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Improving energy use in schools: from IEQ towards Energy Efficient Planning – Method and in-field application to two case-studies

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Abstract

Indoor environmental quality (IEQ) and energy conservation in schools are complex challenges. A significant part of the energy demand in these buildings addresses ventilation and temperature indoors. When confronted with money/energy constraints, the tendency of school boards is to cut on IEQ requirements, compromising the comfort of the occupants or worse, their health. Besides local energy production, either electrical or heating, major focus on Building Management Systems' (BMS) operation has been suggested, aiming at developing evidence-based energy conservation measures.

Based on two field-studies, a joint approach of energy and IEQ auditing was developed, establishing a state-of-the-art of the current situation of the secondary schools in Portugal. The present study aims at enhancing energy efficiency in schools unveiling that it is possible to improve the HVAC systems' operation and optimize energy use and costs, while maintaining good environmental conditions.

This paper also seeks to contribute to the implementation of Energy Efficiency Plans (EEP) in school buildings, presenting a comprehensive methodological approach on energy consumption in this typology of buildings, centered on the fundamental role of BMS and their proper programming. The obtained results show that there is a considerable potential for reducing energy consumption and improving energy use – in one of the schools by simply adjusting the BMS operation schedule, a decrease between 20 – 36 % of the useful thermal energy consumption is expected (14.1 – 24.7 kWh/m^2); in other occasions, a significant IEQ improvement is expected due to longer HVAC running period.

Keywords

Energy efficiency planning; School buildings; Occupancy information; Energy management; Responsible behaviour; Building Management Systems.

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List of nomenclature

3Es	Energy Efficient Schools project (in Portuguese: *Escolas Energeticamente Eficientes*)		
		HVAC	Heating Ventilation and Air Conditioning
AHU	Air Handling Unit	IAQ	Indoor Air Quality
BAC	Building Automation and Control	IEQ	Indoor Environmental Quality
BMS	Building Management Systems	IU	Indoor Unit
C_{CO_2}	CO_2 concentration	LV	Low-voltage
CRT	Cathodic Ray Tube	MMV	Montemor-o-Velho (*school located in*)
DHW	Domestic Hot Water	MTS	Matosinhos (*school located in*)
ECM	Energy Conservation Measures	MV	Mechanical Ventilation
EEP	Energy Efficiency Plan(s)	NG	Natural Gas
EM	Energy Manager	PD	Percentage of Dissatisfied
EPBD	Energy Performance of Buildings Directive	*Q*	Fresh air flow rates (m^3/h)
EU	European Union	R&D	Research and Development
EUI	Energy Use Indicator	SCE	Energy Certification System (in Portuguese: Sistema de Certificação Energética dos Edifícios)
EVS	Electronic variable-speed		
ε_V	ventilation efficiency	Ta	Air temperature
GFA	Gross Floor Area	TC	Thermal Comfort
HDD	Heating Degree Days	TUFA	Total Useful Floor Area
HRU	Heat Recovery Unit	VRF	Variable refrigerant flow

Contents

1. Introduction

1.1 Aim and scope of the paper

Recently, more and more emphasis has been put on the potential of the building sector towards energy efficiency. An example can be found on the EU's 2020 established goal for energy saving in public buildings: 20 % of its primary energy consumption compared to projections [1]. At the same time, an important modernization of secondary school building stock has been developed during the last decade in Portugal - *Modernization of Public Secondary Schools Program* [2].

Against such background, an assessment of this program has been performed, mainly *'focused on energy consumption issues, (...) in the framework of a* research *and development (R&D) project'– Escolas Energeticamente Eficientes* (3Es) [3]. The R&D project has been developed in a combined strategy of energy auditing and Indoor Environmental Quality (IEQ) analysis [4], alike in [5], [6], [7].

Energy and IEQ post-occupancy audits, especially during the first occupancy phase of new and refurbished buildings, are important strategies to improve their energy use [8], [9], [10]. In new buildings, some of the most common errors are due to inadequate operation and management strategies. Indeed, excessive energy consumption in buildings can result from poor control of HVAC systems and/or lighting [11].

Within this context and in the framework of the cited project, based on two case-studies, the current study aims at enhancing energy efficiency in schools unveiling that it is possible to improve the HVAC systems' operation and optimize energy use and costs, while maintaining good indoor environmental conditions [herein, only indoor air quality (IAQ) and thermal comfort (TC) are addressed]. A useful methodology for energy professionals and school managers, for identifying potential energy saving opportunities in schools [based on the analysis of building management systems (BMS) and behaviour practices locally observed] is presented.

The research methodology is provided in section 2, while in section 3, the case-studies are presented. In section 4, some findings are unveiled and in section 5, the energy savings' estimations are presented. Here, it is also presented a discussion on energy efficiency plans for schools. A final section of conclusions summarizes the study.

1.2 IEQ in classrooms. Energy consumption implications

IEQ in a school building is a very important topic – not only children are particularly sensitive to low quality indoor environments because they are still under development [12], but also, classrooms have a high occupancy rate that may degrade the health, comfort and performance conditions [13], [14]. Influence on productivity of TC and IAQ has been an explored topic in school buildings, as well [15], [16]. The relation between energy consumption in schools and IEQ/ventilation has been greatly explored in [17], [18], [19], [20].

A significant part of the new and refurbished educational buildings in Portugal have been designed in compliance with 2006 law ventilation requirements [21], based upon the European Directive 2002/91/CE [22]. For classrooms, for instance, it became mandatory assuring minimum IAQ and TC parameters, while guaranteeing energy efficiency. The maximum concentration limits of the pollutants were tabled, set per occupant and per unit area of space [21], [23]. This regulation, imposed for a room of 25 pupils (average 50 m^2), minimum fresh air flow rates (Q) of 30 m^3/h (8.33 L/s) per occupant and CO_2 concentration lower than 1000 ppm. These values were more demanding than in many other European countries [24], e.g. in England, the requirement limiting daily average of CO_2 concentration to below 1500 ppm recommends the provision of 8.0 L/s/person of fresh air for schools [25].

Broadly, the new projects presented values of total air flow rate between 750 – 1000 m^3/h (208.33 – 277.78 L/s), depending on the ventilation efficiency (ε_V). Recently, this legislation was under revision and a new one is in force since December 2013 [26]. The new mechanical ventilation requirements allow two different methods for the calculation of *Q*: one prescriptive (also based on fixed values) and one analytical (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 [23], [27]. The implications of this new legislation are explored in **section 4.2**.

Thermal adaptation can also make an important contribution in HVAC energy use. In many parts of the globe this issue has been achieving a higher level of concern. In Japan, for instance, due to the 2011 tsunami and succeeding energy accessibility limited conditions, indoor air temperature values in the classrooms during Summer are now kept up to 28 ºC [28],[29], above the reference values [30], [31]. From an opposite perspective [32], through the study of thermal adaptation of university students, in dormitories and classrooms, it was shown that during the heating season in China, *'human adaptability to the coldness'* should be paid more attention and that *'the formation of high thermal comfort zone should be avoided'*. In two previous studies on IAQ and TC in Portuguese classrooms [33], [34], the authors concluded that students accepted indoor temperatures (Ta) higher than 25 ºC, under free running conditions in mid-season, identifying also a preference tendency for slightly warm environments. In other Romanian case [35], the authors found that students considered 18 ºC air temperature as comfortable (and 20 ºC as warm) during winter time.

For the present, the focus of this study is mainly addressed towards the ventilation requirements and time-scheduling of BMS, as laid down in the following sections.

