FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

SCHOOL BUILDING REHABILITATION IN SOUTHERN EUROPEAN CLIMATE COMBINING COMFORT AND LOW ENERGY CONSUMPTION

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à Maria Ana e ao Manel Maria,

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ABSTRACT

Portuguese school buildings are generally characterized by an in-service hygrothermal discomfort, due to the poor envelope thermal properties and the lack of resources for paying energy consumption. Portuguese schools are free-running buildings with a natural ventilation strategy.

Hundreds of high and basic schools have not been refurbished and still have problems or anomalies and inadequate in-service conditions, being in need of rehabilitation in the near future. There will be, therefore, an opportunity to apply the acquired knowledge of comfort, habits, energy consumption and costs that have been studied since the last refurbishments (in 2008).

This Thesis studies the Portuguese *Brandão* schools' model (from the '70s), comprising about 100 non-refurbished basic schools. A prototype classroom was prepared in a *Brandão* school, in Porto. The *in-situ* experimental campaign consisted of temperature, relative humidity, CO_2 concentration and energy consumption measurements.

The main tasks of this work are: (1) the assessment of the students discomfort in the present situation through *in-situ* measurements; (2) preparation of a prototype in a *Brandão* classroom in Porto; (3) the calibration of an advanced hygrothermal model with experimental measurements before and after the prototype refurbishment; (4) a sensitivity study in order to choose the best refurbishment and heating strategies for these buildings regarding their typology, the local climate features and the actual capacity to support the operating costs and (5) the preparation of *Guidelines* or recommendations for the refurbishment of *Brandão* schools. Discomfort indicators have been developed for the assessment of the discomfort.

In order to suggest appropriate refurbishment strategies for the particular situation of these Portuguese buildings, two approaches were followed: (1) A *minimizing discomfort* approach, considering free-running conditions or intermittent heating strategies. In this case, the comfort performance, the indoor air quality performance and the energy consumption (predictably low in this approach, respecting the present strategy in these schools with low energy consumption) were the decision variables to be considered in the decision process. (2) A *comfort* approach, considering a regular heating strategy (during the occupation period), in which the most important decision variable was energy consumption, once the comfort requirements were fulfilled during the occupation period. The quantification of energy consumption and its costs enabled the comparison of solutions and the selection of the best refurbishment strategy, to ensure comfort conditions with a controlled and known increase in operating costs.

Keywords: School buildings, Prototype, Experimental characterization, Sensitivity study, Heating strategies, Refurbishment strategy, *Guidelines*.

RESUMO

Os edifícios escolares Portugueses são geralmente caracterizados por um desconforto higrotérmico em serviço, devido às fracas características térmicas da envolvente e à falta de meios para pagar a energia elétrica associada ao aquecimento. Por esse motivo, os edifícios escolares Portugueses encontram-se em livre flutuação de temperatura e sujeitos a uma estratégia de ventilação natural. Centenas de escolas básicas e secundárias não foram ainda reabilitadas, têm anomalias por resolver e apresentam condições de serviço desadequadas, necessitando de uma reabilitação num futuro próximo. Esta será uma oportunidade para aplicar o conhecimento adquirido na área do conforto, hábitos dos utilizadores, consumo de energia e custos, adquirido desde as últimas intervenções de reabilitação (2008).

Esta Tese estuda as escolas Portuguesas do modelo *Brandão* (anos 70), que são cerca de 100 escolas básicas em todo o país, que se encontram não reabilitadas. A campanha experimental *in-situ* consistiu na medição de temperatura, humidade relativa, concentração de CO_2 e consumos de energia.

As principais tarefas deste trabalho são: (1) a avaliação, através de medições *in-situ*, do desconforto sentido pelos estudantes nas atuais condições de serviço; (2) preparação de um protótipo numa sala de aula *Brandão*, no Porto; (3) validação de um modelo de simulação higrotérmica avançado através da comparação com medições experimentais antes e após a reabilitação do protótipo; (4) realização de um estudo de sensibilidade que permita escolher as melhores soluções de reabilitação para estes edifícios atendendo à sua tipologia, ao clima e às condições para suportar os custos de energia e (5) preparação de *Guidelines* ou recomendações para a reabilitação dos edifícios escolares *Brandão*. Foram desenvolvidos indicadores de desconforto para caracterização e quantificação do desconforto. Para a sugestão de estratégias de reabilitação para estes edifícios, foram seguidas duas abordagens: (1) Uma abordagem de *minimização do desconforto*, considerando condições de livre flutuação de temperatura ou estratégias de aquecimento intermitente. Neste caso, as variáveis de decisão foram o conforto, a qualidade do ar interior e o consumo de energia (previsivelmente baixo nesta abordagem, e de acordo com os atuais padrões de consumos nestas escolas). (2) Uma abordagem de *conforto*, considerando uma estratégia de aquecimento regular (durante o período de ocupação), na qual a mais importante variável de decisão foi o consumo de energia, uma vez que os requisitos de conforto estavam assegurados. A quantificação dos consumos de energia e respetivos custos permitiram a comparação de soluções e a seleção da melhor estratégia de reabilitação, garantindo condições de conforto com um aumento controlado e conhecido dos custos de operação.

Palavras-Chave: Edifícios escolares, Protótipo, Caracterização experimental, Estudo de sensibilidade, Estratégias de aquecimento, Estratégias de reabilitação, *Guidelines*.

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ABBREVIATIONS AND ACRONYMS

ASHRAE	American Society of Heating Refrigerator and Air-conditioning Engineers
ASTM	American Society for Testing and Materials
CEN	European Committee for Standardization
CIBSE	Chartered Institution of Building Services Engineers
DG	Double glazing
DIN	*Deutsches Institut für Normung*
DL	Decree-Law
EcoCore	Eco-Construction and Rehabilitation
EED	Energy Efficiency Directive
EN	European Standard
EPBD	Energy Performance of Buildings Directive
EU	European Union
FCT	Foundation for Science and Technology
FEUP	Faculty of Engineering, University of Porto
GNP	Gross National Product
GSM	Global System for Mobile Communication
HAM	Heat, Air and Moisture transfer
HVAC	Heating, ventilation and air-conditioning
IAQ	Indoor Air Quality
IBP	Fraunhofer Institute for Building Physics
IC	Institute for Construction
INE	Statistics Portugal
IPMA	Portuguese Institute for Sea and Atmosphere

ISO	International Organization for Standardization
LFC	Laboratory of Building Physics
NZEB	Nearly zero-energy buildings
QGIS	Open Source Geographic Information System
RCCTE	Portuguese Regulation of Thermal Performance of Buildings – previous legislation
RECS	Portuguese Energy Regulation for Non-residential Buildings
REH	Portuguese Energy Regulation for Dwellings
RSECE	Portuguese Energy Regulation for Non-residential Buildings – previous legislation
SCE	Energy Certification System of Buildings
SG	Single glazing
SP	Solar protection
TRY	*Test Reference Year*
TVOC	Volatile organic compounds
VPS	*Virtual Power Solutions*
WS	Weather Station
Wufi	*Wärme- und Feuchtetransport instationär*" or *Transient Heat and Moisture Transport*
XPS	Extruded polystyrene

SYMBOLOGY

A_{env}	m^2	Glazing areas sum
A_{eve}	m^2	Building's exterior vertical envelope area
(a)	-	Free-running conditions (experimental heating strategy)
BSk	-	Cold steppe climate
(b)	-	3 h heating (experimental heating strategy)
C	-	Temperate climate

Cs	-	Temperate climate with dry summer
Csa	-	Temperate climate with dry or hot summer
Csb	-	Temperate climate with dry or temperate summer
CET	ºC	Corrected Effective Temperature
CO_2	ppm(v)	Carbon dioxide concentration
Conf	-	Comfort Indoor Temperature and Thermal Comfort Index
c_p	J/(kg.K)	Specific heat capacity
CV(RMSE)	-	Coefficient of variation of the root mean square
(c)	-	10 h heating (experimental heating strategy)
DI	ºC.hour	Discomfort indicator
$DI_{w,b}$	ºC.hour	Winter discomfort indicator, base temperature *b*
$DI_{s,b}$	ºC.hour	Summer discomfort indicator, base temperature *b*
$\frac{dH}{d\vartheta}$	J/m^3K	Heat storage capacity of the moist building material
$\frac{d\vartheta}{dt}$	K/s	Change of temperature in time (solution)
$\frac{dw}{d\varphi}$	kg/m^3	Moisture storage capacity of the building material
$\frac{d\varphi}{dt}$	l/s	Change of relative humidity in time (solution)
D_φ	kg/(m·s)	Liquid conduction coefficient of the building material
EC	kWh	Energy consumption
ET	ºC	Effective Temperature Index
ET*	ºC	New Effective Temperature
F	-	Floor insulation (F0 = 0 cm, F3 = 3 cm)
fit	-	Goodness of fit
GD	ºC	Portuguese number of degree days during heating season, base 18 °C
g_{Tmax}	-	Maximum g-value for windows with all shading systems in use

g_{SP}	-	g-value of solar protection
g_{tvc}	-	g-value of the glazed system with solar protection
$g_{\perp}$	-	g-value of the glazed system for a perpendicular solar incidence
h	m	Height
H	-	Heating strategy during simulation (H1 = 3 h, H2 = 5 h, H3 = 9 h)
H	J/m³	Total enthalpy
h_V	J/kg	Evaporation enthalpy of the water
I_1	-	Portuguese winter climatic zone 1
I_2	-	Portuguese winter climatic zone 2
I_3	-	Portuguese winter climatic zone 3
NMBE	-	Normalized mean error
O	-	Orientation (N = North, S = South, E = East, W = West)
OT	ºC	Operative Temperature
p_{sat}	Pa	Water vapour saturation pressure
PD	%	*Percentage dissatisfied*
PMV	-	*Predicted mean vote*
PPD	%	*Predicted percentage of dissatisfied*
R	-	Roof insulation (R0 = 0 cm, R5 = 5 cm, R7 = 7 cm, R10 = 10 cm)
R	(m².ºC)/W	Thermal resistance
R_{si}	(m².ºC)/W	Thermal resistance (interior surface)
R_{se}	(m².ºC)/W	Thermal resistance (exterior surface)
RH	%	Relative humidity
RT	ºC	Resulting Temperature Index
R^2	-	Coefficient of determination

SBI	kWh/(m^2.ano.GD)	*School Benchmarking Indicator*
SET	ºC	Standard Effective Temperature
SHGC	-	Solar heat gain coefficient
S_h	W/m^3	Heat source of heat sink
S_w	kg/(s.m^3)	Moisture source or moisture sink
T	ºC	Temperature
%TD$_b$	%	Percentage of time of discomfort, base temperature *b*
t	s	Time
t_{conf}	ºC	Optimal operative temperature
T_{ext}	ºC	Outdoor air temperature
t_i	h	Time (for discomfort indicators calculation)
t_m	ºC	Mean monthly outdoor air temperature (ASHRAE 55)
$T_{m,ext}$	ºC	Outdoor air, mean value
T_{mp}	°C	Mean outdoor air temperature (Matias 2010)
U	W/(m^2.ºC)	Thermal transmittance
U_{bf}	W/(m^2.ºC)	Thermal transmittance of ground in touch with the pavement
U_{max}	W/(m^2.ºC)	Maximum thermal transmittance
U_{ref}	W/(m^2.ºC)	Reference thermal transmittance
U_w	W/(m^2.ºC)	Windows thermal transmittance
V	-	Ventilation strategy during simulation (V1 = 260 m^3/h, V2 = 400 m^3/h, V3 = 500 m^3/h)
V_1	-	Portuguese summer climatic zone 1
V_2	-	Portuguese summer climatic zone 2
V_3	-	Portuguese summer climatic zone 3
W	-	Wall insulation (W0 = 0 cm, W5 = 5 cm, W8 = 8 cm)

w	kg/m^3	Water content of the building material layer
W_SP	-	Windows and solar protection
δ_p	kg/(m·s·Pa)	Water vapour permeability of the building material
ε	-	Porosity
θ	ºC	Temperature
θi	°C	Limit value of indoor operative temperature
θ_{rm}	°C	Outdoor running mean temperature
θ_b	ºC	Reference temperature of Comfort
θ_i	ºC	Experimental hourly temperature in each period t_i
λ	W/(m·K) or W/(m.°C)	Thermal conductivity of the moist building material
μ	-	Water vapour diffusion resistance factor
ρ	kg/m^3	Bulk density
φ	-	Relative humidity

1
INTRODUCTION

1.1. SCOPE AND FRAMEWORK

1.1.1. THE IMPACT OF SCHOOL BUILDINGS ON THE EDUCATION QUALITY

Portuguese school buildings are generally characterized by an in-service hygrothermal discomfort due to the poor envelope thermal properties and the lack of resources for paying energy consumption. Most Portuguese schools are free-running buildings with a natural ventilation strategy [1]. For that reason, the highly relevant international studies on schools' energy consumption and potential savings mentioned in bibliography [2-6] do not reflect the Portuguese reality.

In Portugal, children spend most of their time at school, just after their own home. Furthermore, the physical environment affects teaching and learning which justifies the investment in comfort and indoor air quality (IAQ).

The low ventilation rates in classrooms reduce students' attention and vigilance thus negatively affecting memory and concentration [7, 8]. In fact, the low ventilation rates and high temperature fluctuations can reduce 30% of students' performance [9]. Some studies also report that a healthy school environment and an adequate ventilation system reduces the prevalence of asthma symptoms [10]. The investment in appropriate hygrothermal behaviour and IAQ of classrooms to promote a healthy learning environment is, therefore, justified [11].

One of the main challenges in this kind of buildings is the occupation, that can reach up to four times the occupation of an office building [12] and focuses, in general, on five working days of the week and through September to June. The CO_2 concentration (CO_2) is the main pollutant in the air and can reach high values in occupied classrooms [13], once it results from the metabolism. Some authors have performed CO_2 *in-situ* measurements in classrooms with natural ventilation [14-16]. International legislation defines the maximum acceptable level of CO_2 concentration and the minimum airflow in office buildings and particularly in school buildings (Table 1). Although the Portuguese legislation defines 1250 ppm for IAQ in non-residential buildings, in this work the reference value considered is 1500 ppm, in order to achieve a relaxed restriction in accordance with some international legislation.

Table 1 - CO_2 concentration and airflow requirements in school buildings [17-26].

		CO_2 concentration [ppm]	Airflow [m^3/h]	
			Winter	Summer
Standards	ASHRAE 62.1	700 (*1) ≈ 1100	5 l/(s.occupant) + 0,6 l/(s.m^2) = 486 m^3/h (*2)	
	EN 15251	Category II (*3) – 500 (*1) ≈ 900 Category III (*3) – 800 (*1) ≈ 1200	Very low-polluting buildings: Category II (*3) – 3,8 l/(s.m^2) = 684 m^3/h (*2) Category III (*3) – 2,2 l/(s.m^2) = 396 m^3/h (*2)	
	ASTM D6245-12	1000 ppm	7,5 l/(s.occupant) = 567 m^3/h (*2)	
Portuguese legislation	RSECE (until 2006)	1800 mg/m^3 ≈ 1000 ppm	30 m^3/(h.occupant) = 630 m^3/h (*2)	
	RECS	1250 ppm(*4)	24 m^3/(h.occupant) = 504 m^3/h (*2)	
	DL n.º 243/86 (office buildings)	---	30 m^3/(h.occupant) (*5) = 630 m^3/h (*2)	
	Portaria n.º 987/93 (workspaces)	---	30-50 m^3/(h.occupant) = 630-1050 m^3/h (*2)	
International legislation	Building Bulletin 101 (United Kingdom)	1500 (*6)	5 l/(s.occupant) (*6) = 378 m^3/h (*2)	
	DIN 4108 and 4701 (Germany)	1500	315 to 420 m^3/h	

(*1) Above outdoor air CO_2 concentration - [20] indicates 390 ppm at normal atmospheric pressure and for 25 ºC.
(*2) For a 50 m^2 classroom and /or 20 students and a teacher.
(*3) Category II – new buildings and renovations; category III – existing building.
(*4) Mean value during the occupation period.
(*5) Or until 50 m^3, when environmental conditions require an increase.
(*6) Mean daily values. The legislation refers that, at any occupied time, including teaching, the occupants should be able to lower the concentration of carbon dioxide to 1000 ppm and to achieve a minimum of 8 l/s per person at any occupied by opening windows, for example.

Nevertheless, in the non-refurbished Portuguese school buildings, IAQ is not a concerning matter once there is generally a high permeability of the envelope. In refurbished schools, despite the demanding airtightness standard values [20, 27], it is important to consider a reasonable airtightness increase that does not compromise the IAQ, once the active ventilation systems installed in the refurbished Portuguese buildings are sometimes turned off for economic reasons.

1.1.2. Geographic location of public Portuguese School Buildings

Public spending on education (5th to 12th grade) was 2.3% of the Gross National Product (GNP) in 2011 [28]. Since 2009 Portuguese public spending on education has been above the European Union (EU) mean value and also above Spain and Italy, but below France and the United Kingdom. There are about 6000 public schools in Portugal, of which 1000 are basic schools from 5th to 9th grade and

300 are high schools (geographic location in Figure 1) [29, 30], which means an important investment in construction, conservation and in the implementation of the educational system.

Figure 1 – (left) Portuguese public schools, (center) Basic schools from 5th to 9th grade, (right) High schools.

In the recent past (from 2007 to 2011), 175 Portuguese public schools were refurbished. The investment reached 2 400 million euros and focused mainly on high schools [31], with an average investment of 13 million euros per school (about 840 euros per square meter according to *Parque Escolar* program and 877 euros per square meter according to the *General Inspection of Finance*) [31, 32]. Despite the important investment and the high quality of the intervention, these refurbishments have not fully considered the Portuguese climatic diversity and economic reality. Almeida and de Freitas [1] studied some refurbished and non-refurbished schools and concluded that, although the IAQ is worse in non-refurbished schools, the results in the refurbished ones are different from what was expected since mechanical ventilation and air conditioning are frequently turned off. For these reasons, the refurbished buildings do not always have the required in-service comfort conditions.

The *Parque Escolar* modernization program has not fully concluded the rehabilitation process of Portuguese school buildings. Hundreds of high and basic schools have not been refurbished and still have problems or anomalies and inadequate in-service conditions, being in urgent need of rehabilitation in the near future. It will be, therefore, an opportunity to apply the acquired knowledge of comfort, habits, energy consumption and costs that have been studied and monitored since these refurbishments.

1.1.3. Operating costs

Portugal, in southwestern Europe, is mostly defined by a temperate Mediterranean climate, with rainy winters and dry and hot summers (although it may present a considerable climatic diversity). It is possible to find monthly average minimum temperatures of 0.3 ºC (Bragança), 5.0 ºC (Porto) and 8.1

ºC (Lisboa) in January and monthly average maximum temperatures of 28.5 ºC (Bragança), 25.0 ºC (Porto) and 27.8 ºC (Lisboa) in August [33]. Relative humidity ranges from 80 to 90% in the winter months and may decrease to 50 to 60% in the summer months [34]. The Koppen-Geiger Classification system classifies the Portuguese territory as mainly temperate climate – type C, with two variations, Csa and Csb [33]. It is also possible to find the sub-type BSk in a small region of the Baixo Alentejo.

Portugal's climatic pattern is similar to some other southern European countries, namely Spain, southern France, southwest Italy and Greece. However, even with similar climatic conditions and sometimes similar ventilation or heating strategies [35], local preferences and cultural habits have an important role in energy performance, thermal comfort and IAQ in schools [36]. In Portugal, the cultural habits, the non-insulated buildings envelope and the economic restrictions lead to an absence of heating and cooling strategies, which is not expected to change in the near future. Previous studies carried out in Portuguese schools don't indicate any significant differences between the average profile of electricity consumption for schools with or without heating system, suggesting their reduced use [37].

Figure 2 represents the electricity, gas and water operating costs, per square meter and per student, referring to 14 public Portuguese schools of three different typologies (*Brandão* - 70s; *3 x 3* - 80s; *Monoblock* - 90s) [38-51] defined in Figure 3. The three buildings typologies referred to were called Normalized Project Design and were prepared for technical schools and preparatory schools. The solutions found were simple, economic and fast to implement, in order to be quickly replicated throughout the country. The *Brandão* model includes classroom building blocks with one floor and a central courtyard. In the *3 x 3* model the building blocks are linked by exterior galleries. The *Monoblock* model includes only one two-floor block.

In Portugal, the school building operating costs are generally low, resulting from the irregular use (or absence) of heating and cooling strategies. Figure 4 presents the electricity consumption for one year (2007/2008 or 2008/2009) of four *Brandão* schools from the North of Portugal. From October to May (months with higher occupancy), electricity costs are on average 2400 €/month. The annual average electricity consumption in *Brandão* schools is 4.6 €/m^2 and 39.1 €/student (Table 2).

In spite of its absence or irregular use, heating is an important strategy so as to reach comfort in some Portuguese regions. And for that reason, the adaptive models in schools (developed for exclusive free-running behaviour) may not be a solution for a country with a climatic diversity like Portugal. The intermittent and irregular heating in Portuguese schools turns these schools into a particular situation between the analytical and adaptive models. In Portuguese, Italian and Dutch free-running schools, no agreement was found between the Fanger method (PMV Index) and the thermal perception [1, 52-54]. International legislation defines the acceptable hygrothermal parameters - temperature (*T)* and relative humidity (*RH)* - in office buildings and particularly in school buildings (Table 3). In this work, the *T* reference values considered are 20ºC (EN 15251 – category II) [18] and 25ºC (Portuguese Energy Regulation of Buildings – non-residential buildings) [20] for winter and summer respectively.

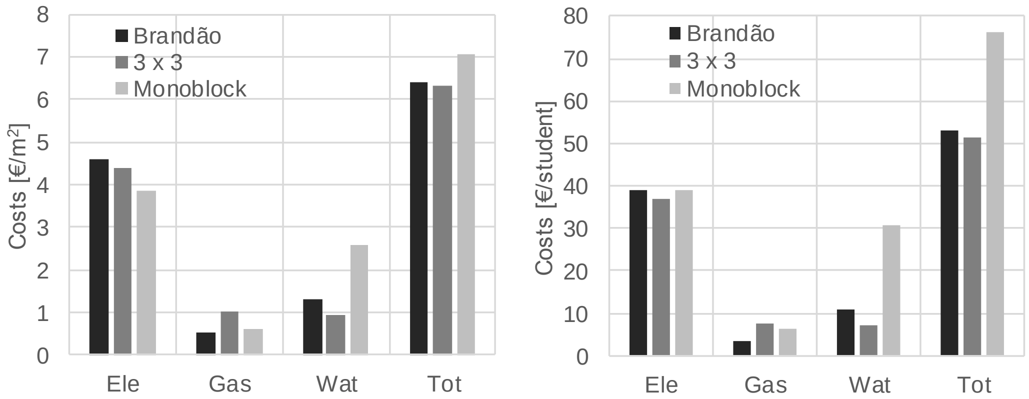


Figure 2 – Operating costs, per square meter and per student (electricity, gas and water).

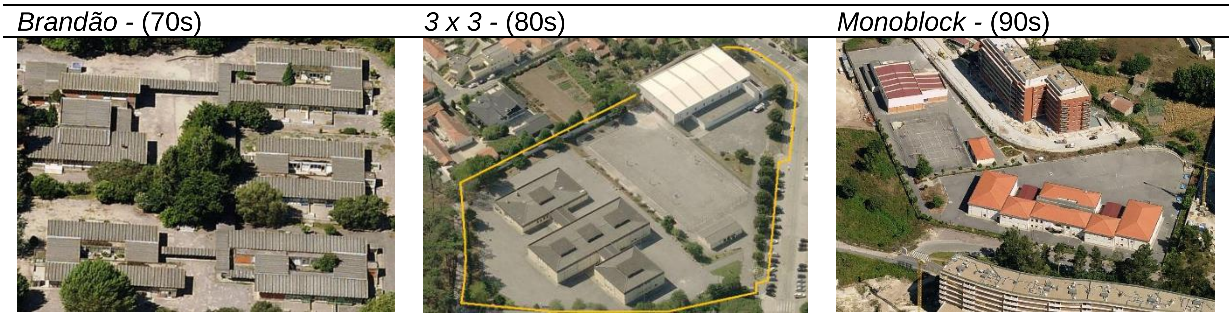


Figure 3 – Three school building typologies: Brandão - 70s, 3 x 3 - 80s, Monoblock - 90s.

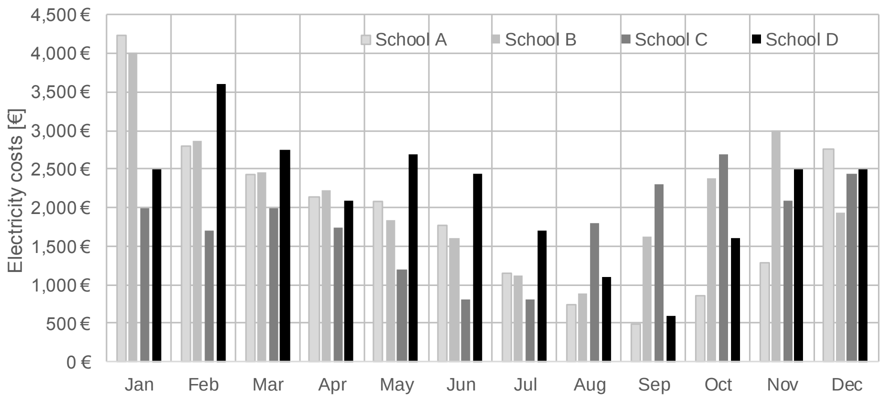


Figure 4 – Monthly electricity consumption (Brandão schools).

Table 2 – Annual energy consumption cost in Brandão schools.

School	Annual cost	
	[€/m^2]	[€/student]
School A	4.55 €	28.46 €
School B	4.29 €	35.10 €
School C	4.91 €	57.60 €
School D	5.15 €	35.33 €

Table 3 – Hygrothermal requirements for school buildings [1, 18, 19, 23, 26, 55-57].

		Temperature [°C]		Relative Humidity [%]	
		Winter	Summer	Winter	Summer
Standards	ISO 7730:2005 (*1)	22,0±2,0	24,5±2,5	40	60
	EN 15251 (2007) (*2)	Category I - 21 Category II – 20 Category III - 19	Category I – 25 Category II – 26 Category III - 27	---	
Portuguese legislation	RCCTE (until 2006) (*3)	20	25	---	50
	REH (*3)	18	25	---	
	RECS	20-25 or 19-27 (*4)		---	
	DL n.º 243/86 (office buildings)	18-22 (*5)		50-70	
International legislation	Building Bulletin 87 and 101	18	<28 (*6)	---	<70 (*7)
	DIN 4108 and 4701	20-23	<26	40-60	

(*1) Classrooms – C category.
(*2) Temperature interval for mechanically heated and/or cooled buildings for each level of expectation – non-adaptive methodology.
(*3) Dwellings.
(*4) 20-25 °C for IEEref calculation and 19-27 °C for IEEpr calculation through the simplified dynamic calculation for hybrid or passive buildings.
(*5) Or until 25ºC for specific climatic features.
(*6) It can be exceeded for 80 hours/year.
(*7) It can be exceeded for 2 hours in 12 hours period.

1.1.4. Refurbishment strategy

In the past, there were some typified projects for the refurbishment of school buildings replicated throughout the country, without the necessary adaptations to the specific climatic features. Likewise, and considering the typical free-running situation or intermittent heating strategy, the replication of the same solution in distinct refurbishment projects will have different repercussions on the hygrothermal environment inside the classrooms.

In addition, Mitterer, Künzel [58] reported that the absence of climate location adjustments and the use of foreign standards by countries with no specific legislation can result in low-comfort buildings. The simplest way to compensate this is the use of mechanical equipment, with an increasing need of energy consumption (which is not a possibility in the Portuguese situation). The updating of thermal legislation that requires greater insulation of the enclosure and airtightness and the demanding construction techniques and trends, with reduced thermal capacity and larger glazed area also contribute to the increasing need for active heating, cooling and ventilation systems. Some studies have been recently prepared in order to choose the best refurbishment strategies for specific school buildings in different countries, regarding their particular needs and legislation [59-61].

Portuguese school users do not heat as much as they want, due to economic restrictions. In general, Portuguese schools are free-running buildings with a natural cooling operation mode in the warmer months. The future challenge will be the refurbishment of the remaining schools taking into account their typology, the local climate features and the actual capacity to support the operating costs.

1.2. METHODOLOGY

1.2.1. MAIN GOALS

This work aims to contribute to the refurbishment of school buildings in free-running conditions or with intermittent heating strategies, considering the temperate Mediterranean climate features and the actual capacity to support the operating costs.

With that purpose, some intermediate goals were defined:

(1) Analyse the in-service hygrothermal discomfort and IAQ in *Brandão* school buildings for the present free-running conditions and compare with some reference values of T, RH and CO_2 from the legislation.

(2) Assessment of a *Brandão* classroom behaviour before and after an intervention. This refurbishment was intended to minimize the discomfort in this classroom with some affordable interventions, regarding the typical in-service conditions in this type of school.

(3) Preparation of *Guidelines*/recommendations for *Brandão* schools refurbishment (roof insulation, walls insulation, floor insulation, windows and solar protection, ventilation and heating) in Portuguese cities with distinct climatic features, following three heating strategies.

1.2.2. STRATEGY AND TOOLS

In order to address the previously proposed main goals, the following tools were developed/implemented:

(1) Reference values and legislation applied to thermal comfort, ventilation, IAQ and energy consumption (EC).

(2) Preparation of a prototype in a *Brandão* classroom in Porto (refurbishment design project and implementation).

(3) Measurement of hygrothermal performance and energy consumption of the *Brandão* classroom prototype in Porto, before and after the refurbishment.

(4) Validation of an advanced hygrothermal model (Wufi Plus) that reproduces the *in-situ* conditions and allows the study of the other Portuguese *Brandão* buildings.

(5) Sensitivity analysis through a numerical hygrothermal model that studies different refurbishment strategies (roof insulation, walls insulation, floor insulation, windows and solar protection, ventilation and heating) in Portuguese cities with distinct climatic features and heating strategies (3 h heating, 5 h heating and 9 h heating).

The refurbishment strategy for *Brandão* schools resulted from the sensitivity study, with the main goal of reducing occupant thermal discomfort. Each refurbishment scenario was classified by the comfort performance (through discomfort indicators and *T* mean values), the IAQ performance (by CO_2 mean values) and EC (for heating), regarding each specific climatic location. The quantification of discomfort/performance classification is an important decision advice tool for the schools' refurbishment. The definition of the required ventilation rate to ensure IAQ in a *Brandão* classroom was also an object of the proposed sensitivity analysis.

In order to suggest appropriate refurbishment strategies for the particular situation of these Portuguese buildings, two approaches were followed:

- ❖ A *minimizing discomfort* approach, considering free-running conditions or intermittent heating strategies. In this case, the comfort performance, the IAQ performance and the EC (predictably low in this approach, respecting the present strategy in these schools with low EC) were the decision variables to be considered in the decision process.
- ❖ A *comfort* approach, considering a regular heating strategy (during the occupation period), in which the most important decision variable was EC, once the comfort requirements were almost fulfilled during the occupation period. The quantification of EC and its costs enabled the comparison and selection of the best rehabilitation solutions, to ensure comfort conditions with a controlled and known increase in operating costs.

The *Guidelines*/recommendations for the rehabilitation of these school buildings must take into account the approach to be privileged once the best scenarios defined for free-running temperatures can be different from comfort scenarios under regular heating. The intervention must be adapted to the climatic features. The *Guidelines*/recommendations may support the decision process on the rehabilitation of school buildings. Figure 5 shows the present situation conditions, the strategies that were followed and the main challenges of this work.

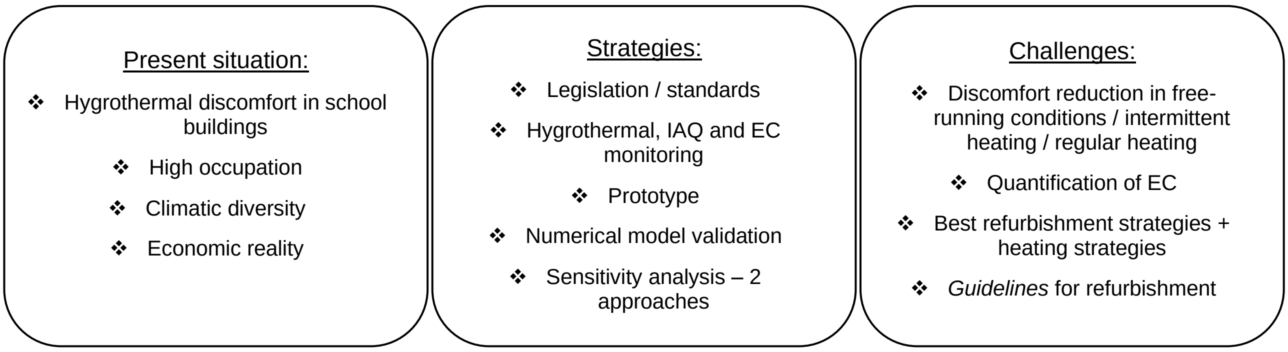


Figure 5 – Present situation, strategies and main challenges.

Considering the previously presented framework, some research questions were defined:

- ❖ Do the students feel discomfort in the present free-running conditions in *Brandão* schools? Is it possible to quantify this discomfort? Is the IAQ acceptable inside the classrooms, regarding the national and international requirements?
- ❖ What are the appropriate intervention measures to reduce discomfort and ensure IAQ in *Brandão* schools, regarding the climate features and the present in-service free-running conditions? Is it possible to define a passive low-cost solution for these *Brandão* schools that reduce the discomfort?
- ❖ In the possibility of heating these schools, what is the best heating strategy? How long should the heating system be active during the day? How much would it cost to heat these schools?
- ❖ What is the improvement in comfort and in IAQ for each refurbishment strategy? And what are the consequences in EC when an intermittent heating strategy is considered?
- ❖ Would it be interesting to consider a regular heating strategy for these schools? What would be the EC and the related cost?
- ❖ In the possibility of a regular heating strategy, what would be the best intervention to minimize the EC in these *Brandão* schools?
- ❖ Would the best refurbishment strategies from the *minimizing discomfort* approach be the same for the *comfort* approach with a regular heating strategy? What would be the main differences?
- ❖ The research results must be clearly organized in order to be successfully applied to practical situations and to help the management of other similar school buildings. Is it possible to define *Guidelines*/recommendations for the refurbishment of these Portuguese *Brandão* schools, considering the climate features of each location?

1.2.3. THESIS SCRIPT

This work is divided into seven main chapters, as follows:

- The present first chapter is the *Introduction*, where the scope and framework of the Portuguese *Brandão* school buildings refurbishment were presented. The main goals of the work, the strategy to follow and the chosen tools were defined. It is an introduction to the problem, where the main research questions and the main challenges were clearly defined.

- The second chapter is the *Critical Assessment of the Literature*, that addresses the main topics about hygrothermal and energy performance in a general way and particularly applied to school buildings. A critical reflection on some international studies and projects is also presented in this chapter.

- The third chapter is the *Experimental Characterization of Thermal Performance and Energy Consumption of a Prototype*. The *Brandão* school typology, its constructive characterization and the passive low-cost refurbishment applied to a *Brandão* classroom prototype in Porto are presented. It also presents the experimental monitoring planning, the equipment and the implementation. The discussion of the experimental results includes the before and after refurbishment thermal comfort behaviour, the IAQ and the EC measurements.

- The fourth chapter is the *Numerical Simulation of Thermal Comfort and Energy Consumption*, in which the advanced hygrothermal model (Wufi Plus) is presented and also the calibration process by comparing and narrowing differences between experimental and numerical results before and after refurbishment, in free-running conditions and with intermittent heating strategies. The model validation is supported by statistical analysis and statistical indexes that suggest the model strength.

- The fifth chapter is the *Sensitivity Study*. It includes the definition of refurbishment scenarios and technical systems. The numerical simulation is prepared for a validated model of a *Brandão* classroom that can be located in different Portuguese cities (Porto, Bragança, Braga, Coimbra and Lisboa). The sensitivity study includes the discomfort and statistical analysis of T, CO_2 and EC for each scenario and also an adaptive assessment of mid-season conditions. The sensitivity study is an important tool to choose the best refurbishment strategies.

- The sixth chapter is the *Guidelines for Refurbishment*. Following the *Sensitivity Study*, some guidelines are defined to the refurbishment of *Brandão* schools in Portugal, for different climatic locations and for *minimizing discomfort* approach (intermittent heating strategy) or *comfort* approach (regular heating strategies during the occupation period). The main decision variables considered are the discomfort performance, the IAQ performance and the EC. A practical refurbishment proposal is presented in this topic, with the purpose of decision advice for managers and engineers.

- The seventh chapter is the *Conclusion*, where the main relevant considerations of this work are presented. Future developments are addressed, considering not only academic research but also practical implementation developments.

2

Critical Assessment of the Literature

2.1. HYGROTHERMAL PERFORMANCE AND ENERGY CONSUMPTION IN SCHOOL BUILDINGS

2.1.1. CONSIDERATIONS

The indoor environmental quality definition includes four main comfort areas: thermal comfort, indoor air quality (IAQ), acoustic comfort and visual comfort. In this work, the hygrothermal performance of school buildings includes the first two areas (thermal comfort and IAQ) and depends on the buildings (envelope and construction materials), on the outdoor conditions (climate and CO_2 concentration) and on the users' profile (occupation and activity).

The users' increasing comfort expectations, the new constructive trends and the widespread use of climatization technical systems have increased energy consumption and a gradual change in users' habits [62]. Given this growth and its environmental impact, the European Union (EU) has set targets for reducing such consumption.

The building energy performance is commonly connected to energy costs and to energy savings through building improvement, equipment improvement and users' behaviour. However, at the present moment, the challenge to reduce energy consumption in northern European countries is not a reality in southern Europe so far. As far as school buildings are concerned and for economic reasons, there is an absence of climatization and schools are generally under free-running conditions (T, RH and CO_2). Therefore, the energy operating costs are usually low and their reduction is not a relevant issue. Considering Portuguese school buildings, the current targets for EC and environmental impact reduction are not appropriate for the present moment.

2.1.2. HYGROTHERMAL PERFORMANCE

2.1.2.1. Thermal comfort

ASHRAE [63] defines thermal comfort as "*that condition of mind that expresses satisfaction with the thermal environment. Because there are large variations, both physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space*".

