in the Appendix C5).

D.6 Case study VI – PTG



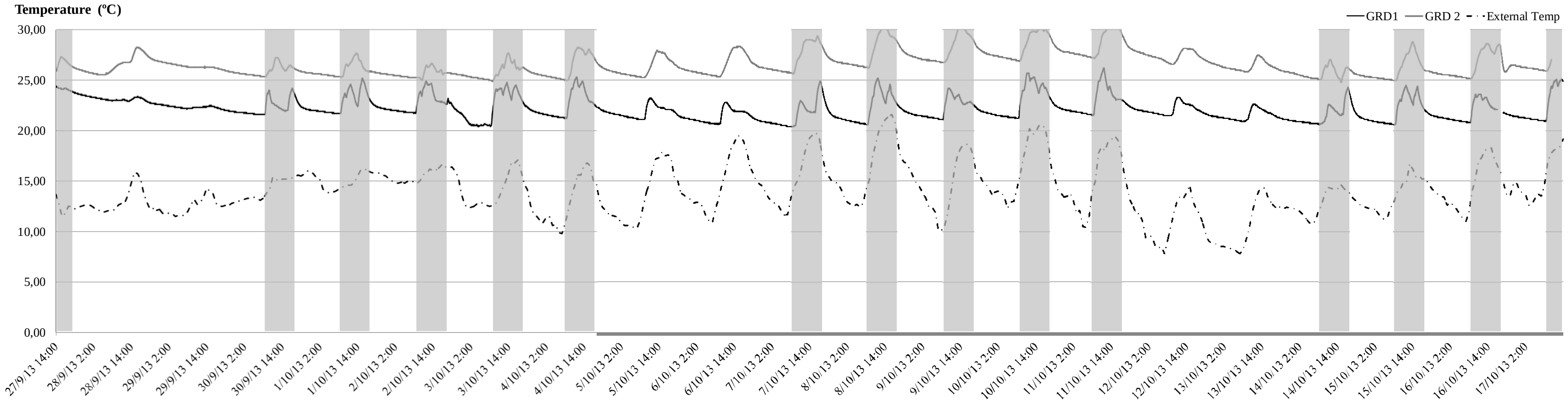
a)



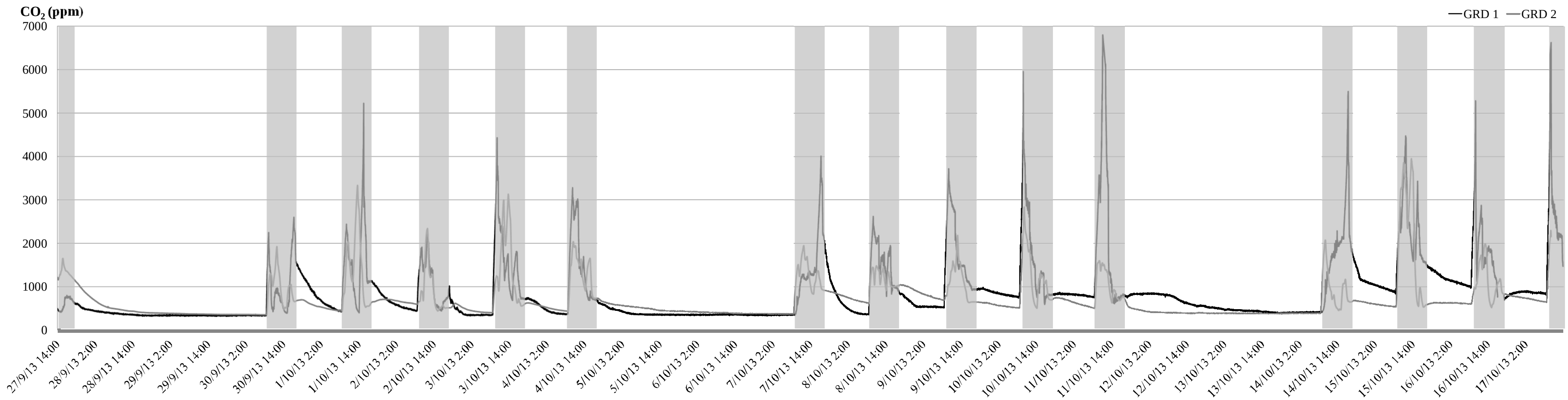
b)

Figure 70 – a) Temperature values in classroom PTG1 and PTG2 between 3rd May – 14th May 2013; b) CO_2 Concentration values (the shadowed areas correspond to the occupancy periods, as defined in the Appendix C6).