1.3 The essential role of BMS

Building Management Systems (BMS) are important tools aiding buildings' operation. BMS have been a reality for more than 20 years and automatic data acquisition systems have been used for spot or long term measurements [36]. Their use has been greatly encouraged by 2010 EPBD revision [37] and reinforced in EN15232:2012 [38]. Different types of BMS can be found: ideally, besides energy monitoring, a complete BMS would provide good IEQ, which cannot be otherwise guaranteed [39], [40]. Theoretically, BMS allow to control different running systems in buildings and assure the accurate management of the energy demand, improving comfort levels and IAQ [41], [42]. Traditionally, three BMS control features influence energy performance [43]:

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

In recent years, more emphasis has been put into HVAC operation/commissioning and its impact on energy consumption [44]: *(i)* in [45], the authors developed an *'in-situ implementation and validation of a* CO_2*-based adaptive demand-controlled ventilation strategy, (…), 'implemented in an independent Intelligent Building Management and Integration platform (IBmanager), which'* communicates with the BMS; *(ii)* in [46], to build *'a smart building management and control leverages', 'an ICT infrastructure made of heterogeneous monitoring and actuation devices'* was developed, and a *'Web-based infrastructure to make transparent to the end-user the underlying devices'* was projected; *(iii)* in [47], the focus is the automated fault detection and diagnosis process, most related to air handling units (AHU) detection of faults and commissioning; *(iv)* in [48], the authors developed a framework for integrating BMS data into a building information model to inform both designers and facility managers; *(v)* in [49], *'hourly smart metering consumption data on electricity and district heating'* has been used *'to analyse complex multivariate data in order to increase knowledge of the* buildings' consumption profiles and energy efficiency'.

Despite all these new developments, to the authors' best knowledge, few in-field applications have been found in literature exhibiting both energy savings and IEQ numbers in schools. In [50], BMS operation is suggested, but not actually tested. In many cases, the outputs of (new) developed tools concern alternatives at the design phase. In [51], the authors unveiled the IntUBE research project and how it will supposedly *'contribute to the development of virtual (collaborative) life cycle building tools'*. In another case-study [52], one interesting example of the HVAC optimization is presented: in this Belgium school, *'the HVAC system was optimized by integrating an additional cooling coil in the exhaust airflow of the air handling unit in order to recuperate waste heat from the exhaust ventilation air'*. Nonetheless, both *'school building and HVAC system were modeled'*.

In the *3Es project* schools' selection, the BMS varied significantly. However, in general these systems allowed managing HVAC systems. In one of the schools, the BMS was slightly more complex, allowing also lighting control and the solar panels' system, besides fire alarms' visualization. Within the current study, the focus was set on steps 1 and 2, displayed above, starting with the analyses of the electricity supply contract and the BMS configuration.

2. Research methodology

The identification of potential energy saving opportunities in buildings has historically been carried out through the 'energy audit' [53], [54] and/or energy simulation tools [55], [56], [57]. Within the *3Es project*, an integrated strategy towards energy efficiency planning in secondary schools was proposed, following the common steps to post-occupancy evaluation [58]. It included energy auditing and IEQ assessment, both objective and subjective [4], in order to identify and evaluate potential Energy Conservation Measures (ECMs) [59]. The IEQ audit (short-term monitoring of air temperature, relative humidity and CO_2 concentrations) allowed also the estimation of air exchange rates through the concentration decay method using metabolic CO_2 as the tracer gas [60][1], determining the current airtightness condition of the refurbished schools.

This joint approach allowed establishing a state-of-the-art of the current situation of the secondary schools in Portugal, both in terms of their IEQ condition and energy consumption, i.e. leading to the development of a ranking and building up reference indicators for educational public buildings in the country for the first time [61], [62], [63]. Two schools were selected for major development: the schools worst performing in terms of two energy use indicators (EUI): kWh/m^2 – case-study MTS, and $student/m^2$ – case-study MMV (**Table 1**).

[1] The IAQ and TC assessment methodology used in the *3Es project* has been earlier published in 2013 [33]. The integrated approach (IEQ + energy audit) presented in [4], applied to another case study was later published in [82].

Table 1 – Energy use indicators of the two case-studies: MTS* and MMV**.

EUI/ School ID	*Gross Floor Area* (GFA)	**EUI (kWh/m²)**	*Total Useful Floor Area* (TUFA)	**EUI (kWh/m²)**	**EUI (kWh/student)*** **
MTS	12695 m²	**66**	10013 m²	**84**	**592**
MMV	8326 m²	**43**	7172 m²	**50**	**1128**

** MTS – school located in Matosinhos; ** school located in Montemor-o-Velho; *** number of students of academic year 2011/12*

By integrating the combined approach on energy and IEQ auditing, centred on the fundamental role of BMS and their proper programming, the research on this field is moved further. The results presented in this paper enlarge the study that has been developed so far, aiming at achieving the implementation of energy efficiency plans (EEP) in mechanically ventilated Portuguese schools (as it is already common practice in other countries [64], [65]).

One of the major contributions of the current study is the time saving in the energy simulation process: instead of a 'traditional' simulation the entire building, the authors propose a simplified method targeted directly at one of the most significant end-use energy consumer, HVAC, while considering IEQ and users' subjective evaluation. Thus, the authors developed a new tool in an Excel file, most user-friendly, addressed to the HVAC system operation [66]. **Figure 1** conveys the proposed implementation process of a replicable strategy towards an energy efficiency plan for new and refurbished school buildings.

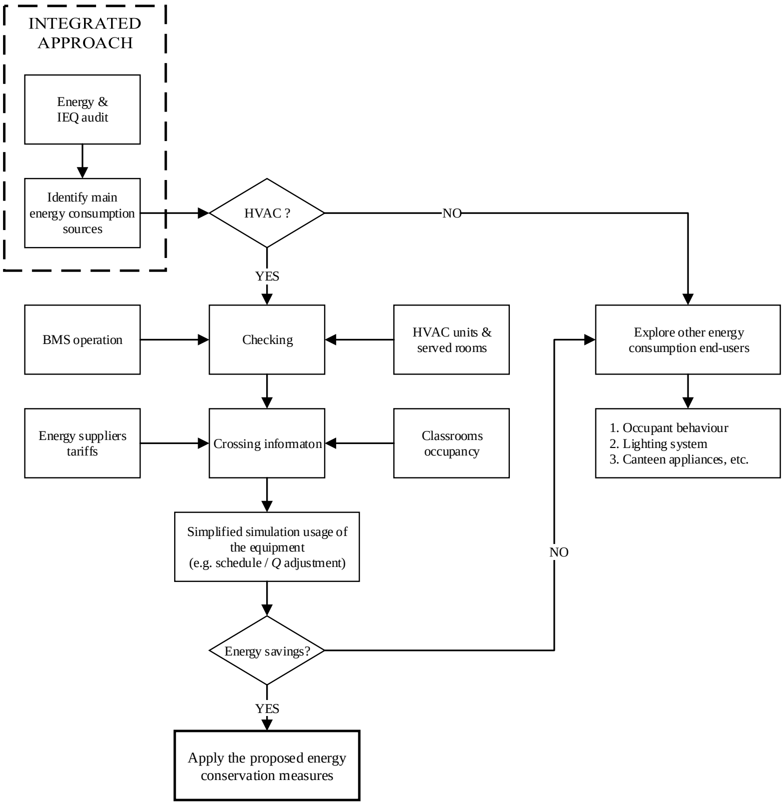
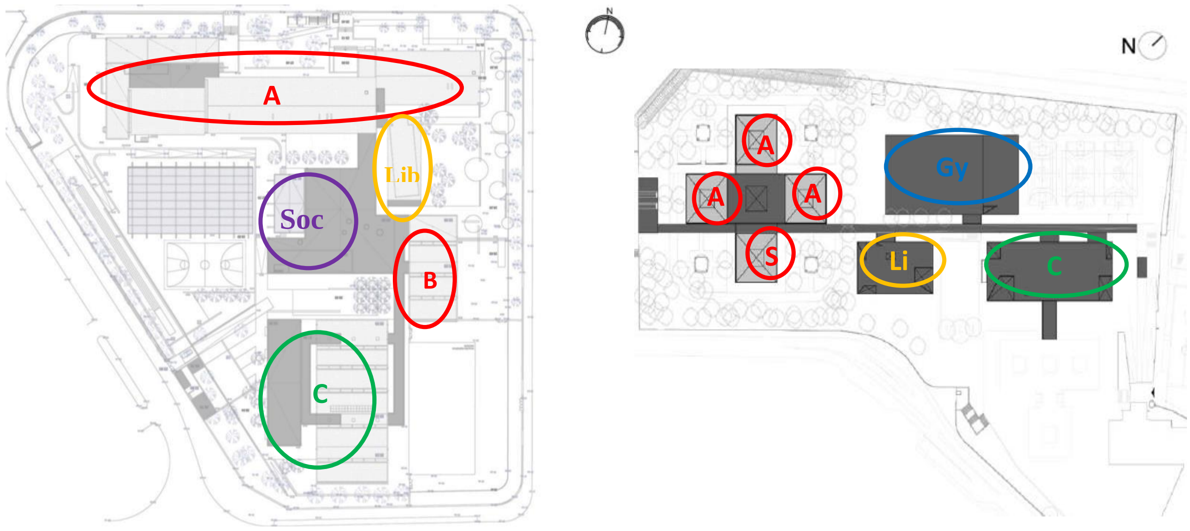