Satisfaction with the thermal environment depends not only on physical environmental factors (thermal balance of the building) but also on individual factors (metabolic activity and clothing resistance) and subjective factors (social, cultural and psychological).

The physical quantities characterizing the environment are independently measured and include: air temperature (ºC), mean radiant temperature (ºC), absolute humidity of the air, expressed by partial vapour pressure (Pa), air velocity (m/s) and surface temperature (ºC) [64].

The individual quantities are defined in the bibliography [55, 63] and include clothing insulation (clo) and metabolic rate (met).

The subjective factors consider the subjective perception of each user and the ability to adapt to changes in the thermal environment. The subjective factors include the behavioural adjustment (opening/closing windows or shades or clothing adjustment), physiological adjustment by a gradual decrease in the strain induced by the exposure (genetic adaptation or acclimatization) and psychological feedback (habituation and changes in expectation) [65, 66] which represent users' adaptive opportunities [67].

Occupants generally need to feel in control and the absence of adaptive opportunities causes stress or discomfort [66]. Brager and de Dear [65] found that occupants in naturally ventilated buildings had more relaxed expectations, were more tolerant of temperature changes, and also preferred a temperature that follows the outdoor climatic trends. In contrast, people living in air-conditioned spaces are highly likely to develop high expectations for homogeneity and cool temperatures and may become quite critical if thermal conditions in their buildings deviate from the center of the comfort zone they have come to expect [68].

The adaptive opportunities for non-residential buildings are naturally different from residential buildings, due to the occupation profile (number and age of users, schedule and calendar) and also due to specific legislation with stricter rules for ventilation and IAQ. Moreover, the expectation and the duration of the occupation can also affect the comfort perception in school buildings.

Given the importance of the users' perception of comfort (or thermal discomfort) in the workplace, the implementation of questionnaires or surveys is a frequent methodology. In order to obtain reliable and standardized results, the surveys must comply with ISO 10551 standard [69].

The first research studies of thermal comfort only considered environmental quantities. The research gradually incorporated individual quantities. Later in the '70s and as a result of the oil crisis, the research focused on energy consumption reduction and devoted greater attention to the users' new expectations for controlling their own comfort [65], by including individual factors in the definition of comfort temperature. The adaptive comfort models emerged as an alternative to the traditional comfort models, due to the awareness of the individual's diversity, thermal preferences, behaviour adjustments, interaction with the environment, and a gradual adaptation of expectations to the thermal environment.

There are thus two major groups of thermal comfort models: analytical models and adaptive models. The first ones are for constant and controlled environmental conditions, requiring the use of climate-controlled systems, and this is the major limitation of these models. The second ones are for free-running temperature conditions and suggest the users' adaptive opportunities to minimise the discomfort and consequently the reduction of energy consumption [62, 70].

The present standards [18, 63] describe models that have been defined after numerous studies along the time. Table 4 and Table 5 present a chronological synthesis of thermal comfort models, divided in two main groups: analytical and adaptive models. All these research works intended to characterize the thermal comfort level of an environment.

At the beginning, the analytical models (Table 4) only considered environmental factors (physical quantities) but they gradually started to include individual factors related to the occupants.

The main differences found between conditioned environments and users' perception in real environments can be explained by the measurement errors (thermal insulation of clothing, occupant activity and difficulty in measuring non-uniform thermal conditions), and also by the need to incorporate subjective factors (behavioural adjustment, physiological acclimatization, adaptation and psychological expectation) [65]. The adaptive models (Table 5) added subjective factors to this comfort analysis, considering the outdoor temperature pattern [71].

In sum, Table 4 and Table 5 reveal that:

- ❖ The main analytical model was developed by Fanger [72] and is described in ASHRAE 55 [63], EN 15251 [18], ISO 7730 [55] and ISO 7726 [64]. Analytical models are exclusively for conditioned environments (climate chamber) and they are not appropriate to the Portuguese school reality.

- The main adaptive models are described in ASHRAE 55 [63], EN 15251 [18] and, in Portugal, by Matias [62]. The operating comfort temperatures are defined with a certain acceptability percentage, depending on outside temperatures. These models are for free-running environments. The monthly average outdoor temperature range is between 5 or 10 °C and about 33 °C and is representative of the Portuguese climate, both in winter and summer, in most districts. Table 6 presents the three main adaptive models. Matias [62] considers the possibility of incorporating climatization systems in buildings and extends the applicability of the standards' adaptive models.

In severe climates (very cold winters or very hot summers) only analytical models can be used, once adaptive models have a fixed range for outdoor temperatures. In any case, analytical models seem to adequately describe these extreme situations, since in severe climates the airtightness of the envelope is generally high and the technical systems have a regular and continuous working strategy.

In the present work, the studied school buildings are in free-running conditions, with no air-conditioning, high occupation rates and irregular attendance of classrooms, and that determines the thermal environment. However, as referred before, in spite of its absence or irregular use, heating is an important strategy for reaching comfort in some Portuguese regions. And for that reason, the adaptive models in schools (developed for exclusive free-running behaviour) may also not be a solution for a country with a climatic diversity like Portugal. The intermittent and irregular heating in Portuguese schools makes these schools a particular situation placing it between the analytical and adaptive models.

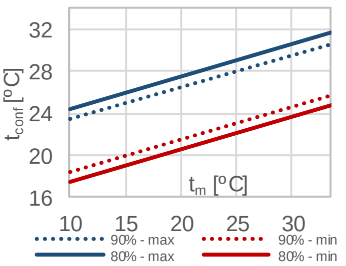
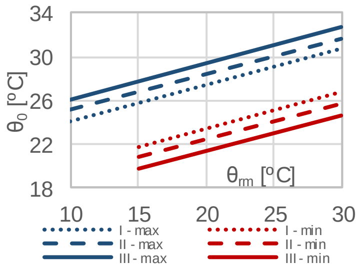
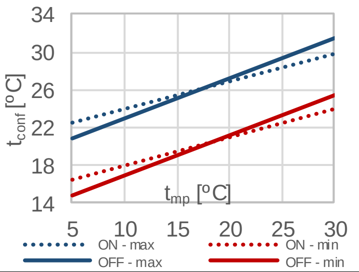
Table 4 – Summary of the chronological evolution of thermal comfort models – analytical models [73].

Index	Author (data)	Parameter	Results	Additional note
Effective Temperature Index (ET)	Houghten, Yaglou and Miller (1923-1925)	Environmental factors	Identification of equal comfort lines on a psychometric chart with the corresponding values of the effective temperature.	Prepared through climatic chamber experimental tests.
Corrected effective temperature (CET)	Vernon (1932), Bedford (1940)	Environmental factors	ET index improvement.	Prepared through black globe thermometer experimental testes.
Resulting Temperature Index (RT)	Missenard (1935)	Environmental factors	Indoor air and contour temperature of a fictional environment that produces the same feeling of comfort as the studied environment.	Considers users' thermal sensation answers after acclimatization.
Establishment of comfort zones for existing indexes	Houghten e Yaglou (1923), Koch et al. (1960), Nevins et al. (1966), Rohles (1973)	Environmental factors	Definition of comfort zones in which a large percentage of people (80, 90%) consider themselves to be in neutral thermal conditions.	Considers thermal sensation answers on a seven-level scale.
Operative temperature (OT)	Winslow, Herrington and Gagge (1973)	Environmental factors	The uniform temperature of a fictional black radiant enclosure, in which the subject suffers heat losses from radiation and convection equal to those of the given (non-uniform) environment.	---
New effective temperature (ET*)	Gagge, Stolwijk and Nishi (1971)	Environmental and individual factors	Operating temperature of a fictional environment that produces the same sensible and latent heat exchanges in users as in the real environment. It was not possible to define a universal abacus.	A dynamic model of sensitive and latent heat fluxes between the environment, skin surface and central body inside.
Standard effective temperature (SET)	Gagge, Nishi & Gonzalez (1972)	Environmental and individual factors	The uniform temperature in a fictional environment where a person wearing clothing that is tailored to their physical activity has the same heat exchange as in the real environment.	For sedentary activity and light clothing (1met, 0.6clo) the SET value agrees with the ET *.
PMV-PPD Index	Fanger [72] EN ISO 7730 (2005) ASHRAE 55 (2010)	Environmental and individual factors	The expected value of the individuals' thermal sensation vows and the expected percentage of dissatisfied with the thermal environment (seven-level scale). EN ISO 7730 (2005) defines the thermal environment categories of buildings (A, B and C). ASHRAE 55-2004 defines the graphical method with the same purpose and an adaptive approach.	Definition of thermal neutrality, S = 0. S deviations from equilibrium produce dissatisfaction.

Table 5 – Summary of the chronological evolution of thermal comfort models – adaptive models [18, 62, 63, 66, 70, 73].

Index	Author (data)	Parameter	Results	Additional note
Neutral indoor temperature	Humphreys (1978)	Environmental, individual and subjective factors	Correlation between the indoor comfort temperature and the average monthly outdoor temperature, in free-running conditions (the indoor comfort temperature increased by half a degree for each degree increase in the average outdoor temperature).	Assessment of users' perception when exposed to their normal activity environment, whether or not acclimatized and with appropriate clothing.
Neutral indoor temperature	Auliciems (1981)	Environmental, individual and subjective factors	Correlation between comfort indoor temperature and average monthly outdoor temperature and average indoor temperature.	---
Neutral indoor temperature	Baker and Standeven [66]	Environmental, individual and subjective factors	Adaptive increments for comfort temperature calculation. Adaptive opportunity definition (when the adaptive opportunity is null, any change to neutrality may cause dissatisfaction).	It pretends to resolve the differences between the empiric Humphreys expression and the Fanger's comfort temperature. Implementation of questionnaires.
Neutral indoor temperature	Brager and de Dear [65]	Environmental, individual and subjective factors	Correlation between average monthly outdoor temperature and neutral indoor temperature; the basis of ASHRAE 55-2004. Lists the main reasons for the discrepancies between observation and prevision models. Thermal adaptation: behavioural adjustment, physiological acclimatization and psychological habituation or expectation - user as an active agent.	It appears as a result of the PMV being suitable for air-conditioned environments but not for naturally ventilated buildings.
Operative indoor temperature	ASHRAE 55 (2010) EN 15251 (2007)	Environmental, individual and subjective factors	Indoor operating temperatures allowed, as a function of the weighted outside temperature. Once it considers the localized discomfort, there is no need to follow EN ISO 7730.	Model requirements: opening/closing windows management; without mechanical cooling systems or mechanical heating systems (or without their operation).
Comfort indoor temperature and Thermal comfort index (Conf)	Matias [62]	Environmental, individual and subjective factors	Calculates the indoor comfort temperature as a function of a thermal comfort index. Correlation between comfort temperature and outdoor temperature depending on the possibility of adapting the climatization options. Acceptable temperature ranges are set for different climatization options (ON and OFF).	Climatic monitoring and thermal preference questionnaires. The limits of thermal comfort in non air-conditioned spaces are more flexible than those in air-conditioned spaces.

Table 6 – Adaptive models [18, 62, 63].

	ASHRAE 55 (2010)	EN 15251 (2007)	Matias (2010)
Output	Operative temperature [t_o]	Operative temperature [θ_o]	Thermal comfort index [Conf] and Comfort indoor temperature [T_{conf}]
Graph			
Equations	$t_{conf} = 0{,}31.t_m + 17{,}8$ Where t_m is the mean monthly outdoor air temperture, °C. Sets of operative temperature: 5°C for 90% acceptability and 7°C for 80%, both centered on optimal operative temperature, t_{conf} [68].	Category I: $\theta i_{max} = 0{,}33.\theta_{rm} + 18{,}8 + 2$ $\theta i_{min} = 0{,}33.\theta_{rm} + 18{,}8 - 2$ Category II: $\theta i_{max} = 0{,}33.\theta_{rm} + 18{,}8 + 3$ $\theta i_{min} = 0{,}33.\theta_{rm} + 18{,}8 - 3$ Category III: $\theta i_{max} = 0{,}33.\theta_{rm} + 18{,}8 + 4$ $\theta i_{min} = 0{,}33.\theta_{rm} + 18{,}8 – 4$ Where θi is the limit value of indoor operative temperature, °C and θ_{rm} is the outdoor running mean temperature, °C [18].	Climatization ON: $T_{conf} = 0,\ 30.T_{mp} + 17{,}9$ Climatization OFF: $T_{conf} = 0{,}43.T_{mp} + 15{,}6$ Where T_{mp} is the mean outdoor air temperature, °C. Set of 6°C for 90% acceptability, centered on comfort temperature [62].
Outdoor temperature	Mean monthly outdoor air (the arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry-bulb) temperatures for the month in question).	Outdoor running mean temperature is the exponentially weighted running mean of the daily mean external air temperature from the previous seven days.	Mean outdoor air temperature is the exponentially weighted daily average values from the previous seven days.
Applicability and limitations	Healthy adults at atmospheric pressure equivalent to altitudes up to 3000 m in indoor spaces designed for human occupancy for periods not less than 15 minutes. Sedentary or near sedentary physical levels, typical of office work (including classrooms) (between 1,0 and 1,3 met). Mean monthly outdoor temperature between 10°C and 33,5°C. Naturally thermal conditioned spaces. Operable windows, no mechanical cooling system, it is permissible to use mechanical ventilation with unconditioned air, it is permissible a heating system but without operation. The occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions.	Single-family houses, apartments, apartment buildings, offices, educational buildings, set by sedentary human occupancy and where the production or process does not have a major impact on the indoor environment. Running mean outdoor temperature between 10°C and 30°C. Naturally thermal conditioned spaces. Operable windows, no mechanical cooling system, it is permissible to use mechanical ventilation with unconditioned air, it is permissible a heating system but without operation. The occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions.	Office buildings, higher education buildings, dwellings and nursing homes. Mean outdoor air temperature between 5°C and 30°C. Naturally or mechanically conditioned buildings.

Discomfort indicators are developed in this work for *Brandão* buildings thermal discomfort characterization in free-running conditions and intermittent heating. Reference T values were defined in winter and summer, according to the requirements. The reference T values considered are 20 ºC and 25 ºC for winter and summer respectively.

Despite the definition of a summer comfort T, an adaptive approach must be also considered. ASHRAE 55 adaptive model considers the comfort T depending on the outdoor temperature, which represents 26-27 °C in summer in most European cities. These values are in accordance with the analytical models' recommendations (from ISO 7730 and ASHRAE 55). However, in warmer climates, the adaptive model leads to higher comfort T. Olesen [13] also assesses the variability of summer comfort T for different climatic conditions in free-running buildings.

The Portuguese *Brandão* schools (about 100 throughout the country) have distinct climatic locations and the adaptive models may consider a variability in the reference summer comfort T. Each school building can be classified within a climate zone (V1, V2 and V3) and an outdoor summer temperature that should reflect the climate severity of the location (Figure 6) [74].

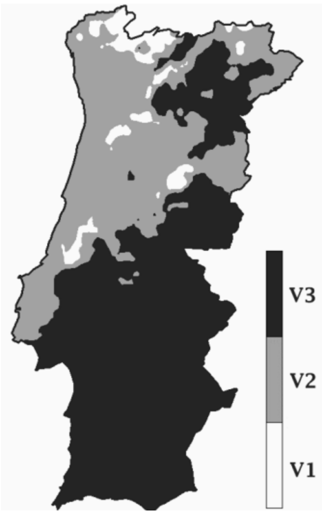


Figure 6 – Portuguese climatic zones for the cooling season ([74]).

In sum, there are two major groups of thermal comfort models: analytical models and adaptive models. The first ones are for constant and controlled environmental conditions, which is not the Portuguese schools' reality. The second ones are for free-running T conditions, which is the present in-service situation. However, intermittent heating is required in Portuguese climate and for that reason, Portuguese schools are a particular situation between the analytical and the adaptive models.

In this Thesis, some T reference values were defined, reflecting the users' acceptance of the thermal environment. The reference values (20 ºC in winter and 25 ºC in summer) will have an important role in the assessment of the occupants' discomfort. Moreover, regarding the absence of cooling systems, an adaptive assessment of summer conditions will be considered.

Relative humidity will also be assessed, although this parameter may have little influence on the thermal environment preference [13].

2.1.2.2. Indoor air quality

Following ASHRAE 62.1 [17] the indoor air quality (IAQ) is acceptable when *“(...) there are no contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction*.”

Recently, the IAQ of buildings is at risk, as a result of the increased demands on the airtightness of the envelope defined by regulation, and of the use of active HVAC systems that are in many situations turned off due to the lack of resources to cover energy costs. On the other hand, in Europe, the implementation of natural ventilation in new buildings is a challenge, since it is required to prove that the system actually leads to the airflow rates prescribed by regulations [75].

The air renovation in buildings should remove the heat load, eliminate pollutants and moisture, ensure adequate oxygen levels for human metabolism and control the risk of condensation. However, the implementation of a stronger ventilation strategy with higher air renovation rates may cause drafts and users' discomfort.

In order to ensure IAQ, a proper design and the use of a ventilation system are important. The ventilation strategy and the permeability of the envelope should consider the users’ habits (opening/closing windows) that are often associated with the heating strategy. When it is not possible to heat a building, users often choose not to open the windows in the winter period, and in that case, it is of the utmost importance to ensure the indoor air renovation. On the other hand, the opening windows habit makes it difficult to implement a mechanical ventilation system that does not allow manual control by occupants. The heating (and cooling) strategy must consider this reality.

In Portugal, the air infiltration rate is generally high once there are not usually any active ventilation system. Moreover, the opening of the windows is a cultural habit that persists even after the installation of the ventilation system. In this specific situation, the existence of high uncontrolled natural ventilation rates reduces the importance of the airtightness assessment.

In *Brandão* schools, the envelope, the opening of windows and the opening of doors have an important role in IAQ. There is no partition wall between classrooms and the circulation zone that promotes indoor circulation to the neighbour classrooms. Some doors communicate from each classroom directly to the outside and some doors communicate from each classroom to the neighbour classroom, by a common circulation zone. This layout results in variable renovation air rates that are difficult to calculate and predict. In spite of the potentially high natural ventilation rate, the high occupation rate deserves special attention. The occupants have the opportunity to open or close windows whenever they want but during classes in winter this behaviour may not happen so often in an attempt to prevent the internal heat loss.

One of the main challenges in non-refurbished school buildings is the occupation, that can reach up to four times the occupation of an office building [12] and focuses, in general, on five working days of the week and through September to June. CO_2 is the main pollutant and can reach high values in occupied classrooms [13], once it results from the metabolism.

In school buildings, the occupation is the main source of internal pollution. The CO_2 is used as an indicator of human bio-effluents (generated according to occupation). CO_2 is the most important and easily quantified human bio-effluent and is proportional to metabolism [13, 76, 77].

The limitation of CO_2 values in schools has two main goals: the reduction of health risks and the users' satisfaction in the perception of air quality. These two aspects may lead to different reference values. In fact, it is possible to have a pollutant concentration within the defined health limits and yet occupants not feeling comfortable with IAQ [77]. It is recommended to adopt a ventilation rate that meets simultaneously the health and the perception of IAQ criteria.

Moreover, people adapt to bio-effluents over time, and adapted occupants will find a space acceptable at a higher level of body odour than unadapted visitors. For an adapted person, the ventilation rate per person to provide the same acceptance is approximately one-third of the value for an unadapted person, and the corresponding CO_2 concentrations above outdoors are three times higher [25].

High CO_2 concentration values increase users' difficulties in concentration, headaches, physical discomfort and breathing. Some studies have been developed in order to understand how IAQ and thermal sensation affect students' performance. Wargocki and Wyon [9] developed some tests for elementary school students and assessed the speed of responses and errors. It was observed that classroom air renovation increases the answer speed and, with less relevance and weak correlation, reduces the prevalence of the error. It was also observed that a higher temperature inside the classroom (24-26 ºC) is harmful to the speed of response but does not have a very significant influence on the error prevalence (Figure 7).

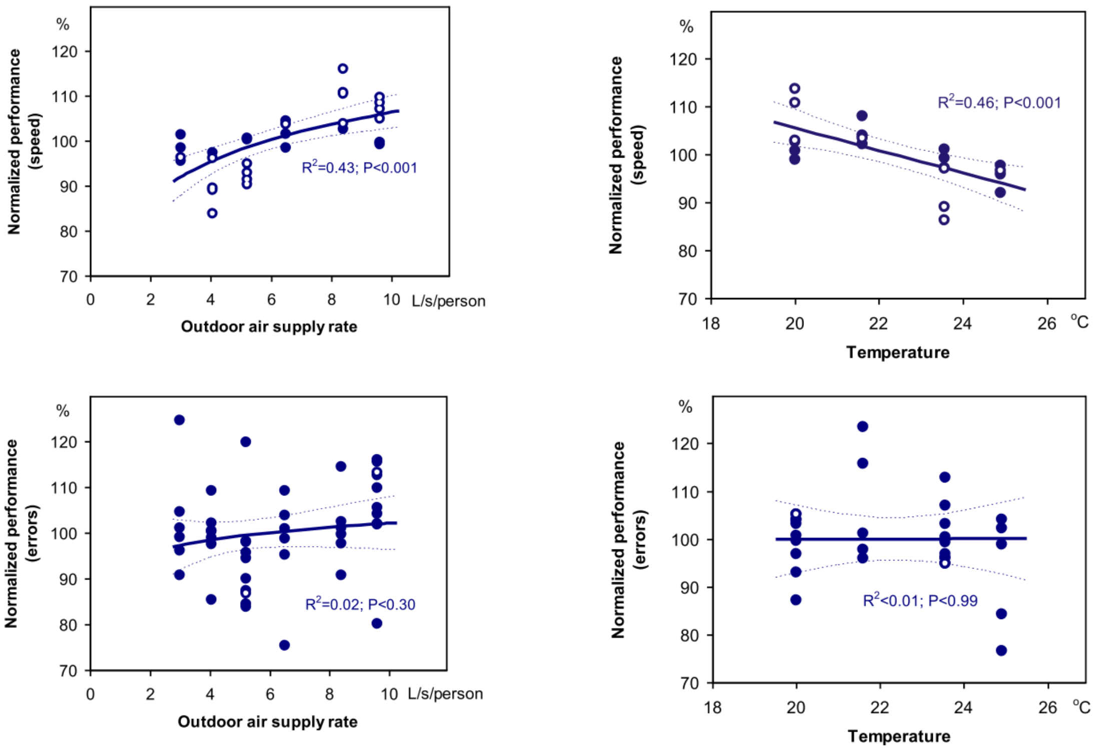


Figure 7 – Students' performance by outdoor air supply rate and inside temperature [9].

ASHRAE 62.1 specifies minimum ventilation rates and IAQ for buildings, regarding users' satisfaction, comfort and health (Table 1). ASTM D6245-12 also estimates the building ventilation rate using CO_2 quantification as an indicator of visitors' perception (ie newcomers) of bio-effluents [25].

Since the visitor's dissatisfaction (newcomer) is different from that of space-adapted people, ASTM D6245-12 represents the predictable percentage of dissatisfied newcomers as a result of the CO_2 concentration in the air (above outdoor air reference value), for spaces where occupants are the only source of pollution (Figure 8). According to this, the CO_2 concentration above outdoor air for 15%, 20% and 30% acceptance are 460 ppm, 660 ppm and 1190 ppm, respectively [13]. In Figure 8, equation PD represents the percentage of unadapted persons (visitors) who are dissatisfied with the level of body odor in space and CO_2 represents the CO_2 concentration above outdoors, in ppmv.

ASTM D6245-12 [25] quantifies the ventilation rate by CO_2 concentration development, considering two distinct procedures:

- ❖ Tracer Gas Method decay technique ("a concentration decay method") to determine air exchange by ventilation, using the amount of CO_2 generated by the occupants as a tracer gas. This method can be used immediately after occupants leave the space, when CO_2 concentration is uniform and when the building is completely unoccupied. If the period of evacuation is too long, the CO_2 concentration may not be sufficient for the application of the method. In addition, the method requires CO_2 concentration uniformity throughout the building, which is difficult to achieve in school buildings.

- ❖ Constant injection tracer gas technique ("a build-up method") considers indoor CO_2 concentrations generated by the users, in order to estimate outdoor air ventilation rates. The application of the constant injection technique using occupant-generated CO_2 is sometimes referred to as equilibrium CO_2 analysis, is applicable during the occupation period and is a special case of the previously referred technique.

As an alternative to the conventional tracer gas measurement, some authors have also used CO_2 as a tracer gas [78] and after them, other authors [26, 79] have applied this methodology in schools in order to find ventilation when the indoor concentration is greater than the outdoor concentration.

Occupant-generated CO_2 methods are very interesting because they do not require the injection of any tracer gas, taking advantage of a gas directly produced by occupants. Four main methods using occupant-generated CO_2 were identified: the concentration decay, the build-up method, the steady-state method, and the Transient Mass Balance Equation method [75]. The main problem arising from these methods is the uncertainty in the estimation of the emission rate, which depends on each occupant, occupancy, activity and gender. The interpretation of data also requires recording all the actions taken on ventilation and heating [80].

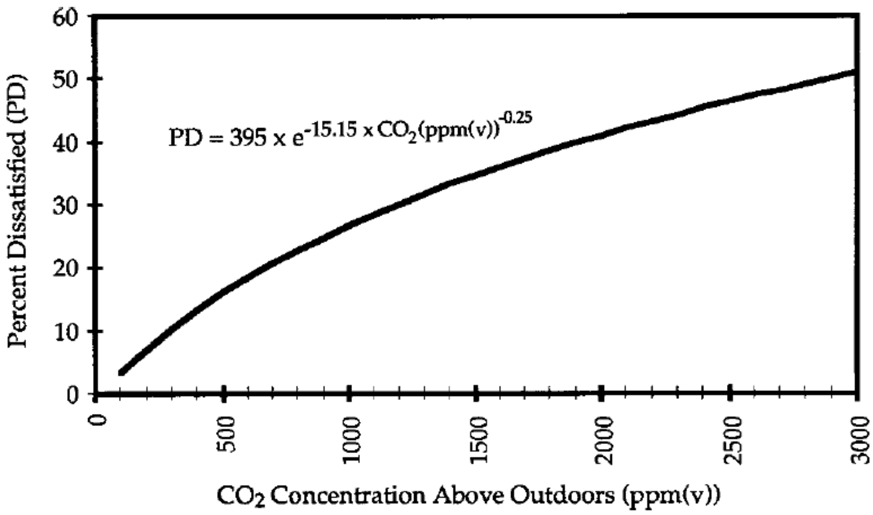


Figure 8 – Percentage of visitors dissatisfied as a result of the CO_2 concentration [25].

In sum, the IAQ affects students' performance and the high occupation is a challenge in schools. In Portuguese non-refurbished schools, the present uncontrolled natural ventilation rates are generally high and reduce the importance of the airtightness assessment (which is difficult to predict due to the opening of windows and doors and occupation variability). The increasing demands on the envelope airtightness and on the use of active HVAC systems (that are in many situations disabled due to the lack of resources for paying energy) must be carefully considered in a refurbishment.

Although the Portuguese legislation defines 1250 ppm for IAQ, in this work the reference value considered is 1500 ppm, in order to achieve a relaxed restriction in accordance with some international legislation.

2.1.2.3. Discomfort indicators

The performance evaluation of a building may include adequate indicators or criteria of performance of the actual conditions of each aspect at a time (such as thermal comfort or energy consumption) in order to compare the performance in different contexts [81].

As referred by Silva, Ghisi [81], global indicators can resume the behaviour of a building throughout the year but many individual observations can be compromised in view of the most representative trend of the data. For instance, energy consumption variables are globally characterized by an annual sum (“long-term assessment” indexes) but for thermal comfort, the approach should be different and there is not a unique and well-recognized index that can resume the thermal behaviour in all hours of all internal zones of a building. A “thermal comfort sum” and an “average thermal comfort” do not describe all the thermal comfort features. The most recent thermal comfort standards as ISO 7730 [55], ASHRAE 55 [63] and EN 15251 [18] contain some common long-term indices for global evaluation, but do not recommend a specific one.

Carlucci and Pagliano [82] performed a very complete review of long-term evaluation of general thermal discomfort in buildings. They have divided the existing indicators into four groups (Table 7): (i) percentage indicators, (ii) cumulative indicators, (iii) risk indicators and (iv) average indicators, described as follows:

i. The comfort performance of a building is assessed by calculating the percentage of likely discomfort hours concerning the total number of occupied hours.
ii. Discomfort is the result of the accumulation of thermal stress during the occupied period and expresses the severity level of discomfort.
iii. They measure the human thermal perception of the thermal environment to which an individual or a group is exposed, using a non-linear relationship between perception of discomfort and the exceeder from a comfort temperature.
iv. They are calculated by the mean value of an indicator (the indoor PPD or the outdoor air temperature) through a specific period.

In order to assess the comfort or discomfort in free-running/intermittently heated buildings, some indicators have been developed and applied by several authors. EN 15251 [18] defines an hourly-criterion (% of the time when the criterion is met or not) and a degree-hour criterion (degree hours outside the upper or lower boundary that can be used as a performance indicator of building for the warm or cold season). Previous works have also considered discomfort indicators based on EN 15251 hourly and degree-hour criteria. Curado and de Freitas [83] have studied Portuguese social houses; Ribeiro, De Freitas [84] have assessed Portuguese rural houses; Magalhães and de Freitas [85] have studied renovated dwellings in southern Europe. Paula [86] has studied the hygrothermal performance of Brazilian plaster houses. Other international studies have considered EN 15251 hourly and degree-hour criteria in order to analyse the buildings' thermal conditions [87-92]. All these studies have shown the possibility to use different long-term indicators.

Table 7 – Carlucci and Pagliano [82]'s long-term evaluation indicators of general thermal discomfort.

	Percentage	Cumulative	Risk	Average
Indicators	(1) % outside the range (2) % of occupied hours above a reference T	(1) PPD-weighted criterion (2) Accumulated PPD (3) Degree-hours criterion (4) Exceedance$_M$	(1) Nicol et al.'s overheating risk [93] (2) Robinson and Haldi's overheating risk [94]	(1) Average PPD (2) Difference between peak temperature and annual average temperature
Standards /Source	(1) At first by ISO 7730 and then by EN 15251 (2) Chartered Institution of Building Services Engineers (CIBSE)	(1) Fanger model (2) Fanger model and ISO 7730 (3) At first by ISO 7730 and then by EN 15251 (4) Borgeson and Brager [95]	(1) Nicol, Hacker [93] and EN 15251 (2) Robinson and Haldi [94]	(1) ISO 7730 (2) Difference between the indoor summer operative temperature and the annual average outdoor dry-bulb temperature
Application	(1) Winter and summer; analytical and adaptive models (2) Summer; not related to comfort models	(1) Warm and cold periods, separately; Fanger model (2) Warm and cold periods; Fanger model (3) Winter and summer; analytical and adaptive models (4) Summer; Fanger and adaptive model	(1) Warm periods, adaptive model (2) Warm periods	(1) Winter and summer; Fanger model (2) Summer
Limitations	Do not give information about the severity of the discomfort conditions.	(1) Does not consider overcooling and overheating effect; it depends on the boundary of categories (2) Not able to compare the severity of thermal conditions (3) It cannot be plotted on an absolute scale; (4) It does not consider the severity of the thermal exceedance.	(1) Is not suggested for mechanically cooled buildings (2) For continuous period and not just for occupied hours; calibrated only for temperate climate; based on a reference T of 25 ºC, chosen without a justification based on existing comfort models.	(1) It is not applicable to naturally ventilated buildings and to adaptive models (2) Does not consider the frequency and severity of overheating

The hourly-criterion (% of the time when the criterion is met or not) and the degree-hour criterion (degree hours outside the upper or lower boundary that can be used as a performance indicator of buildings for the warm or cold season) are long-term assessment indicators that can be used as performance and severity indicators for free-running /intermittently heated school buildings during warm and cold season.

2.1.2.4. Hygrothermal performance of school buildings

Thermal comfort

Most Portuguese schools are free-running buildings with a natural ventilation strategy [1] and for that reason, the analytical models (for regular heating and conditioned environment) are not suitable for these buildings. But despite the absence or irregular heating use, heating is an important strategy for reaching comfort in some Portuguese regions. The intermittent and irregular heating in Portuguese schools turns these schools into a particular situation between the analytical and adaptive models. Moreover, adaptive models were mainly developed by adults' surveys and mostly in office buildings, and there is still some lack of knowledge about the differences between adults and children in the perception of thermal comfort.

Regarding these subjects and main topics, some conclusions about classrooms’ thermal comfort are here synthesized:

- In Portuguese, Italian and Dutch free-running schools, no agreement was found between the Fanger method (PMV Index) and the thermal perception [1, 52-54].
- de Dear and Brager [68] proved that the PMV model predicts with accuracy the comfort temperatures for air-conditioned buildings. However, De Giuli, Da Pos [96] observed that in free-running elementary schools the PMV model underestimates thermal sensation in winter and overestimates it in summer.
- In Portugal, Almeida, Ramos [97] compared the Fanger analytical model with the EN 15251 model and concluded that the PMV index is more restrictive.
- Children were not included in the Fanger model climate chamber tests or in the definition of the standards' adaptive model and the comfort standards developed for adults may possibly not be adequate to assess children's thermal comfort. Once school buildings are mostly occupied by children, the differences between adults and children’s thermal perception may have consequences on the study of thermal comfort in school buildings. Teli, Jentsch [98] suggest that children are more sensitive to higher temperatures than adults with the comfort temperatures being about 4 ºC and 2 ºC lower than the PMV and the EN 15251 adaptive

comfort model predictions, respectively. Some possible explanations for this are the following: the higher metabolic rate per kg of body weight; the limited available adaptive opportunities in classrooms; the fact that children do not always adapt their clothing to their thermal sensation; the influence of their familiar indoor environments; the daily school schedule that includes a lot of outdoor playing. In the Netherlands, Mors, Hensen [54] also report that children prefer lower temperatures than those obtained through adaptive models. In Portugal, Almeida, Ramos [97] concluded that the correction of children's metabolism with the body surface area (10% lower than adults) leads to a better correlation between PMV-PPD indices and surveys.

- Buildings' constructive solutions have been studied by several authors. Almeida and de Freitas [99] observed that the buildings' behaviour depends on their orientation. As expected, preferential south orientation reduces heating needs and north orientation reduces the risk of overheating. Increasing roof insulation can reduce the heating needs and in some locations improve the summer comfort. They also concluded that the walls' insulation and the glazing upgrade improves the building behaviour in winter but may worsen comfort conditions in summer. Conceição and Lúcio [100] observed that rooms with north oriented windows, rooms with solar protections and interior rooms (without windows) with low occupation rates have worse thermal performance in winter. In heated schools, it is common to find located discomfort near the heaters and the openings [101].

School performance, occupants' health and IAQ

Recent studies report that a healthy school environment promotes students' attention, performance and health. Concerning this, several studies about IAQ have been performed:

- The fresh air ventilation rate in schools is often below standard values. At the same time, CO_2 concentration values are often above standard values and occupants are improperly exposed to other pollutants (such as volatile organic compounds (TVOC), microbiological contaminants, fungi, molds and allergens) [10, 102].
- The main reason for an inadequate ventilation strategy in schools is the lack of financial resources for systems maintenance and the concern with the conservation of thermal energy [9].
- The installation of new ventilation systems and the increase of air ventilation rates in schools reduce the occupant exposure to pollutants and improve the environment and the perception of air quality [8, 10, 103, 104].

- Improving IAQ in classrooms may decrease asthma symptoms, the *Sick Building Syndrome* and other respiratory symptoms [10, 102]. Children exposed to higher concentrations of TVOC have an increased risk of asthma-related symptoms [105].
- The physical environment affects teaching and learning: low air ventilation rates in classrooms reduce attention and vigilance and negatively affects memory and concentration [7]; low ventilation rates and high fluctuations of temperature inside the classroom can reduce children's performance by up to 30% [9]; the air quality improves the performance in standardized tests [8]; pupils in schools with balanced mechanical ventilation had significantly higher achievement indicators (adjusted for a socioeconomic reference index) than pupils in schools with natural ventilation [104].
- Enabling children to complete routine exercises more quickly would leave more time for learning, leisure and other school activities, all of which may be expected to improve the longterm learning process. The society and economic costs of the observed results have not yet been estimated. However, children in classrooms with poor indoor environmental quality will require teachers to spend more time and effort, so the costs can be quantified in terms of the extra time for which teachers must be paid [9].
- Either excessive stimulus amplitude or insufficient adaptive opportunity are both potential causes of dissatisfaction. Limiting adaptive opportunities may also increase occupant sensitivity to other stimuli [66]. Kim and de Dear [106] observed that the occupants' perception of the indoor environmental quality depends on the ventilation strategy (natural, mixed or mechanical), suggesting an important role in users' expectations.
- In Portugal, some studies revealed that IAQ (traduced by CO_2 concentration in the air) in refurbished classrooms is better than in non-refurbished ones. However, the results in refurbished classrooms are different than the expected because mechanical ventilation is often turned off [1]. Experimental measurements reveal different in-service IAQ conditions from what would be expected due to financial restrictions in HVAC operation [107].
- CO_2 concentration inside classrooms start to rise at the beginning of the school day, with a peak at the end of the morning, a decreasing period during lunchtime and rising again until the end of the last class of the day. The short intervals between classes (5 minutes) do not allow the equilibrium of the CO_2 concentration of the indoor and outdoor air. Moreover, sometimes students stay inside the classrooms between classes. Finally, the ventilation strategy was not always effective [108].

- CO_2 fluctuations are much higher in classrooms with natural or mixed ventilation. In mechanically ventilated classrooms, CO_2 remains stable throughout the day, with some fluctuations due to occupant behaviour resulting from opening and closing windows [108].
- Some discomfort related to using outdoor air ventilation systems may arise, caused by drafts and also by the reduction of the indoor temperature in winter. The *in-situ* implementation of ventilation systems controlled by temperature were found: (1) in Norway, Mysen, Schild [109] suggest a strategy for controlling indoor CO_2 by temperature monitoring in order to control the airflow, to improve thermal comfort and to reduce energy consumption without compromising users' IAQ perception during heating season; Mysen, Schild [109] define that CO_2 should not exceed 800 ppm preferably, but allow a lower concentration when the indoor air temperature is above 22 ºC and a higher concentration when the temperature is below 20 ºC. (2) In Portugal, Almeida and De Freitas [107] also suggest a ventilation system for school refurbishment, including a management system that receives information from sensors inside the classroom (T and CO_2) and from an outdoor T sensor; the fan speed is set according to T and CO_2 criteria; in addition, when the ventilation system is operating and the outside air T is below 8 ºC, the management system controls the heating system 5 minutes before ventilation begins; if CO_2 concentration exceeds 2000 ppm, ventilation assumes its maximum speed; the ventilation system works only during the occupation period, starting 1 hour before the morning classes and ending half an hour after the end of the afternoon classes.