D.7 Case study VII – GRD



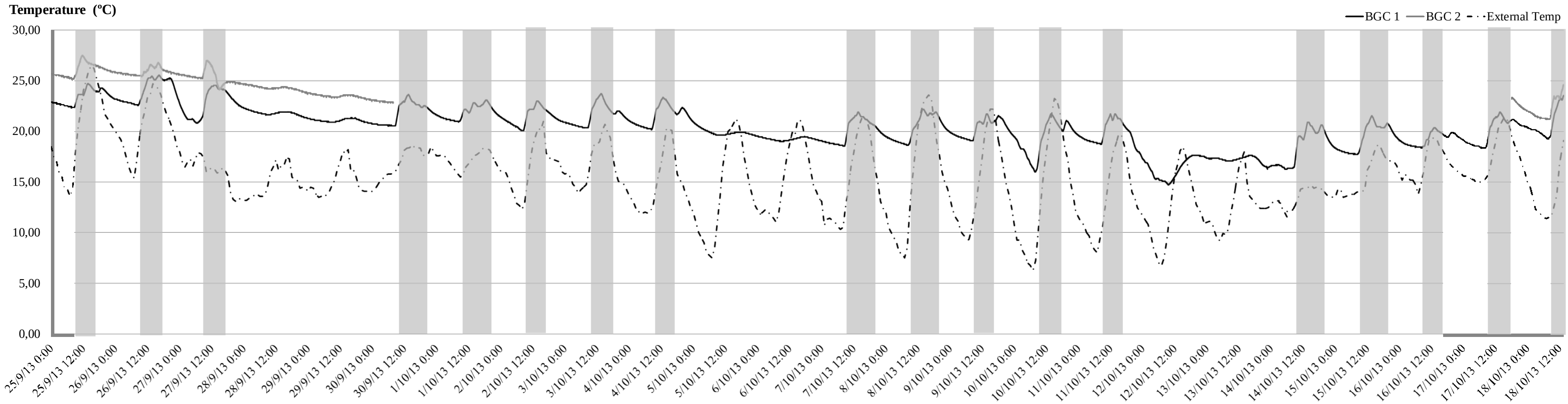
a)



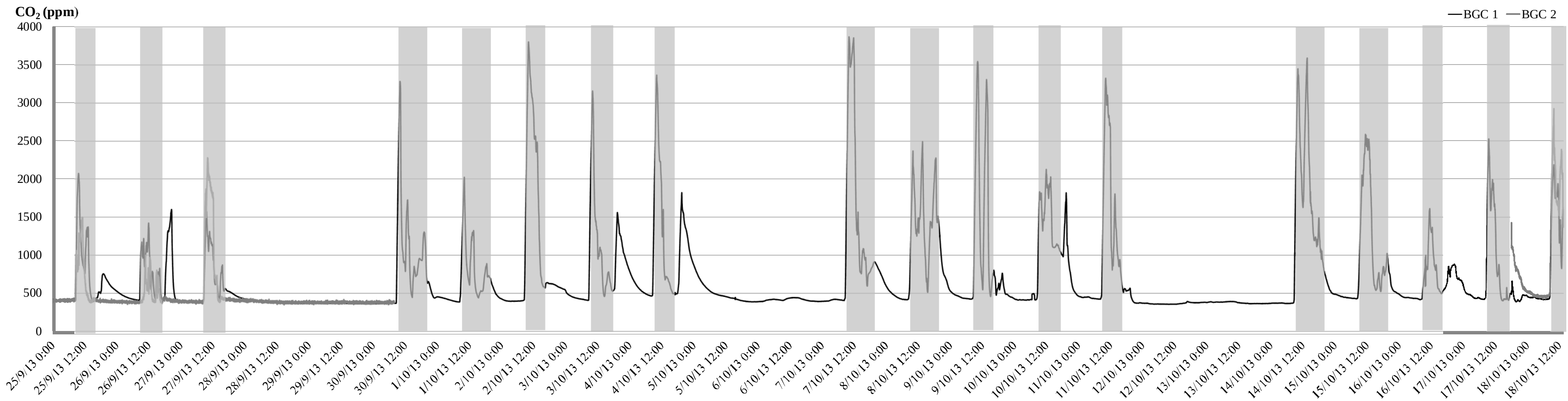
b)