Figure 1 – Implementation process of a primary energy efficiency plan for new and refurbished school buildings

3. Case-studies presentation

The first case-study (MTS) is located in the north of the country, nearby the city of Porto in Matosinhos; the other school (MMV) is located in Montemor-o-Velho, nearby Coimbra.

MTS, located 1.5 km away from the European Atlantic coast, was formerly opened in 1969. Between September 2008 and June 2010, it has undergone a significant retrofitting process. Besides the refurbishment of the existing buildings (A, B and C), the intervention foresaw the construction of two new buildings: one with social character (living area/leisure) and the labs' buildings, associated to the workshops (C). The library (Lib) was not physically intervened, only the HVAC system was refurbished. **Figure 2.a)** illustrates the space and corresponding organisation of the school. The city of Porto, less than 7 km away, is characterized by its temperate Mediterranean climate (maritime feature), corresponding to mild winters and mild summers, due to the softening effect of the ocean. Average monthly mean (AMM) temperatures are not very high, usually not exceeding 20 ºC in summer and occasionally lowering 10 ºC in winter. The annual temperature amplitude is low but the average monthly rainfall (AMR) values are quite significant, registering higher values during winter (e.g. 194.7 mm in December).



a) **b)**

Figure 2 –Schools layout plan (post-intervention): (a) Matosinhos (MTS); (b) Montemor-o-Velho (MMV) [Source: *Parque Escolar*, EPE (2012)]

The second case-study, MMV is part of a wider school complex, including *Escola Básica 2/3 Jorge de Montemor* and a kindergarten. Once inaugurated in the 70's, the school was subject to rehabilitation works from July 2009 until November 2010. This intervention, which in a preliminary stage only foresaw major refurbishing works in the existing buildings (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), as presented in **Figure 2.b)**. MMV is furthest from the Atlantic coast (17.5 km) and its weather is influenced by this distance, approaching the characteristics of the city of Coimbra: lower average wind speed between 2.6-3 m/s and lower AMR, between 103-127 mm during the rainiest period of the year (October-February). The AMM temperatures vary between 9.6-21.6 ºC, registered in January and in July, respectively.

Given the school period, September – June / July (period of exams), and the observation of normal climatological for the cities of Porto and Coimbra, it is expected that the schools have higher heating than cooling needs. The calendar of the main visits promoted to the schools under study is shown in **Table 2**.

Table 2 – Scheduling of the main visits promoted to the secondary schools under study.

School ID	Visit I – Preliminary inspection	Visit II – Monitoring campaign (Energy + IAQ)	Visit III – Monitoring campaign (IAQ)	Visit 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 – 06/06/2013*	13/06/2013 – 02/07/2013	11, 22 & 23/06/2015

Due to the schools' recent refurbishment, the main characteristics of the envelope have been optimized. In MTS, two major solutions have been found: *1)* thermal insulation placed on the inside of the existing exterior concrete/masonry wall (50 mm rock wool layer); *2)* ETICS (External Thermal Insulation Composite System) over new walls (thermal perforated brick – 200 and 300 mm width). Most of the ceilings are suspended in *microperforated* plasterboard. In terms of glazing surfaces, lacquered aluminium frames with double glazing solution prevail, provided of transparent internal shading devices.

In MMV the external walls present three types of generic solutions, namely: *(i)* walls composed 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); *(ii)* walls composed of 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) or *(iii)* 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 50 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 by double glazing elements in aluminium frames with thermal break.

3.1 Schools' energy consumption

Both schools consume electricity and natural gas (NG). In MTS, electricity is supplied according to a Medium Voltage tariff contract (292.95 kVA), with four different daily periods and energy prices (Appendix A, **Table A.1)**. In 2011/12, NG accounted for 40 % of the total energy consumed. This is particularly significant when considering the average values of the *3Es* project schools' selection: 76 % electricity vs. 24 % NG [62]. Regarding renewable energy, only domestic hot water (DHW) production has been provided, covering part of the DHW demand (15 solar panels of 2 m^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 preparation of meals.

In MMV, electricity is supplied according to the same tariff (372 kVA contracted power, instead). In 2011/12, NG accounted for 22.2 % of the total energy consumed. This value is closer to the *3Es* values [62], but significantly lower than MTS': here, heat transfer in classrooms is assured through hot water radiators. NG consumption numbers relate DHW production and the preparation of meals[2]. DHW is prepared in two different locations: in the canteen and in the gym (1+2 boilers, 96.5 kW/each). In the latest, hot water production serves both DHW and air heating. Renewable energy has not been considered in the current analysis since the 32 solar panels' system (installed on top of the Gym) was not operating during the monitoring campaign period.

Further information regarding other energy-using equipment, such as ICT equipment and lighting systems can be found in **Appendix B**.

[2] During the scholar year 2011/12 over 36200 meals were prepared in MTS, while in MMV this number equals 9900.

3.2 HVAC systems characterization

Regarding thermal energy production, MTS has a central heating and cooling water system. An air-to-water chiller provides cold water. Its main characteristics are given in **Table 3**, along with the characteristics of the DHW production and air heating (two NG boilers) equipment. Thermal diffusion is provided by fan coil units, hot water radiators and ventilation grids. The air renewal is ensured through air handling units (AHU) equipped with heating and cooling coils – the AHUs plan distribution is presented in **Figure 3**.