The thermal comfort and IAQ performance of schools have been widely studied by several international and national authors. The application of comfort models and ventilation requirements depends on the existing heating and ventilation strategies. The improvement of comfort conditions and IAQ in Portuguese schools must consider the free-running or intermittent heating conditions, the poor thermal properties of the envelope, the uncontrolled natural ventilation strategy, the low airtightness of the envelope and also the lack of resources for paying energy consumption. The refurbishment of Portuguese schools justifies the investment in studying specific strategies for these specific conditions.

2.1.3. Energy performance

2.1.3.1. Energy consumption

The world energy expectation has been changing and is strongly dependent on the global economy and climate changes. Portugal has been trying to follow the global trends of energy consumption reduction [110]. Recently, some strategies have been discussed in order to reduce fossil fuel dependence and greenhouse gas emissions.

The building construction sector has particularly high environmental and financial impacts and is related to the consumption of many resources, namely energy consumption [111].

Portuguese building area represents 452 000 000 m^2. Residential buildings share is 77% and non-residential buildings 23%, of which 21% are school buildings, 26% are office buildings and 28% are commercial buildings (Figure 9) [112].

According to Direção-Geral de Energia e Geologia, the total number of new buildings in Portugal has decreased in recent years (from about 65 000 buildings in 2002 to approximately 26 000 buildings in 2014). However, the rehabilitation, refurbishment and reconstruction sector has increased and represents a potential promotion of energy efficiency and economic activity. In the reconstruction sector, the number of residential interventions has been decreasing and there is a slight increase in the remaining (non-residential) buildings [112].

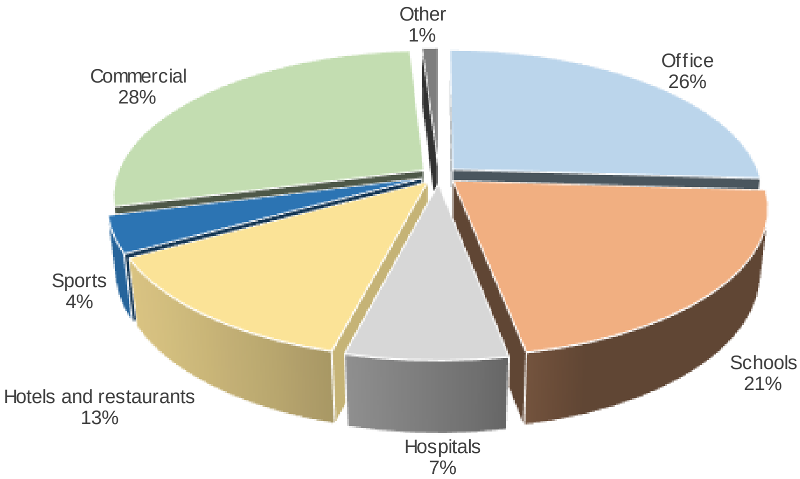


Figure 9 – Non-residential buildings in Portugal (adapted from [112]).

2.1.3.2. European and Portuguese legislation

The development of Portuguese regulation of thermal requirements and energy certification has been following the European Union (EU) legislative strategy. The most recent European guidelines (EPBD and EED) were transposed into Portuguese law through Decree-Law No. 251/2015 (republication of Decree-Law No. 118/2013) (Figure 10).

European Directives EED 2012/27/EU and EPBD 2010/31/EU promote the reduction of energy consumption in buildings through their improvement and renovation and also the implementation of alternative measures. They were defined for heated and/or cooled buildings and are based on minimum energy performance requirements [113].

The updated European EPBD refers that (residential and non-residential) buildings represent 40% of UE total energy consumption and proposes the binding target of reducing primary energy consumption by 20% until 2020, a greenhouse gas emissions reduction of 20% and the use of renewables representing 20% of final energy consumption [114].

For 2030, the European targets are the 40% reduction in greenhouse gas emissions in comparison with 1990, the reduction of a share of 27% of renewable energy consumed in the EU and headline energy efficiency target of at least 32.5% (defined by the amended directive 2018/2002) [115]. For 2050, EU target is the greenhouse gas emissions to reduce 80 to 95%, compared to 1990 [116].

The main challenges defined by EPBD are:

- ❖ Methodology for calculating the integrated energy performance of buildings and its fractions;
- ❖ Minimum requirements for the energy performance of new and existing buildings (and its fractions) under major renovation;
- ❖ Development of national plans to increase the number of Nearly zero-energy buildings (NZEBs);
- ❖ Energy certification of buildings and independent control systems of energy performance certification;
- ❖ Regular inspection of boilers and air conditioning installations in buildings and, in addition, assessment of heating installation when boilers are over 15 years old.

1990 • PORTUGAL - RCCTE - Decree-Law No. 40/90

1998 • PORTUGAL - RSECE - Decree-Law No. 118/98

2002 • EUROPEAN UNION - EPBD - Directive 2002/91/CE

2006 • PORTUGAL - SCE - Decree-Law No. 78/2006; RSECE - Decree-Law No. 79/2006; RCCTE - Decree-Law No. 80/2006

2010 • EUROPEAN UNION - EPBD - Directive 2010/31/UE

2012 • EUROPEAN UNION - EED - Directive 2012/27/UE

2013 • PORTUGAL - SCE REH RECS - Decree-Law No. 118/2013

2015 • PORTUGAL - SCE REH RECS - Decree-Law No. 251/2015 (republication of Decree-Law No. 118/2013)

Figure 10 – Thermal requirements and energy certification development strategy.

The European Energy Efficiency Directive (EED) defines some measures to promote energy efficiency in the EU in order to achieve the 20% energy efficiency target by 2020 [117]. Some national energy efficiency targets emerge from the EED application. The main challenges that came up from EED are [118]:

- The exemplary role of public buildings and the annual renovation of 3% of the total built area of heated and/or cooled buildings in order to meet the minimum energy performance requirements (EPBD);
- Energy efficiency obligation schemes (final energy savings);
- Energy audits and energy management systems available to all the consumers;
- Energy production and distribution efficiency (possibility of high-efficiency cogeneration and efficient district heating/cooling implementation).

In order to fulfil the defined targets, the European guidelines propose the implementation of improvement measures that reflect these environmental and energy concerns and the implementation of methodologies to determine the optimum cost-effective solutions. Public buildings must be the first to implement these measures [114].

At the national level, Decree-Law No. 251/2015 of 25 November transposes the Community Directive into the Portuguese legislation and includes, in a single diploma, the Energy Certification System of Buildings (SCE), the Regulation of Energy Performance of Residential Buildings (REH) and the Energy Performance Regulation of Non-residential Buildings (RECS). This decree-law provides some exceptions (for the renovation of existing buildings) to the fulfilment of certain requirements when incompatibilities are shown. The regulation of non-residential buildings includes the thermal behaviour of buildings, the ventilation and IAQ and the efficiency of technical systems.

In Portugal, Decree No. 17-A/2016 of 4 February (replacing Decree No. 349-D/2013 of 2 December) establishes design requirements for the thermal performance of the envelope and for the system efficiency (for new and existing non-residential buildings) [119, 120]. The decree No. 353-A of 4 December establishes, for these same buildings, the minimum fresh airflow, the reference conditions and the IAQ protection limits [20].

The legislation for non-residential buildings promotes the introduction of improvement measures to guarantee continuous comfort conditions, while the Portuguese schools' situation is mainly the free-running conditions and eventual intermittent heating strategies with very low energy consumption.

For that reason, the development of refurbishment strategies that decrease thermal discomfort regarding the present low energy consumption is the main challenge for the next years.

2.1.3.3. Energy consumption in school buildings

The European guidelines, adapted by each State Member, promote the renovation of existing buildings, taking into account their energy performance to achieve the proposed environmental goals. The energy consumption and the potential energy savings through the rehabilitation should be assessed for each building. Public schools have an important social interest and represent an opportunity to improve energy efficiency and the quality of the indoor environment [3].

Several studies on energy consumption in schools have been developed. Some important differences between the real and numerically calculated energy consumptions were found, and these differences may have increased importance in free-running buildings with intermittent and uncontrolled heating strategies (in some southern European countries).

In this work, the assessment of energy consumption is exclusively associated with the comfort inside classrooms, excluding energy consumption for hot water, cooking and other activities outside classrooms.

The main conclusions of the studies about the real energy consumption in different European countries and the strategies for reducing energy consumption are the following:

Real energy consumption

- The energy consumption in Portugal and in some southern European countries is presented in Table 8. In most European studies, electrical consumption is generally distinct from heating consumption (gas or other). However, in Portuguese school buildings, the eventual intermittent heating is electric heating and for that reason, the comparison of the Portuguese electric consumption with the other European countries is difficult.
- Different education levels have distinct schedules and occupation and may, therefore, have different patterns of energy consumption [3].
- In order to compare data, Dias Pereira, Bernardo [121] propose a *School Benchmarking Indicator* (SBI) that considers the energy consumption and a climatic adjustment, in kWh/m^2/year/DH, where DH represents the heating degree-hour.
- Through the energy consumption analysis (invoices) of the 23 schools studied by Almeida, Ramos [37], it was concluded that the electric consumption presented a seasonal behaviour, with higher values in winter. The mean value of the total annual consumption cost was 6 €/m^2 [37].

- The energy consumption in Portuguese schools with and without heating is not very different, suggesting the reduced heating use [37].

- Several authors have developed indexes and methodologies to predict energy consumption in school buildings: Beusker, Stoy [122] proposed an energy consumption estimation model for German schools, based on critical construction parameters and its correlation with energy consumption; Rospi, Cardinale [123] assessed the energy needs according to Italian energetic certification, by comparing the dynamic results (Energy Plus model) with the real energy consumption; Zanni, Righi [124] developed an analysis tool for school buildings that predicts the possible heating energy consumption reduction and its CO_2 emission, by the introduction of simple information; Desideri and Proietti [125] developed a methodology for analysing energy-saving procedures in Italian school buildings, which included energy consumption data collection and potential savings assessment.

- The school buildings' energy consumption estimation should take into consideration the building's typology and should be based on representative samples [3] [126].

Table 8 – Energy consumption in Portuguese and south European school buildings.

Country	Reference	Unit	Heating (gas / other)	Electricity	Sample
Portugal	Lourenço, Pinheiro [127], Wang [128]	kWh/m²/year	16	51	8 high schools
	Dias Pereira, Raimondo [3], Dias Pereira, Bernardo [121]	kWh/m²/year	---	29 (percentile 25) 33 (median)	57 high schools
	Almeida, Ramos [37]	€/m²/year	0.66 0.58 (median)	3.89 3.98 (median)	23 schools
Greek	Santamouris, Mihalakakou [129]	kWh/m²/year	68	27	320 schools
	Wang [128]	kWh/m²/year	71.18	8.64	10 basic schools
	Dascalaki and Sermpetzoglou [130]	kWh/m²/year	57	12	135 schools
	Dimoudi and Kostarela [6]	kWh/m²/year	123.3	14.3	9 schools (heating) 6 schools (electricity)
Italy	Dias Pereira, Bernardo [121]	kWh/m²/year	110	---	---
	Desideri and Proietti [125]	kWh/m³/year	24.2	3.1	28 schools (heating) 13 schools (electricity)

Energy Consumption Reduction Strategies

- Energy consumption reduction strategies may include intervention in the building envelope, in technical systems and/or in users' and managers' behaviour, but the social and behavioural issues are still not enough reported by the scientific literature [127].
- de Santoli, Fraticelli [60] focused their study on energy consumption for space heating, considering that it is the most important share of energy consumption. The analysis was performed by comparing the costs parameterized for standard retrofit interventions for the existing envelopes and technical systems to the energy and money benefits achievable by the interventions. The authors assessed the roof thermal insulation, the replacement of windows and the improvement of heating systems. In almost 30–40% of the cases, the global intervention will be advantageous, having a simple payback time lower than the life of the intervention itself. Other authors have performed similar studies: In Italy, Zinzi, Battistini [131], in Slovenia, Butala and Novak [132] and in Greek, Dascalaki and Sermpetzoglou [130], also associated with an assessment of the reduction of greenhouse gas emissions. Also in Greek, Dimoudi and Kostarela [6] found that increasing the thickness of the wall insulation reduced heating and energy consumption by up to 5.58%, and the combination of different energy efficiency interventions (thermal bridges reduction, increased wall insulation thickness, reduction of air infiltration and shading devices removal) resulted in energy savings of about 28.75%. Theodosiou and Ordoumpozanis [133] suggested the implementation of heat consumption meters and controls, the proper installation of thermostats, the thermal insulation of the envelope and window replacement as energy-saving, economic and indoor thermal environment improvement interventions.

The energy consumption of schools has been widely studied by several international and national authors. However, the improvement measures to guarantee continuous comfort conditions are not adequate for Portuguese schools' situation (mainly free-running conditions and eventual intermittent heating strategies) with very low energy consumption. An assessment of energy consumption in free-running/intermittently heated schools and its improvement after refurbishment would be an interesting approach for Portuguese schools.

2.1.4. International projects

Recently, some international projects/studies about school building rehabilitation have been developed, since these buildings have an important social interest and will need some interventions soon, which will represent an important investment.

Some studies focus on constructive strategies, others on energetic efficiency and others on cost management. Despite its main focus, all studies try to define the best refurbishment strategies for school buildings, regarding the constructive, political and economic constraints of each country where it is developed.

Some relevant international projects of school building rehabilitation:

- ❖ *Annex 36 - Retrofitting of Educational Buildings – International Energy Agency* working group, with the main purpose of the development of an 'energy concept adviser' for use during the planning and implementation phases of a project that would help decision-makers to optimize the energy-saving measures to be applied and avoid exaggerated expectations [134-136]. Analysing real cases, it was found that energy heating needs can decrease by up to 75% and that electricity consumption can decrease by 40%. However, these results report to mainly northern and central European school buildings and must be carefully undertaken when considering a climatic reality like Portugal.
- ❖ *Renew School* – Implementation of advanced rehabilitation solutions: wood prefabrication (quickness and sustainability); ventilation (indoor air quality); intelligent daylight and shading control; integration of renewable energy. This work was developed in 18 European school buildings: Belgium, Germany, Denmark, Sweden, Norway, Poland, Austria, Slovenia, Italy. Some visits to refurbished schools were scheduled in order to convince school owners and decision-makers and also to motivate principals by inviting them to see the rehabilitation benefits and improvements. Architects and engineers were also invited to assist these visits and the *media* were called for spreading the information. At the same time, some conferences and *workshops* were also prepared for the knowledge spreading [137].
- ❖ *School of the Future: Towards Zero-Emission with High-Performance Indoor Environment* – The aim of the "School of the Future" project was to design, demonstrate, evaluate and communicate shining examples of how to reach the future high-performance building level. Both, the energy and indoor environment performance of 4 demo buildings in 4 European countries and climates has been greatly improved due to the holistic retrofit of the building envelope, the service systems, the integration of renewables and building management systems [138] [139].
- ❖ *EnergySmart Schools* – The *U.S. Department of Energy's EnergySmart Schools Program* was developed in the United States of America (EUA) in 2008 and promotes the reduction of energy consumption of 30% in existing school buildings [140]. This program was supported

by ASHRAE and resulted in some guidelines with recommendations for building envelope and technical systems [141] [26].

- *Building Schools for the Future* – This program was promoted by the British Government to ensure that all pupils in England have a proper high school education. This program had an early finish in 2010, due to the country's economic restrictions [142].
- *ENERESCOLAS Program* – The main goal of this Portuguese program is the reduction of energy consumption in schools and its associated costs, by the awareness of the educational community (students, parents, teachers and others) about the importance of the energy efficiency and of the adoption of some new behaviour patterns. This learning project on energy efficiency and management has included energy consumption and comfort parameters monitoring in Portuguese elementary schools. VPS was the project coordinator and integrated the energy performance monitoring technologies [143].
- *Teenergy Schools* – This program was developed in Italy, Spain, Cyprus and Greek (between 2009 and 2011). It consisted of the development of a platform for data collection, spreading of knowledge and practical guidelines for the rehabilitation and energy efficiency of high schools in Mediterranean climates. The lack of practical energy efficient applications in southern European climatic is the main limitation of this project [144, 145].
- *SchoolVentCool* - The *School Vent Cool* project, “Ventilation, cooling and strategies for high performance school renovations” (between 2010 and 2013) had several European partners: Austria, Switzerland, Belgium, Germany and Denmark, among others. Some refurbishment strategies of the envelope were developed to promote energy efficiency, thermal comfort and IAQ in schools. Prefabrication and modular design concepts were explored and also new solutions for natural ventilation systems to prevent overheating [144, 146].
- *ZEMedS – ZEMedS* program, “Promoting Renovation of Schools In a Mediterranean Climate Up to Nearly Zero-Energy” (between June and December of 2013) had several European partners like Italy, Spain, France and Greek. It was co-financed by the European Commission under the program Intelligent Energy Europe Programme (IEE). The main goal was the awareness of Mediterranean countries about the NZEB refurbishment of school buildings [144, 147].

The international projects promote funding and incentives for the refurbishment of schools. The results are also important to spreading strategies and best practices among other countries [61], even if the main goals, energy efficiency targets and in-service Portuguese schools conditions are different from other European countries.

2.1.5. Final considerations

Considering the presented framework, the final considerations of this chapter are:

- ❖ In Portugal, children spend most of their time in school, just after their own home. Furthermore, the physical environment affects teaching and learning which justifies the investment in comfort and IAQ.
- ❖ The users' perception of indoor environmental quality has an important role and depends on the ventilation system, heating system and envelope.
- ❖ Most Portuguese schools are free-running buildings with a natural ventilation strategy.
- ❖ There are two major groups of thermal comfort models: analytical models and adaptive models. The first ones are for constant and controlled environmental conditions, which is not the Portuguese schools' reality. The second ones are for free-running T conditions, which is the present in-service situation. However, intermittent heating is a possible strategy in the Portuguese climate and for that reason, Portuguese schools are a particular situation between the analytical and the adaptive models.
- ❖ Some studies have been recently prepared in order to choose the best refurbishment strategies for specific school buildings in different countries, regarding their particular needs and legislation but most of them have nothing to do with Portuguese reality.
- ❖ The non-refurbished Portuguese schools show very low comfort and inadequate hygrothermal conditions and will require intervention in the near future. The opportunity to refurbish these schools must consider the acquired knowledge in this type of buildings by experimental monitoring of in-service free-running schools.
- ❖ The energy performance of school buildings has been studied by several authors of different countries in Europe and around the world. The methodology proposed by the recent European guidelines regards continuous comfort conditions, which is not the Portuguese reality. An assessment of energy consumption in intermittently heated schools and its improvement after refurbishment would be an interesting approach for Portuguese schools.

Some practical conclusions, regarding the strategy of the next chapters:

1) Thermal comfort: the T reference values are 20 ºC (EN 15251 – category II) [18] and 25 ºC (Portuguese Energy Regulation of Buildings – non-residential buildings) [20] for winter and summer, respectively. The reference values will have an important role in the assessment of the occupants' discomfort. Moreover, regarding the absence of cooling

systems, an adaptive assessment of summer conditions will be considered. Relative humidity will also be assessed, although this parameter may have little influence on the thermal environment preference.

2) Discomfort indicators: The hourly-criterion (percentage of the time when the criterion is met or not) and the degree-hour criterion (degree hours outside the upper or lower boundary that can be used as a performance indicator of building for the warm or cold season) are long-term assessment indicators that can be used as performance and severity indicators for free-running /intermittently heated school buildings during warm and cold seasons.

3) Indoor air quality: although the Portuguese legislation defines 1250 ppm for IAQ, in this work the reference value considered is 1500 ppm, in order to achieve a relaxed restriction in accordance with some international legislation (Table 1).

3
Experimental characterization of thermal performance and energy consumption of a prototype

3.1. MAIN GOALS AND MOTIVATION

This work studies the Portuguese *Brandão* school model (from the '70s), which comprises about 100 non-refurbished basic schools. It studies the passive refurbishment of these public schools with some affordable interventions, regarding the climate features and the reduced capacity to support the operating costs.

A prototype classroom was prepared in a *Brandão* school, in Porto. The *in-situ* experimental campaign consisted of temperature, relative humidity, CO_2 concentration and energy consumption measurements. The prototype construction included the improvement of the envelope and of the technical systems. The main goals of this chapter are:

(1) The implementation of a reduced cost refurbishment of a prototype classroom in a *Brandão* school in Porto, Portugal.

(2) The comparison of the prototype in-service thermal performance in pre-existing conditions and the improvement after the refurbishment in free-running conditions or with some intermittent heating strategies, winter and mid-season analysis.

(3) The quantification of discomfort indicators for the assessment of the winter and mid-season discomfort for the Mediterranean temperate climate without heating or with intermittent heating strategies;

(4) The quantification of the energy consumption *vs* discomfort in winter, regarding the passive refurbishment strategy and the intermittent heating strategies.

The experimental work developed in an in-service typical *Brandão* classroom (prototype) may be replicated in other *Brandão* schools, regarding its particular features and climatic conditions. The energy consumption monitoring of the prototype allowed the estimation of the whole building energy consumption.

The experimental results of T, RH and CO_2 were also an important tool during the calibration process, in order to validate a hygrothermal numerical model of a *Brandão* classroom.

3.2. CASE STUDY

3.2.1. TYPIFIED PROJECTS

Some typified projects were developed (starting in the ’60s) to be implemented in basic and elementary schools, technical schools and high schools (*Projetos Normalizados Tipo*). They were promoted by *Ministério da Educação* (through *Direção Geral da Administração Escolar*) and by *Ministério das Obras Públicas* (through *Direção Geral das Construções Escolares*).

The typified projects had as concern the simplicity, the expedition of implementation and a provident economy of construction, in order to be easily replicated throughout the country. These projects included independent building blocks, adaptable to the ground features and usually linked by outdoor galleries.

The schools' buildings had distinct configurations according to the level of education and its program (basic and elementary schools, technical schools and high schools) [148] and there were only slight differences according to the year of implementation.

There are 4 highlighted projects of this period [149]:

1) *Base Liceal* – The *Projeto Normalizado de Liceus Tipo* has 4 building blocks type: (1) single-storey general block with common and administrative areas, (2) two-storey block for laboratories, with quadrangular plant and an uncovered inner courtyard, (3) two-storey block for classrooms and (4) a sports block.
2) *Base Técnica* - The *Projeto Normalizado de Escola Técnica Tipo* has 3 building blocks type: (1) two-storey general block with common and administrative areas, (2) two or three-storey quadrangular block for classrooms with a skylight-covered central courtyard, (3) single floor block for manual works and (4) a sports block.
3) *3 x 3* – A typified project from the ’80s, composed by building blocks connected by galleries. It has two building blocks type: (1) two-storey quadrangular block for classes and

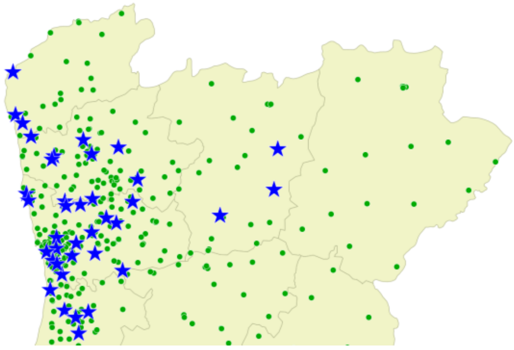
administrative areas, with stairs in the center and a lantern roof and (2) a single-storey rectangular block for the canteen, kitchen and common area.

4) *Brandão* - The *Estudo Normalizado de Escola Preparatória* has 2 building blocks: (1) one block with one and a half floor with common and administrative areas (2) single floor quadrangular classrooms blocks with a central courtyard, (3) a sports block [38].

3.2.2. *BRANDÃO* SCHOOLS

The object of this study is the Portuguese *Brandão* model, developed by Arq. Augusto Brandão (MOP-JCETS) in 1968, which comprises 100 basic schools replicated throughout the country in the 70s [150].

There are 38 identified *Brandão* schools in the North of Portugal (Figure 11) [144]. Presently, these school buildings are mostly occupied by students from the fifth to the ninth grade of elementary school, as happened in the past, when they were implemented.



District	No. of schools
Aveiro	5
Braga	8
Porto	19
Viana do Castelo	3
Vila Real	3
TOTAL (North)	38
TOTAL - estimation (Portugal)	100
★	*Brandão schools*
●	Schools from 5th to 9th grade

Figure 11 – Geographic location of Brandão schools in the North of Portugal.

This is a pavilion type project, composed by quadrangular single floor blocks of classrooms with a central courtyard (Figure 12) [38]. Classrooms can be accessed around the building (outdoor circulation) or through the neighbouring classrooms (indoor circulation), once they are clustered by a common circulation zone. This layout results in variable renovation air rates that are difficult to calculate and predict. Despite the potentially high natural ventilation rate, the high occupation rate deserves special attention. The occupants have the opportunity to open or close windows whenever they want but during classes in winter, this may not usually happen in order to prevent the internal heat loss.

These non-refurbished schools have very low comfort and inadequate hygrothermal conditions and will possibly require some interventions in the near future. It is thus important to define some strategies for the refurbishment of these basic schools, considering passive low-cost interventions and the appropriate use of affordable intermittent heating strategies.

The research topic focuses on a specific school typology in order to validate an intervention methodology in these schools. This is justified by the refurbishment investment estimated in €2-3 million per school (€400 to €600 per square meter). The investment can reach 200 to 300 million euros for the refurbishment of all the Portuguese *Brandão* schools.

Figure 12 – Aerial view of a Brandão school [38].

3.2.3. CONSTRUCTION CHARACTERIZATION OF THE *BRANDÃO* SCHOOL BUILDINGS

These schools have not had any important intervention since their construction except for particular little renovations or maintenance operations. For this reason, it is possible to characterize the present *Brandão* buildings (with the same original solutions), and particularly the envelope solutions (exterior walls, roofs, glazing systems, sunscreen devices), the ventilation and heating systems. There are not any renewable energy system installed.

<u>Constructive Solutions of the envelope</u>

The envelope constructive solutions of the *Brandão* schools are presented in Table 9. The solutions described are the original ones, currently in use in most situations.

Some practical conclusions about the constructive characterization of the *Brandão* buildings:

- ❖ These buildings have a mainly horizontal development and thus an important implantation area and consequent high roof area. For that reason, the thermal exchanges through the horizontal envelope are higher than through the vertical opaque envelope. The roof insulation may represent important benefits in thermal comfort.
- ❖ The walls' thermal insulation is poor and its influence in the global thermal performance must be studied.
- ❖ The non-opaque envelope is a significant part of the total vertical envelope. For that reason, the windows thermal transmittance and its g-value (considering the heating needs but also the overheating risk) may have an important role in the *Brandão* buildings refurbishment.

- The installation of shading devices as a protection against summer heat gains without restricting the relevant winter heat gains should be considered.

Table 9 – Constructive solutions of the Brandão school envelope [38-41].

Element	Characterization
Roof	There are two different solutions, originally without thermal insulation, although they may have had a later intervention in some cases: (1) sloped roof with metallic or fiber cement coating, a ventilated attic (inaccessible) and a concrete slab (2) horizontal roof with concrete tiles, self-protected asphalt screen waterproofing, a lightweight concrete layer and a concrete slab.
Exterior walls	There are three different solutions, all without thermal insulation: (1) simple solid brick masonry without cover, (2) simple brick masonry with painted mortar plaster (or decorative tiles eventually) and (3) simple concrete wall uncoated or painted.
Windows	Aluminum or iron window frames (in classrooms) (tilting windows, sliding or fixed). Single glazing (sometimes with films) in some cases with interior solar protection in bright colours (Venetian blinds); sometimes barred windows.
Exterior doors	Aluminum window frames. Single glazing, sometimes with interior solar protection in bright colours (Venetian blinds).
Pavement	Ground floor with coating: (1) pine wood floor (in classrooms) or (2) concrete screed (in corridors and common areas). Other solutions: ceramic or synthetic tiles, limestone, cork tiles and floating floor.
Interior walls	There are two different solutions, both without thermal insulation: (1) simple solid brick masonry without cover and (2) simple brick masonry with painted mortar plaster. Other solutions: ceramic tiles (kitchen, *buffet* and restrooms) and single concrete wall uncoated.
Ceiling	Painted ceiling, cork agglomerate, structural concrete (uncoated) or acoustic suspended ceiling (sometimes) or gypsum board.
Other interior elements	Wooden doors (between classrooms) or aluminum glazed doors (common areas); removable wooden elements between classrooms and the circulation area; metallic doors (kitchen).

Technical systems

Inside the *Brandão* classrooms, there is a natural ventilation strategy that depends on the users' windows and doors management. The occupants have the opportunity to open or close windows whenever they want but during classes in winter, it may not be, in some cases, a usual behaviour, in order to prevent the internal heat loss. Given the difficulty in predicting users' behaviour, IAQ in classrooms is variable.

There are no regular heating systems in *Brandão* classrooms. In some cases, electrical heaters are installed in some classrooms, with an intermittent and not predictable heating use.

3.2.4. Portuguese legislation for refurbishment

The constructive solutions of new or refurbished buildings must be properly characterized by thermal properties and technical conditions that may affect the thermal behaviour.

The thermal transmittance of the non-residential buildings' elements (including school buildings) must not be higher than those presented in Table 10. The maximum g-values for windows in Portugal (continental) are presented in Table 11. Moreover, the treatment of the building envelope should regard that the non-linear thermal bridges must not be above 0.90 W / (m^2.ºC) [151].

Table 10 – Reference and maximum thermal transmittance of the envelope, U_{ref}, U_{max} [W/(m^2.ºC)] – non-residential buildings in Portugal (continental) [120].

Current envelope	I1	I2	I3
Opaque vertical elements (exterior and interior)	0.70	0.60	0.50
Opaque horizontal elements (exterior and interior)	0.50	0.45	0.40
Exterior glazed system (doors and windows)	4.30	3.30	3.30

Table 11 – Reference and maximum g-values for windows for each summer climatic zone [120].

g-value	V1	V2	V3
g-value of reference windows (without shading systems)	0.25	0.20	0.15
Maximum g-value for windows with all shading systems in use (g_{Tmax}) (*1)	0.56	0.56	0.50

(*1) In large non-residential buildings and when the sum of the vertical glazing area (by orientation) is greater than 30% of the façade area (where windows belong), g_{Tmax} shall be multiplied by 0.30/(A_{env}/A_{eve}), where A_{env} is the glazing areas sum (by orientation) and A_{eve} is the building's exterior vertical envelope area (by orientation). This requirement may not be fulfilled when there is an evident increase in energy consumption.

3.2.5. The prototype

A prototype west-sided classroom has been studied in a *Brandão* school in Porto (previous Figure 12). The prototype is in a typical *Brandão* basic school (5^{th} to 9^{th} grade) from 1978.

The main glazing area is west-sided. On the east side, the classroom is limited by a common area and a courtyard and in the north and south side by similar classrooms (Figure 13).
This classroom was monitored and refurbished under the scope of this Thesis. The experimental campaign consisted of temperature (T), relative humidity (RH), CO_2 concentration (CO_2) and energy consumption (EC) measurements, before and after the prototype refurbishment.

The classroom configuration is repeated in each classrooms' block. The typical classroom is rectangular and has 60 m^2 (or 44 m^2, excluding the common circulation area) (Table 12). Figure 14 presents some classroom drawings: plan view, longitudinal and transverse cross-sections, and vertical plans.

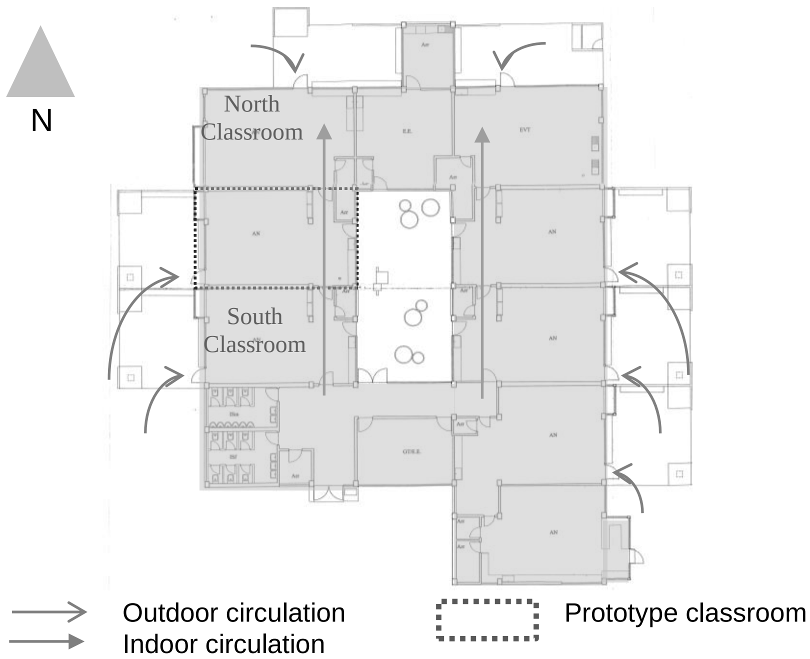


Figure 13 - Classroom block of a Brandão school.

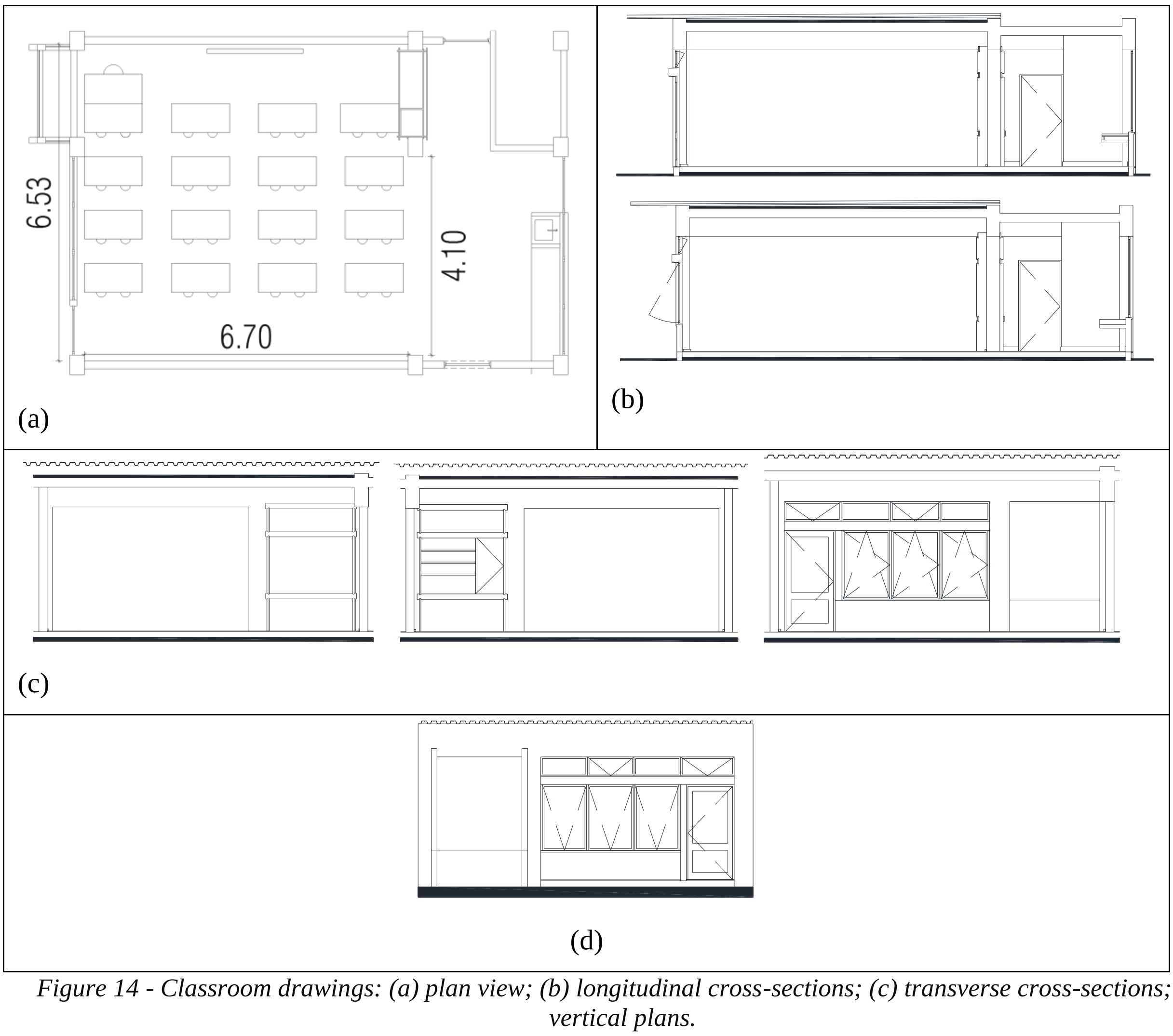


Figure 14 - Classroom drawings: (a) plan view; (b) longitudinal cross-sections; (c) transverse cross-sections; (d) vertical plans.

Table 12 - Classroom dimensions.

High wall [m]	3.0
Total area [m^2]	60
Area (excluding circulation zone) [m^2]	44
Volume [m^3]	180
Exterior wall area – west [m^2]	19
Exterior wall area – east [m^2]	12

3.2.6. THE REFURBISHMENT

The main goal of the prototype construction is the assessment of the classroom behaviour before and after the intervention. This refurbishment intended to minimize the discomfort in this classroom with some affordable interventions, regarding the typical in-service conditions in this type of school.

Additionally, the prototype intended to:

- ❖ Assess the users' discomfort before and after the refurbishment.
- ❖ Validate an advanced dynamic hygrothermal model of Heat, Air and Moisture transfer – Wufi Plus – before and after refurbishment
- ❖ Improve the numerical model that duplicates the *in-situ* conditions and allows the studying of the other Portuguese *Brandão* buildings.

The drawing components of the refurbishment process is presented in Appendix A.