Figure 71 – a) Temperature values in classroom GRD1 and GRD2 between 27th September – 17th October 2013; b) CO_2 concentration values (the shadowed areas correspond to the occupancy periods, as defined in the Appendix C7).

D.8 Case study VIII – BGC



a)

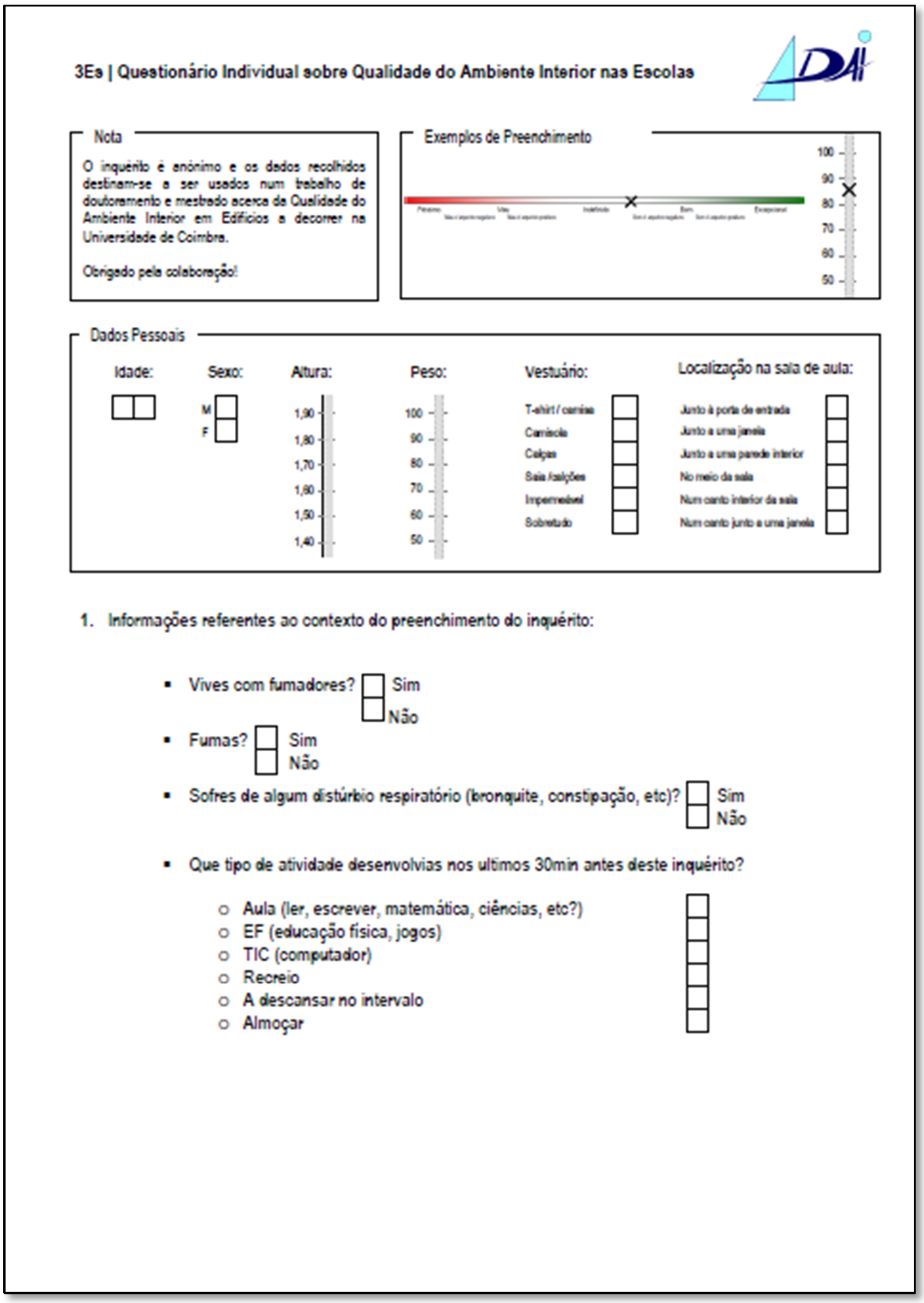


b)

Figure 72 – a) Temperature values in classroom BCG1 and BGC2 between 25th September – 18th October 2013; b) CO_2 concentration values (the shadowed areas correspond to the occupancy periods, as defined in the Appendix C8).

Appendix E. Questionnaire layout

The individual questionnaire layout on indoor environment quality in schools is next presented .



3Es | Questionário Individual sobre Qualidade do Ambiente Interior nas Escolas

Nota

O inquérito é anónimo e os dados recolhidos destinam-se a ser usados num trabalho de doutoramento e mestrado acerca da Qualidade do Ambiente Interior em Edifícios a decorrer na Universidade de Coimbra.

Obrigado pela colaboração!

Exemplos de Preenchimento

100, 90, 80, 70, 60, 50

Dados Pessoais

Idade:

Sexo: M / F

Altura: 1,90 / 1,80 / 1,70 / 1,60 / 1,50 / 1,40

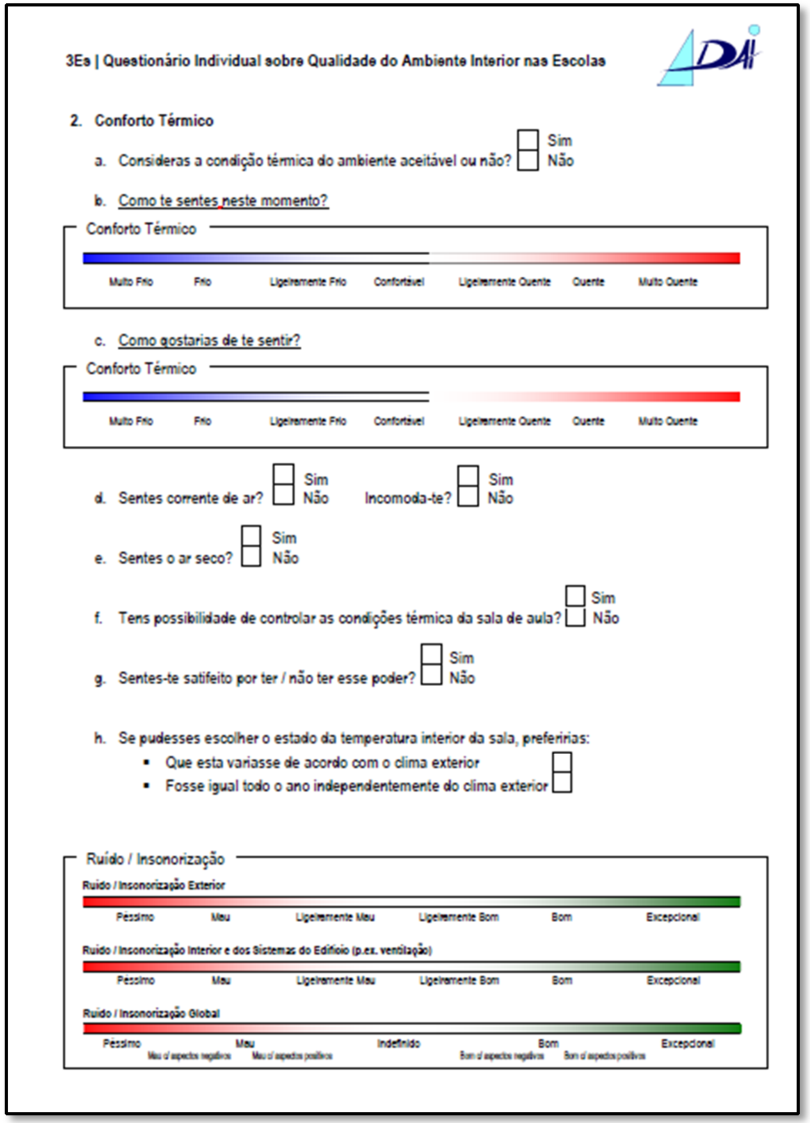
Peso: 100 / 90 / 80 / 70 / 60 / 50

Vestuário:
- T-shirt / camisa
- Camisola
- Calças
- Saia /calções
- Impermeável
- Sobretudo

Localização na sala de aula:
- Junto à porta de entrada
- Junto a uma janela
- Junto a uma parede interior
- No meio da sala
- Num canto interior da sala
- Num canto junto a uma janela

1. Informações referentes ao contexto do preenchimento do inquérito:

- Vives com fumadores? Sim / Não
- Fumas? Sim / Não
- Sofres de algum distúrbio respiratório (bronquite, constipação, etc)? Sim / Não
- Que tipo de atividade desenvolvias nos ultimos 30min antes deste inquérito?
  - Aula (ler, escrever, matemática, ciências, etc?)
  - EF (educação física, jogos)
  - TIC (computador)
  - Recreio
  - A descansar no intervalo
  - Almoçar



3Es | Questionário Individual sobre Qualidade do Ambiente Interior nas Escolas

2. Conforto Térmico

a. Consideras a condição térmica do ambiente aceitável ou não? ☐ Sim ☐ Não

b. Como te sentes neste momento?

Conforto Térmico

Muito Frio | Frio | Ligeiramente Frio | Confortável | Ligeiramente Quente | Quente | Muito Quente

c. Como gostarias de te sentir?

Conforto Térmico

Muito Frio | Frio | Ligeiramente Frio | Confortável | Ligeiramente Quente | Quente | Muito Quente

d. Sentes corrente de ar? ☐ Sim ☐ Não Incomoda-te? ☐ Sim ☐ Não

e. Sentes o ar seco? ☐ Sim ☐ Não

f. Tens possibilidade de controlar as condições térmica da sala de aula? ☐ Sim ☐ Não

g. Sentes-te satifeito por ter / não ter esse poder? ☐ Sim ☐ Não

h. Se pudesses escolher o estado da temperatura interior da sala, preferirias:

- Que esta variasse de acordo com o clima exterior ☐
- Fosse igual todo o ano independentemente do clima exterior ☐