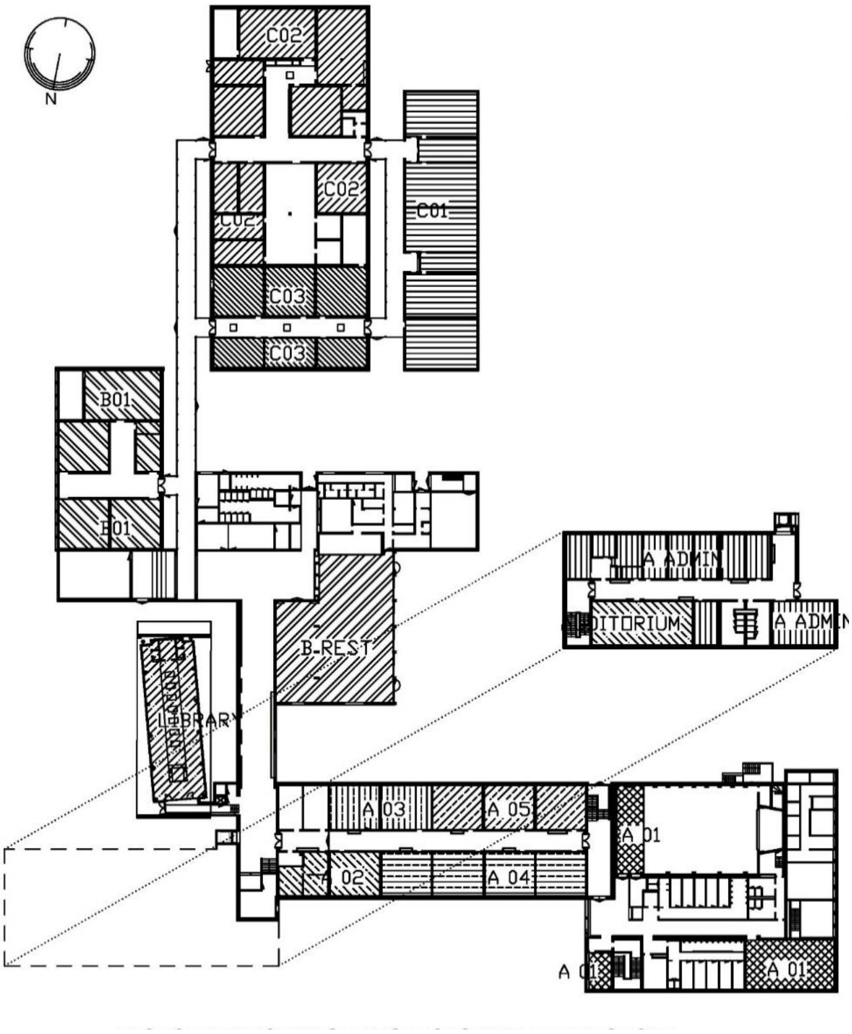


Figure 3 – Simplified floor plan of the school buildings (level -1: A, B, C and level 2: A) and main thermal zoning (AHUs plan distribution).

Typically, indoor climate control in a school building is divided into zones. Since each zone includes several rooms, the zones are designated as *'under-actuated'* [67], e.g. each classroom climate cannot be independently controlled, since they share the same AHU.

Table 3 – Main characteristics of the thermal energy equipment.

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

*Note: *COP = 2.8; ** Efficiency 92 %. Data provided from the manufacturer.*

Contrarily, in MMV the thermal energy production follows a decentralized heating/cooling strategy – each building has its own air-conditioning system (type VRF with indoor and outdoor units) and heat recovery ventilation unit (HRU). In the Central Building (A1-S) the thermal energy is obtained through VRF units with cooling and heating capacity (varying between 7.75 – 11.6 kW). The indoor units are ceiling-mounted, installed just before each classroom, while the external units are installed in the roof of each of the buildings. Similarly, the HRUs that provide air renewal are also here located (each unit is equipped with heating and cooling coils). In the library, canteen and cafeteria, the thermal energy production is assured through *rooftop* units with cooling and heating capacity (varying between 6.79 – 21.9 kW). The main characteristics and thermal zoning of the HVAC systems, controlled by the BMS, are presented in **Table 4** and **Figure 4**, respectively.

Table 4 – Main characteristics of the VRF and *roofto*p 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*

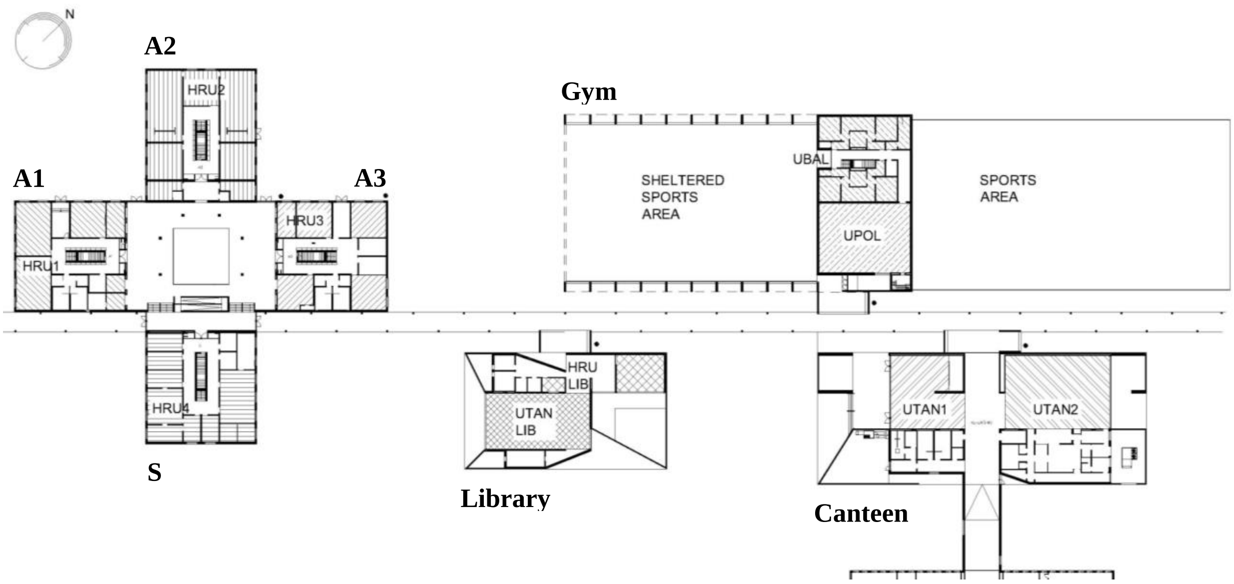


Figure 4 –Simplified floor plan (level -1) of the various school buildings in MMV (A1 – S, Lib, Gym & Canteen) and main thermal zoning

4. Findings

In a first approach to the BMS interface of MTS, some inconsistencies between the plans in the BMS and the signalled spaces and naming in the classrooms have been found. Naturally, this circumstance makes the BMS correct programming harder. The central heating and cooling equipment (**Table 3**) operate in a stand-alone configuration: through the BMS it can just be turned on/off. In terms of the AHUs, the temperature control is piloted through sensors placed in the supply and return air ducts (5 out of 14 AHUs, **Table A.3**). In contrast to other cases under the same *Modernization Program* [68] or within the *3Es* project [69], this BMS does not allow lighting control. It allows controlling and managing numerous HVAC equipment of the school, time scheduling of the various equipment, besides set point temperature definition of the acclimatized areas, and commanding supplying and extraction fans.

In contrast, the indoor climate of each classroom in MMV can be controlled independently – each zone consists of a single room, therefore designated as 'fully activated' [67]. 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 exhaustion fans, may be dis/enabled through their operation time. For this reason, the BMS is complemented with a software package from the manufacturer. Each classroom's air temperature (Ta) can be individually controlled, by setting Ta set points at each indoor VRF unit dedicated to the classroom.

4.1 Improving the energy use - Time scheduling

Concerning MTS, it was assumed that classrooms' occupancy corresponded to the time-table occupancy defined at the beginning of the school year (8:15-18:00 + 19:00-22:50[3] – 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 A.1**, relating the electricity supply contract, with the AHUs scheduling in the BMS (**Table 5**), it was verified that there was not a grounded reason for AHUs' trigger at 5:00 am. Avoiding a peak-load at 8:00 am, 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).

Table 5 – Main automatic systems operational times (MTS).