The following interventions were implemented (Figure 15): construction of a partition wall between the classroom and the circulation zone (laminated glass 44.1), resulting in an enclosed classroom (which was not the case before the renovation); installation of a ventilation system with naturally filtered inflow through the envelope and forced airflow to the circulation zone; application of roof insulation (rock wool 70 kg/m^3, until reaching a minimum of 6 cm of insulation); application of mobile exterior blinds; installation of an electric convective heating system (2 + 2 kW) with thermostat. The theoretical airflow (570/430 m^3/h) [20] and the final thermal transmittance of the roof was 0.43 W/(m^2.ºC) [120] complied with Portuguese legislation for school buildings (I1 climatic zone). Both the implementation of a partition wall to enclose the classroom and the upgrade of the envelope allowed the introduction of heating strategies and the improvement of hygrothermal behaviour. Additionally, the partition wall allowed the control of the ventilation in order to ensure IAQ. The ventilation system was operated by the school workers, turned on in the morning and turned off in the afternoon, from Monday to Friday. After the first year of operation, the strategy has changed and the ventilation was always on in order to reduce the unexpected faults on the manual turning on and off. The opening of the windows as a natural ventilation strategy persisted even after the installation of the ventilation system.

Figure 15 – Prototype interventions: (a) exterior blinds; (b) naturally filtered inflow through the envelope; (c) partition wall; (d) ventilation system - forced airflow to the circulation zone; (e) roof insulation; (f) electric heating system.

3.3. EXPERIMENTAL MONITORING

3.3.1. PLANIFICATION

This experimental campaign (three and a half academic years) has started in February 2016 and finished in June 2019. The refurbishment was carried out during the summer of 2017. The in-service conditions before intervention were the free-running T, RH and CO_2. After the refurbishment the prototype was analysed in three situations implemented in a weekly based calendar: (a) free-running T and RH, without climatization; (b) reduced heating strategy with 4kW power (3 h per day in early morning during winter, from 7h30 am to 10h30 am) and (c) regular heating strategy with the same heating power (10 h per day during winter, from 7h30 am to 5h30 pm), always with a controlled ventilation system. After the refurbishment, the scheduled heating strategies started in January of 2018. The winter and mid-season periods analysed in this work before and after refurbishment are presented in Table 13.

The main goal of this chapter is the assessment of the thermal discomfort in this prototype before and after the refurbishment in free-running conditions or with the defined heating strategies, without compromising IAQ. The discomfort indicators have been developed for the assessment of the discomfort. This work presents the prototype thermal performance in pre-existing in-service conditions and the improvement in the thermal behaviour of the environment after the refurbishment. It also discusses the hygrothermal performance of the passive low-cost refurbishment and the EC resulting from the heating strategies. A winter and mid-season analysis of the discomfort is performed.

Table 13 – Calendar of measurement analysis.

		Statistical analysis	Winter and summer discomfort by indicators analysis
Winter	Before refurbishment	Feb, Mar, Apr, Nov, Dec 2016	11 Feb – 18 Mar 2016
	After refurbishment	3 Jan – 23 Mar 2018	3 Jan – 23 Mar 2018
Mid-season	Before refurbishment	19 Sep - 23 Oct 2016	19 Sep - 23 Oct 2016
	After refurbishment	13 Sep – 27 Oct 2017 and 18 Sep – 26 Oct 2018	13 Sep – 27 Oct 2017 and 18 Sep – 26 Oct 2018

3.3.2. EQUIPMENT

The hygrothermal and IAQ monitoring included the continuous measurement of T, RH and CO_2 before and after the refurbishment. ISO 7726 [64] defines some general indications for minimum requirements and localization for air temperature and air absolute humidity sensors. Some authors [152] have also registered the challenges of indoor residential sensing and some manufacturers have defined practical indications for the installation of the sensors [153].

In this prototype, the T and RH dataloggers were in an oblique profile (*window*, *center* and *door*), with the configuration presented in Figure 16 and Table 14, and at two levels (*ceiling* and *desk* level), in order to analyse the T stratification. This profile assesses the global classroom behaviour and also the critical zones (*window* and *door*) and the classroom mid-point (*center*) in order to compare to the simulation results. The CO_2 dataloggers were near the *window*, at the *ceiling* level, due to the localization of the nearest electrical connection. The dataloggers were protected inside aluminum boxes (10 cm apart from the nearest surface) and weren't easily reached by students. T and RH dataloggers were installed in the neighbouring classrooms in order to assess the boundary conditions. Exterior T and RH were measured by LFC-FEUP Weather Station (WS).

The energy consumption (EC) monitoring system (Figure 16 and Table 15) included the EC measurement of illumination, PC device, interactive board, ventilation and heating system. One heater was installed near the teacher's desk (*window*) and the other near the classroom door (*door*).

The hygrothermal monitoring was done by a Wireless *Aptinov* system composed by a 3G router with GSM, a *GW357-2* gateway, 11 *Aptinov WLS-05* dataloggers for T and RH and 2 Telaire7001 sensors coupled to 2 *Aptinov WLS-07* dataloggers for CO_2 (Figure 17). The communication between the sensors and the system was performed through electromagnetic transmission of radio waves. The specifications are presented in Table 16 and the dataloggers calibration results (in a climatic test chamber) are presented in Appendix B.

The EC monitoring was done by a *Wireless Cloogy Smart Living* connected to a 3G router with GSM, a *Cloogy Hub* concentration, 2 mini-transmitters coupled to ammeter clamps for lighting and ventilation monitoring and 4 smart plugs for the equipment connected to electrical plugs (Figure 17). The specifications of each sensor are presented in Table 17.

Both monitoring systems were a long-distance acquisition of data systems. In addition, the energy consumption system was linked to a web management platform that facilitated real-time processing of data.

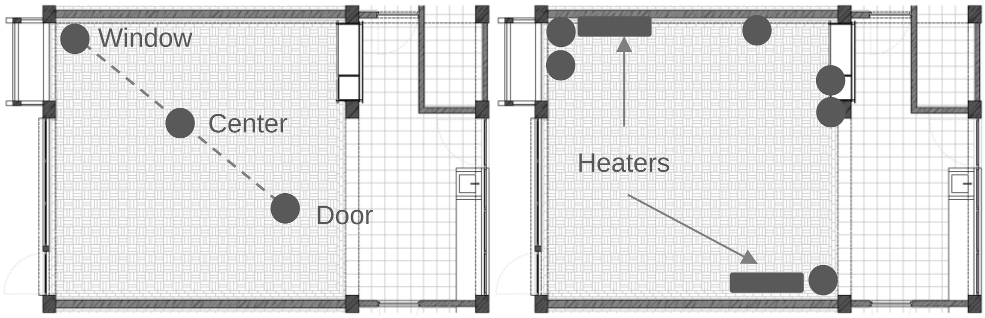


Figure 16 – (left) Hygrothermal monitoring sensors, (right) Energy consumption sensors and heaters.

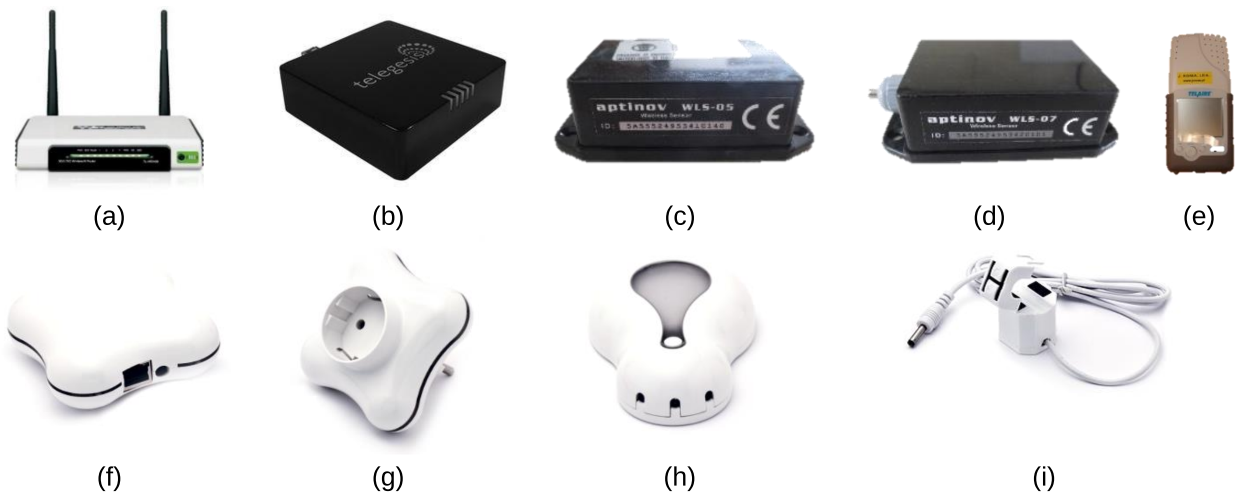


Figure 17 – (a) 3G Wireless N Router Model No. TL-MR3420, (b) gateway GW357-2 with GSM, (c) T and RH datalogger, (d) T and CO_2 datalogger, (e) CO_2 sensor, (f) Cloogy Hub concentration, (g) smart plug, (h) mini-transmitter and (i) ammeter clamp.

Table 14 – Hygrothermal monitoring equipment location.

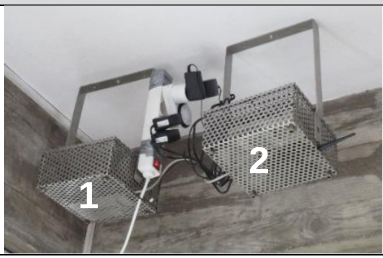
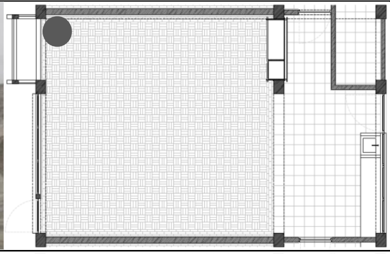
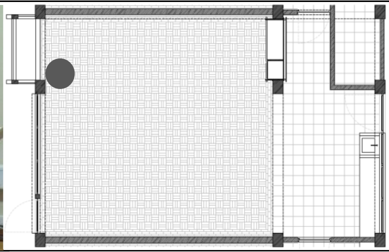
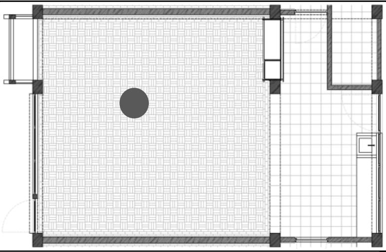
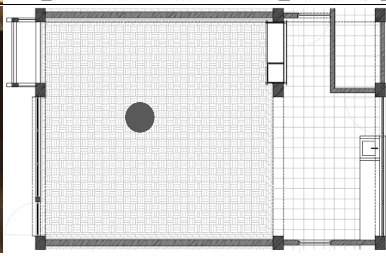
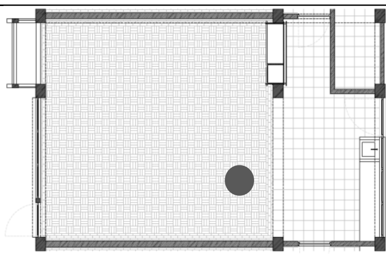
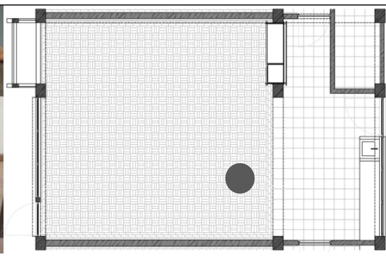
Equipment	Location	
Box 1 (h = 2,70m): ▪ Router Box 2 (h = 2,70m): ▪ 2 T and CO_2 dataloggers ▪ 1 T and RH datalogger ▪ *Gateway*		
Box 3 (h = 0,75m): ▪ 2 T and RH dataloggers		
Box 4 (h = 2,90m): 2 T and RH dataloggers		
Box 5 (h = 0,55m): ▪ 2 T and RH dataloggers		
Box 6 (h = 2,90m): ▪ 1 T and RH datalogger		
Box 7 (h = 0,55m): ▪ 1 T and RH datalogger		
Legend: (T) – temperature; (RH) – relative humidity; (CO_2) – CO_2 concentration; (h) – height above floor.		

Table 15 – Energy consumption equipment location.

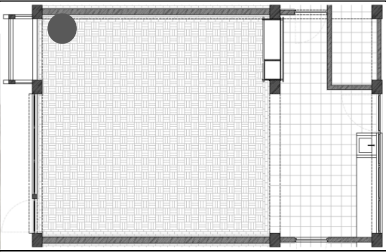
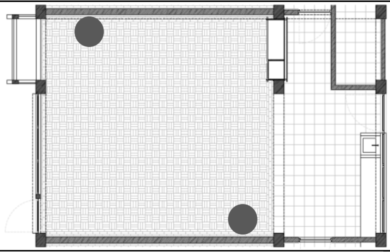
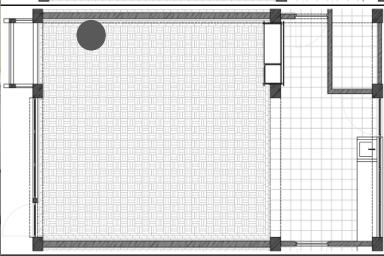
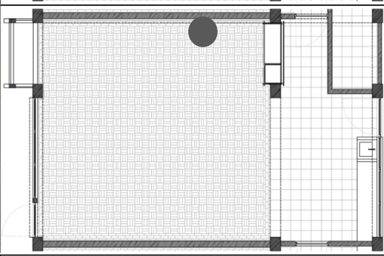
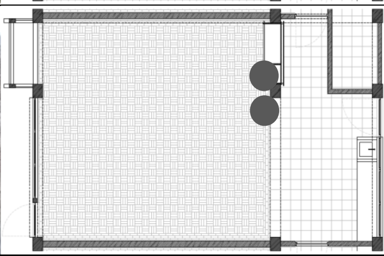
Equipment	Location	
Box 1 (h = 2,70m): ▪ Router ▪ *Cloogy Hub* concentration		
Heaters ▪ 2 smart plug		
PC ▪ 1 smart plug		
Interactive board ▪ 1 smart plug		
Illumination and ventilation system ▪ 2 mini-transmitters ▪ 2 ammeter clamps		

Table 16 – T, RH and CO_2 concentration dataloggers specification.

	Datalogger *WLS-05*		Sensor and datalogger *Telaire 7001* and *WLS-07*	
	Temperature	Relative Humidity	Temperature	CO_2 concentration
Operation range	-30 to 60 ºC	0 to 100%	-30 to 60 ºC	0 to 4000 ppm
Precision	0.01 ºC	0,1%	0,01 ºC	10 ppm
Accuracy	0.5 ºC*	3%**	0.5 ºC*	50 ppm (below 1000 ppm) and 5% (above 1000 ppm)
Distance between measurements	10 minutes			

* From 0 to 60 ºC.

** From 20% to 80% RH, at 25 ºC.

Table 17 – Energy consumption equipment specification.

	Smart plugs	Plug and mini-transmitter
Maximum current	16A	50A *
Accuracy	±1% ± 0,5W **	±3% ± 15W ***
Distance between measurements	15 minutes	

* 50A per phase, for three-phase installations.
** Test conditions: V=230AC 50Hz, electrical resistance≤70 kΩ.
*** Test conditions: V=230AC 50Hz, electrical resistance≤530 Ω.

3.3.3. Discussion of the results

3.3.3.1. Discomfort indicators

The in-service conditions before intervention were the free-running T, RH and CO_2. After the refurbishment, the prototype was analysed in three situations: (a) free-running T and RH; (b) reduced heating strategy (3 h per day during winter) and (c) regular heating strategy (10 h per day during winter), always with a controlled ventilation system.

The discomfort indicators defined in this work quantify how long occupants are experiencing discomfort (above or below reference) and the effort required to achieve reference comfort conditions. The indicators of discomfort (for the period of occupation) compare preexisting discomfort with discomfort after refurbishment. EN 15251 [18] also defines an hourly-criteria (% of the time when the criterion is met or not) and a degree-hour criterion (degree hours outside the upper or lower boundary that can be used as a performance indicator of building for the warm or cold season).

The discomfort indicator for winter ($DI_{w,b}$) is the sum of positive differences between comfort temperature (20 ºC) and real temperature, in ºC.hour (equation [1]). When the reference temperature of comfort is 20 ºC, $DI_{w,b}$ is classified as $DI_{w,20}$.

$$DI_{w,b} = \sum_{t_i}^{t_n} (\theta_b - \theta_i), \text{ when } \theta_i < \theta_b \qquad [1]$$

where $DI_{w,b}$ is the discomfort indicator in ºC.hour, θ_b is the reference temperature of comfort (20 ºC) and θ_i is the experimental hourly temperature in each period t_i.

The discomfort indicator for summer ($DI_{s,b}$) is the sum of positive differences between real temperature and comfort temperature (25 ºC), in ºC.hour (equation [2]). When the reference temperature of comfort is 25 ºC, $DI_{s,b}$ is classified as $DI_{s,25}$.

$$DI_{s,b} = \sum_{t_i}^{t_n} (\theta_i - \theta_b), \text{ when } \theta_i > \theta_b \qquad [2]$$

where $DI_{s,b}$ is the discomfort indicator in ºC.hour, θ_b is the reference temperature of comfort (25 ºC) and θ_i is the experimental hourly temperature in each period t_i.

The discomfort percentage of time ($\%TD_b$) represents the proportion of the discomfort periods during the analysed occupation period (equation [3]).

$$\%TD_b = \frac{\sum t_{i\,discomfort}}{\sum t_{i\,occupation}} \quad [3]$$

3.3.3.2. Occupation period

In school buildings, hygrothermal conditions assessment is restricted to the occupation period that reflects the real users' discomfort. Simanic, Nordquist [154] have also discussed the importance of considering only weekdays and working hours in school buildings.

The occupation period considered was the real in-service schedule (complete mornings from Monday to Friday and two or three afternoons before and after refurbishment, respectively) (Appendix C). There were on average 20 to 25 occupants before and after refurbishment.

Figure 18 shows the mean T of the occupation period and the total period before and after the intervention in free-running conditions. The differences observed were as expected: the mean T was higher when considering the occupation period, due to internal and solar gains once the night period is not included. There are not important differences amongst different locations inside the classroom. The mean differences between the occupation period and the total period before refurbishment were 1.4 ºC in a winter month (February) and 1.1 ºC in a mid-season month (May); after the refurbishment, the differences were 1.1 ºC in winter weeks and 0.5 ºC in a mid-season month (May).

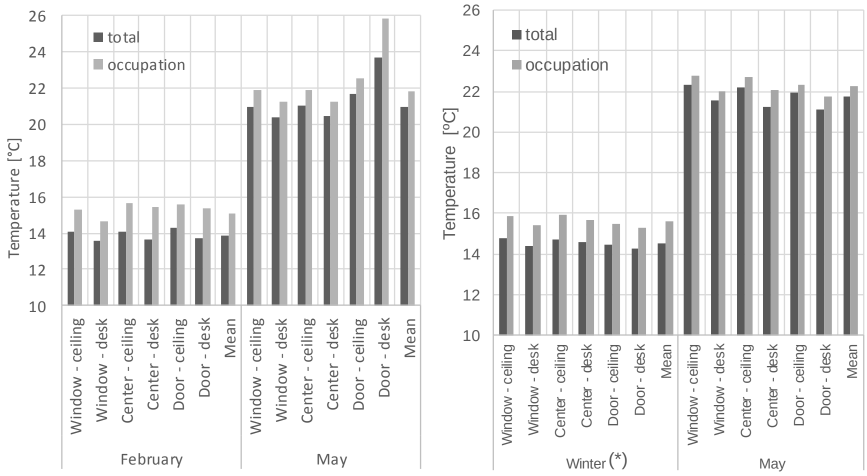


Figure 18 – Mean T during the occupation and the total period: (left) before refurbishment: Feb and May 2016; (right) after refurbishment: winter (without heating) and May 2018.

(*) After refurbishment, different heating strategies were adopted in a weekly schedule. Therefore, and in order to have comparable results, Winter refers to free-running weeks, which were the previous conditions before refurbishment.

The CO_2 concentration was also higher during the occupation period once the CO_2 is an important evidence of human metabolism and is produced mainly during the occupation (Figure 19). The partition wall and the fact that the ventilation system was not in full working capacity justify the increase in CO_2 after refurbishment. However, its mean concentration is below 1500 ppm (and not far from 1250 ppm), even during winter when the windows were closed.

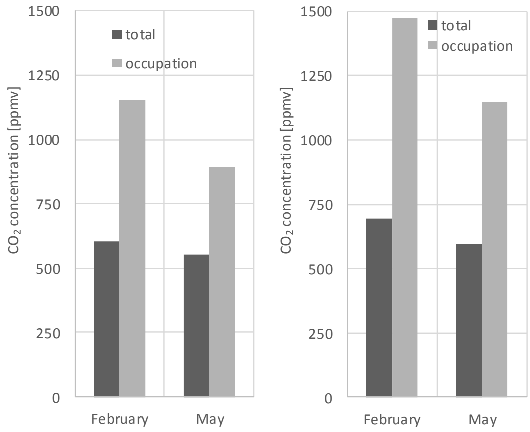


Figure 19 – Mean CO_2 during the occupation and the total period: (left) before refurbishment: Feb and May 2016; (right) after refurbishment: Feb and May 2018.

3.3.3.3. Winter analysis before the prototype refurbishment

The free-running temperature development in winter before the refurbishment clearly reveals a temperature increase during each day, due to internal gains and also solar gains. There was also a clear discomfort most of the time, with temperatures below 18 ºC. Figure 20 shows the temperature in winter during the occupation period, before the intervention and any heating strategy. It also presents the statistical distribution of temperature during the occupation period in 2016 winter, through a probabilistic analysis of the results by temperature ranges. T values were calculated by the mean value of all location measurements (*window*, *center* and *door, desk* level and *ceiling* level). It confirms that the temperature in the prototype was not adequate, considering the reference values of T. In February, the temperature was below 18 ºC during 100% of the occupation period, in March during 85%, in December during 83%, in November during 72% and in April during 39%. An increasing requirement of 20 ºC would enhance this analysis. The RH inside the classroom followed the T evolution, with higher mean values in February and December (periods with lower T) but generally between the 50-70% range (Figure 21). In winter, the CO_2 was below 1250 ppm [20] during 50-80% of the occupation period, below 1500 ppm [23] during 70-90% and below 2000 ppm during 90-100%, here defined as the maximum acceptable value (Figure 22).

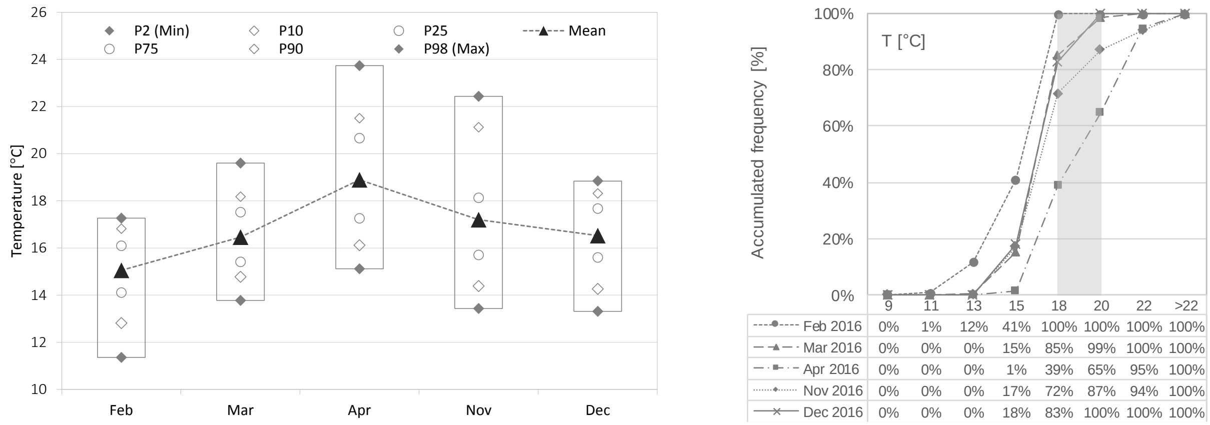


Figure 20 – T in the winter before the refurbishment of the prototype.

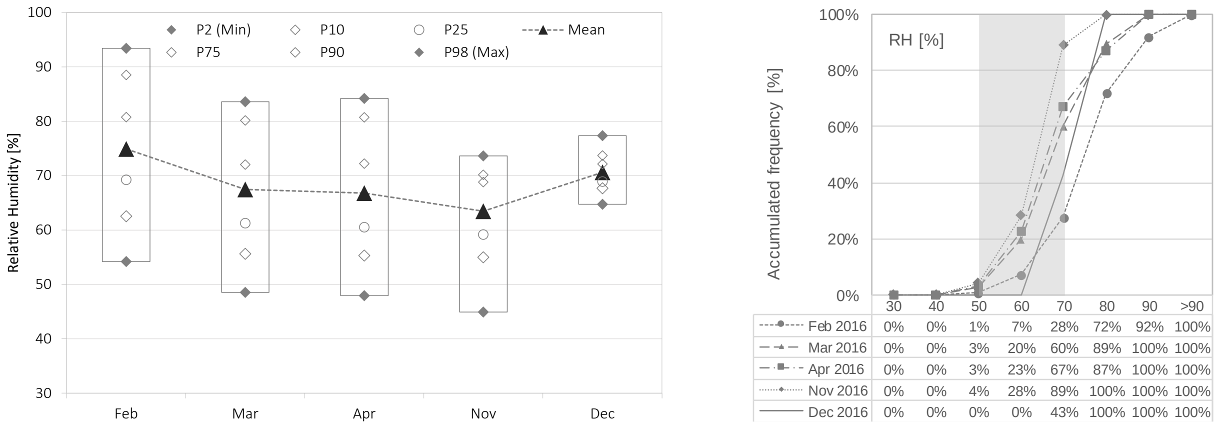


Figure 21 - RH in the winter before the refurbishment of the prototype.

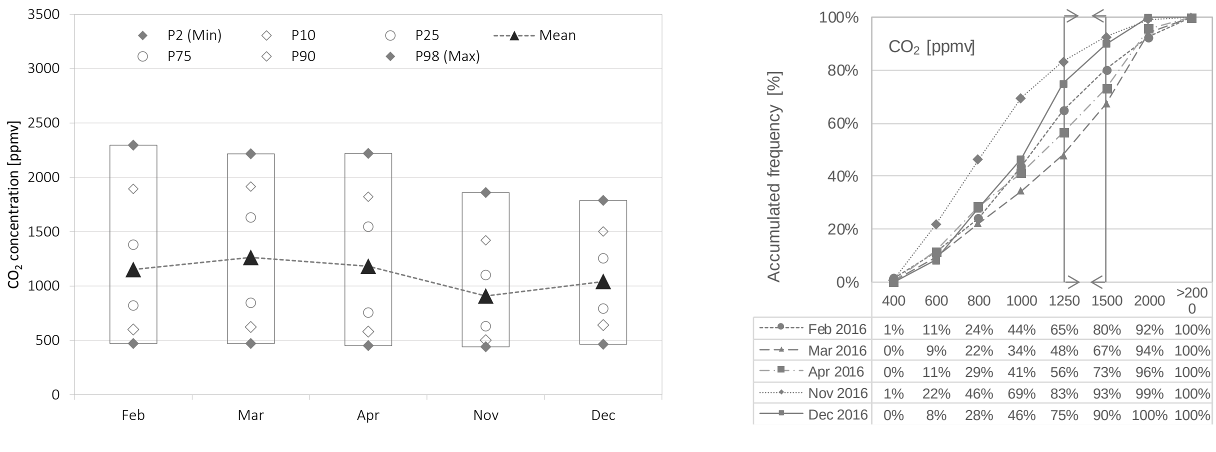


Figure 22 – CO_2 concentration in the winter before the refurbishment of the prototype.

The discomfort indicators during the winter before the refurbishment (2016) were calculated for each week. Before the refurbishment, there was no heating system available, which is a common situation in these Portuguese buildings, as previously mentioned. In a normal five-day week, the $DI_{w,20}$ were above 120 °C.hour and the discomfort represented 100% of the occupation period (Figure 23).

Table 18 presents a detailed analysis of the $DI_{w,20}$, $\%TD_{20}$, $DI_{w,18}$ and $\%TD_{18}$ before refurbishment and the outdoor mean temperature in each winter week ($T_{m,ext}$), since $T_{m,ext}$ affects the inside thermal behaviour and it is not a controlled variable in an *in-situ* experimental work developed in an in-service building. The daily mean values of $DI_{w,20}$ and $\%TD_{20}$ were 34.7 °C.hour and 99%, respectively.

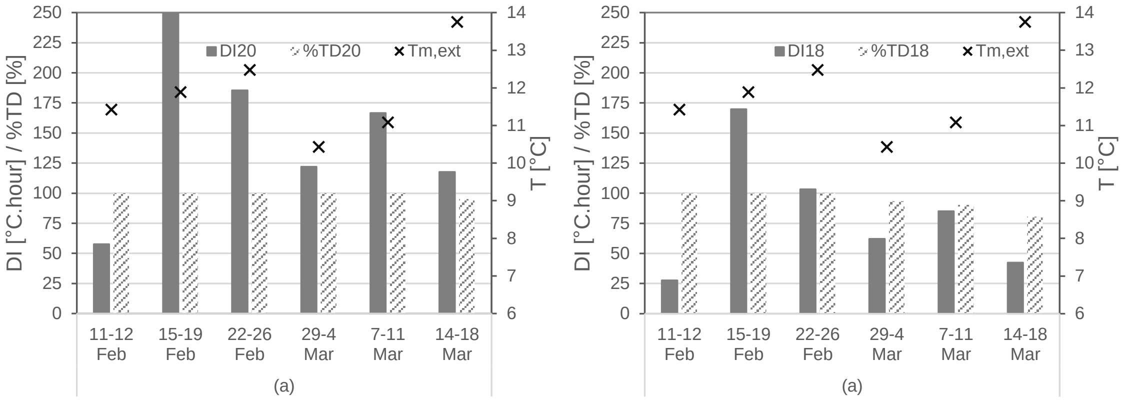


Figure 23 – Discomfort indicators for each winter week: (left) DI_{20} and $\%TD_{20}$, (right) DI_{18} and $\%TD_{18}$.

Table 18 – Discomfort indicators in winter before refurbishment.

week	No. of days	strategy	$T_{m,ext}$	$DI_{w,20}$	$\%TD_{20}$	$DI_{w,18}$	$\%TD_{18}$
11-12 Feb	2	(a)	11.4	57.6	100%	27.6	100%
15-19 Feb	5	(a)	11.9	251.9	100%	169.9	100%
22-26 Feb	5	(a)	12.5	185.4	100%	103.4	100%
29-4 Mar	4	(a)	10.4	122.0	100%	62.2	93%
7-11 Mar	5	(a)	11.1	166.6	100%	85.2	90%
14-18 Mar	5	(a)	13.7	117.7	95%	42.4	80%
daily mean	---	**(a)**	---	34.7	99%	18.9	93%

Legend: (a) free-running temperature

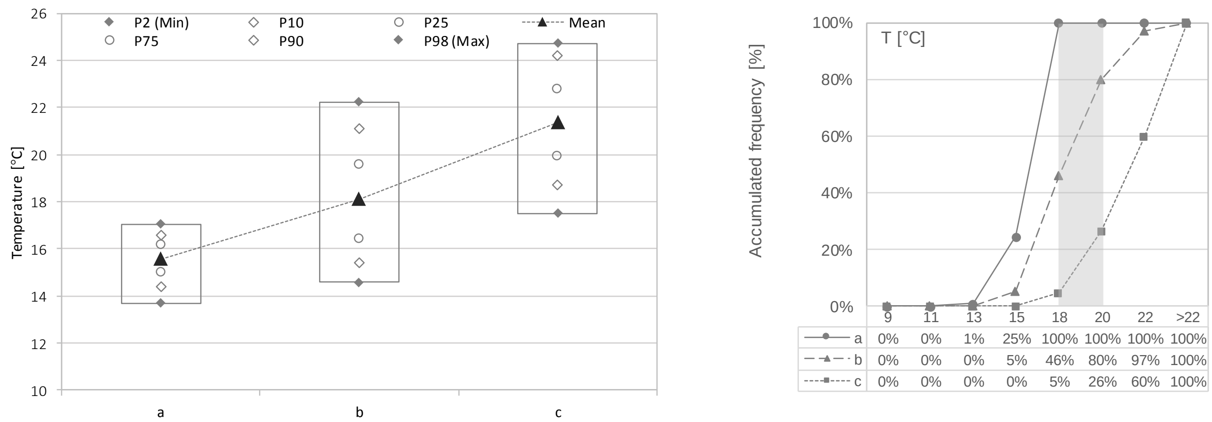
3.3.3.4. Winter analysis after the prototype refurbishment

In the winter after the prototype refurbishment (2018), the (a), (b) and (c) heating strategies presented above were adopted in a weekly schedule. For that reason, the T, RH and CO_2 statistical analysis is not defined by month but by strategy. When comparing the (a) heating strategy after refurbishment with the previous conditions, the results reflect the improvement due to the envelope and ventilation. It is important to confirm that this refurbishment strategy was a good choice even without adding a heating strategy. It was previously mentioned that the passive refurbishment is an important goal of this work, as the economic restrictions define a free-running behaviour in so many cases. Through the (a) strategy, we expected to minimize the discomfort after the refurbishment, but it was unlikely to achieve the 18 or 20 ºC of comfort during all the occupation period. However, the establishment of some affordable heating strategies was also an aim of this work. The (b) and (c) heating strategies

(3 h and 10 h heating, respectively) were implemented to get closer to comfort T (18 or 20 ºC) during the occupation period. The Portuguese regional habits and the low use of heating systems (subject to each school management) determined the choice of a heating system with a low initial investment, easy to operate and with a flexible schedule use. All the chosen refurbishment solutions of this prototype were required to be low-cost and adjustable to the 100 *Brandão* schools throughout the country.

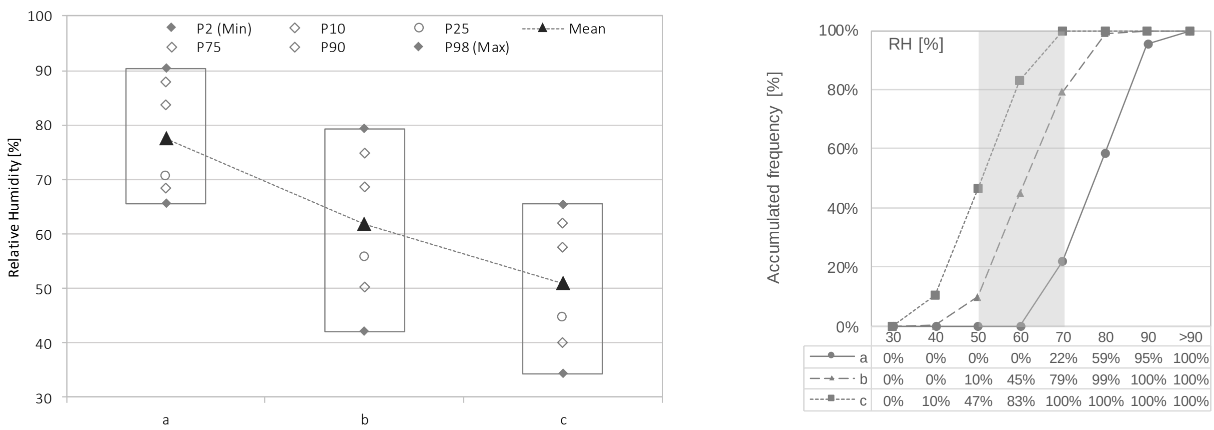
The temperature inside the classroom in the winter after the refurbishment had a distinct behaviour according to the heating strategy (Table 19). Figure 24 shows the temperature in winter during the occupation after refurbishment. It also presents the statistical distribution of temperature in 2018 winter. In free-running conditions, the mean T remained below 18 ºC. The increasing heating strategies (b) and (c) improved the mean indoor T for 18.1 ºC and 21.4 ºC. The T was below 18 ºC during 100% of the occupation period for (a) strategy, 46% for (b) strategy and 5% for (c) strategy. An increasing requirement of 20 ºC represented discomfort during 26% of the occupation period during (c) strategy. The RH inside the classroom followed the T evolution (Figure 25) and was not a concern. The CO_2 did not have a direct relationship with the heating strategy and the mean values were similar for the three strategies (Figure 26). Regardless of the adopted heating strategy, in winter the CO_2 was below 1250 ppm [20] in 30-40% of the occupation period, below 1500 ppm [23] in 50-60% and below 2000 ppm in 90%. Once there was no partition wall in pre-existing conditions, an increase of CO_2 was expected after the refurbishment (Figure 27). The Portuguese legislation defines for classrooms a minimum airflow of 24 m^3/(hour.person) and the ventilation system in the prototype was prepared to 570/430 m^3/h (theoretical airflow). However, the real ventilation was between 260 and 380 m^3/h, corresponding to 2.0 and 2.9 h^{-1}. Although the mean CO_2 after the refurbishment was below the requirement of 1500 ppm (Table 1), the real ventilation rate, which was under the expected values, was not enough and there was indeed an increase of CO_2 inside the classroom, for the corresponding months before and after refurbishment.

Figure 28 represents the evolution of inside and outside T in a winter week for each strategy, considering only the occupation period. The inside T had a growing pattern through the day in (a) strategy due to internal and solar gains and in (c) strategy also due to heating during the occupation but (b) strategy showed an inflection of T after early morning heating.