Ruído / Insonorização

Ruído / Insonorização Exterior

Péssimo | Mau | Ligeiramente Mau | Ligeiramente Bom | Bom | Excepcional

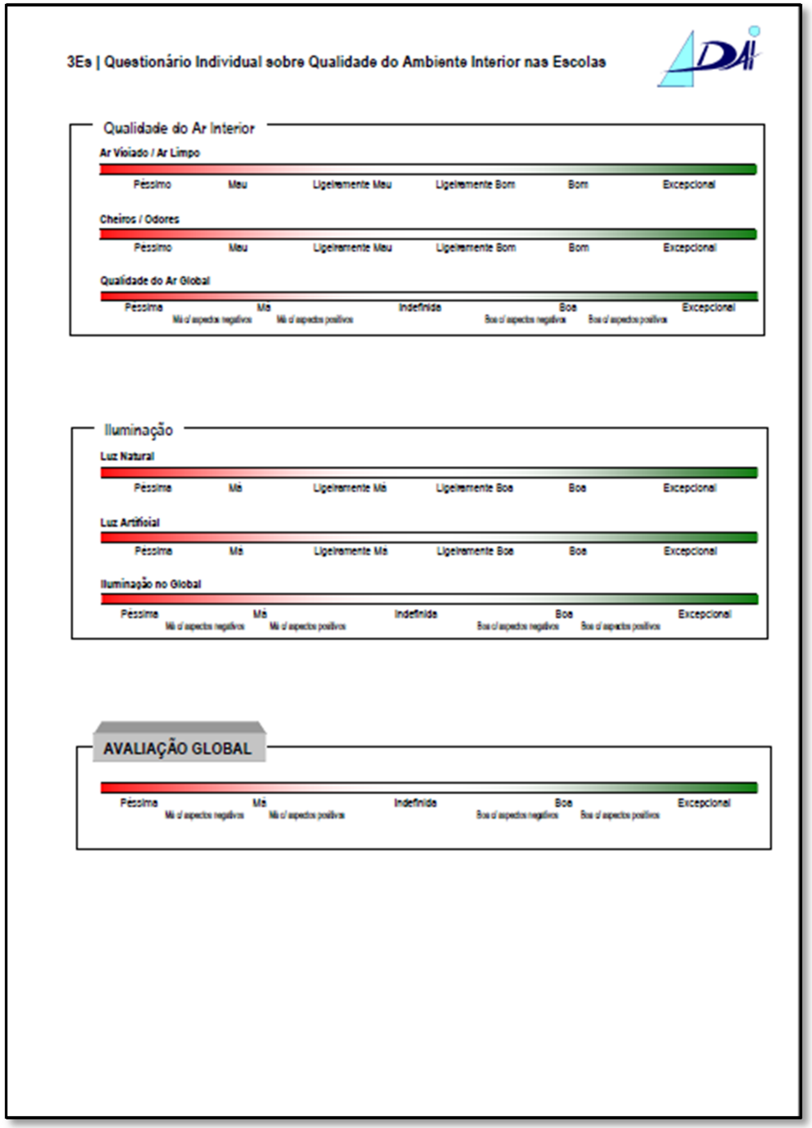
Ruído / Insonorização Interior e dos Sistemas do Edifício (p.ex. ventilação)

Péssimo | Mau | Ligeiramente Mau | Ligeiramente Bom | Bom | Excepcional

Ruído / Insonorização Global

Péssimo | Mau | Indefinido | Bom | Excepcional

Mau c/ aspectos negativos | Mau c/ aspectos positivos | Bom c/ aspectos negativos | Bom c/ aspectos positivos



3Es | Questionário Individual sobre Qualidade do Ambiente Interior nas Escolas

Qualidade do Ar Interior

Ar Viciado / Ar Limpo

Péssimo | Mau | Ligeiramente Mau | Ligeiramente Bom | Bom | Excepcional

Cheiros / Odores

Péssimo | Mau | Ligeiramente Mau | Ligeiramente Bom | Bom | Excepcional

Qualidade do Ar Global

Péssima | Má | Indefinida | Boa | Excepcional

Má c/ aspectos negativos | Má c/ aspectos positivos | Boa c/ aspectos negativos | Boa c/ aspectos positivos

Iluminação

Luz Natural

Péssima | Má | Ligeiramente Má | Ligeiramente Boa | Boa | Excepcional

Luz Artificial

Péssima | Má | Ligeiramente Má | Ligeiramente Boa | Boa | Excepcional

Iluminação no Global

Péssima | Má | Indefinida | Boa | Excepcional

Má c/ aspectos negativos | Má c/ aspectos positivos | Boa c/ aspectos negativos | Boa c/ aspectos positivos

AVALIAÇÃO GLOBAL

Péssima | Má | Indefinida | Boa | Excepcional

Má c/ aspectos negativos | Má c/ aspectos positivos | Boa c/ aspectos negativos | Boa c/ aspectos positivos

Appendix F. PPD & PMV indices. Simulation results: estimation on comfort indices

Table 53 – Summary table of the simulated results in the six schools.
The bold values in this table differentiate the parameter that was changed in each of the simulations. It highlights the fact that the results are due to the different input value of this parameter, since it is the only one being changed in all the simulations.