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, ICT rooms, labs	C
Extraction Fan	**-**	**Various schedules**		**Bathrooms / Kitchen area**	**Various**

In terms of IAQ, for example, the results obtained from the monitoring carried out in classrooms (visits II and III in **Table 2**), revealed the classrooms' capacity to remove CO_2 during night time. The IAQ analysis, based on the measured CO_2 average concentration during the occupancy periods above the outdoor concentration[4] also revealed that the Percentage of Dissatisfied (PD) varied between 8.3 % – 31.3 % (the extreme noncompliance values were obtained in the classrooms where the occupancy load was higher than projected).

Some other mismatches were found (**Table 5**): *i)* considering the library opening (9:00 am), it would be possible to activate this AHU only at 8:30 am (instead of 6:00 am). Additionally, it could be turned off earlier, as this room is not daily open until 17:00; *ii)* AHU A1 (serving the secretariat) was unadjusted to room occupancy

[3] Only very few classrooms were occupied between 22:55 – 23:45.

[4] PD(%) = 395*EXP (-15,15*C_{CO2}^-0,25) [83] – where PD stands for Percentage of Dissatisfied and C_{CO2} for the CO_2 concentration.

period (9:00 – 17:30); *iii)* since there were only a few night classes, bathrooms air exhaustion fans operation could be reduced during the non-occupancy period (as schedule 'All-day' was also found). A proper AHU scheduling also optimizes the running time of the heating and cooling systems (here, classrooms are only provided a heating system).

As previously stated, in MMV, Ta can be individually controlled in each classroom - nevertheless, the school has opted by blocking each building classrooms' Ta. In some indoor units' (IU) – part of the VRF system, Ta is blocked on the software package. **Figure A.1** (Appendix A), corresponding to building A2, shows one of these situations. In here, besides being shown the graphical interface software package, a detailed view module of the HRU, serving the same building, controlled from the BMS is also displayed.

Building S – that holds the major administrative areas – is given total fan velocity and Ta autonomy. **Table A.2** (Appendix A) presents a synthesis of the school's main HVAC systems scheduling. This BMS only allows a weekly agenda. It does not allow a monthly scheduling or holiday data integration.

4.2 Improving the energy use - Ventilation system sizing

Although having undergone recent interventions, the ventilation parameters were out-dated. This was due to the schools' HVAC systems, which were designed complying with the legislation implemented in 2006 [21]. A comparison between the former and current values is presented in **Table 6** [23]. Additionally, another difference can be found in the ongoing 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 slightly lower than EN 15251 ventilation rates' reference value 7.0 L/s/person [31].

Table 6 – Synthesis table of the old and new fresh air flow rates (*Q*) [23]

Space	Design conditions (2007 legislation [21])		Prescriptive method (2013 legislation [26])		Analytical method (2013 legislation [26])	
	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

In [23], through simulation, the authors revealed that by simply estimating air flow rates through the prescriptive method, for a typical classroom (25 students and 1 teacher) the total air flow rate decreased from 975 m^3/h (270.33 L/s) – estimated in the design phase – to 624 m^3/h (172.33 L/s). The conclusions were quite pointed: the new legislation revealed a potential reduction on the total primary energy consumption of over 30 % in the heating and ventilation components. The influence of using the requirements of current regulation in the final energy consumption of school buildings has been formerly simulated [23], and it has been concluded that these could lead up to 5 % decrease in the final energy consumption of the studied school.

Given these figures, it can be stated that (re)dimensioning/adjusting the ventilation system of a school to its real needs might have a significant contribution to its sustainability.

In **Table A.3** (Appendix A) it is displayed a list of the AHUs in MTS and corresponding fresh air flow rates (*Q*) – existing and proposed values. Adapting the existing AHUs to the current IAQ requirements is a good opportunity for energy savings: if less air is supplied into the spaces, besides decreasing Q, less air needs to be heated or cooled. As presented by Masy & André (2012) [70], *'well controlled ventilation can save up to 44% of heating energy'*. Potential energy savings of this measure are further developed in **section 5.2**. Since the canteen area (served by *AHU B REST*) is over pressured, no change was suggested. In this particular case, the amount of supply air is not determined by the ventilation requirements but by the thermal load of the room.

Alike MTS, also MMV's HVAC systems were designed in accordance with the precedent legislation. Therefore, they were also oversized. Besides *rooftop* units serving the bar/canteen and library, all the other spaces were oversized relating the current legislation requirements. A summary of the Q requirements for each space/equipment, is presented in **Table A.4** (Appendix A).

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). Contrarily to MTS, in MMV the *all-air systems* were considered to supply simultaneously fresh air and acclimatize indoor spaces – for this reason Q cannot be simply 'cut'. Otherwise, the comfort of the occupants could be compromised.

4.3 Human Factors, technological illiteracy or sins of omission

In [71], the authors explored through simulation, the occupancy based indoor climate control contribution towards energy-efficiency in commercial buildings. Another study, on Swiss office buildings equipped with integrated room automation, investigated the potential of using occupancy information to implement a more energy efficient building climate control [72]. In other cases, as in [73], the impact of a special proactive strategy in order to reduce energy consumption in a three-story university building was simulated. Besides lighting and temperature adjustment to *'predicted occupancy and occupant preferences based on occupant schedules'*, the coordination of meetings, *'originally scheduled in 3 different thermal zones, were investigated for relocation'*. This control strategy revealed improvements both in terms of the comfort of the occupants and reduced energy consumption during times of peak occupancy.

Behavioural issues are not limited to the thermal adaptation indoors. In the present study, the authors support that human occupancy – based on the classrooms' occupancy schedule/time-table, should be integrated in the HVAC system operation/BMS programming. As stated in [74], *'constant change of use and poor maintenance can significantly reduce the effectiveness of any BMS'*. Besides space occupancy, human behaviour strongly influences energy consumption: an example is the library in MTS. Architecturally, it works as an independent rectangular glass box, developed according to the N-S axis. The lighting installed power is almost 1700 W (lighting density of approximately 8.9 W/m^2). This operation system is locally controlled by the person responsible for this space. Strongly illuminated by natural light from E and W, lights were frequently found turned ON because curtains were down to prevent glaring. Since sun does not face East and West simultaneously, more careful behaviours should be implemented, once different lighting circuits allow turning ON/OFF the E and W luminaires at different times.

Another suggestion, derived from our study in MTS, was that classes lectured in building A 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 programs 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 could emerge.

Relating IAQ and given the current Energy Certification System [26], 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. A natural decay of the CO_2 concentration is expected, 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.

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

5. Calculation and Discussion - Energy Efficiency Plan Proposal

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 electricity supply contract);

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

5.1 Potential energy savings – ventilation requirements readjustment

In both case-studies, MTS and MMV, IAQ is assured by mechanical ventilation. In MTS, AHUs are used to supply fresh air at the room conditions (temperature and eventually humidity) or at certain conditions, to provide the desired temperature and humidity set points. In the classrooms, thermal loads are suppressed by terminal units, e.g. hot water radiators (used for heating conditions at 20 ºC). Some heating capacity is also due to a differential temperature between the outdoor air entering the AHU and the supply air into the room.

Based upon these considerations and specifically for air-supplying at room conditions, the authors developed an excel tool, aiming at estimating the heating energy demands of the AHUs serving classrooms during an entire school year, *i.e.* the integration of the computed heat transfer rate over the considered period of time. A detailed description of the methodology developed to build this tool – which is mostly rooted on *The 2013 ASHRAE Handbook of Fundamentals (Chapter 1)* [75] – is presented in [66]. This working file includes the integration of an *‘EnergyPlus’* weather file that may vary according to the building site. Therefore, the energy estimations account on the supplied air temperature differential, between the outside air temperature and the 20 ºC supplied air during the occupancy period.