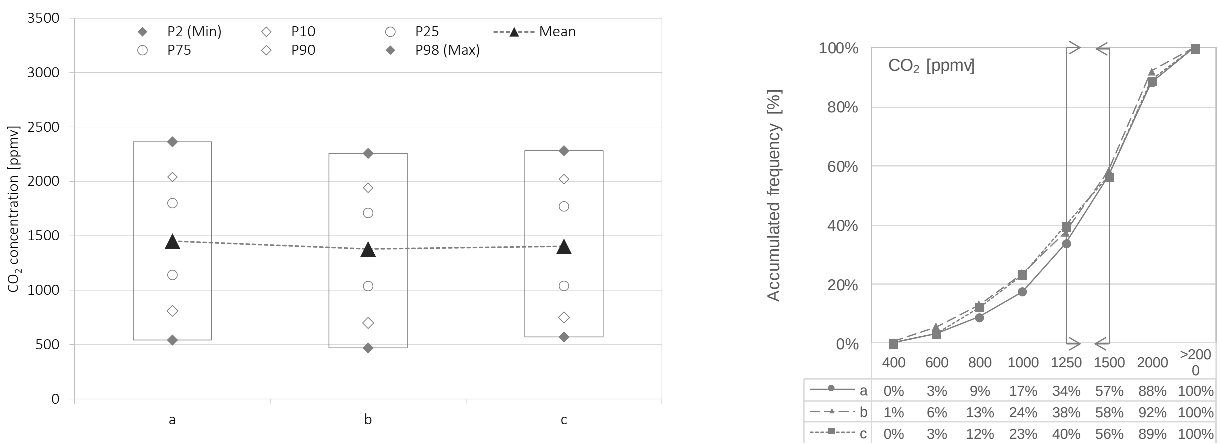
Legend: (a) free-running T; (b) 3 h heating per day (c) 10 h heating per day.

Figure 24 - T in the winter after the refurbishment of the prototype.



Legend: (a) free-running T; (b) 3 h heating per day (c) 10 h heating per day.

Figure 25 - RH in the winter after the refurbishment of the prototype.



Legend: (a) free-running T; (b) 3 h heating per day (c) 10 h heating per day.

Figure 26 – CO_2 concentration in the winter after the refurbishment of the prototype.

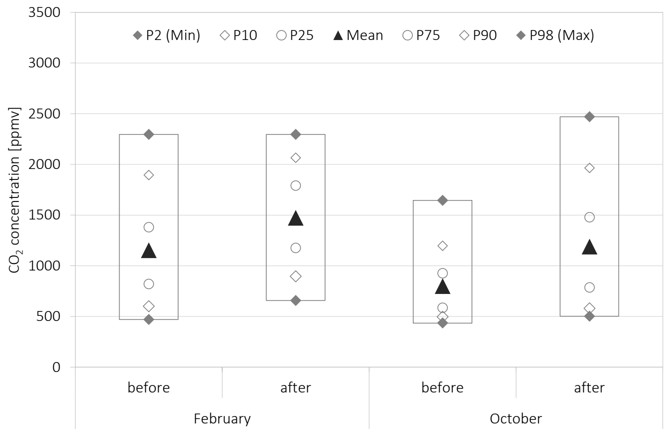
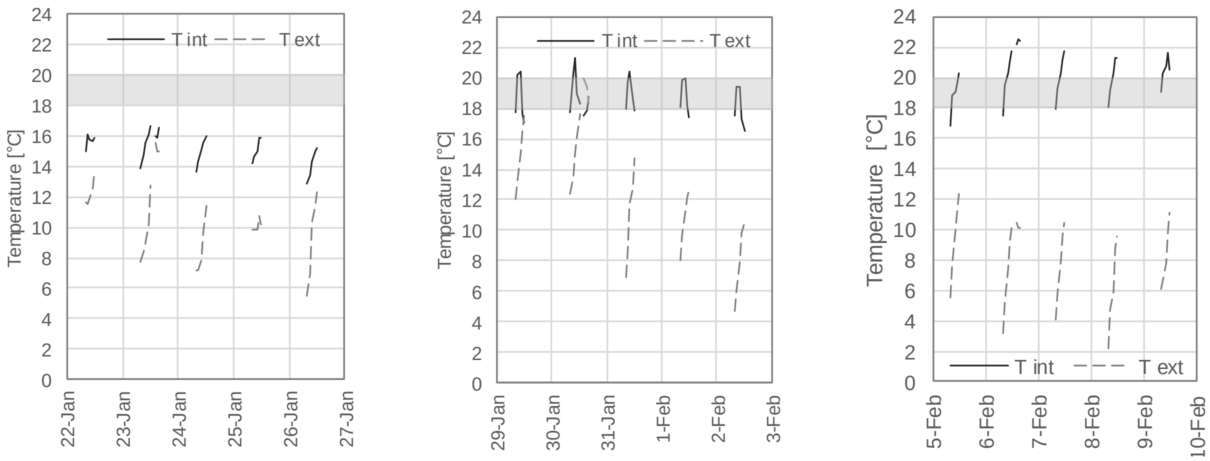


Figure 27 – CO_2 before (2016) and after (2018) the refurbishment of the prototype.

Table 19 – Statistical information of T, RH and CO_2 during the occupation, in winter.

	T [ºC]			RH [%]			CO_2 [ppmv]		
	a (*)	b (*)	c (*)	a (*)	b (*)	c (*)	a (*)	b (*)	c (*)
Mean	15,6	18,1	21,4	78	62	51	1451	1378	1404
P2 (Min)	12,9	14,0	16,7	66	42	34	542	470	570
P10	14,4	15,4	18,7	68	50	40	810	700	750
P25	15,0	16,4	19,9	71	56	45	1140	1039	1040
P75	16,2	19,6	22,8	84	69	58	1800	1710	1770
P90	16,6	21,1	24,2	88	75	62	2040	1941	2022
P98 (Max)	17,5	22,7	25,7	90	79	65	2364	2258	2282
St Dev	0,7	1,7	1,6	6	8	7	371	374	388

(*) *a*, *b* and *c* refer to the period from January to March.



(a) (b) (c)

Figure 28 - Indoor and outdoor T in a winter week, considering only the occupation period: (left) strategy (a); (center) strategy (b); (right) strategy (c).

The $DI_{w,20}$, $\%TD_{20}$, $DI_{w,18}$ and $\%TD_{18}$ after refurbishment in 2018 were calculated in each winter week for (a), (b) and (c) heating strategies, always with a controlled ventilation system (Figure 29 and 30).

In free-running winter weeks of 2018, the mean $\%TD_{20}$ remained near 100%, although $DI_{w,20}$ values have decreased when compared with the pre-existing situation (from 34.7 ºC.hour to 25.2 ºC.hour, mean daily values) (Table 20), that confirms the advantage of the refurbishment strategy even without adding a heating strategy (regarding the passive refurbishment for reducing discomfort).

The $\%TD_{20}$ decreased from an average of 100% to 80% for the adopted strategy (b) and to about 30% for the (c) heating strategy. $DI_{w,20}$ decreased from 25.2 to 11.9 ºC.hour when comparing free-running T and RH to 3 heating hours and from 11.9 to 2.5 ºC.hour when comparing 3 with 10 heating hours (Table 20). The implementation of intermittent heating strategies was very important for an effective reduction of winter discomfort. This reduction could have been more noticeable if we had the same exterior conditions (which did not happen since $T_{m,ext}$ is not a controlled variable).

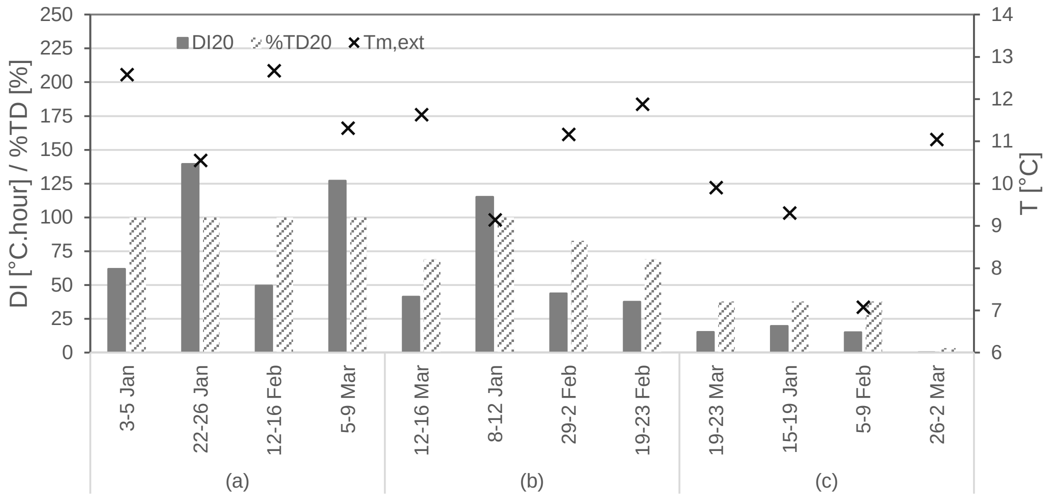


Figure 29 - DI_{20}, $\%TD_{20}$ and $T_{m,ext}$ for each winter week after refurbishment.

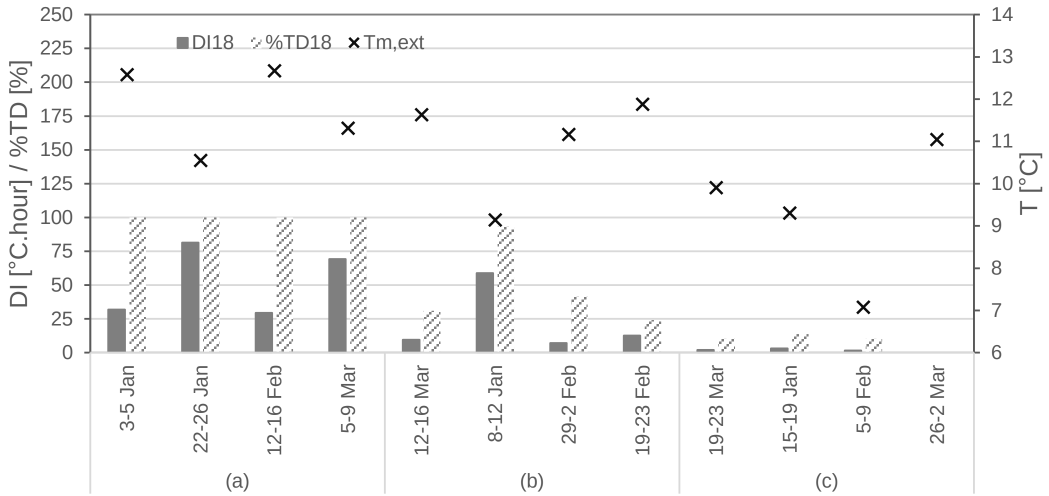


Figure 30 – DI_{18}, $\%TD_{18}$ and $T_{m,ext}$ for each winter week after refurbishment.

Table 20 – Discomfort indicators in winter after refurbishment.

week	No. of days	strategy	$T_{m,ext}$	Energy [kWh]	$DI_{w,20}$	$\%TD_{20}$	$DI_{w,18}$	$\%TD_{18}$
3-5 Jan	3	(a)	12.6	0	61.9	100%	31.9	100%
8-12 Jan	5	(b)	9.1	43	115.3	100%	58.9	93%
15-19 Jan	5	(c)	9.3	170	19.7	38%	3.3	14%
22-26 Jan	5	(a)	10.5	0	139.5	100%	81.5	100%
29-2 Feb	5	(b)	11.2	59	43.9	83%	7.1	41%
5-9 Feb	5	(c)	7.1	199	15.0	38%	1.7	10%
12-16 Feb	2	(a)	12.7	0	49.5	100%	29.5	100%
19-23 Feb	5	(b)	11.9	48	37.7	69%	12.8	24%
26-2 Mar	5	(c)	11.0	197	0.02	3%	0.0	0%
5-9 Mar	5	(a)	11.3	0	127.3	100%	69.3	100%
12-16 Mar	5	(b)	11.6	52	41.4	69%	9.7	31%
19-23 Mar	5	(c)	9.9	147	15.3	38%	2.1	10%
daily mean	---	**(a)**	---	0	25.2	100%	14.1	100%
	---	**(b)**	---	10	11.9	80%	4.4	47%
	---	**(c)**	---	36	2.5	29%	0.4	9%

The first three hours of heating (from (a) to (b) strategy) represented the most important share of discomfort decrease (in ºC.hour) with a low increase in energy consumption (Figure 31) and this was more noticeable in DI_{20} than in DI_{18}. The point between strategies (b) and (c) corresponds to the experimental results of some weeks with (c) heating strategy when the heating systems were not in full operation (one heater on and the other off), and represents the behaviour with nearly half of the heating capacity (EC between 19 and 25 kWh/day). Considering *EC/%TD*, the results revealed a linear relationship between energy consumption *vs* decreased discomfort (Figure 31).

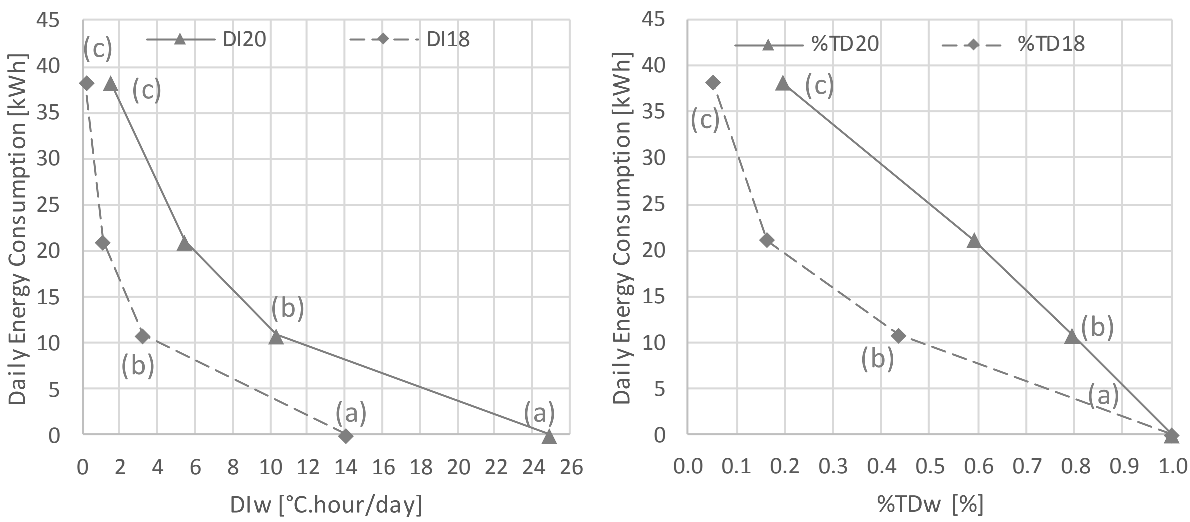


Figure 31 – (left): EC and DI_w in winter after refurbishment - strategies (a), (b) and (c); (right): EC and $\%TD_w$ in winter after refurbishment - strategies (a), (b) and (c).

3.3.3.5. Temperature stratification before and after refurbishment

The T development before refurbishment during a winter day revealed discomfort (below 18 ºC) in all locations (Figure 32) and a mean stratification of 0.6 ºC, 0.2 ºC and 0.3 ºC (respectively *window*, *center* and *door*), detailed for each month and location in Figure 33 (left side). After the refurbishment, there was an important stratification of temperature, with higher values at the *ceiling* level and lower at the *desk* level, mostly during heating periods (Figure 33, right side). The stratification was more relevant the greater the heating strategy was and was also more important near the *window* heater. The mean values during the winter months in 2018 were 8.9 ºC, 5.9 ºC and 5.9 ºC for (c) heating strategy, 3.6 ºC, 2.3 ºC and 2.3 ºC for (b) heating strategy and 0.4 ºC, 0.3 ºC and 0.2 ºC for (a) heating strategy (for each heating strategy, respectively *window*, *center* and *door*). The mitigation of the stratification effect, resulting from the chosen heating system, must be considered in future developments.

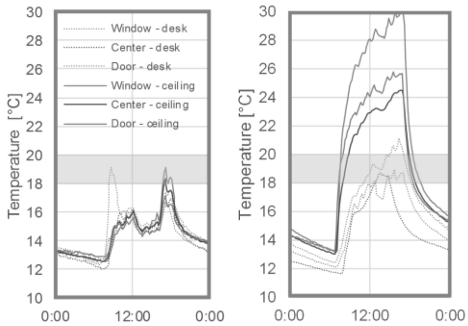


Figure 32 – T on a winter day in different measurement locations: (left) before refurbishment; (right) after refurbishment – heating period.

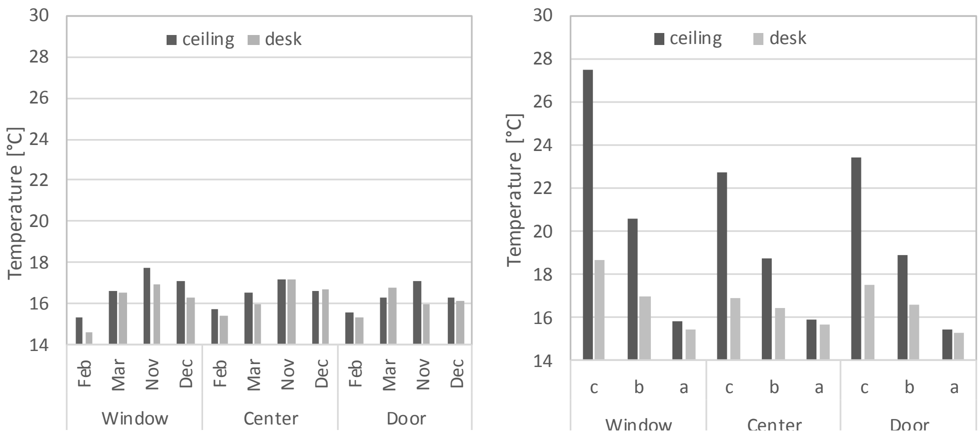


Figure 33 – Temperature stratification: (left) before refurbishment – free-running conditions; (right) after refurbishment – (a), (b) and (c) heating strategies.

3.3.3.6. Energy consumption

The energy consumption system monitors the individual EC of each equipment in the prototype classroom (1st heater, 2nd heater, PC device, interactive board, illumination and ventilation). The monthly and annual consumption of the prototype must be carefully analysed, regarding the different conditions purposely defined in this work (1st heater installation, 2nd heater installation and refurbishment). The EC measurement gives important information about the EC in *Brandão* classrooms and schools in Porto climate conditions.

The EC measurement started in January 2017 and finished in August 2019. The 1st heater was installed in January 2017 and the 2nd heater in August 2017, during the refurbishment process. The heating months (from December to April) had some heating strategies: free-using (manually operated by the teacher and school workers) and the previously referred (a), (b) and (c) strategies). The mid-season months always considered a free-cooling strategy (natural before refurbishment and with a mixed ventilation system after refurbishment). The calendar of winter and mid-season periods and the heating/cooling strategy considered are presented in Table 21.

Table 21 – Calendar of energy consumption measurement analysis.

Before/ After refurbishment	Period	Heating/cooling strategy
Before	Jan 2017 – Apr 2017	1 heater (2kW) in free using strategy
Before	May 2017 – Aug 2017	Free-cooling
After	Sep 2017 – Nov 2017	Free-cooling
After	Dec 2017	2 heaters (2+2kW) in free using strategy
After	Jan 2018 – Apr 2018	2 heaters (2+2kW) in weekly schedule strategy (a), (b), and (c) from Jan to middle Apr
After	Apr 2018 – Aug 2018	Free-cooling from middle Apr
After	Sep 2018 – Oct 2018	Free-cooling
After	Nov 2018 – Apr 2019	2 heaters (2+2kW) in weekly schedule strategy (b) and (c)
After	May 2019 – Aug 2019	Free-cooling

(*) (heating – blue; cooling – orange)

Considering the winter weeks after refurbishment, there are two important heating periods to analyse: Jan-Apr 2018 and Nov-Apr 2019. The (b) and (c) heating strategies represent 10 and 36 kWh/day and 11 and 37 kWh/day, for each period respectively. The energy consumption of the two heaters during Jan-Apr 2018 winter weeks was referred in the previous Table 20. There is a similarity between the daily average measured energy consumption for each strategy.

Before the refurbishment (winter of 2017), the heating strategy was a free-using strategy, controlled by the teacher and by the school workers. However, it was verified that the most common usage pattern was the 10 heating hours' strategy, starting at the beginning of the first class and ending at the end of the day, when the classroom was closed. Figure 34a) presents the energy consumption during a winter week before refurbishment with a free-using strategy (2 kW). The average T was mostly below 18 ºC, confirming the discomfort before refurbishment with this heating strategy. It was also observed that a stop in the heating strategy (during lunch time, for example) decreases the average T for a while. After the refurbishment with 10 heating hours strategy (4kW) the average T during the occupation period was between 18 ºC-22 ºC (Figure 34b). However, if a 3 heating hours' strategy is considered (Figure 34c) the average T reaches the 18-20 ºC in the morning but decreases to the mean 16 ºC during the afternoon. In free-running conditions, even after the refurbishment, there is a clear discomfort during all week (Figure 34d). An important limitation previously referred is that the mean T value includes higher T values at the ceiling level and lower T values at the desk level. A better heating system inside the classroom could have had, as a consequence, some differences in the overall comfort performance.

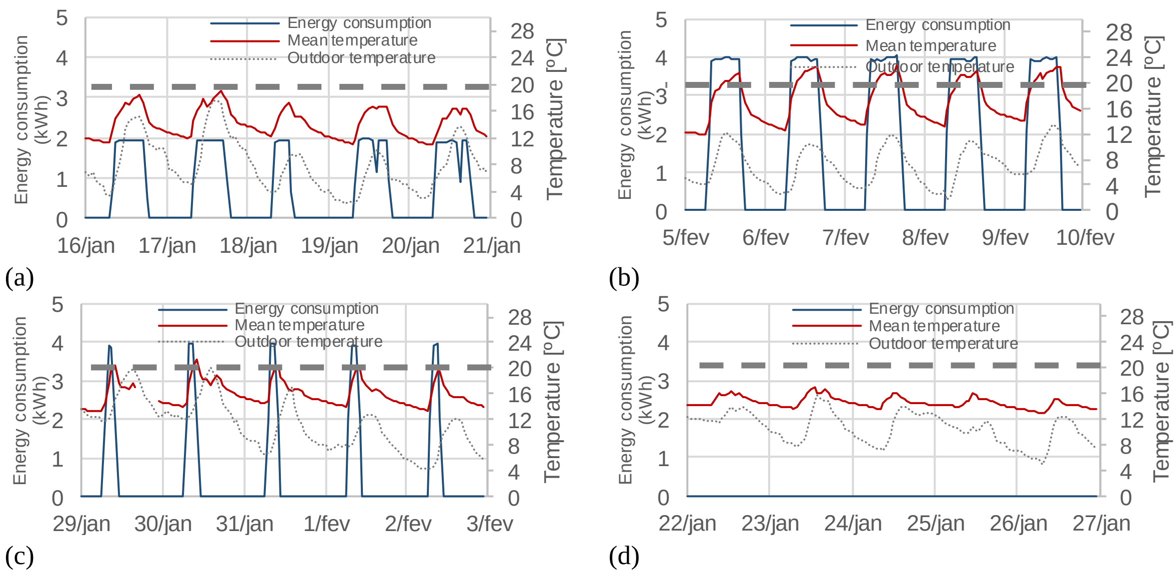
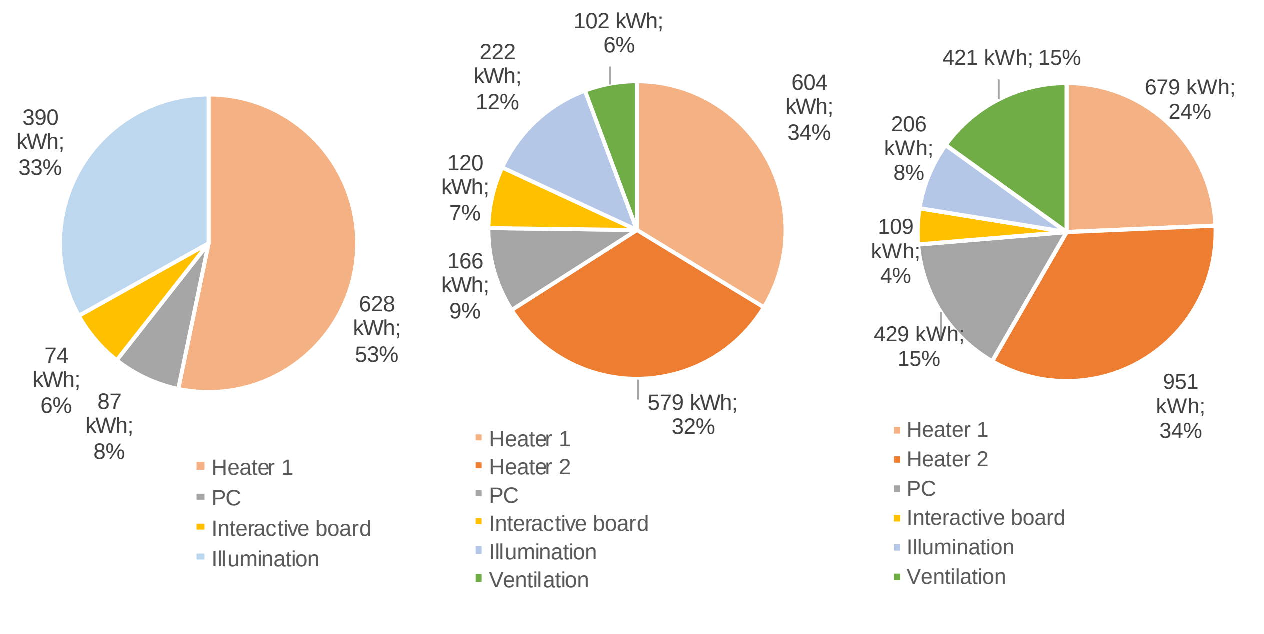


Figure 34 – (a) Before refurbishment, 1 heater (2kW) in free using strategy; (b) After refurbishment, 2 heaters and 10 heating hours per day; (c) After refurbishment, 2 heaters and 3 heating hours per day; (d) After refurbishment, without heating.

Considering the individual energy consumption of each equipment in the prototype classroom (1st heater, 2nd heater, PC device, interactive board, illumination and ventilation system), Figure 35 represents a global overview of the whole year's energy consumption before and after refurbishment in the *Brandão* prototype. The energy consumption for classroom heating represented 50-70% of the total energy consumption. It is possible to observe that the energy consumption of the ventilation has increased in 2018/2019 once the constant ventilation strategy (380 m^3/h, 24h per day) has started in that year (in 2017/2018 the ventilation system was manually operated by the school assistants). The EC of the interactive board has a constant behaviour throughout the years, but the EC of the PC and illumination are very irregular.



(a) (b) (c)

Figure 35 – Energy consumption measurement of each equipment: (a) before refurbishment (Jan 2017 - Jun 2017); after refurbishment (Sep 2017 - Jun 2018); after refurbishment (Sep 2018 - Jun 2019).

3.3.3.7. Mid-season comfort before and after the prototype refurbishment

Porto temperate climate with dry or temperate summer enables mid-season comfort in the prototype (Figure 36) and that has been confirmed during monitoring before refurbishment. Although the refurbishment was not focused on summer or mid-season comfort, it was necessary not to worsen the previous conditions (Figure 37 and 38). After the refurbishment, the mean T (during the occupation period) in each mid-season week was between 22 ºC and 25 ºC, except for a September week in 2018. The CO_2 was also below 1250 ppm, except for an October week in 2018 (although it did not exceed 1500 ppm).

The DI_{25} and $\%TD_{25}$ for the mid-season weeks before the intervention were low and confirmed that the mid-season was not a real concern in the pre-existing scenario (Figure 39). The mean daily DI_{25} was 0.7 ºC.hour/day and the $\%TD_{25}$ was 13%. After the refurbishment, the DI_{25} and $\%TD_{25}$ for the mid-season weeks were also low and their mean daily values were 0.3 ºC.hour/day and 7% for the 2017 mid-season and 2.3 ºC.hour/day and 32% for the 2018 mid-season (Figure 40). These mean values show a small reduction of $DI_{s,25}$ and $\%TD_{25}$ in 2017 mid-season weeks (after refurbishment) even though the exterior blinds were not installed in September and October and the ventilation system was not in full working capacity. However, the small increase in $DI_{s,25}$ and $\%TD_{25}$ in 2018 (when the exterior blinds and the ventilation system were in full operation) reveals the dependence on the weather conditions. While the enclosure classroom option would benefit conditions in the winter, it can complicate mid-season conditions depending on the weather severity.

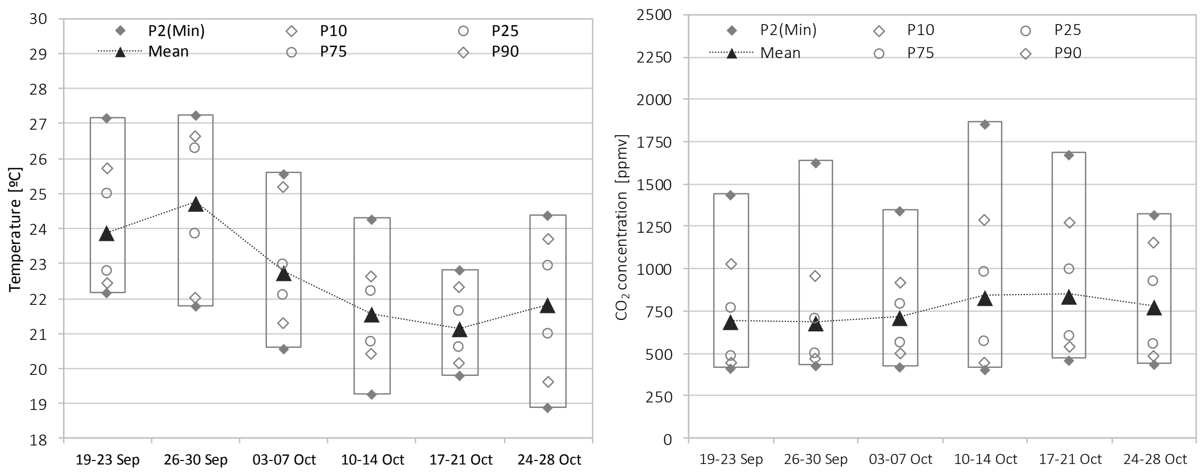


Figure 36 – T and CO_2 in mid-season weeks before refurbishment (2016).

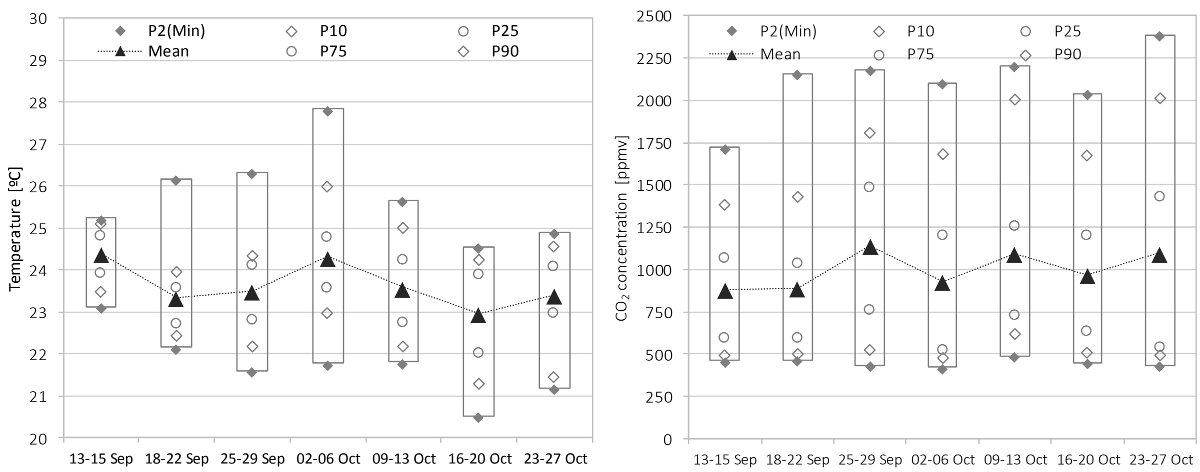


Figure 37 – T and CO_2 in mid-season weeks after refurbishment (2017).

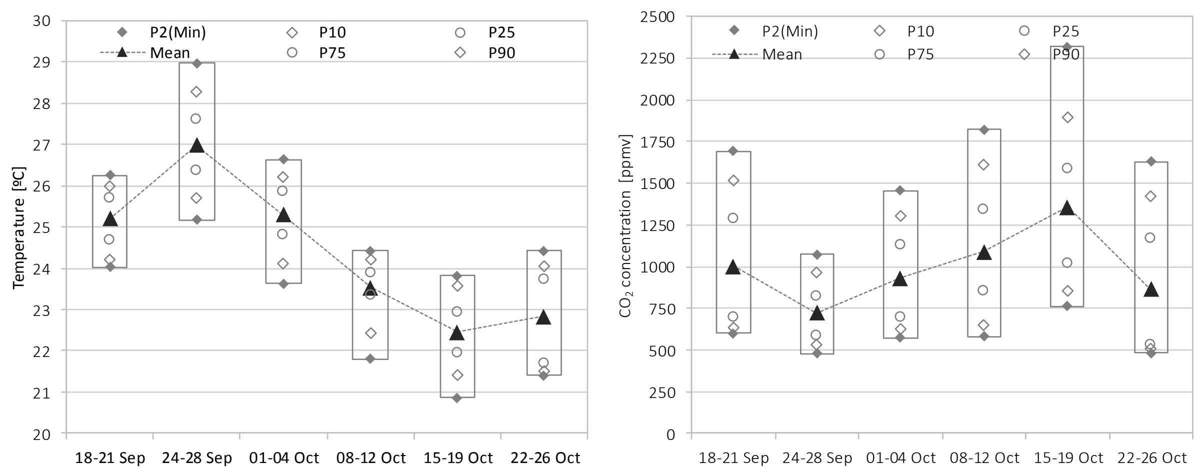


Figure 38 – T and CO_2 in mid-season weeks after refurbishment (2018).

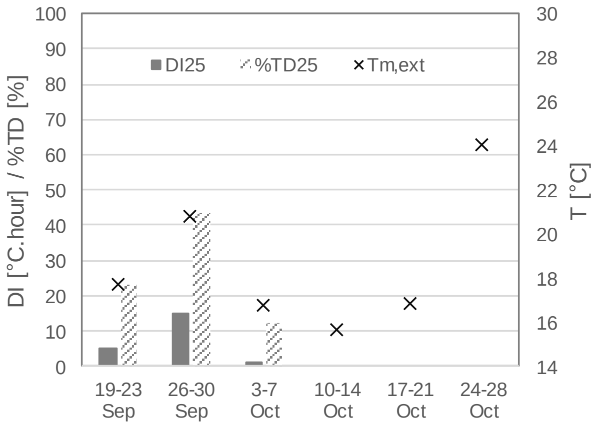


Figure 39 - DI_{25} and $\%TD_{25}$ in summer weeks before refurbishment (2016).

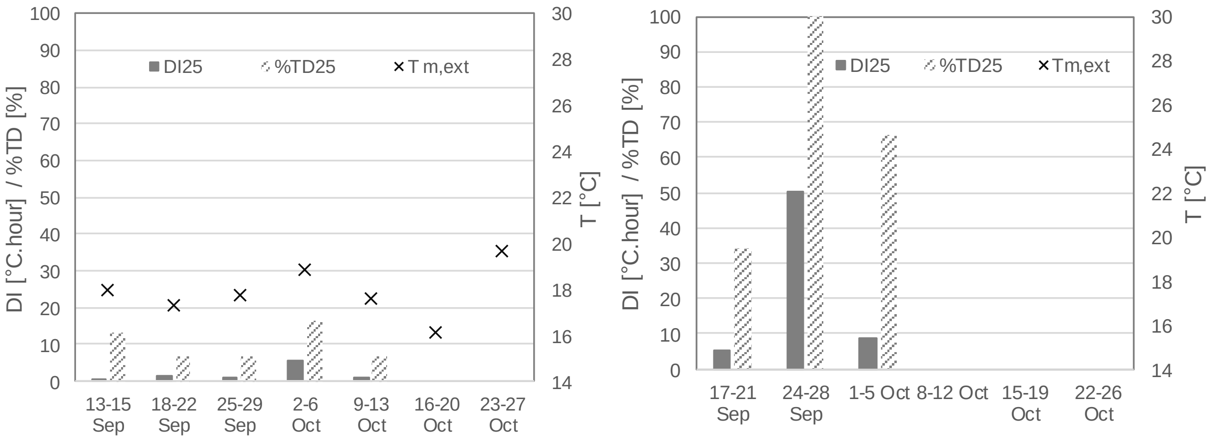


Figure 40 - DI_{25} and $\%TD_{25}$ in mid-season weeks after refurbishment: (left) 2017; (right) 2018.

The mid-season discomfort assessment was made through a non-adaptive approach (DI_{25} and $\%TD_{25}$) with a reference comfort T of 25 ºC. The temperate Porto climate allows this analysis once it is not a strict climate with special requirements, although an adaptive approach will complement this analysis in the sensitivity analysis chapter.

Nevertheless, classroom users were asked to fill in some written questions during the mid-season weeks (Appendix D). The data were collected through 6 mid-season weeks with occupation in free-running hygrothermal conditions for all class-weeks (one answer per user per class). The questionnaires were a useful tool for gathering some information about the users’ perception of comfort.

The results confirmed the users’ satisfaction after the refurbishment. Figure 41 shows a general satisfaction of the users (above 85% very satisfied – green answers; and about 10% medium satisfied – yellow answers).

The mean indoor T during occupation did not have important fluctuations. Two ventilation strategies were implemented (280 m^3/h and 380 m^3/h) but an agreement between the ventilation rate and the

CO_2 concentration was not found. The users' answers did not reveal any discomfort related to CO_2 concentration, which is an expected result since the mean value during occupation remained below 1500 ppm.