Parameters	**Simulation MMV1**			**Simulation MMV2**			**Simulation PBL1**			**Simulation PBL2**		
	I	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
M (met)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
W (met)	0	0	0	0	0	0	0	0	0	0	0	0
I_{cl} (clo)	0.52	0.52	0.52	0.58	0.58	0.58	0.49	0.49	0.49	0.53	0.53	0.53
T_a (ºC)	25.7	25.7	25.7	28.3	28.3	28.3	24.7	24.7	24.7	24.1	24.1	24.1
HR (%)	45.5	45.5	45.5	50	50	50	55.2	55.2	55.2	58.7	58.7	58.7
T_r (ºC)	**25.7**	**24.7**	**26.7**	**28.3**	**27.3**	**29.3**	**24.7**	**23.7**	**25.7**	**24.1**	**23.1**	**25.1**
V_{ar} (m/s)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
PMV	0.29	0.15	0.44	1.17	1.03	1.31	0.01	-0.13	0.15	-0.07	-0.20	0.07
PPD	6.8	5.5	8.9	33.8	27.5	40.7	5.0	5.4	5.5	5.1	5.9	5.1

	Simulation BJA1			**Simulation BJA2**			**Simulation PTG1**			**Simulation PTG2**		
	I	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
M (met)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
W (met)	0	0	0	0	0	0	0	0	0	0	0	0
I_{cl} (clo)	0.46	0.46	0.46	0.45	0.45	0.45	0.54	0.54	0.54	0.55	0.55	0.55
T_a (ºC)	22.1	22.1	22.1	25.2	25.2	25.2	23.8	23.8	23.8	24.9	24.9	24.9
HR (%)	55.2	55.2	55.2	41.4	41.4	41.4	50.8	50.8	50.8	35.1	35.1	35.1
T_r (ºC)	**22.1**	**21.1**	**23.1**	**25.2**	**24.2**	**26.2**	**23.8**	**22.8**	**24.8**	**24.9**	**23.9**	**25.9**
V_{ar} (m/s)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.54	0.54	0.1	0.1	0.1
PMV	-0.85	-0.99	-0,72	-0.01	-0.15	0.14	-0.19	-0.32	-0.05	0.04	-0.10	0.18
PPD	20.4	25.6	15.8	5.0	5.5	5.4	5.7	7.2	5.0	5.0	5.2	5.7

	Simulation GRD1			**Simulation GRD2**			**Simulation BGC1**			**Simulation BGC2**		
	I	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
M (met)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
W (met)	0	0	0	0	0	0	0	0	0	0	0	0
I_{cl} (clo)	0.56	0.56	0.56	0.58	0.58	0.58	0.60	0.60	0.60	0.60	0.60	0.60
T_a (ºC)	24.4	24.4	24.4	26.8	26.8	26.8	22.0	22.0	22.0	24.3	24.3	24.3
HR (%)	59.7	59.7	59.7	49.3	49.3	49.3	68.1	68.1	68.1	65.9	65.9	65.9
T_r (ºC)	**24.4**	**23.4**	**25.4**	**26.8**	**25.8**	**27.8**	**22.0**	**21.0**	**23.0**	**24.3**	**23.3**	**25.3**
V_{ar} (m/s)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
PMV	0.08	-0.05	0.22	0.73	0.60	0.87	-0.46	-0.59	-0.34	0.17	0.04	0.30
PPD	5.1	5.1	6.0	16.3	12.4	20.9	9.5	12.4	7.3	5.6	5.0	6.9