In **Table 7,** some of the results (regarding MTS) obtained from this simulation tool are presented. School breaks, holidays and three vacation periods were considered (Christmas, Easter and summer holidays). From the simple adjustment of the fresh air flow rates (Q) of these AHUs to the current legislation requirements, a decrease of 35817 kWh/yr of the useful energy in the thermal heating energy of the air supplied into the classrooms in MTS (38932 kWh/yr in terms of final energy if considered the 92 % efficiency of the boilers – that work alternately) can be expected. In practice, as the fan power is a cubic function of *Q* [23], a *Q* reduction of 20 % in the air volume (in the scenery of the prescriptive method – **Table A.3**), 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 (**Figure 3**) – have an electronic variable-speed (EVS) drive that can be operated in 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 supplied and replaced for fan speed regulation. In this case, some investment is required – a budget of 320 € ($361.6) /each (price without VAT) has been proposed by one HVAC installer. From the energy estimation presented in **Table 7**, through a rough approximation on the energy reduction costs, assuming an average price 0.12 kWh, it is expected an annual saving of more than 4600 EUR (5200 USD). In terms of a simple payback period estimation, this would mean that these changes may pay for themselves in less than four months, without accounting for the monthly decrease of the utility bill.

Table 7 – MTS | Energy consumption of the AHUs serving teaching rooms (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 Constant Air Volume (CAV) systems their contribution is very small when compared with the fan component.

Concerning MMV, it is again reminded, that all the *Q* values suggested for buildings [A1, A2, A3, S] 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 energy simulation software *Designbuilder* [76], [77]. These four buildings were divided into 40 thermal zones [78]. Alongside the zoning, another 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 8**. Besides HVAC systems and ventilators, the simulation model also considered the internal loads of electrical equipment and lighting.

For energy simulations purposes, besides the main vacation 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 (MMV was refurbished aiming at receiving 11-18 year old students, 5 days/week from 8:30–17:55 maximum daily occupancy).

Table 8 – MMV | General data input of the school simulation model [23]

Area (m^2)	Ceiling height (m)	Roof	External walls		Glazing	
		U [W/(m^2.ºC)]	Insulation Position	U [W/(m^2.ºC)]	Solar factor	U [W/(m^2.ºC)]
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 [79], the energy 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 VEVs provided (by placing pulleys or substituting belts). Secondly, attention should be paid to the indoor units (IU) serving each room – since most of IU velocity equals 1000 m^3/h, the immediate consequence is that this will 'pick the air' somewhere else. Therefore, the resolution could be:

1. 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;

2. Ideally, introducing some air recirculation. By looking at the return air and the classroom Ta, 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 A.3**, captured on June 9th 2015, this proposal finds expression very easily: although by the time this image was captured the HRU was off (12:00), it can be accurately observed that the external temperature 33.1ºC (signalled with the red dashed ellipse) would highly influence the supplied air temperature into the IU (29.1ºC, signalled with the red dotted ellipse) and therefore the classrooms' Ta. 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 (vide the IUs' scheduling in **Table A.4**).

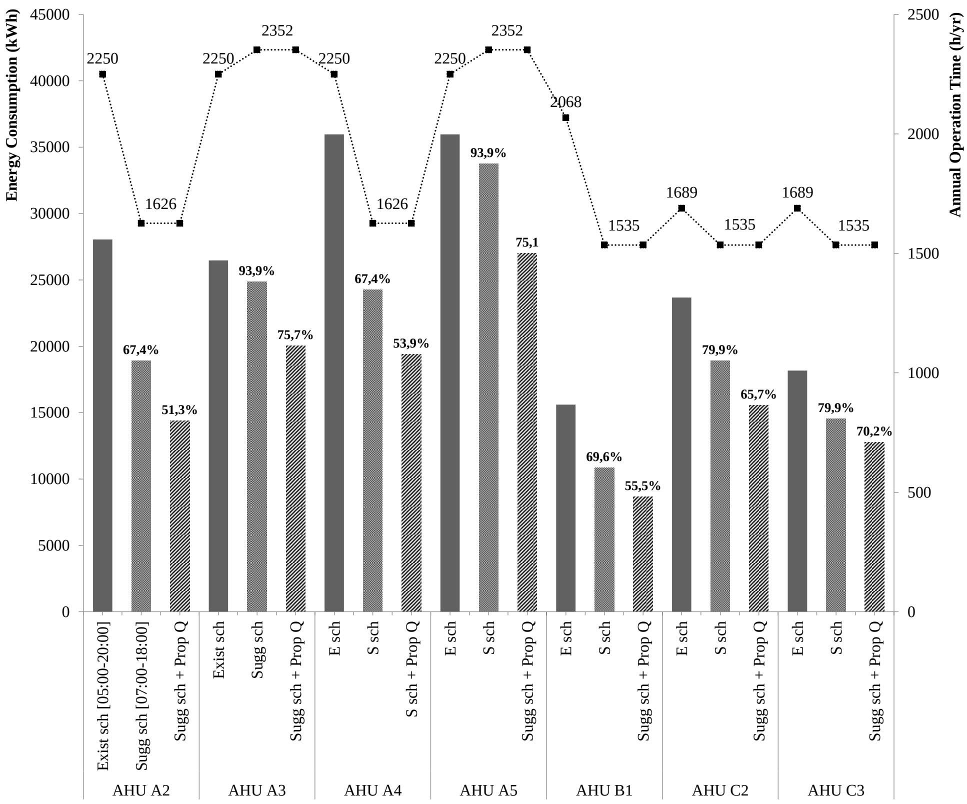
For the Gym, the Library and the Canteen building in MMV, simulation was performed with the tool developed by the authors [66]. For reasons of brevity, these steps are not described here.

5.2 Potential energy savings – BMS rescheduling

Improving energy efficiency in buildings does not necessarily mean reducing energy costs. For the present simulation, it was suggested an improvement on the BMS scheduling, i.e. changing AHUs operation time in accordance with the rooms' occupancy, and the electricity supply contract.

In MTS, it was suggested changing the morning kick-off: instead of 6:00, it was 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 those AHUs serving classrooms with late occupancy, aiming at improving IAQ in those rooms. **Figure 5** unveiled the crucial role of the BMS – by simply adjusting the BMS schedule, the thermal heating energy consumption of the AHUs might decrease up to 67.4 %. The percentage in bold, above each bar in the graph, represents the energy ratio: between the existing and the new schedule and, between schedules considering also the proposed *Q* – the first and the second values on the right of each solid column, respectively.

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.



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.

Figure 5 – MTS | Energy consumption of the AHUs serving teaching rooms (thermal heating energy).

In MMV, on the other hand, from the analysis of the scheduling of the unit serving the *Multipurpose room* in the gym (**Table A.4)** some remarks can be pointed out: this unit was active solely half an hour during the morning period and one hour again in the afternoon. Therefore, it was assumed it was being operated only due to ventilation demands, and not for space heating. As such, suggesting *Q* reduction, could not be the best solution. Nevertheless, energy heating estimations were simulated (using the developed excel tool) 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[5]. 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 in this space/area could be rescheduling the boiler. According to the BMS, **Table A.4**, it was 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.

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

Alongside the potential reduction of the fresh air flow rates, it is worth reminding that at no case, IAQ should be compromised. Alike the majority of the monitored classrooms within the *3Es* project [63], 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). These results were in agreement with other studies on the Portuguese schools condition: in [80], it was clearly stated that IAQ was being compromised due to *'to financial incapacity of the school board to maintain and operate the HVAC systems'*. As such, 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 CO_2 concentration values were achieved around 10:00 or between 11:30 and 12:00. This was 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 HRU programed scheduling, totally missed the classrooms' occupancy (**Figure A.4**).