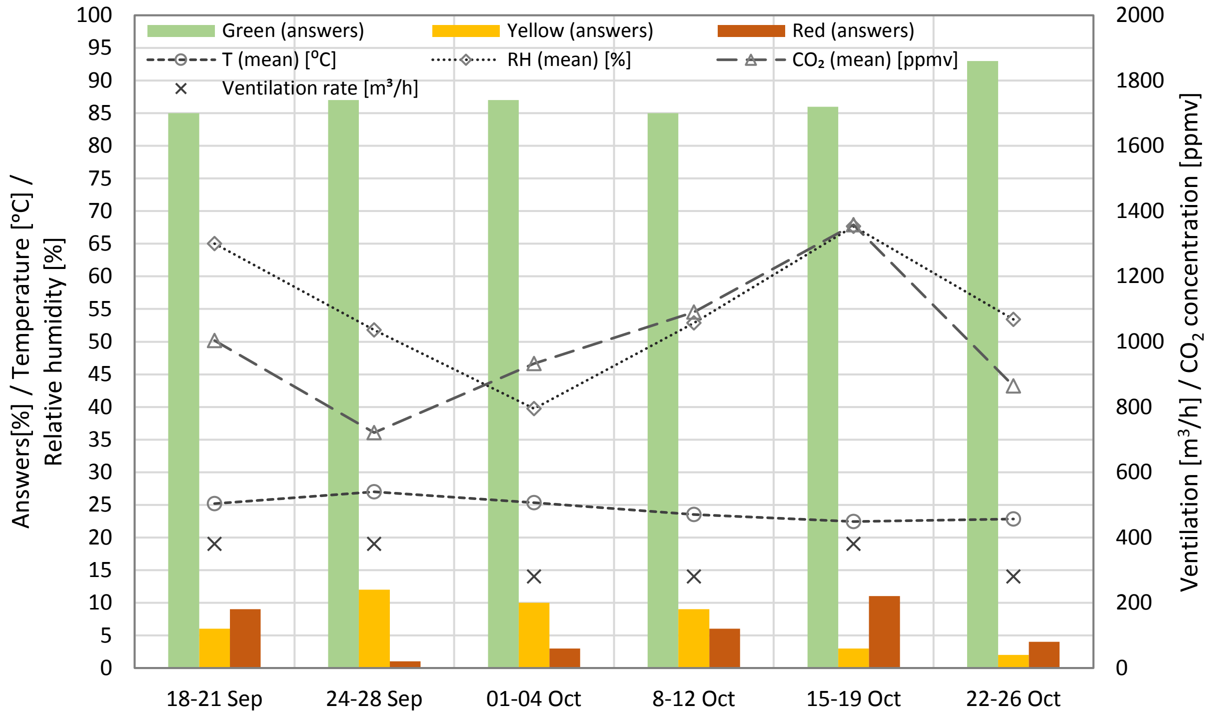


Figure 41 – Users' answers about comfort, mean T, RH, CO_2 and ventilation rates in autumn weeks after refurbishment.

3.4. FINAL CONSIDERATIONS

The non-refurbished *Brandão* schools show very low comfort and inadequate hygrothermal conditions and will require intervention in the near future. The opportunity to refurbish these schools must consider the acquired knowledge in this type of buildings by experimental monitoring of in-service free-running schools. The balance between hygrothermal comfort, IAQ, low energy consumption and affordable costs is a very strict commitment that must consider the climatic features, the users' habits, the economic restrictions and the requirements defined by international standards and also international/national legislation.

The experimental work of the *Brandão* school before and after refurbishment consisted of T, RH, CO_2 and EC monitoring of the prototype, developed in a west-sided classroom in Porto. The prototype was developed within the scope of this work and had an important role in the proposal of a low-cost refurbishment strategy to improve the hygrothermal conditions of these schools (with a controlled increase of EC). This refurbishment can be replicated in other *Brandão* schools and the methodology can be applied to other typologies.

The main conclusions of the experimental work are:

- The analysis of users' discomfort must consider the occupation period of the classrooms. Before and after refurbishment, for the same free-running conditions, the mean differences between the occupation period and the total period were higher in winter than in mid-season.
- The refurbishment has decreased the winter thermal discomfort. There was an important reduction of the discomfort after the refurbishment in free-running conditions. Although the mean $\%TD_{20}$ remained 100%, $DI_{w,20}$ values have decreased from 34.7 ºC.hour to 25.2 ºC.hour, mean daily values.
- After the refurbishment, the $DI_{w,20}$ values decreased from 25.2 to 11.9 ºC.hour when comparing free-running T and RH to 3 heating hours; and from 11.9 to 2.5 ºC.hour when the heating period was increased to 10 hours per day. The (c) heating strategy was the most appropriate for reaching the 20 ºC comfort T and represented an energy consumption of 36 kWh/day (experimental measurement) for this classroom, which is 5€/day (0,1409 €/kWh) [155]. Considering a typical *Brandão* school with four blocks (28 classrooms) the investment would represent about 12 000 €/year for electric heating.
- Despite the benefits of the low-cost refurbishment even in free-running conditions, heating has an important role in the reduction of the discomfort. The first three hours of heating (from (a) to (b) strategy) represented the most important share of discomfort decrease (in ºC.hour) with a low increase in energy consumption.
- The experimental monitoring of the prototype showed an important T stratification during winter, which was increasingly relevant for greater heating strategies. It was also more important near the *window* heater. The mean difference values during the winter months in the center of the classroom were 5.9 ºC for (c) heating strategy, 2.3 ºC for (b) heating strategy and 0.3 ºC for (a) heating strategy. The experimental monitoring contributed to the understanding of the real in-service conditions of these classrooms.
- There was an expected increase of CO_2 inside the classroom for the corresponding months before and after refurbishment, although the mean CO_2 was below the required 1500 ppm. Nevertheless, numerical simulation studies show that it will be necessary to upgrade the real ventilation to 500 m^3/h to satisfy the 1500 ppm requirement for 100% of the occupation period. The CO_2 did not have a direct relationship with the heating strategy and the mean values were similar for the three strategies. The IAQ was not a concerning matter in *Brandão* schools since in pre-existing conditions the CO_2 was below the requirement and remained acceptable after the refurbishment.

- The summer or mid-season was not an actual concern in the pre-existing situation. After the refurbishment, it was found that the mid-season performance of the west-sided *Brandão* classroom depends on the climate severity in each year.
- The results of the survey confirmed the users' satisfaction after the refurbishment, but it was not found any agreement between the users' perception and the hygrothermal and IAQ conditions inside the classroom.

The experimental results were published in a journal paper, presented in Appendix E.

4
Numerical simulation of thermal comfort and energy consumption

4.1. MAIN GOALS AND MOTIVATION

In the past, there were some typified projects for school buildings replicated throughout the country, without the necessary adaptations to the particular climatic situation. Likewise, the replication of rehabilitation solutions, without considering the climatic reality, will have repercussions on the hygrothermal environment inside the classrooms.

In the prototype classroom, prepared in a *Brandão* school, in Porto, some studies were carried out regarding the thermal behaviour before and after a refurbishment process, by experimental monitoring. This extended experimental campaign (three academic years) was a crucial tool to validate an advanced dynamic hygrothermal model of Heat, Air and Moisture transfer – Wufi Plus. The validation consisted of comparing and minoring differences between experimental and numerical results of T, RH and CO_2 concentration. Given the duration of an experimental campaign like this and also the cost of the prototype, it was important to dominate and improve the numerical model that duplicates the *in-situ* conditions and allows the studying of the other Portuguese *Brandão* buildings.

The main goal of this chapter is the validation of a model to describe the thermal and energy performance of *Brandão* school buildings. A validated model allows the study of refurbishment solutions for Portuguese *Brandão* schools, in different climatic conditions. Other authors have validated school building models to find the best refurbishment strategies for specific schools [59, 156].

There are also some studies of models' validation that, even comparing T, RH and CO_2 parameters, are in most cases defined with the purpose of energy consumption analysis (and mainly for EnergyPlus software) [157], which is not the main goal in this work.
Hygrothermal performance analysis of buildings can be done through dynamic hygrothermal simulation considering a heat, air and moisture transfer (HAM) software. An assessment of hygrothermal models has been done by Hens [158].

The hygrothermal model chosen in this work was the Wufi software ("*Wärme- und Feuchtetransport instationär*", that is "*Transient Heat and Moisture Transport*"), developed by Fraunhofer IBP, regarding Kunzel [159] calculation model fundamentals. Wufi performs a finite-volume based simulation by simultaneous heat and moisture transfer. Wufi Pro, Wufi 2D and Wufi Plus analyse 1D transfer, 2D transfer and a whole building by 1D transfer in three geometric dimensions.

The software includes the building geometry definition, the envelope properties and boundary conditions, outdoor complete climatic data (solar radiation, air temperature, relative humidity and precipitation), indoor climatic data (temperature and relative humidity), internal heat gains and users' behaviour and also heating/cooling and ventilation technical systems (Figure 42). All these inputs and boundary conditions make this software suitable for these calculation models under study (Appendix F – Table 1).

The outputs can be grouped into four classes: climatic data, energy consumption, comfort and relative humidity (Appendix F – Table 2). These main outputs are the key to the building's hygrothermal and energy performance analysis.

Despite the existence of different software for thermal performance or energy analysis, Wufi Plus performs a whole hygrothermal/energy analysis, is very user-friendly for technicians and has been extensively studied for building analysis (Table 22). Software acceptance by the scientific community is also very important.

This chapter presents the validation of this model in three distinct situations: (1) before refurbishment without heating, (2) after refurbishment without heating and (3) after refurbishment with heating. The main inputs were climatic data, building envelope, inner gains, solar gains, ventilation and heating strategies and the main outputs were T, RH, CO_2 concentration and EC.

Table 22 – Validation studies using Wufi Plus.

	Author, local	Description
International	Antretter, Sauer [160], IBP Fraunhofer, Holzkirchen, Germany	*Validation of a hygrothermal whole building simulation software*. Validation tools, namely energy component validation standards (ANSI / ASHRAE 140-2007 and VDI Richtline 6020 2001) and other tools for validation of the hygrothermal component (Annex 41 and experimental measurements).
	Antretter, Jan Radon [161]	*Coupling of Dynamic Thermal Bridge and Whole-Building Simulation*. Preparation of the coupling of a hygrothermal whole-building model with a transient 3-D thermal bridge calculation. The validation of the thermal bridge model under steady-state conditions according to DIN EN ISO 10211 (DIN 2008) was successful. Assessment of the effect of the dynamic thermal bridge performance on the overall energy demand of a building. Assessment of moisture-related problems on the thermal bridges.
	Holm, Kuenzel [162], IBP Fraunhofer, Holzkirchen, Germany	*The hygrothermal behaviour of rooms: combining thermal building simulation and hygrothermal envelope calculation.* Comparison of the results from WUFI+ with those from TRNSYS and with experimental results.
	Hens [163], Laboratory of Building Physics, Leuven, Belgium	*Project Summary Report – EBC Annex 41 – Whole Building Heat-Air-Moisture Response.* This project aimed to acquire a better knowledge of whole-building heat, air and moisture (HAM) balance and their effects on comfort, enclosure durability and energy consumption. Assessment of the influence of relative humidity on perceived indoor air quality through HAM software (Wufi, Delphin). Model validation through experimental results.
	Moon, Ryu [164], Republic of Korea	*The effect of moisture transportation on energy efficiency and IAQ in residential buildings.* A hygrothermal calculation model (in Wufi Plus) was calibrated with the measurement data of indoor air temperature and relative humidity in residential buildings.
National	Ribeiro, De Freitas [84], LFC-FEUP, Porto, Portugal	*Comfort and energy efficiency optimization in retrofitted rural buildings.* Temperature validation (in Wufi Plus) of a specific construction typology by comparison with experimental measurement.
	Ferreira, de Freitas [165], LFC-FEUP, Porto, Portugal	*The Influence of Hygroscopic Materials on the Fluctuation of Relative Humidity in Museums Located in Historical Buildings.* Temperature and relative humidity validation (in Wufi Plus) of a model by comparison with experimental measurement.
	Paula [86], LFC-FEUP, Porto, Portugal	*Hygrothermal performance of plaster houses in Brazil.* Temperature validation of a model by comparison with experimental measurement.

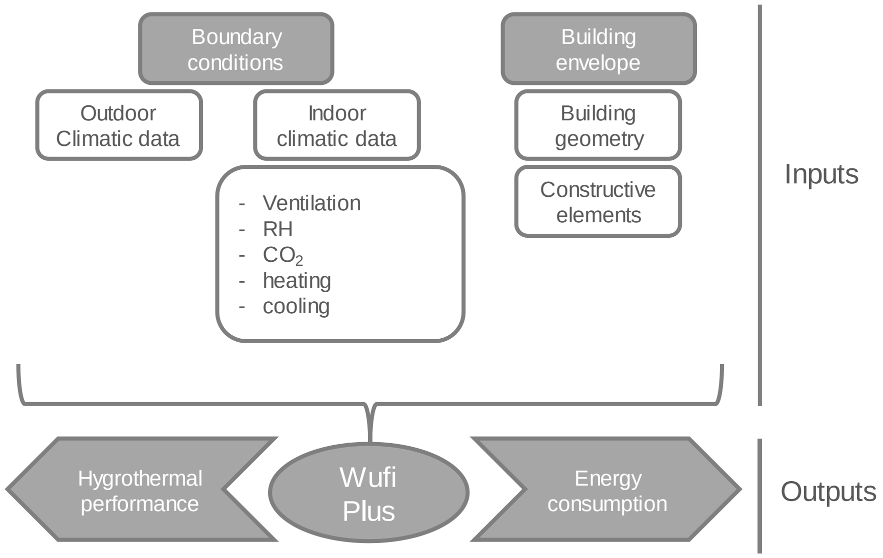


Figure 42 – Wufi Plus software organization chart.

As stated by Lara, Naboni [156], the use of well-calibrated energy simulation models is the key to successful buildings' retrofit or operation management and the optimization techniques can improve the reliability of the results.

The accuracy of the calibration must be confirmed by statistical indexes. The R^2 describes the correlation between measured and simulated values (equation [4]). The goodness-of-fit (*fit*), which correlates the two data series and assesses their fluctuation, facilitates the comparison between series (equation [5]). The normalized mean bias error (*NMBE)* expresses the general normalized mean error and shows the influence of smaller errors (equation [6]). The coefficient of variation of the root mean square error (*CVRMSE)* demonstrates how the model fits the measured data, overcoming possible compensation mistakes of the *NMBE* and it shows the influence of the higher errors [166-168] (equation [7]).

$$R^2 = \left(\frac{\sum_{i=1}^{N} (X_{i,exp} - \overline{X_{exp}}).(X_{i,sim} - \overline{X_{sim}})}{\sqrt{\sum_{i=1}^{N} \left((X_{i,exp} - \overline{X_{exp}})^2 . \sum_{i=1}^{N} (X_{i,sim} - \overline{X_{sim}})^2 \right)}} \right)^2 \quad [4]$$

$$fit = \left(1 - \frac{\sqrt{\sum_{i=1}^{N} (X_{i,exp} - X_{i,sim})^2}}{\sqrt{\sum_{i=1}^{N} (X_{i,sim} - \overline{X_{exp}})^2}} \right).100 \quad [5]$$

$$NMBE = 100.\frac{\sum_{i=1}^{N} (X_{i,exp} - X_{i,sim})}{\overline{X_{exp}}.(n-1)} \quad [6]$$

$$CV(RMSE) = 100.\frac{\sqrt{\frac{\sum_{i=1}^{N} (X_{i,exp} - X_{i,sim})^2}{(n-1)}}}{\overline{X_{exp}}} \quad [7]$$

where $X_{i,exp}$ is the experimental value of T at the time period i, $X_{i,sim}$ is the simulated value of T and $\overline{X_{exp}}$ is the average of the measured values of T during the studied complete period n.

The acceptable calibration tolerances defined by energy guidelines are presented in Table 23. These tolerances were also considered to the hygrothermal validation here adopted.

Table 23 - Acceptable Calibration Tolerances [166-169].

Index	Acceptable Values	
R^2	> 0,75	EVO - Efficiency Valuation Organization [169]
fit	> 80%	Coelho, Silva [166], Kramer, van Schijndel [167]
NMBE	< ±5% | ±10% (monthly | hourly)	ASHRAE [168]
CV(RMSE)	< 15% | 30% (monthly | hourly)	ASHRAE [168]

4.2. VALIDATION

4.2.1. CALIBRATION TOOLS

In this work, the main calibration tool was the Wufi Plus software. The calibration work also considered the climatic data (that represent the real climatic conditions during experimental measurements), the experimental measurements (to compare with the simulation results) and the prototype refurbishment (to control the envelope conditions and the ventilation rate and also to perform different conditions to strongly validate the model – before and after refurbishment, with and without heating).

4.2.1.1. Wufi Plus software

Kunzel [159] described physical principles of heat and moisture transport which have been used to compute the heat and moisture transport in Wufi (equations [8] and [9]). The temperature and relative humidity are the driving potentials.

$$\frac{\partial H}{\partial \theta}.\frac{\partial \theta}{\partial t} = \nabla.(\lambda \nabla \theta) + h_v \nabla.\left(\delta_p \nabla(\varphi.p_{sat})\right) + S_h \qquad [8]$$

Where

$\frac{dH}{d\vartheta}$	Heat storage capacity of the moist building material [J/m^{3}K]
$\frac{d\vartheta}{dt}$	Change of temperature in time (solution) [K/s]
λ	Thermal conductivity of the moist building material [W/(m·K)]
ϑ	Temperature [ºC]
h_V	Evaporation enthalpy of the water [J/kg]
δ_p	Water vapour permeability of the building material [kg/(m·s·Pa)]
φ	Relative humidity [-]
p_{sat}	Water vapour saturation pressure [Pa]
t	Time [s]

S_h Heat source or heat sink [W/m³]

H Total enthalpy [J/m³]

$$\frac{\partial w}{\partial \varphi}.\frac{\partial \varphi}{\partial t} = \nabla\left(D_{\varphi}.\nabla\varphi + \delta_p.\nabla(\varphi.p_{sat})\right) + S_w \qquad [9]$$

Where

$\frac{dw}{d\varphi}$ Moisture storage capacity of the building material [kg/m³]

$\frac{d\varphi}{dt}$ Change of the relative humidity in time (solution) [l/s]

D_{φ} Liquid conduction coefficient of the building material [kg/(m·s)]

φ Relative humidity [-]

δ_p Water vapour permeability of the building material [kg/(m·s·Pa)]

p_{sat} Water vapour saturation pressure [Pa]

t Time [s]

w Water content of the building material layer [kg/m³]

S_w Moisture source or moisture sink [kg/(s.m³)]

The energy balance of a building is an energy conservation system and includes the heat transfer through the envelope, the air renovation (natural or mechanical ventilation) and thermal gains (internal heat sources and solar gains) [57].

Heat transfer in buildings includes conduction, convection and radiation in building elements (roofs, floors, windows, walls), promoted by temperature differences and consequent pressure differences between the elements [73, 170].

Wufi Plus solves equations [8] and [9] individually for each element. The balance of heat and moisture transfer in the building as a whole is shown in Figure 43.

In this classroom model, the indoor air T depends on the heat fluxes inside the classroom (internal gains, natural convection and HVAC systems) and outside the classroom (transmission and solar gains) [162]. Likewise, the indoor RH depends on the inside moisture flows on interior surfaces, on the water vapour users' production and on the air permeability, natural ventilation and mechanical ventilation [162].

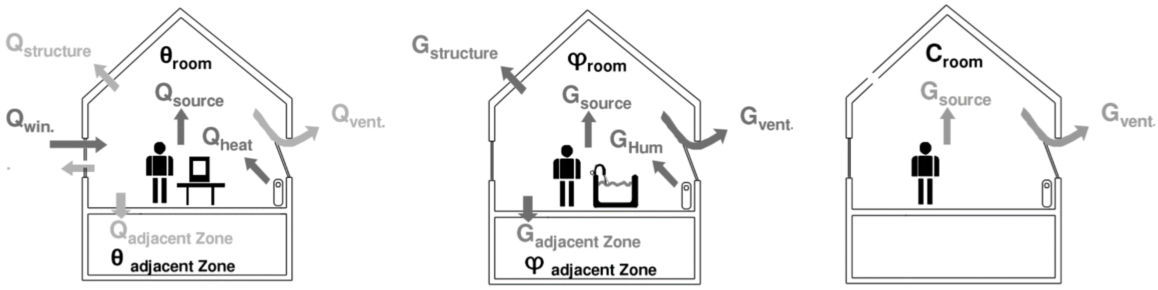


Figure 43 – Heat and moisture transfer in buildings – Wufi Plus [171].

4.2.1.2. Climatic data

4.2.1.2.1. Outdoor climatic data

Wufi Plus includes some weather files from different locations around the world. Moreover, it is possible to use other weather files in .wac, .try and .dat format files.

A complete weather file includes hourly data of outdoor air temperature [°C], outdoor air relative humidity [-], counterradiation atmosferic horizontal [W/m²], solar diffuse horizontal [W/m²], solar global horizontal [W/m²], air pressure [hPa], wind direction [º], wind speed [m/s] and precipitation [L/(m².h)].

To validate this school model the hourly data from Weather Station (WS) of LFC-FEUP from 2016, 2017 and 2018 was used, since the prototype is in Paranhos, near the WS (Figure 44 and Figure 45) [172]. The .wac file from Porto (WS LFC-FEUP 2016) used for calibration before refurbishment was prepared with an increase of 2 ºC from the 1st of May to the 31st of October 2016, due to an iterative process that suggested higher temperature values in summer days near the school building facade. The inlet air from the outdoors to the classroom is located below the roof overhang (Figure 46). The air below the roof overhang is possibly warmer than the outdoor air and for that reason, it is necessary to calibrate the model with a warmer overall outdoor air temperature of the climatic data in mid-season and summer months. The .wac file from Porto (WS LFC-FEUP 2017 and 2018) used for calibration after refurbishment was completed with ISEP 2017 and 2018 data [173] and prepared with an increase of 2 ºC from the 1st of May to the 31st of October 2017 and from the 1st of May to the 30th of June 2018, due to the previously referred reasons.

When comparing the Porto statistical data from different sources, TRY traduces the WS LFC-FEUP 2016 and WS LFC-FEUP 2017 data with important similarity (Figure 47). However, it is observed that IPMA2012 has lower mean, minimum and maximum values when comparing with TRY.

There is an important resemblance between the annual solar global radiation in different situations, although IPMA2012 has a higher value (Figure 48). Precipitation has very different behaviour amongst the analysed data, with 1200 l/(m^2.year) in TRY, 1800 l/(m^2.year) in WS LFC-FEUP 2016 and 600 l/(m^2.year) in WS LFC-FEUP 2017 (Figure 48). However, the hygrothermal calculation in Wufi Plus does not have a strong dependence on precipitation (it depends mostly on RH).

The differences observed are justified by the climate file preparation methodology. While TRY was prepared with several hourly data from different years, WS data refers to a specific year, which may have had a specific behaviour. For this reason, to the model validation, it was used the WS LFC-FEUP data from the corresponding experimental data measurement.

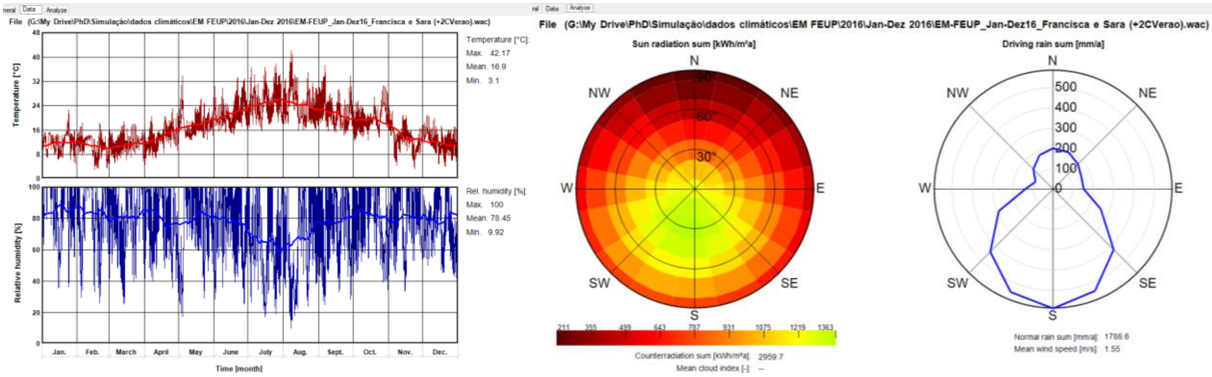


Figure 44 – .wac file from Porto (WS2016).

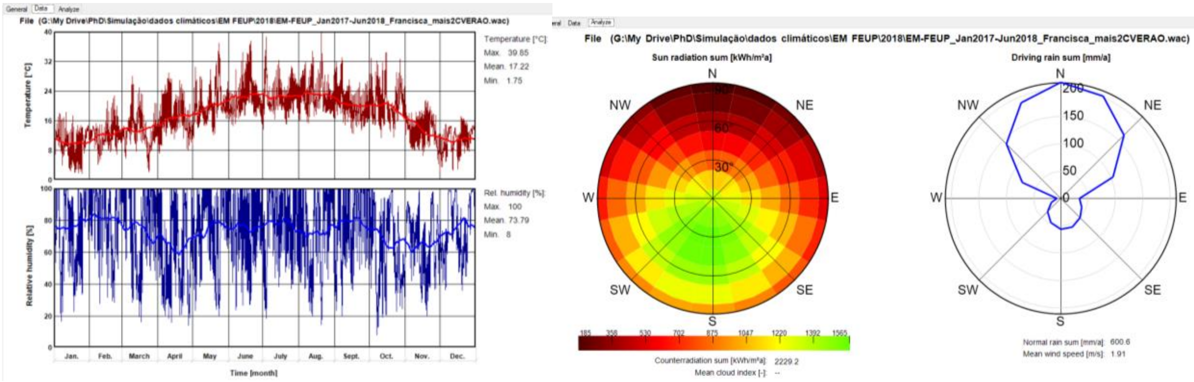


Figure 45 – .wac file from Porto (WS2017 and WS2018).

Figure 46 – Inlet air below the roof overhang.

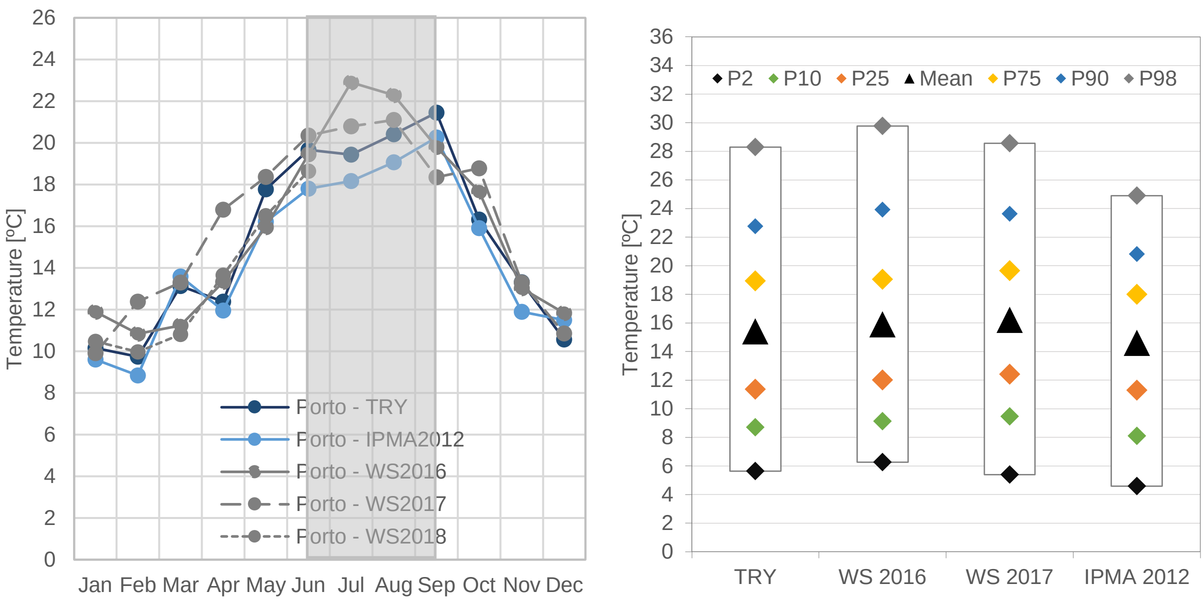


Figure 47 – (left) Porto monthly temperature, (right) Porto temperature statistical analysis.

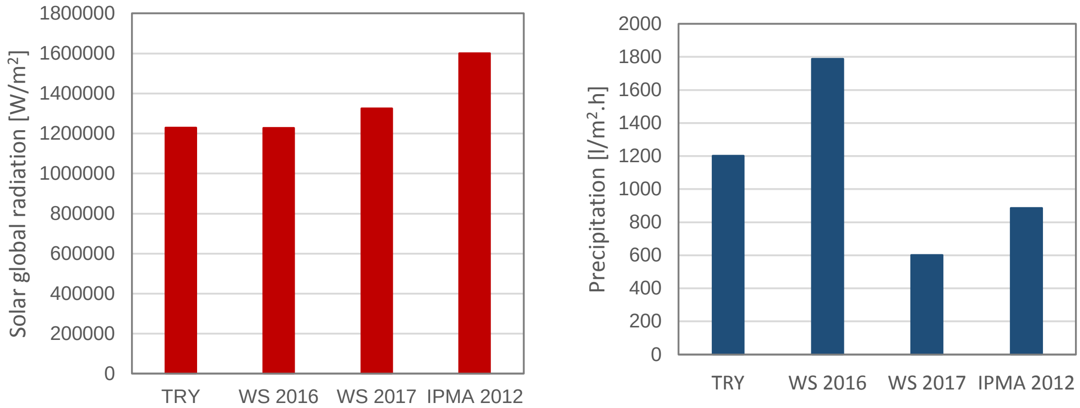


Figure 48 – Porto annual solar global radiation and precipitation.

After the validation, some numerical studies were prepared using a Test Reference Year of Porto (TRY) prepared with hourly data from WS of LFC-FEUP [174], according to CEN indications [175]. However, to the sensibility study of different Portuguese cities it was used the Portuguese Institute for Sea and Atmosphere (IPMA) hourly data from Braga, Bragança, Coimbra, Lisboa and Porto, prepared, under the scope of this Thesis, with the support of the Weather application of Energy Plus [176]. In sum, for sensitivity studies, the TRY was preferably used, although for the comparison amongst different cities the option was a specific climatic year from IPMA, in order to ensure the same conditions for each location.

Figure 49 presents the monthly air T for Portuguese cities and statistical analysis of IPMA 2012 data. There are no important differences between the average T values of Porto, Braga and Coimbra but Lisboa is characterized by higher average outdoor T and Bragança by a lower average T. Bragança and Braga have the lower minimum values (or P2 – percentile 2) and Bragança, Lisboa and Braga have the higher maximum values (or P98 – percentile 98). This analysis was made for the whole year.

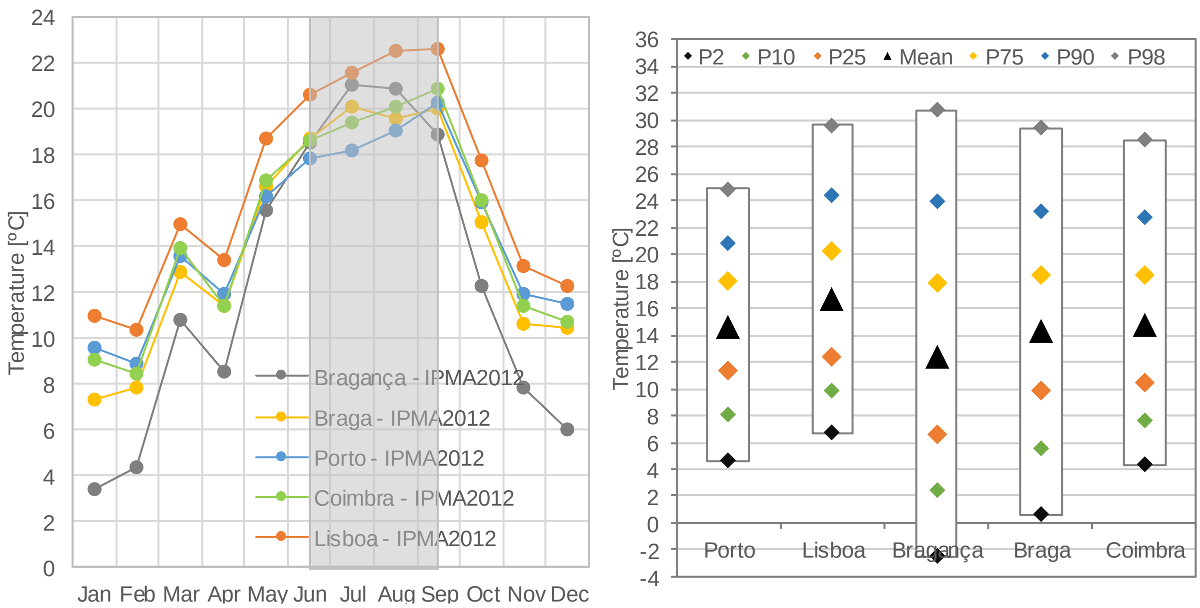


Figure 49 – (left) IPMA 2012 monthly temperature, (right) IPMA 2012 statistical analysis of temperature.

4.2.1.2.2. Additional climatic data

When the envelope contacts specific climatic conditions, such as the ground and the neighbour rooms with known/experimentally measured behaviour, it is also possible to define some additional climatic data in Wufi Plus.

Pallin and Kehrer [177] referred that ground temperature fluctuations are related to superficial temperature and that the yearly average temperature amplitude decreases with depth.

Wufi Plus defines the ground temperature as a sinusoidal, with a maximum two months after the summer solstice (northern hemisphere), which means in middle August [178]. The amplitude is the difference between the maximum average ground temperature in the warm season and the minimum average ground temperature in the cold season. Continental climates are characterized by higher temperature amplitude (high summer temperatures, very cold winters), but maritime climates are characterized by lower amplitude. In addition, the average temperature should be adjusted according to each location and the T behaviour must follow average annual air temperature.

Wufi Plus offers the ground temperature of Holzkirchen (mean T of 6 ºC and the amplitude of 5.5 ºC) [178]. Some complex studies were made in order to model the ground temperature under the buildings [179] but it is very difficult to monitor and characterize. Following a simplified approach, other authors have shown that the ambient temperature is the dominant parameter on the undisturbed ground temperature [180]. Some measurements of ground temperature were made in different countries [181, 182] but Portuguese reality was studied by Pinto, Rodrigues [180] in Figure 50, representing average monthly values of air temperature and ground temperature in Aveiro (warm-summer Mediterranean climate, I2, V2). Porto climate was defined considering the previous results in Aveiro and the mean exterior air temperature. The sinusoidal of the Porto ground climate is shown in Figure 51. To the definition of RH it was accepted the 99% value [178].

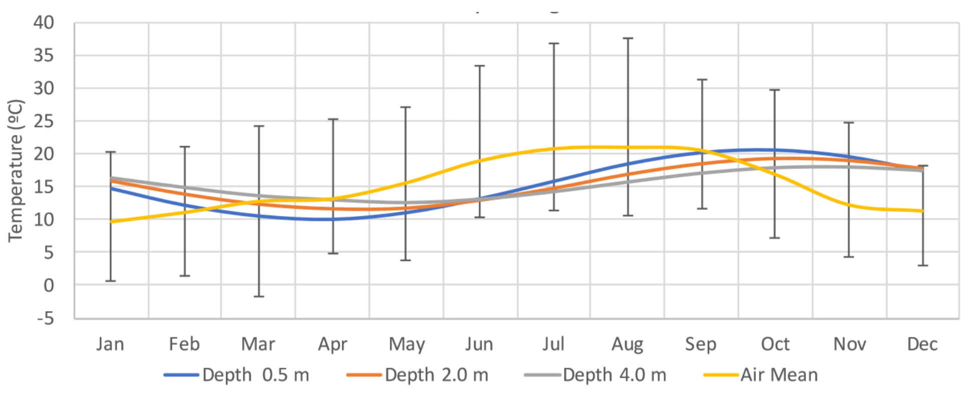


Figure 50 – Average monthly values of air temperature and ground temperature in Aveiro [180].

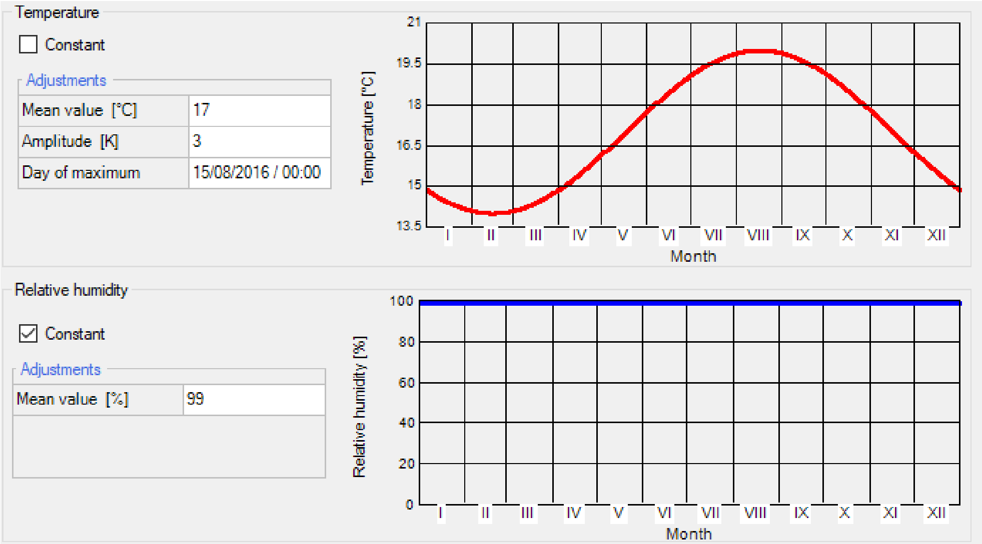


Figure 51 – Porto ground climate.

The T and RH experimental measurements of north and south classrooms were also defined as an additional climate for each boundary condition (north and south) in order to calibrate the model after the refurbishment.

4.2.2. Inputs for calibration

The classroom model geometry was prepared in Wufi Plus with the real dimensions. It is a west-sided classroom and the model includes not only the classroom but also two neighbour classrooms and three storage divisions (boundary conditions) in order to have a realistic behaviour of the studied classroom (Figure 52). The envelope assemblies are presented in Figure 53 (and Appendix G) and the material construction characterization in Table 24. The improvement in the roof thermal transmittance before and after the refurbishment of the prototype was from 0.85 to 0.43 W/(m^2.ºC), respectively. Some general parameters and additional data of the location, ground characteristics and initial conditions were defined in Table 25. During the calibration process, the stabilization of the outputs was analysed (and some first outputs were discarded) in order to minimize the impact of the initial conditions.