Since the IAQ monitoring unveiled the classrooms' capacity of CO_2 removal during night-time, in here (MMV) as in MTS [63], the morning kick-off was 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 was not very understandable (**Figure A.4**). Likewise, there was 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 (**Figure A.4**). Again, during the afternoon, the activation of the equipment between 17:00–17:30 was also not very effective. First, most classes end at 16:15; secondly, since afternoon classes initiate at 14:45, by 17:00 the classrooms have been occupied for more than two hours without no air renewal (considering no window is open). Anticipating this forth activation moment (**Figure A.4**) was therefore preferable.

In resume, the operation time of the HVAC systems (2h30min/day in total) was not enough to comply with the IAQ legislation requirements. From the monitored data, it was verified that IAQ problems were more significant than TC. Readjusting the HRUs operation, as suggested, would probably help improving such results. Moreover, in case the school opted 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 could contribute to a better IAQ condition at reduced energy costs than those initially foreseen.

[5] 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 Drafting an Energy Efficiency Plan (EEP)

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 and headed by an energy manager (EM).

Making the analysis of a school building as an energy system, six main components are found: 1) building envelope; 2) HVAC systems; 3) lighting; 4) electrical equipment and installations; 5) local energy production; 6) 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[6], 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 school year, particularly when there are significant changes – 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 school year.

Aiming at contributing to the development of a nationwide school building indicator (an official and precise rating), a school energy performance ID document was proposed. Based on the billed energy consumption, *'incorporating national-scale statistical data, covering bottom-up details of individual buildings'* [81], this document is directly related to the EEP and should be available in a public area of each school. The example provided as reference is shown in [63] (Figure 55, p. 140). This S–EPC (School – Energy Performance Certificate) follows the policy implemented in the UK. Since October 2008, it is mandatory for public buildings over 1000 m^2 to obtain a DEC (Display Energy Certificate) each year [81]. Although the EEP is especially driven towards the school community, this S–EPC, which is part of the suggested 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.

5.3.1 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 equipment that consume energy;

- Energy Manager functions (more details can be found in [63], p. 137-139)

E.g. promoting campaigns to monitor energy consumption 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;

[6] 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.

- 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).

More detailed recommendations and actions for potential follow up are presented in [63] (Table 36, p. 135-137).

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 exterior shading devices in windows facing south (*louvres*), was explored and, in fact, the results obtained from four different simulations (different *louvres* size and distance between axes) unveiled the inefficiency of this measure [78]. Although cooling requirements were reduced, the thermal heating energy consumption increased due to lower solar gains during 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.

6. Conclusions and outlook

Aiming at developing an Energy Efficiency Plan (EEP) for secondary schools, a strategy was developed based on two case-studies of and R&D project. From a relatively simple research method, the current study consolidates the integration of IEQ and Energy auditing, in a conjunct initiative.

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 (*Q*) requirements] was performed as well as its repercussions on energy consumption. It was verified in both cases that the pre-set HVAC system, operated by the BMS, was not considered the contracted energy tariff or occupancy status. Some gaps relating day to day operation of the BMS were also found and could be implemented at very low or even negligible costs, without compromising IAQ (assessed in terms of the CO_2 concentration values), one of the IEQ components, which has been verified that was jeopardized (mostly due to the non-operation of the HVAC systems).

The potential energy savings achieved through the rescheduling of the BMS and *Q* 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) were also pointed out.

In addition to the traditional construction of energy building simulation models, quite time-consuming, the authors were able to estimate potential energy savings through the development of a simplified energy estimation tool for AHUs operation. The estimations disclosed in **section 5** were encouraging. In the first school, by simply adjusting the BMS and corresponding AHUs schedule, a decrease between 20 – 36 % of the useful thermal energy consumption of these equipment could be achieved, corresponding to 14.1 – 24.7 kWh/m^2. Moreover, considering the 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.

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 Energy Efficiency Measures. Within this document, leaded by a S–EPC (School–Energy Performance Certificate), it was proposed the creation of the figure of the Energy Manager. The authors truly believe that the applicability of such a plan can span to other schools of the *3Es* project and help energy/facility managers to plan optimum schedules for the automated systems. The presented energy conservation measures are possible to be replicable in other similar cases, augmenting the significance of the present study.

Appendix A

Table A.1 – MTS | The supplier schedule for active energy prices in winter and summer

	Winter time	**Summer** time	**Active Energy EUR/kWh Quarterly Period**	
			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

Table A.2 – MMV | Main automatic systems operational time (Monday – Friday)

System	**Naming**	**Start (am)**	**Finish (pm)**	**Space**	**Building**
HRU	URC1, URC 2, URC 3	07:00 10:00 13:00 17:00	08:00 10:30 13:30 17:30	Classrooms/laboratories, ITC rooms	A1, A2, A3
HRU	URC 4	Data unavailable		Administrative / staff	S
AHU	UPOL	10:30 15:00	11:00 16:00	Multipurpose room	Gym
AHU	UBAL	09:00 14:00	12:00 16:00	Locker rooms	Gym
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 equipment are controlled from the BMS and complementary software program.*

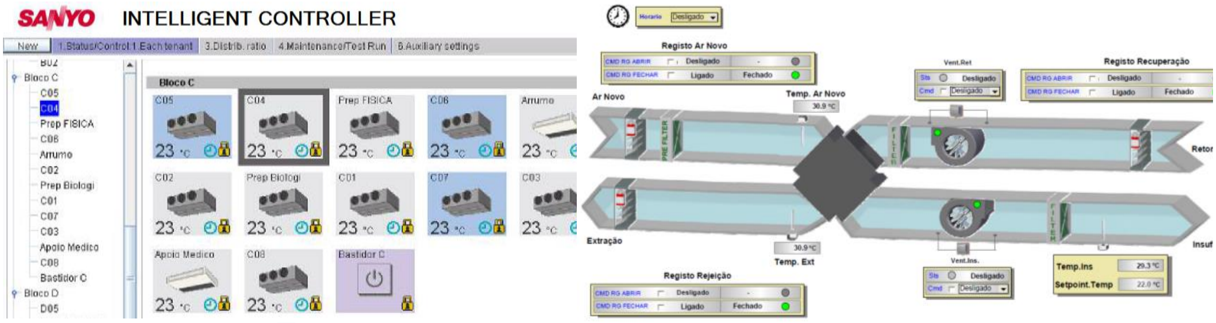
Table A.3 – Synthesis of the MTS' AHUs and corresponding fresh air flow rates (*Q*).

Equipment Designation	**Fans nº Velocities**	**Design/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*/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; *** new* Q *values were estimated accounting on the same expected number of people considered at the design phase.*

Table A.4 – MMV | Summary of the equipment and corresponding fresh air flow rates (*Q*) into various spaces (estimated upon the prescriptive method)

Space/ Building	**Equipment / 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 [79])
Multipurpose room (Gym)	AHU	9600	2200	23	Estimation based on $35m^3$/ occup., nº 50
Reading area (Library)	Rooftop / AHU	2625	1750	67	Estimation based on $20m^3$/ occup., nº 70
Meeting area & management room (Library)	Mini VRF	1580	1260	80	Estimation based on $24m^3$/ occup., nº 40
Bar/Cafeteria	Rooftop	3500	2800	80	Estimation based on $28m^3$/ occup., nº 80
Canteen	Rooftop	10500	8400	80	Estimation based on $28m^3$/ occup., nº 240
A1/ Classrooms	HRU1	9415	7530	80	Estimation based on $24m^3$/ occup. [79], nº 26
A2/ Classrooms & laboratories	HRU2	9200	8290	90	Estimation based on $24m^3$/ occup., nº 26 (classrooms) & $35m^3$/ occup. [79], nº 17 (labs)
A3/ Classrooms	HRU3	11530	9620	83	Estimation based on $24m^3$/ occup., nº 26
S	HRU4	7305	4870	67	Estimation based on $24m^3$/ occup. for offices and $28m^3$/ occup. for the teachers' room



a) b)

Figure A.1 – MMV | Space investigator of the graphical interface provided by the manufacturer. Detailed information on Building A2, a); Detailed view module of the HRU 2 (the unit serving building A2) on the BMS, b).

a)

b)

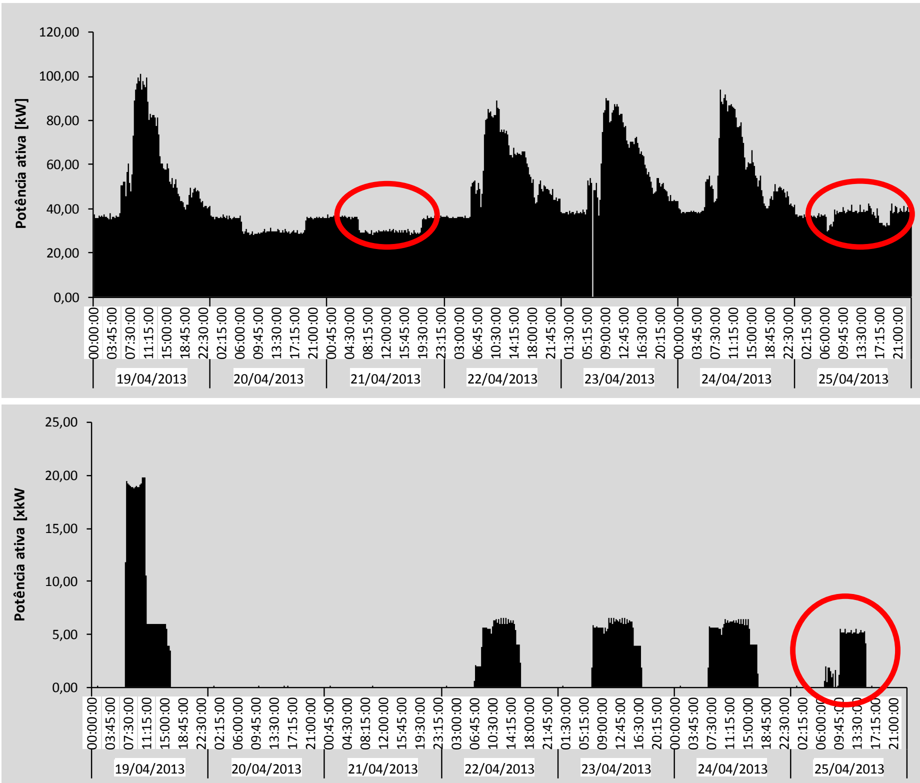


Figure A.2 – MTS | Load diagrams obtained during energy consumption monitoring, 19th April – 25th April 2013 (25th April is a national holiday in Portugal); a) Main LV Board; b) Thermal power plant electrical board.

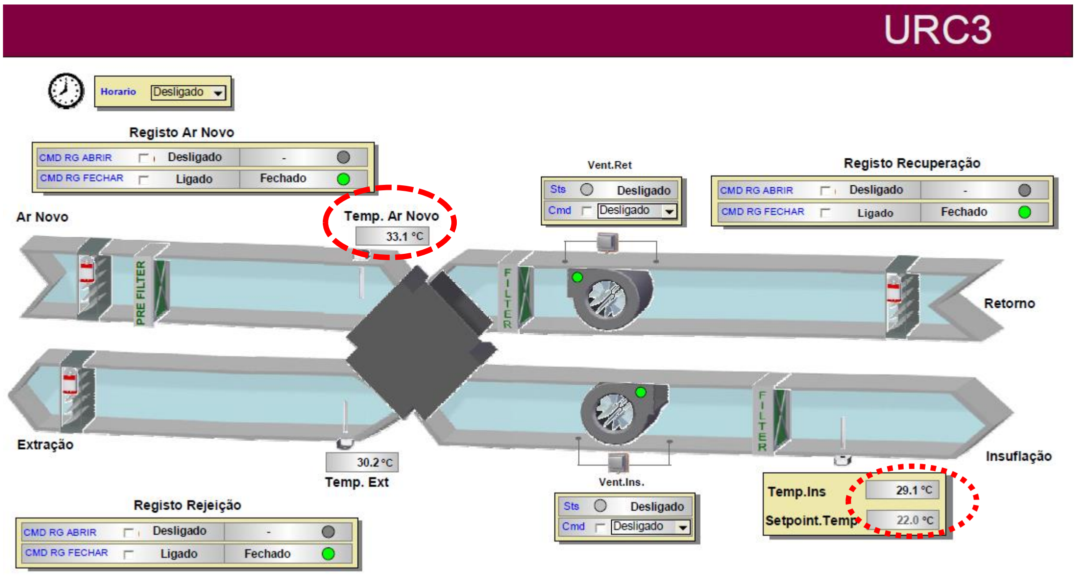


Figure A.3 – MMV | Detailed view module of the HRU3 in the BMS.

Anoletivo: 2012 - 2013

Tempos	Segunda	Terça	Quarta	Quinta	Sexta
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
11:05 - 11:50					
12:00 - 12:45		Mat B / A.12D	Inglês / A.11C	Mat A / A.11A	
12:45 - 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					

Entrada em vigor: 01/10/2012

Data de Validade: 31 de Agosto de 2013

07:00 – 08:00

10:00 - 10:30

13:00 - 13:30

17:00 - 17:30

Figure A.4 – MMV | One classroom occupancy time-table (accompanied by HRU 3 operation schedule – in red)

Appendix B

ITC and lighting systems in the case-studies

As regards energy-using equipment, e.g. IT equipment such as personal computers (PC), inter-active or video projectors, the account is summarized in **Figure B.1** [screens were divided in CRT (Cathodic Ray Tube) and TFT/LCD (thin-film-transistor liquid-crystal display)].

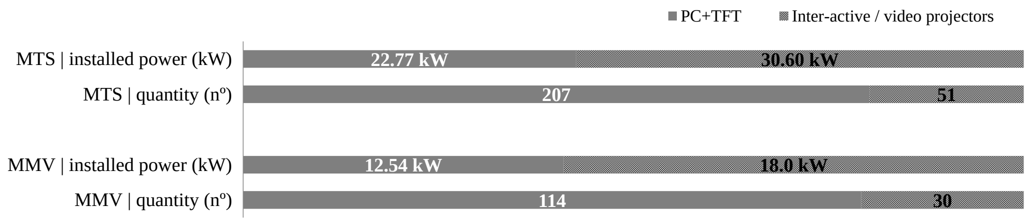


Figure B.1 – IT equipment synthesis

In order to reduce the energy consumption of unused computers in MTS, 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 it is coincident with the end of the night classes. As regards the video projectors, according to the collected information, programed shutdown is not possible due to the lack of network points.

Relating lighting, 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). There are also presence sensors, both in bathrooms and cloakrooms serving the shower rooms. More data are presented in **Table B.1**.

Table B.1 – MTS | 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.

As in MTS, in MMV 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 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*' and '*workshop*' present higher power to floor ratios – 26.2 /23.6 W/m^2 vs. 21.9/22.2 W/m^2. In contrast to MTS, in MMV there is not a computer network management system programed to shut down the computers or projectors.

As stated in the main text, the BMS in MTS does not allow lighting control. In MMV, instead, lighting is partially controlled from the BMS: in fact, the information presented in **Table B.2**, 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 corresponded to the time occupancy of this space.

Table B.2 – 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

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