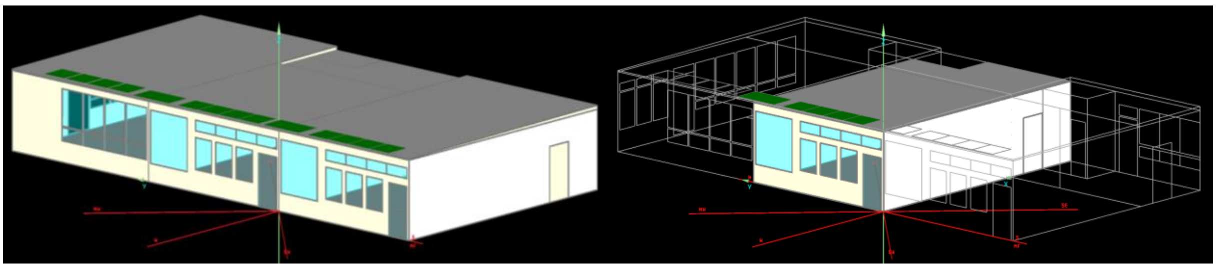


Figure 52 – (left) Model geometry, (right) Classroom geometry.

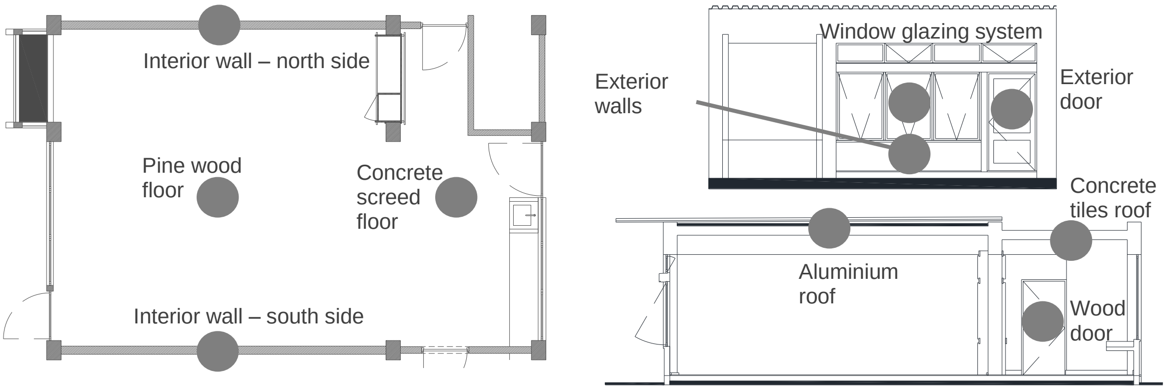


Figure 53 – Envelope assemblies location.

Table 24 – Construction material characterization.

	Bulk density	Thermal conductivity, dry 10 ºC / 50 ºF	Specific heat capacity	Water vapour diffusion resistance factor	Porosity
	ρ [kg/m³]	λ [W/(m.°C)]	c_p [J/(kg.K)]	μ [-]	ε [-]
Concrete slab / Structures [183-186]	2300	2.00	1000	130	0.16
Lightweight concrete layer [184-186]	1800	1.15	1000	110	0.16
Mortar plaster [183, 185, 186]	2000	1.30	1000	25	0.30
Tiles (roofing) concrete [185]	2100	1.50	1000	100	0.175
Concrete screed, bottom layer [186]	1990	1.60	850	99	0.175
Simple solid brick masonry [183, 184, 186, 187]	2060	0.85	920	19	0.28
Aluminium roof coating [183, 185, 186]	2800	160	880	0.73	0.999
PVC waterproofing roof membrane [183, 185-187]	1200	0.14	1500	20000	0.0002
Ventilated attic (inaccessible) [186]	1,3	0.59	1000	0.15	0.999
Wood (chipboard – vertical elements) [185, 186]	600	0.14	1700	50	0.50
Pine wood floor [183, 186, 187]	600	0.18	1600	70	0.73
XPS Surface Skin [186]	40	0.035	1500	450	0.95
Mineral Wool ALPHAROCK-E 225 [186, 188]	60	0.034	850	1	0.95
Cement wood board	1350	0.22	4000	50	0.5
Air layer 50 mm [186]	1,3	0.28	1000	0.32	0.999
Air layer 90 mm [186]	1,3	0.523	1000	0.17	0.999

Table 25 – Localization parameters and additional data.

Latitude [º]	41.13
Longitude [º]	-8.6
Height MSL [m]	100
Time zone (Hours from UTC)	0
Ground reflectance short [-]	0.2
Ground reflectance long [-]	0.1
Ground emission [-]	0.9
Cloud index (only WET-file) [-]	0.66
CO_2 concentration [ppmv]	350 / 450
Initial room temperature [ºC]	20
Initial relative humidity [%]	55
Initial CO_2 concentration [ppmv]	400
Distribution of solar gains on inner surfaces	Proportional to area
Solar radiation direct to inner air [-]	0.1
In the case of negative air balance (interzone ventilation, explicit)	Increase air supply from outer air

4.2.2.1. Before refurbishment

Occupation

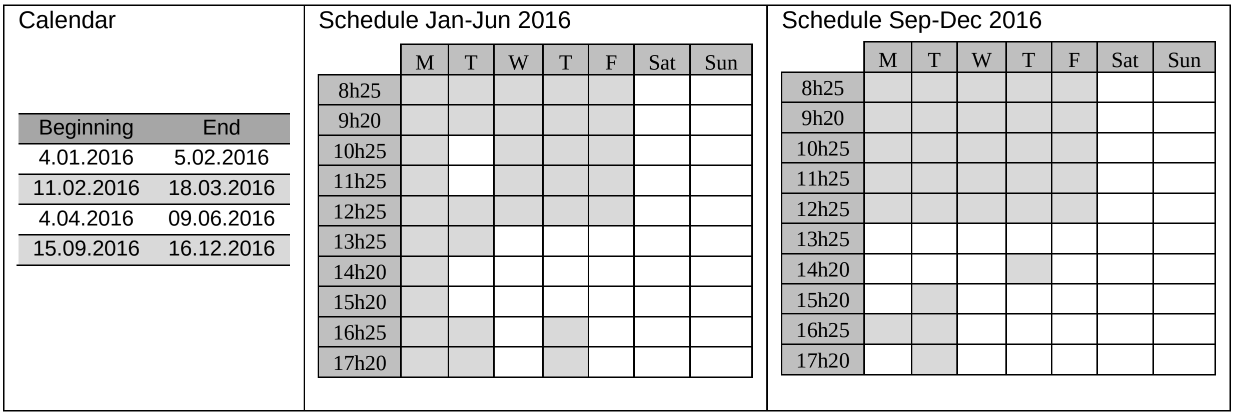
One of the main challenges in this kind of buildings is the occupation. The schools are generally occupied through September to June and within five working days of the week. CO_2 is the main pollutant and can reach high values in occupied classrooms [13], once it results from the metabolism. Once the occupation has an important role in the water vapour production, on the CO_2 production and in internal heat production, it was important to define a realistic calendar and schedule to validate the model (Figure 54).

The school building's internal loads result from occupation and other sources such as lighting and equipment. Table 26 presents some internal loads referred to in the bibliography. Wufi Plus database was used for the validation of the model (considering 20 students and 1 teacher) and also 15 W / m^2 for lighting inside the classroom. Since conventional classrooms do not have equipment with relevant heat production, it was not considered any additional heating loads.

The same internal loads for occupation were considered in the neighbour classrooms and also the same occupation’s calendar. For these classrooms, the schedule was simplified, with classes starting at 8h25 every day and ending at 17h00 on Monday, Tuesday and Thursday and at 13h15 on Wednesday and Friday.

The heat exchange between the users and the environment happens through skin and clothing. It is assumed that 24% of metabolic heat loss is done by evaporation through the skin. The remaining 44.2 W/m^2 may be transferred by conduction, convection and radiation through clothing [189]. The higher the thermal resistance, the lower the heat exchange is. The clo unit (0.155 (m^2 °C)/W) represents the strength of clothing that keeps a sedentary and sitting person comfortable in a normally ventilated space (airspeed of 0.1 m/s), with 21°C of T and less than 50% of RH. EN 15251 [18] and ASHRAE

55 [63] define 1.0 clo as a reference value during the heating period and 0.5 clo during the cooling period. These were also the reference values considered in the model.



grey → With occupation
white → Without occupation

Figure 54 – Calendar and schedule of the studied classroom before refurbishment.

Table 26 – Internal loads in classrooms [18, 20, 26, 55, 63, 71, 76, 186].

	Internal loads		Source
	[W/m^2]	met	
Sedentary occupation (school)	70	1.2	ISO 7730
Sedentary occupation	70	1.2	ASHRAE 55
Sedentary occupation (classroom)	---	1.2	EN 15251
Office occupation (reading)	55	1.0	2013 ASHRAE Handbook - Fundamentals
Office occupation (writing)	60	1.0	2013 ASHRAE Handbook - Fundamentals
Sedentary occupation (classroom)	---	1.2	Portaria No. 353-A/2013
Student 14-16 years occupation (*1)	**50 (*2)**	**1.2**	**Wufi Plus**
Adult (sitting, working) (*1)	**67 (*2)**	**1.2**	**Wufi Plus**
Occupation	74.6	---	Moret Rodrigues, Canha da Piedade [73]
Illumination	15	---	ASHRAE 90.1
Illumination (low heating-level)	5	---	Moret Rodrigues, Canha da Piedade [73]
Illumination (intermediate heating-level) (*1)	**15**	**---**	**Moret Rodrigues, Canha da Piedade [73]**
Illumination (high heating-level)	25	---	Moret Rodrigues, Canha da Piedade [73]

(*1) Used as input in the school model.
(*2) Student 14-16 years: 70 (heat convective) / 20 (heat radiant); teacher: 80 (heat convective) / 41 (heat radiant). Wufi considers 1,8 m^2 for body surface area.

Design conditions

Since the studied classroom is in free-running conditions (without mechanical ventilation and heating/cooling equipment), the design conditions are not a very relevant input, except for the definition of the maximum T (26º C) that was used for the activation of solar protections.

Ventilation

For natural ventilation, it was considered 1 h^{-1} in classrooms (prototype, north and south classrooms) during winter and mid-season/summer (Table 27).

Table 27 – Natural ventilation strategy before the refurbishment.

			Prototype classroom	Calendar	
				Beginning	End
Ventilation	Winter	night	0	1.01.2016	09.06.2016
		day (8h-18h)	1	15.09.2016	16.12.2016
	Summer	night	0		
		day (8h-18h)	1		
Infiltration			0.5	Beginning	End
				1.01.2016	31.12.2016

Windows and Solar Protection

The prototype has single-glazing windows, with windows thermal transmittance (U_w value) of 6.2 W/m^2.K, a frame factor of 0.9 for windows and 0.7 for doors and with no shading obstacles. The g-value considered was 0.85 which corresponds to both SHGC (short-wave radiation average) and SHGC (hemispherical) in Wufi Plus. The long-wave radiation emissivity (mean glazing/frame) is 0.8. The overall heat gain due to incident solar radiation through a transparent component is calculated by multiplying the incident solar radiation (direct and diffuse) with the respective shading factor and the respective SHGC value.

West-sided windows have Venetian interior blinds with solar exposure for sunscreen device of 0.53, which corresponds to equation [10] and the g-values of Table 28. The thermal resistance solar protection is 0.10 (m^2.K)/W and the operation mode was activated by reducing overheating (when indoor T exceeds the 26º C defined in design conditions). East-sided windows do not have solar protections.

$$g_{SP} = {g_{T_{vc}}}/{g_{\perp}} \qquad [10]$$

where g_{SP} is the solar protection g-value, g_{Tvc} is the glazed system with solar protection g-value and $g_{\perp}$ is the glazed system g-value for a perpendicular solar incidence.

Table 28 – g-values of west-sided glazing systems.

	Characterization	Value
$g_{T_{vc}}$	Indoor Venetian blinds, bright colour	0.45 [19]
$g_{\perp}$	Single glazing 6 mm	0.85 [19]
g_{SP}	Solar exposure for sunscreen device	0.53 (equation [10], adapted from [186])

4.2.2.2. After refurbishment

Occupation

The calendar and schedule after the refurbishment are presented in Figure 55.

The occupation and lighting inputs were the same before and after the prototype refurbishment (Wufi Plus database for occupation considering 20 students and 1 teacher and 15 W/m^2 for lighting). The occupation's calendar and the internal loads considered for the neighbour classrooms were the same used before the refurbishment.

Calendar

Beginning	End
13.09.2017	15.12.2017
03.01.2018	09.02.2018
15.02.2018	23.03.2018
09.04.2018	15.06.2018

Schedule 2017/2018

	M	T	W	T	F	Sat	Sun
8h25							
9h20							
10h25							
11h25							
12h25							
13h25							
14h20							
15h20							
16h25							
17h20							

Figure 55 – Calendar and schedule of the studied classroom after refurbishment.

Design conditions

North and south classrooms, storage rooms and the ventilated roof are in free-running conditions and for that reason, the design conditions are not relevant. However, in the studied classroom (prototype) 2 heaters (2 + 2 kW) were installed and the design conditions are relevant during heating strategies. A temperature of 26 ºC was defined as design condition (which is above the real comfort T) in order to ensure the heating system turning off only when reaching 26 ºC, which is close to the experimentally observed behaviour.

Ventilation

After the refurbishment and the construction of a partition wall between the classroom and the circulation zone, a ventilation system with naturally filtered inflow through the envelope and forced airflow to the circulation zone was installed. The partition wall allowed control of the ventilation in order to ensure IAQ. The airflow considered during the calibration months after refurbishment was about 260 m^3/h (ventilation and infiltration), which means 2,0 h^{-1} (value obtained by inlet air speed measurement). The ventilation and infiltration considered after refurbishment are presented in Table 29.

Table 29 – Natural/mechanical ventilation strategy.

			Prototype classroom	Calendar	
Ventilation	Winter	night	0	Beginning	End
		day (8h25-13h15/17h15) (according to occupation schedule)	1,5	03.01.2017	16.06.2017
				13.09.2017	15.12.2017
	Summer	night	0	03.01.2018	09.02.2018
				15.02.2018	23.03.2018
		day (8h25-13h15/17h15) (according to occupation schedule)	1,5	09.04.2018	15.06.2018
Infiltration			0.5	Beginning	End
				1.01.2017	30.06.2018

Windows and Solar Protection

After the refurbishment, some exterior blinds were installed in the prototype west-sided windows. Nevertheless, the exterior blinds were not usually activated by the users. The operation mode of the solar protection was defined in Wufi Plus by a calendar and schedule that reflected the real conditions of the prototype (Table 30, considering the previous equation [10]).

Table 30 – Solar protections (sunscreen device) from September 2017 until June 2018.

	Door	Current zone and solarium (Sep-Dec)	Current zone (Jan-Jun)	Solarium (Jan-Jun)
	Blackout	Blackout	Exterior blinds	Semi-exterior Venetian
$g_{T_{vc}}$	0.44	0.44	0,14	0.09
[19]	Indoor curtain, medium colour	Indoor curtain, medium colour	Outdoor metallic Venetian blinds, bright colour	Outdoor metallic Venetian blinds, bright colour
$g_{\perp}$	0.85	0.85	0.85	0.78
[19]	Single glazing 6 mm	Single glazing 6 mm	Single glazing 6 mm	Double glazing 4 to 8 mm
g_{SP} (equation [10], adapted from [186])	0.52	0.52	0.165	0.115
Thermal resistance solar protection [m^2.K/W]	0.10	0.10	0.10	0.10
Day-profile	0	0.5 – default value 0 – from Monday to Friday during 8h00-17h15	0.5 – default value 0 – from Monday to Friday during 8h00-17h15	0.5 – default value 0 – from Monday to Friday during 8h00-17h15

Day-profile operation mode: 0 – completely open; 1 – totally closed

Heating system

The heating system installed after refurbishment was an electric heating system (two heaters with 2 + 2 kW). The experimental monitoring of EC allowed the calibration of the in-service conditions, considering the real heating strategy calendar (Table 31).

Table 31 – Heating system calendar and schedule for the prototype classroom.

	Calendar	Schedule	Power
Sep-Dec	6-7 Dec 2017	7h30-10h30	4kW
	11-14 Dec 2017	7h30-17h30	4kW
Jan-Jun	8 Jan 2018	6h30-9h30	4kW
	9-11 Jan 2018	7h30-10h30	2kW
	12 Jan 2018	7h30-10h30	4kW
	15-19 Jan 2018	7h30-17h30	4kW
	29-2 Feb 2018	7h30-10h30	4kW
	5-9 Feb 2018	7h30-17h30	4kW
	20-23 Feb 2018	7h30-10h30	4kW
	26-2 Mar 2018	7h30-17h30	4kW
	12-15 Mar 2018	7h30-10h30	4kW
	16 Mar 2018	7h30-10h30	2kW
	19-20 Mar 2018	7h30-17h30	2kW
	21-23 Mar 2018	7h30-17h30	4kW
	9-16 Apr 2018	7h30-10h30	4kW

4.2.3. Results from validation

For the validation of the *Brandão* school model, some calibration tests were done by comparing the indoor environmental measurements (at *center*, *desk* level) obtained from *in-situ* monitoring with simulation results. Two parameters were considered for the validation of the model before and after refurbishment: average hourly indoor T and RH. The prototype classroom was chosen for the calibration tests but the neighbour classrooms were also monitored to assess the boundary conditions of the classroom after refurbishment. Moreover, the simulation results of CO_2 were compared with the CO_2 measurements after refurbishment.

The validation was divided into three steps: (1) before the intervention in free-running conditions (2016); (2) after the intervention in free-running conditions (Sep-Dec 2017); (3) after the intervention with three heating strategies in a weekly schedule calendar (Jan-Jun 2018).
Although the comparison has been made for the full-time period, the main goal is the model validation during the occupation and for that reason, it was not a concern to validate the model during the summer (without classes).

4.2.3.1. Before refurbishment

Table 32 presents the monthly statistical analysis of the obtained absolute differences between experimental and numerical T results for the same input conditions (envelope, solar gains, inner gains, ventilation, climate) and for the total period, excluding summer interruption. Figure 56 presents T development during measurements and simulation. A detailed weekly analysis is carried out in Table 33 and Figure 57. The same information for RH is presented in Table 34, Table 35, Figure 58 and Figure 59.

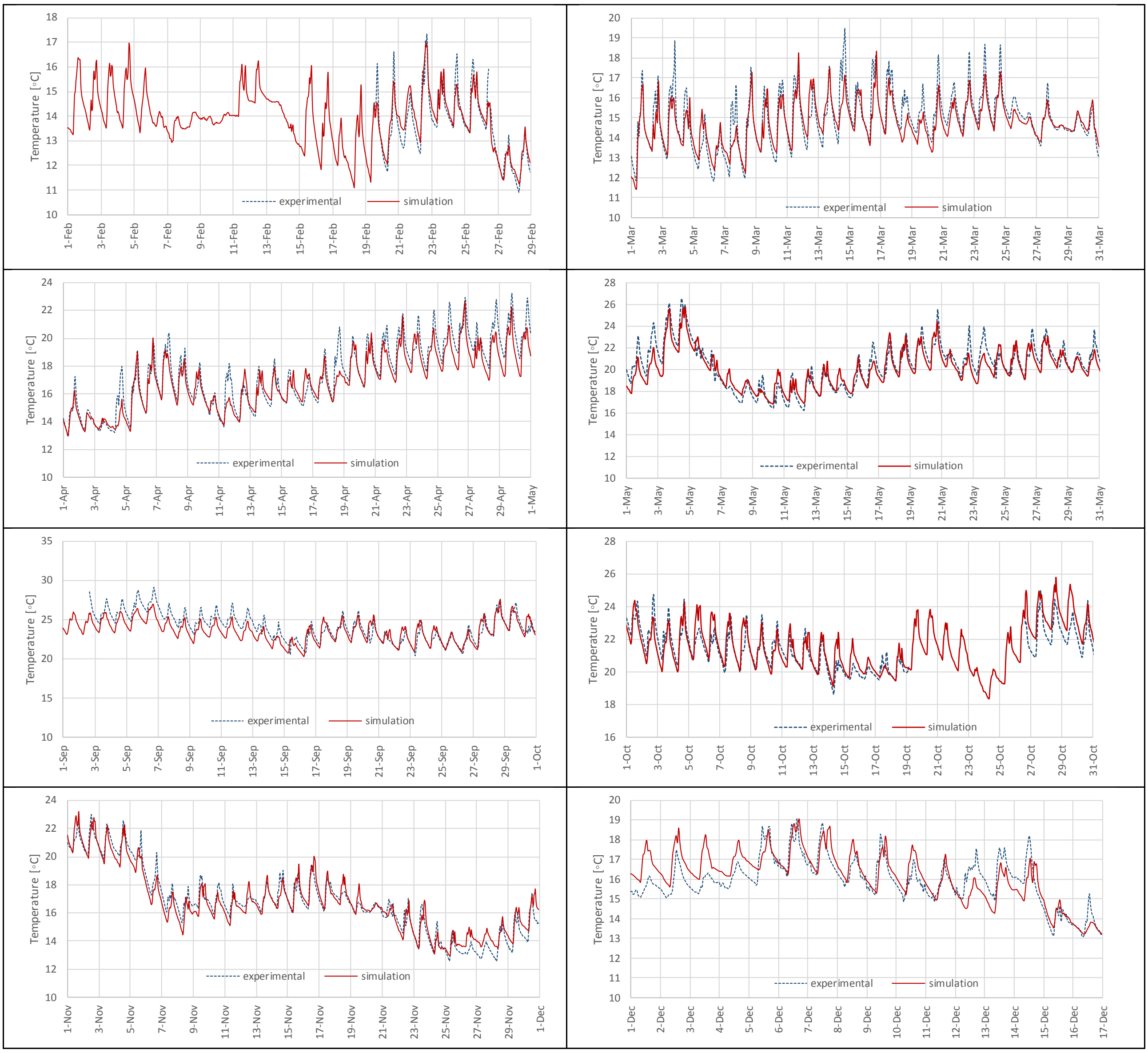


Figure 56 – Monthly experimental and simulated development of T before the prototype refurbishment.

Table 32 – Monthly statistical analysis of T differences before the prototype refurbishment.

	Temperature [ºC]									
	Feb	Mar	Apr	May	Jun	Sep	Oct	Nov	Dec	TOTAL (Feb-Dec) (*)
Mean	**0.34**	**0.49**	**0.66**	**0.70**	**1.65**	**0.90**	**0.59**	**0.49**	**0.62**	**0.79**
Maximum	1.61	3.69	3.15	2.95	6.98	2.74	2.66	2.23	2.23	6.98
Percentile 25	0.13	0.16	0.22	0.34	1.10	0.33	0.24	0.21	0.29	0.27
Percentile 75	0.49	0.63	1.00	0.94	2.06	1.40	0.85	0.71	0.83	1.16
Percentile 95	0.95	1.49	1.93	1.69	3.02	1.91	1.49	1.12	1.47	2.03

(*) Excluding summer

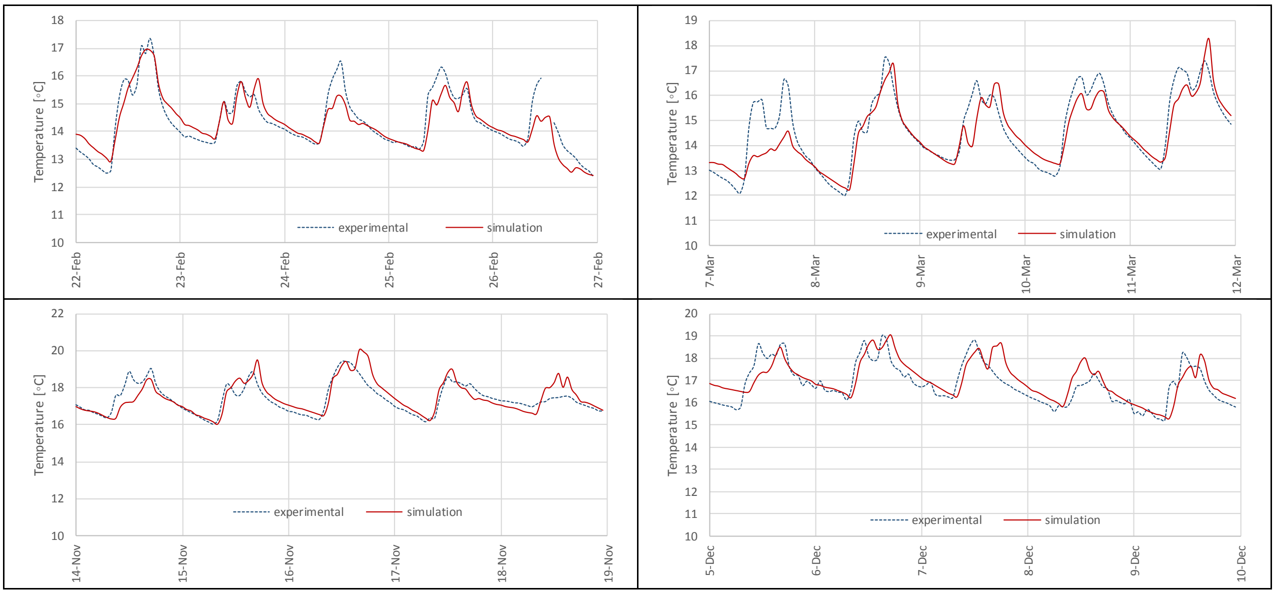


Figure 57 – Weekly experimental and simulated development of T before the prototype refurbishment.

Table 33 – Weekly statistical analysis of T differences before the prototype refurbishment.

	Temperature [ºC]				
	22-26 Feb	7-11 Mar	4-8 Apr	14-18 Nov	5-9 Dec
Mean	**0.36**	**0.52**	**0.62**	**0.38**	**0.47**
Maximum	1.53	2.29	2.61	1.64	1.66
Percentile 25	0.26	0.43	0.36	0.29	0.40
Percentile 75	0.13	0.18	0.22	0.16	0.17
Percentile 95	0.54	0.68	0.75	0.49	0.68

Before the refurbishment, the prototype was under free-running conditions, without heating and with a natural ventilation strategy. The mean T difference from February to December (excluding summer) is 0.79 ºC, with lower values in winter months (February, March, November and December) and higher values in mid-season (May, June and September). Looking at the detailed weekly analysis it is possible to observe, in some days, a gap between measured and simulated data, mainly during the occupation period. In fact, it is very difficult to predict the occupation, once each class has a distinct number of students and the attendance may fluctuate throughout the year. Moreover, before the refurbishment, the prototype did not have a partition wall and the opening and closing doors during classes and breaks was very difficult to predict and probably affected the real ventilation rate and consequently the indoor T. The RH differences followed the T differences behaviour, with better results during free-running winter and worse results in mid-season.

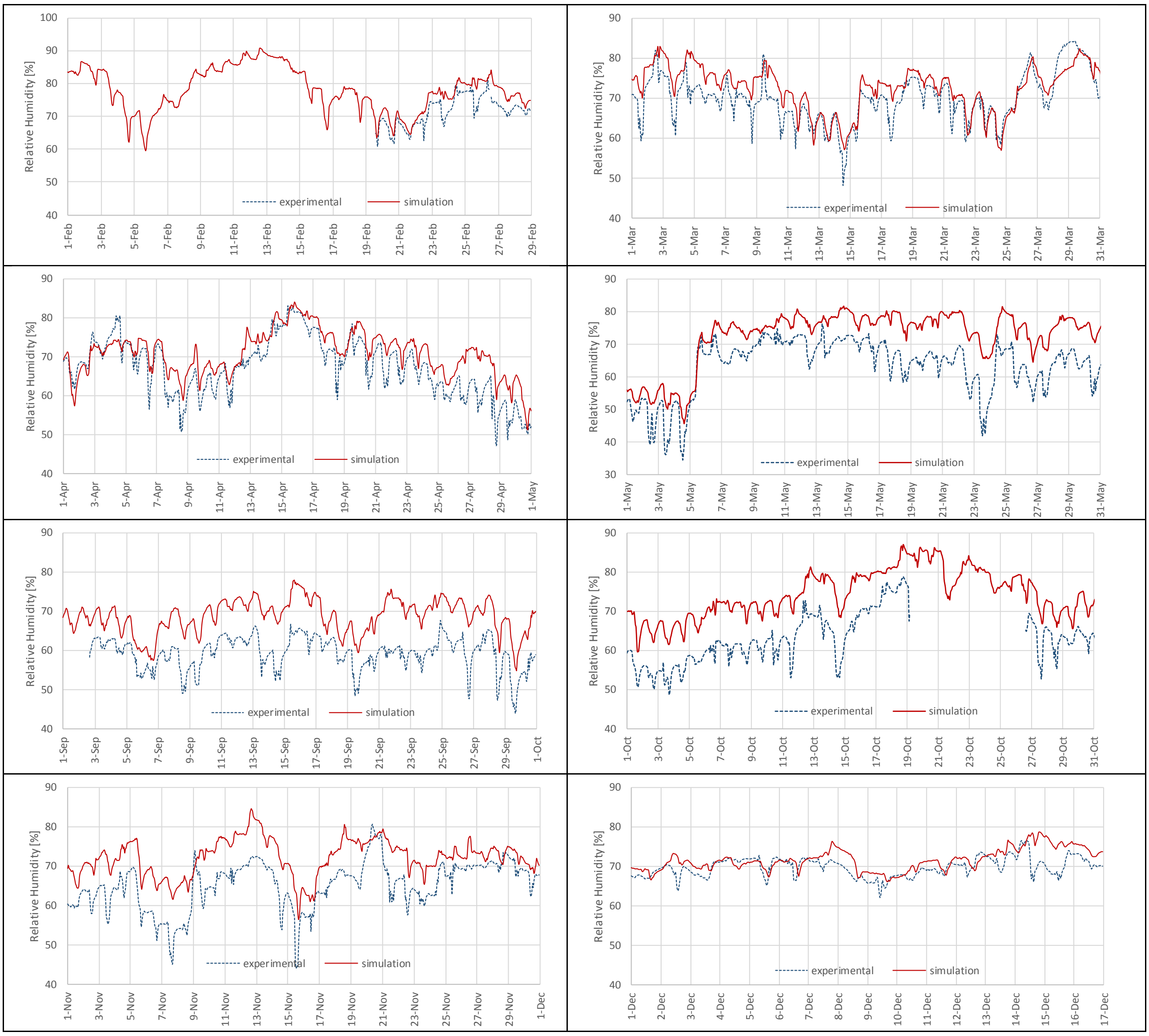


Figure 58 – Monthly experimental and simulated development of RH before the prototype refurbishment.

Table 34 – Monthly statistical analysis of RH differences before the prototype refurbishment.

	Relative Humidity [%]									
	Feb	Mar	Apr	May	Jun	Sep	Oct	Nov	Dec	TOTAL (Feb-Dec) (*)
Mean	**4**	**4**	**4**	**9**	**11**	**9**	**10**	**7**	**2**	**7**
Maximum	12	14	14	24	23	19	20	19	11	24
Percentile 25	2	2	2	6	10	8	8	4	1	3
Percentile 75	5	5	6	12	13	11	11	9	3	10
Percentile 95	8	8	10	16	15	14	14	12	7	14

(*) Excluding summer

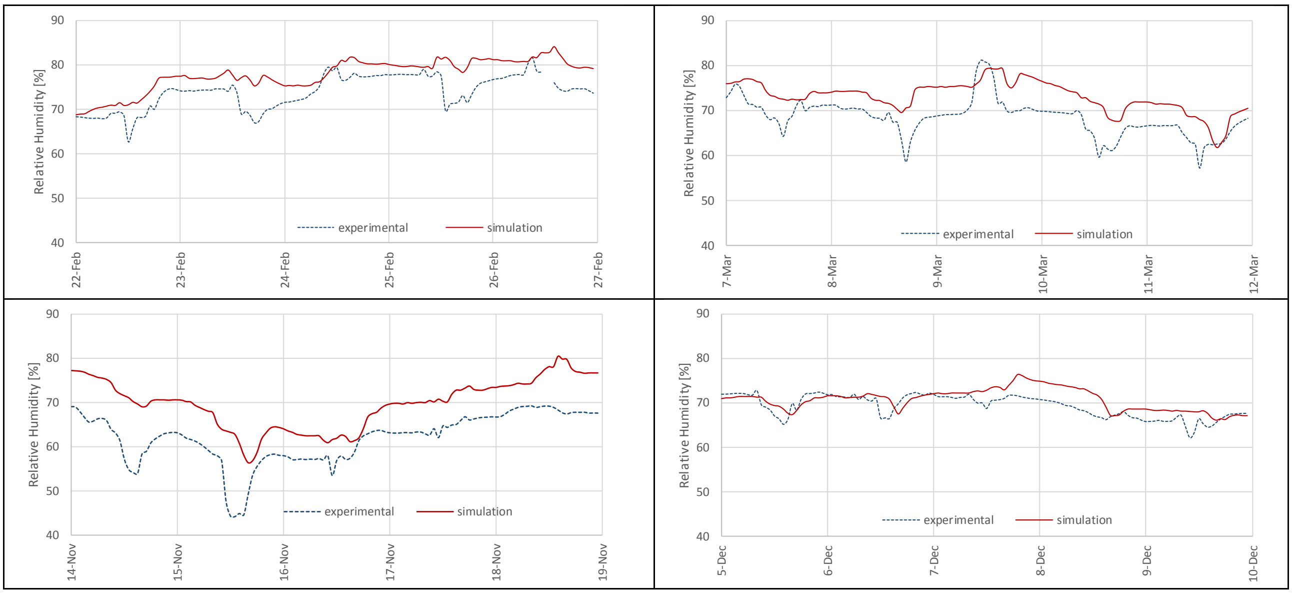


Figure 59 – Weekly experimental and simulated development of RH before the prototype refurbishment.

Table 35 – Weekly statistical analysis of RH differences before the prototype refurbishment.

	Relative Humidity [%]				
	22-26 Feb	7-11 Mar	4-8 Apr	14-18 Nov	5-9 Dec
Mean	**4**	**5**	**4**	**8**	**2**
Maximum	12	12	12	19	6
Percentile 25	3	5	3	7	2
Percentile 75	2	4	2	6	1
Percentile 95	5	6	6	9	3

4.2.3.2. After refurbishment

After the refurbishment, the prototype was analysed in three situations implemented in a weekly based calendar: (a) free-running *T* and *RH*, without climatization; (b) reduced heating strategy with 4kW power (3 h per day at early morning during winter) and (c) regular heating strategy with the same heating power (10 h per day during winter), always with a controlled ventilation system.

Therefore, and in order to have comparable results, January, February and March weeks were divided into three groups: (a), (b) and (c) heating strategy. For that reason, the most relevant statistical analysis of T and RH in winter was not defined by month but by strategy.

Table 36 presents the statistical analysis (by month or by strategy) of the obtained absolute differences between experimental and numerical results of T for the same input conditions (envelope, solar gains, inner gains, ventilation, climate) for the total period, excluding summer interruption. Figure 60 presents T development during measurements and simulation. A detailed weekly analysis to understand the behaviour of experimental and simulation results is carried out in Table 37 and Figure 61. The same information for RH is presented in Table 38, Table 39, Figure 62 and Figure 63 and an average statistical analysis for CO_2 is presented in Table 40.

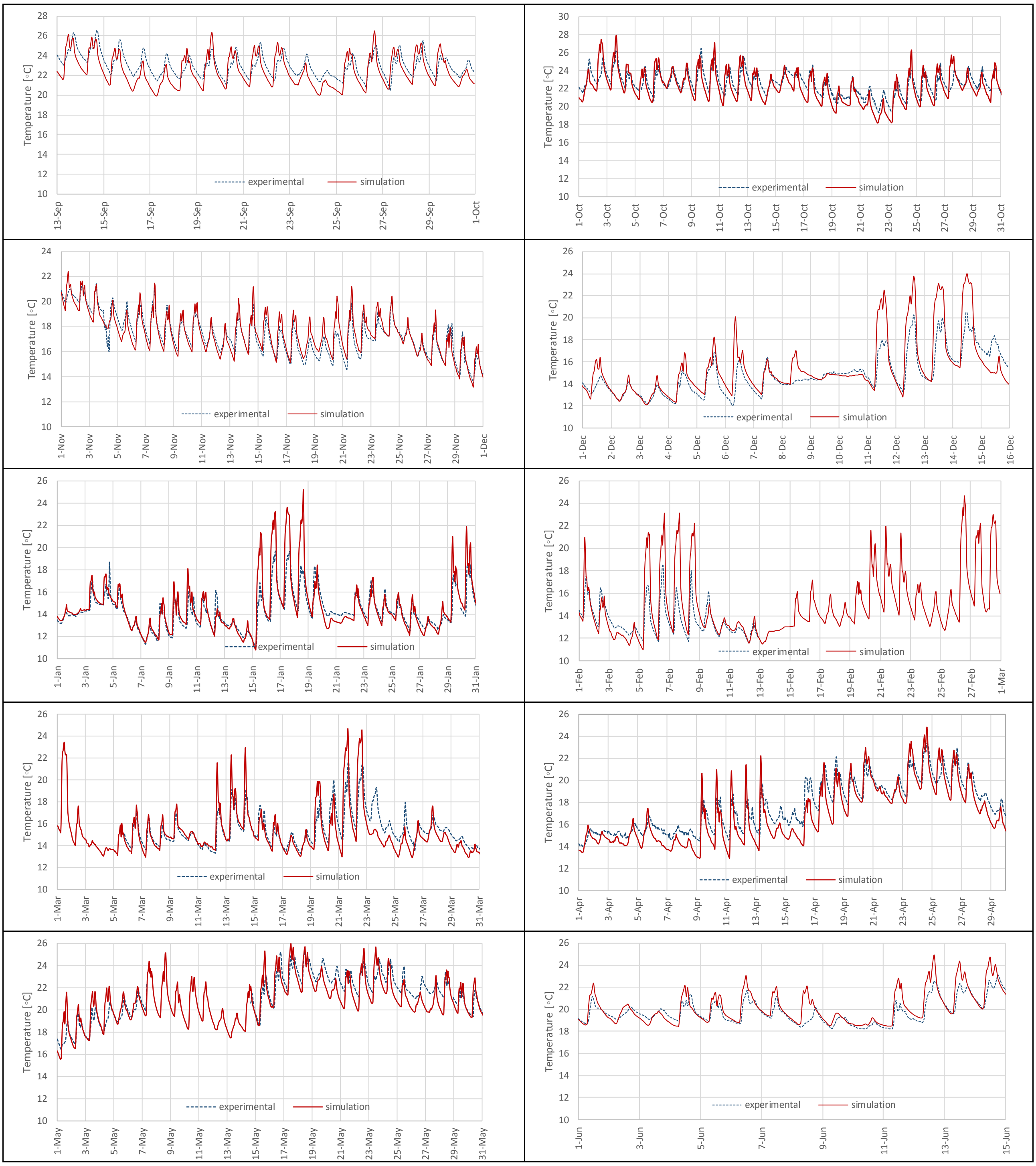


Figure 60 – Monthly experimental and simulated development of T after the prototype refurbishment.

Table 36 – Monthly statistical analysis of T differences after the prototype refurbishment.

	Temperature [ºC]												
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Mean	(a)(*)	(b)(*)	(c)(*)
Mean	**0.99**	**0.90**	**0.54**	**0.94**	**0.69**	**1.23**	**0.83**	**1.03**	**0.86**	**0.56**	**0.84**	**0.40**	**0.70**	**1.94**
Maximum	2.35	3.82	3.10	6.39	7.22	8.59	4.95	4.43	3.33	3.24	8.59	2.95	6.04	8.59
Percentile 25	0.70	0.47	0.22	0.19	0.17	0.24	0.26	0.60	0.28	0.14	---	---	---	---
Percentile 75	1.25	1.21	0.78	1.11	0.66	1.11	1.12	1.35	1.30	0.68	---	---	---	---
Percentile 95	1.73	1.95	1.40	3.72	3.55	5.06	3.06	2.06	2.02	1.84	---	---	---	---

(*) Weeks with (a), (b) and (c) heating strategy in Jan-Mar; (a) free-running T and RH, (b) 3 h heating, (c) 10 h heating.

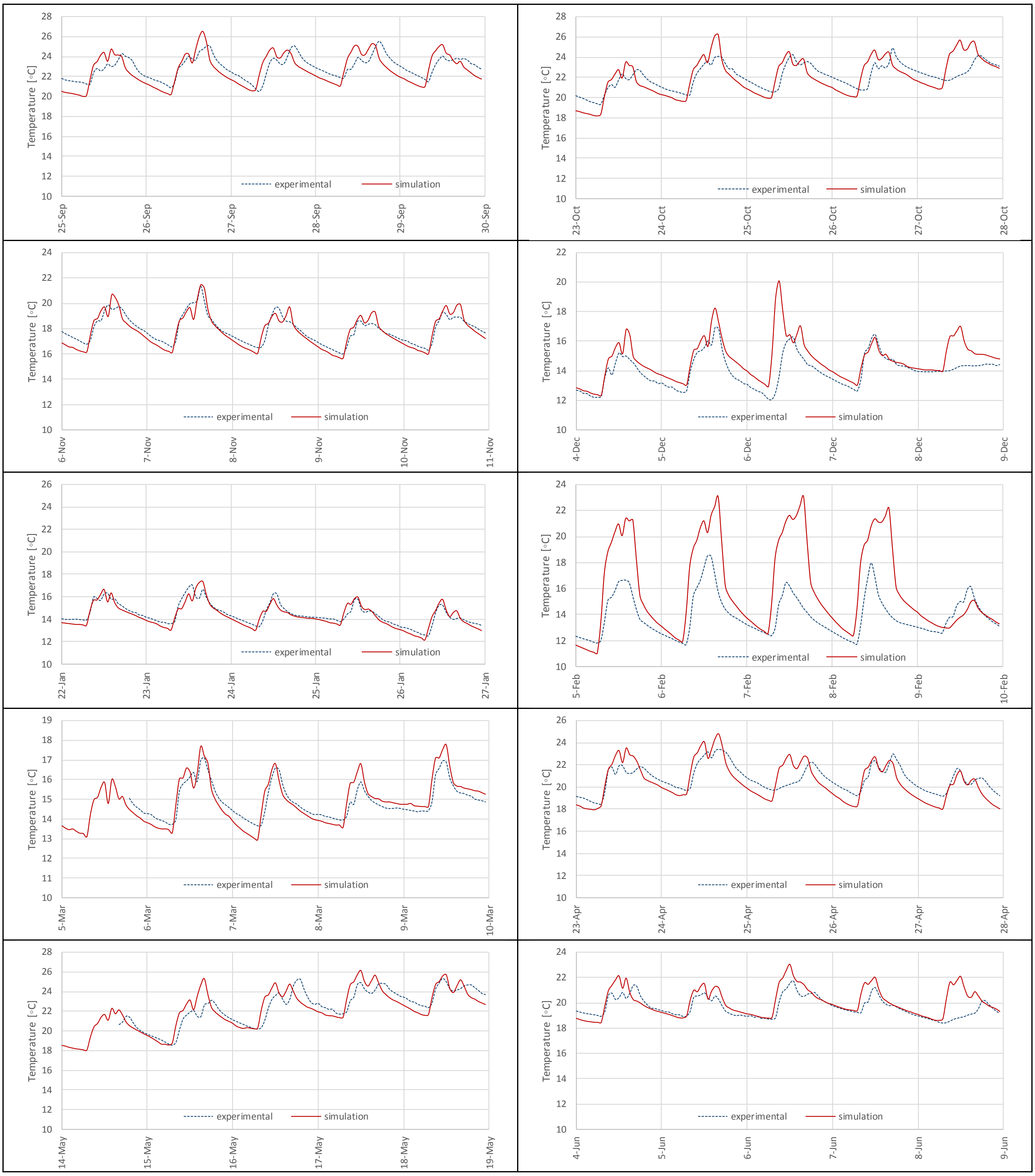


Figure 61 – Weekly experimental and simulated development of T after the prototype refurbishment.

Table 37 – Weekly statistical analysis of T differences after the prototype refurbishment.

	Temperature [ºC]									
	25-29 Sep	23-27 Oct	6-10 Nov	4-8 Dec	22-26 Jan	5-9 Feb	5-9 Mar	23-27 Apr	14-18 May	4-8 Jun
Mean	**0.95**	**1.05**	**0.45**	**0.76**	**0.38**	**2.23**	**0.43**	**0.95**	**0.80**	**0.57**
Maximum	2.35	3.52	1.35	6.39	1.42	8.59	1.17	2.71	3.21	3.24
Percentile 25	0.69	0.71	0.25	0.25	0.22	0.62	0.28	0.60	0.34	0.10
Percentile 75	1.20	1.19	0.51	0.82	0.46	3.81	0.56	1.20	1.11	0.75
Percentile 95	1.73	2.45	0.99	2.31	0.81	6.21	0.91	1.73	1.81	1.72

Note: Free-running weeks, except for 4-8 December ((b) heating strategy) and 5-9 February ((c) heating strategy).

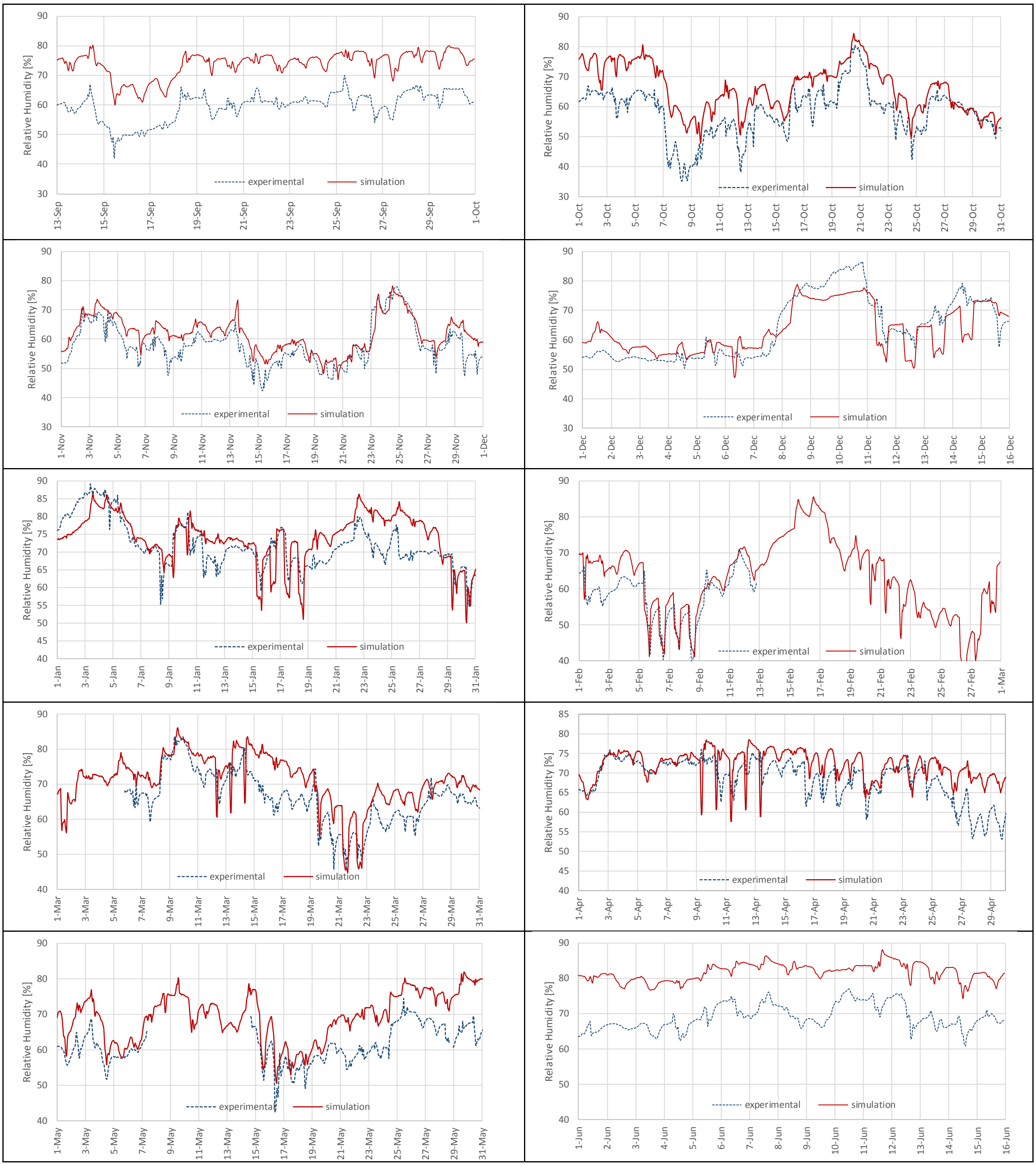


Figure 62 – Monthly experimental and simulated development of RH after the prototype refurbishment.

Table 38 – Monthly statistical analysis of RH differences after the prototype refurbishment.

	Relative Humidity [%]												
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Mean	(a)(*)	(b)(*)	(c)(*)
Mean	**14**	**8**	**4**	**5**	**5**	**5**	**6**	**4**	**8**	**13**	**7**	**6**	**6**	**5**
Maximum	20	23	16	20	16	14	16	17	18	19	23	15	16	15
Percentile 25	12	5	2	2	2	2	4	1	5	11	---	---	---	---
Percentile 75	15	11	6	7	7	6	8	6	10	15	---	---	---	---
Percentile 95	17	15	9	11	11	10	12	11	15	17	---	---	---	---

(*) Weeks with (a), (b) and (c) heating strategy in Jan-Mar.

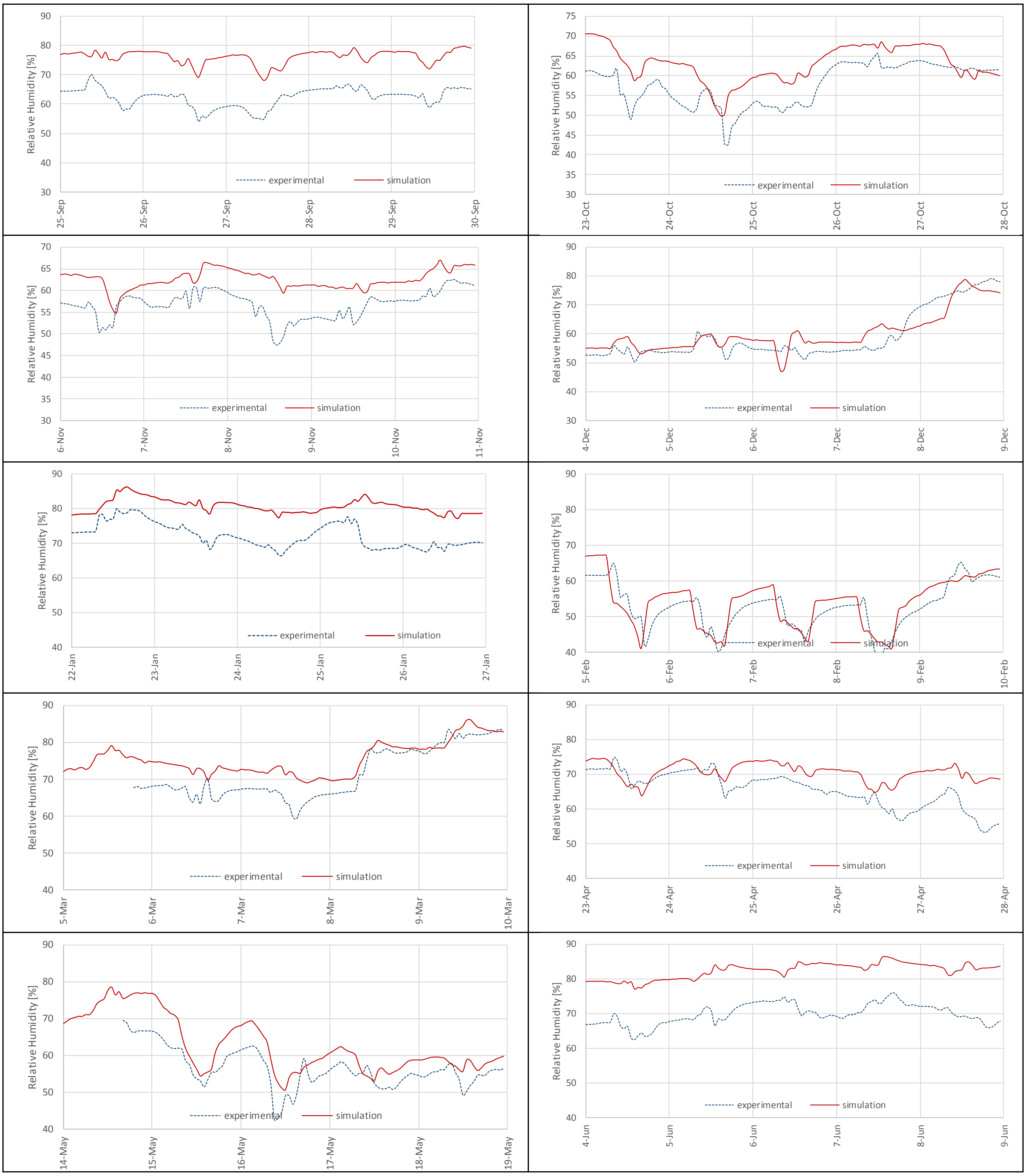


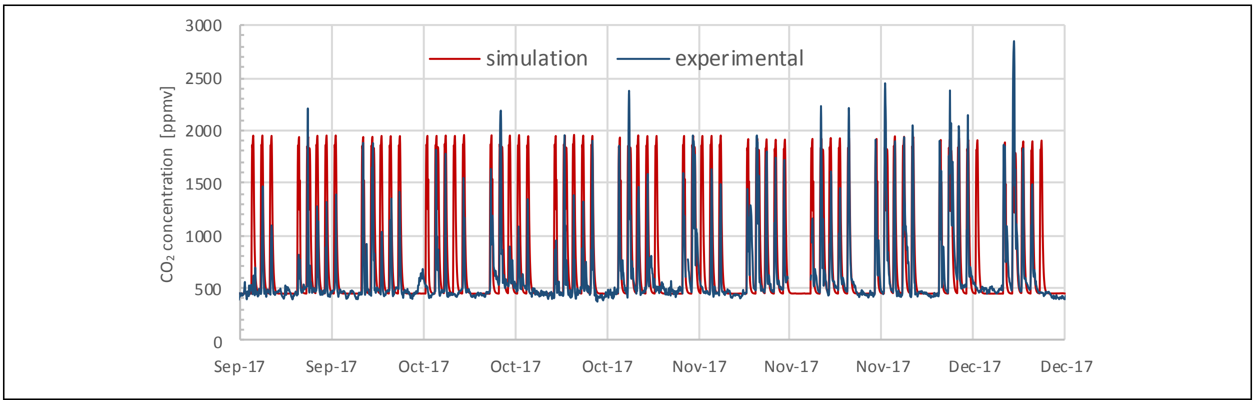
Figure 63 – Weekly experimental and simulated development of RH after the prototype refurbishment.

Table 39 – Weekly statistical analysis of RH differences after the prototype refurbishment.

	Relative Humidity [%]									
	25-29 Sep	23-27 Oct	6-10 Nov	4-8 Dec	22-26 Jan	5-9 Feb	5-9 Mar	23-27 Apr	14-18 May	4-8 Jun
Mean	**14**	**6**	**6**	**3**	**8**	**4**	**4**	**6**	**5**	**12**
Maximum	20	12	15	8	15	11	12	15	12	17
Percentile 25	13	4	4	2	6	2	2	3	3	11
Percentile 75	15	8	7	4	10	4	6	7	7	14
Percentile 95	19	10	10	8	13	8	8	13	10	16

Note: Free-running weeks, except for 4-8 December ((b) heating strategy) and 5-9 February ((c) heating strategy).

The mean T difference from September 2017 to June 2018 (excluding summer) is 0.84 ºC, with lower values in November and June and higher values in winter months, unlike the results before refurbishment. Considering the detailed weekly analysis, it is possible to observe that the higher gaps between measured and simulated data are during the heating weeks. In fact, Wufi considers an efficient heating system uniformly distributed in the classroom and also an instantaneously heating strategy that does not traduce the reality in the prototype. The analysis of the RH differences shows better results in winter (differences between 4 and 6%), whatever the heating strategies are and shows worse results in mid-season months. The CO_2 mean absolute differences between measured and simulated data are 233 ppm before heating and 175 ppm after heating (Table 40), which are low values considering the uncertainty of the occupation and of the windows/doors opening strategy (Figure 64 and 65).



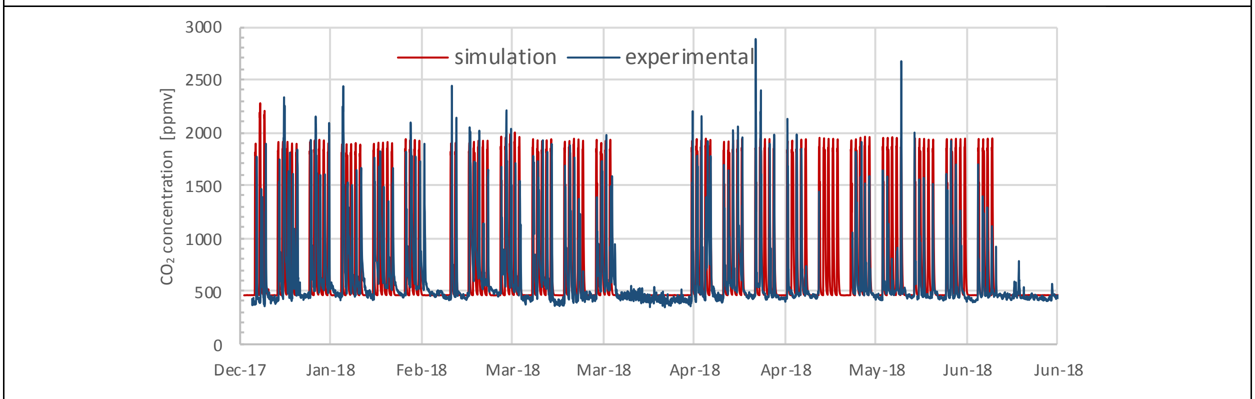


Figure 64 –Experimental and simulated development of CO_2 during the year, after the prototype refurbishment.

Table 40 – Statistical analysis of CO_2 differences after the prototype refurbishment.

	Sep-Dec	Jan-Jun
∆Mean	233	175
Percentile 25	19	20
Percentile 75	279	172
Percentile 95	1127	882

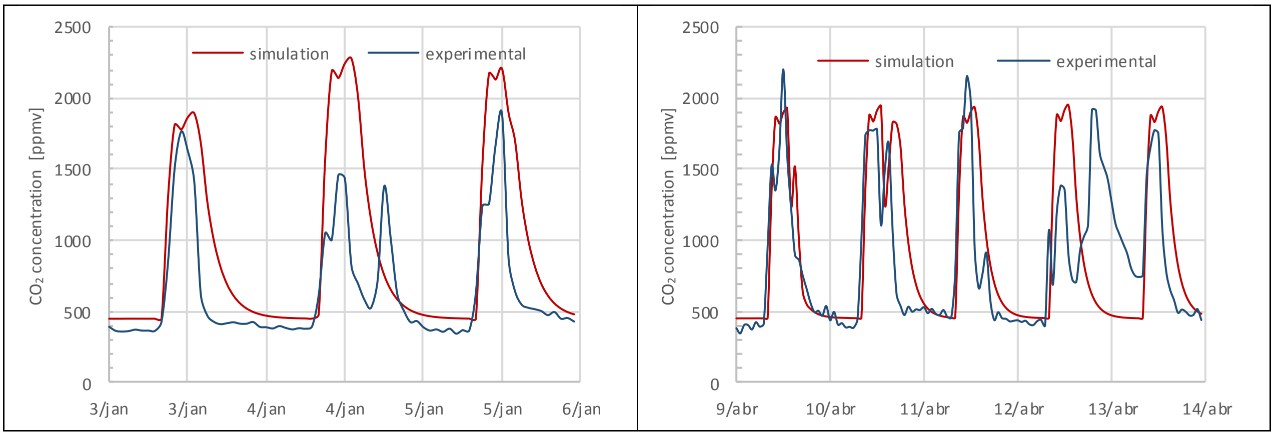


Figure 65 – Weekly experimental and simulated development of CO_2 after the prototype refurbishment.

4.2.4. Statistical analysis

Some statistical indexes of the correlation between experimental and simulation data after refurbishment are described in Table 41. This analysis was made for the whole year (excluding summer) and also for the occupation period. The model is more accurate when the R^2 and *fit* are higher and the *CV(RMSE)* and *NMBE* are lower. The NMBE is an indicator of the overall bias in the regression estimate. Positive NMBE indicates that the regression tends to overstate the actual values [169].

The T statistical indexes indicate a good correlation between measurements (at *center*, *desk* level) and simulation results. The correlation is better when considering the whole period (excluding summer) (R^2 = 0.91) than when considering only the occupation period (R^2 = 0.80). It is also an expected result, once the real occupation is difficult to predict. The graphic of T correlation (R^2) is shown in Figure 66. The *NMBE* is 0.4%, which is a very good result and the *CV(RMSE)* is 6.1%, also fulfilling the requirement. The RH statistical indexes indicate a medium relation, with an acceptable R^2 of 0.54, considering the whole period and a reasonable *fit* value (68,9%). In spite of the mean differences between measured and experimental results, CO_2 does not have a good correlation between the two series, with low R^2, low *fit*, high *NMBE* and high *CV(RMSE)*.

Table 41 – T, RH and CO_2 statistical indexes.

	T				RH				CO_2		Classification (Table 23)
	All-time		Occupation		All-time		Occupation		All-time		
Coefficient of Variation (St deviation/mean)	0.06		0.08		0.09		0.11		0.55		
R^2	**0.91**	+	**0.80**	+	0.54	±	0.51	-	0.47	-	>0.75
fit	70.3	±	54,6	-	68.9	±	21.3	-	31.0	-	>80%
NMBE	**0.4**	+	**-1.9**	+	**-7.6**	+	**-7.1**	+	-17.4	-	< ±5% | ±10% (monthly | hourly)
CV(RMSE)	**6.1**	+	**7.9**	+	**12.3**	+	**13.3**	+	60.2	-	<15% | 30% (monthly | hourly)

(+) requirement fulfilled; (±) not far from the requirement; (-) requirement not fulfilled

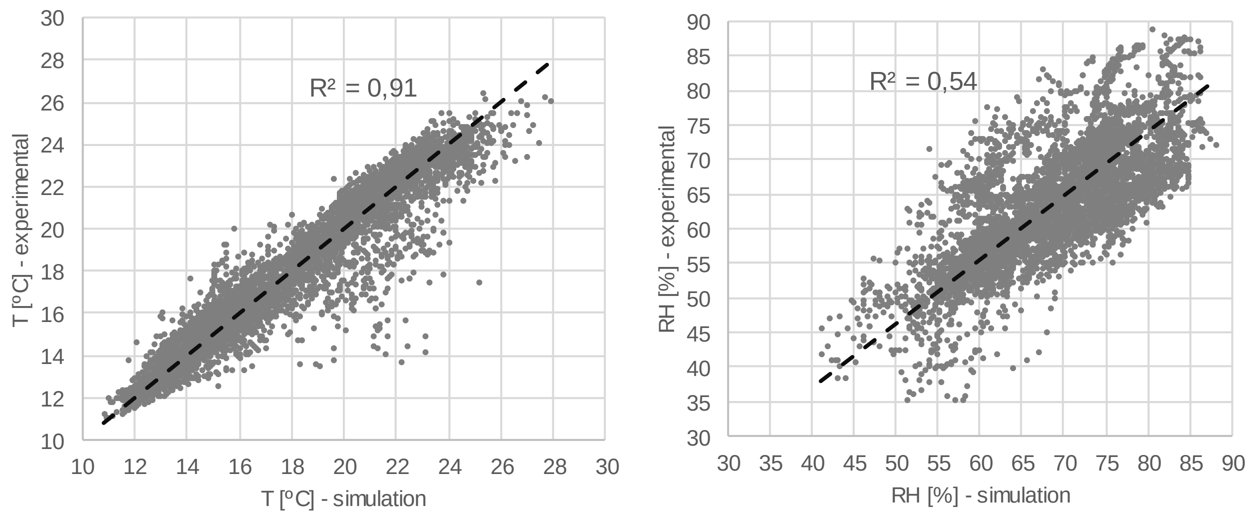


Figure 66 – T and RH correlation between measurements and simulation.

As previously referred, the main differences between experimental and simulated T are in winter weeks, during heating strategies (3 and 10 heating hours) (Figure 67), due to Wufi limitations in reproducing a real heating system. The RH mean differences are not affected by the heating strategy. The measured in-service temperature stratification in different classroom locations may justify the differences between experimental data and simulation.

As referred in experimental results “Temperature stratification before and after refurbishment”, the stratification was more relevant the greater the heating strategy was and was also more important near the heaters. It means that the stratification was not relevant in free-running conditions and justifies the better validation results during free-running weeks.

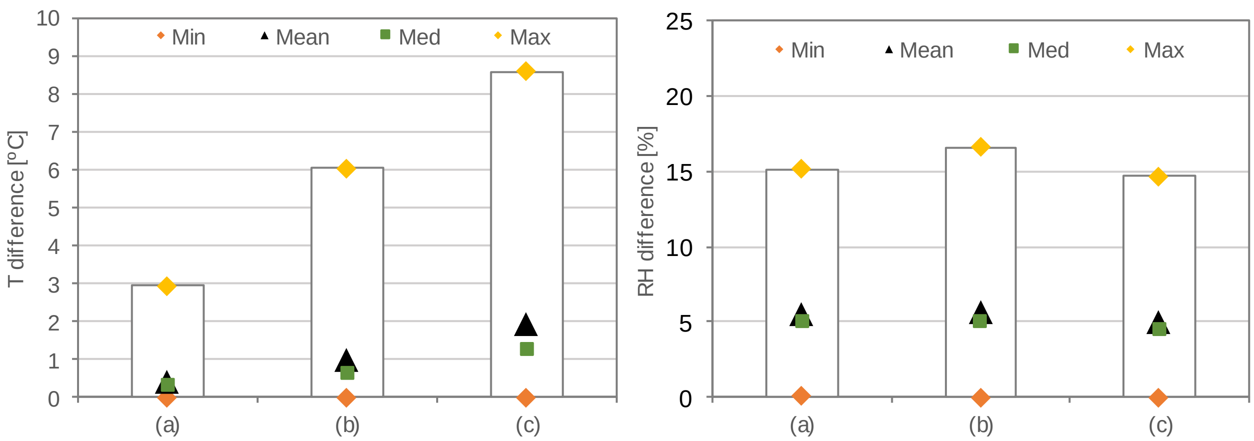


Figure 67 – Statistical analysis of T and RH differences after refurbishment for each heating strategy.

4.3. FINAL CONSIDERATIONS

This work presented a *Brandão* prototype model validation that replicates the *in-situ* conditions and allows the studying of the other Portuguese *Brandão* buildings.

There are some studies about model validation in Wufi Plus but it is important to validate each numerical model attending its specificity and the focus of the study (hygrothermal conditions, IAQ, energy).

The *Brandão* school model validation was performed considering the climatic data from WS LFC-FEUP and some microclimatic adjustments were made in order to represent the real conditions.

The main conclusions of this chapter are:

- The inputs characterization during the experimental work is very important and also a challenge once in schools it is very difficult to predict the real hourly attendance of classes, the unexpected schedule changes, the door and windows opening and the operation of the blinds.
- Before the refurbishment, in free-running conditions, the mean T differences between experimental and simulation results were lower in winter than in mid-season.
- After the refurbishment, from September to December, the prototype was under free-running conditions and the heating strategies started in January, in a weekly based calendar. The mean T difference from September 2017 to June 2018 was 0.84 ºC, with lower values in November and June and higher values in winter months, unlike the results before refurbishment.
- After the refurbishment, the higher gaps between measured and simulated T were verified during the heating weeks. In fact, Wufi considers a heating system uniformly distributed in the classroom and also an instantaneously heating strategy that does not answer the reality in the prototype and rejects the stratification phenomena that was verified by experimental monitoring. The analysis of the RH differences showed better results in winter whatever the heating strategy was and worse results in mid-season months. The CO_2 mean differences were low, considering the uncertainty of the occupation and of the windows opening strategy.
- The statistical indexes indicated a good correlation between T measurements and simulation results after refurbishment. The correlation was better when considering the whole period (excluding summer) (R^2 = 0.91) than when considering only the occupation period (R^2 = 0.80). It is also an expected result, once the real occupation is difficult to predict. Although the reasonable mean differences between measured and experimental results, CO_2 does not have a good correlation between the two series, with low R^2.
- Despite the limitations previously referred, the advanced hygrothermal model was strongly validated for T and the statistical analysis proved its strength. The model is prepared for the study of rehabilitation solutions for the other Portuguese *Brandão* schools, in different climatic conditions.

5
Sensitivity study of the refurbishment solutions

5.1. MAIN GOALS AND MOTIVATION

The validated numerical simulation model in Wufi Plus is the main tool for quantifying the hygrothermal and energy performance of the *Brandão* schools under different rehabilitation scenarios.

The sensitivity study starts with the existing conditions before the refurbishment and proceeds with the progressing improvement in each constructive element, technical systems and building particulars and the combination of each new feature. All the improvements must be low-cost, easy to implement, with low maintenance costs and in accordance with the Portuguese constructive habits.

The sensitivity study intends to assess:

- ❖ The importance of the envelope. The assessment of insulation benefits (considering each element: roof, walls and floor) and the possible consequences on the overheating during the cooling season.
- ❖ The importance of ventilation. The definition of the ventilation rate that ensures the required IAQ. This analysis must consider a confined traditional classroom instead of the open common circulation that had to be modified due to thermal comfort requirements.
- ❖ Heating strategies. The assessment of users' thermal comfort improvement when the classroom is strategically heated during defined periods.
- ❖ The importance of building orientation. The aim is to identify the critical solar orientations and choose suitable solar protection solutions.

- The importance of the climatic conditions. The assessment of the hygrothermal and energy performance of the *Brandão* schools in different Portuguese cities. The critical analysis of winter and summer conditions, taking into account the climatic diversity.

After the assessment of the Porto *Brandão* schools in free-running conditions and with intermittent and regular heating strategies (chapter 3), the strategy defined for the sensitivity study was:

- A *minimizing discomfort* approach, not considering free-running conditions but some intermittent heating strategies (3 h and 5 h heating per day). In this case, the comfort performance (T and RH), the IAQ performance and the EC (predictably low in this approach, respecting the present strategy in these schools with low EC) were the decision variables to be considered in the decision process.
- A *comfort* approach, considering a regular heating strategy (during the occupation period or 9 h heating per day), in which the most important decision variable was EC, once the comfort requirements were almost fulfilled during the occupation period. The quantification of EC and its costs enabled the comparison and selection of the best rehabilitation solutions, to ensure comfort conditions with a controlled and known increase in operating costs.

While in the first approach the main goal was to quantify the thermal performance (by the quantification of occupants' discomfort with low energy consumption strategies), in the second approach the main goal was to quantify the energy consumption for heating (considering an ensured users' comfort).

5.2. REFURBISHMENT SCENARIOS

The refurbishment scenarios were defined considering the sensitivity study main goals. Three main groups of variables were identified: constructive systems (roof, walls and floor insulation, windows and solar protections), technical systems (heating and ventilation strategy) and building features (climatic conditions and building orientation).

Table 42 presents the three groups of variables. All combinations were simulated for Porto city with TRY (1260 simulations). For the remain cities and also for Porto city (2012 IPMA climatic data), some constructive systems and ventilation strategies were excluded (1350 simulations, 270 simulations per city). Porto was also simulated with IPMA climatic data in order to compare and propose refurbishment solutions for different climatic locations regarding the same climatic year.

Table 42 – Groups of variables for sensitivity study.

L	Location
	Bragança
	Braga
	Porto
	Coimbra
	Lisboa

O	Orientation
N	North
S	South
W	West

R	Roof insulation Mineral Wool ALPHAROCK-E 225 (λ=0.034)
R0	0 cm (U_{roof} = 3.17 W/(m^2.ºC))
R5	5 cm (U_{roof} = 0.56 W/(m^2.ºC))
R7	7 cm (U_{roof} = 0.42 W/(m^2.ºC))
R10	10 cm (U_{roof} = 0.31 W/(m^2.ºC))

W	Wall insulation Mineral Wool ALPHAROCK-E 225 (λ=0.034)
W0	0 cm (U_{wall} = 3.03 W/(m^2.ºC))
W5	5 cm (U_{wall} = 0.53 W/(m^2.ºC))
W8	8 cm (U_{wall} = 0.36 W/(m^2.ºC))

F	Floor insulation XPS (λ=0.035)
F0	0 cm
F3	3 cm

W_SP (*)	Windows and solar protection
0_0	SG without SP
0_1	SG with SP
1_1	DG1 with SP
2_1	DG2 with SP

V1	Ventilation
V1	2.0 h^{-1} (260 m^3/h)
V2	3.0 h^{-1} (400 m^3/h)
V3	3.8 h^{-1} (500 m^3/h)

H	Heating 4 kW
H1	3 h
H2	5 h
H3	energy for comfort (9 h)

(*) Legend: SG – Single glazing U=5.8 W/(m^2.ºC) and g=0.85; DG1 – Double glazing U=3.3 W/(m^2.ºC) and g=0.75; DG2 – Double glazing U=2.8 W/(m^2.ºC) and g=0.42; SP – Solar protection

After the first sensitivity study with the TRY Porto climate, the ventilation was fixed in V3. For the other Portuguese cities, the roof and walls with higher thickness insulation solution (R10 and W8) were excluded and also the windows solution without solar protection (W0SP0).

The ground temperature was defined as a sinusoidal, with a maximum two months after the summer solstice (northern hemisphere). The ground temperature considered for each studied Portuguese city is presented in Table 43, considering the absence of more available information in bibliography.

Table 43 – Ground temperature for each studied Portuguese city.

	Porto	Bragança	Braga	Coimbra	Lisboa
T_{min}	14	8	13	14	14
T_{max}	20	20	20	20	20
T_{mean} / amplitude	17.0 / 3.0	14.0 / 6.0	16.5 / 3.5	17.0 / 3.0	17.0 / 3.0

The sensitivity analysis has considered a typical Portuguese academic year, from September to June. Some breaks were also considered (Christmas, Carnival and Easter). The winter and mid-season periods analysed in this sensitivity study are presented in Table 44.

The occupation period considered was a typical in-service schedule (complete mornings from Monday to Friday and three afternoons (Figure 68). The occupation was defined by 20 students and 1 teacher. The internal heat gains were previously defined during the model validation (15 W / m^2 for lighting). The heating strategies (H1, H2 and H3), presented in Table 42, started at 7h00 am from Monday to Friday, and considered only the occupation periods (except for lunch breaks). The exterior solar protections were completely close after 12 am and during all afternoon and night until the first class at 8 am, when the solar protections were opened.

Table 44 – Academic calendar – winter and mid-season.

Academic year	15^{th} of September – 15^{th} of June
Breaks	16^{th} of December – 2^{nd} of January 10^{th} of February – 14^{th} of February 24^{th} of March – 8^{th} of April
Winter period	1^{st} November – 30^{th} April
Mid-season period	15^{th} of September – 31^{st} of October 1^{st} May – 15^{th} June

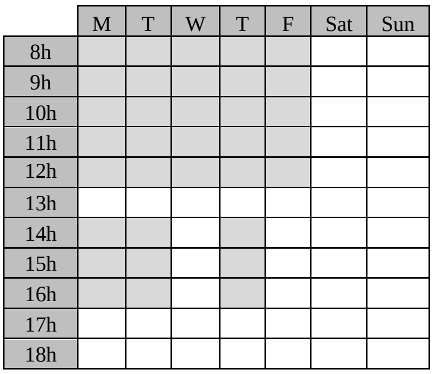


Figure 68 – Hourly schedule for the sensitivity analysis.

5.3. DISCUSSION OF RESULTS

5.3.1. ANALYSIS TOOLS

The main goal of this section is to present the increase or decrease in comfort conditions, IAQ and energy consumption related to each refurbishment scenario and heating and ventilation strategies. The results are presented by graphs that will support the final section (*Guidelines for Refurbishment*) and the selection of the optimized refurbishment solution for different climatic conditions. The hygrothermal performance and IAQ quantification must consider the occupation period.

In the *minimizing discomfort* approach, considering an intermittent heating strategy (3 h and 5 h heating per day) the comfort performance (T), the IAQ performance (CO_2) and the EC (predictably low in this approach) must be analysed by thermal discomfort indicators (DI_w, DI_s e $\%TD_b$) and its statistical parameters, by the accumulated frequency of CO_2 and by the annual sum of EC (kWh).

In the *comfort* approach, considering a regular heating strategy (during the occupation period or 9 h heating per day) the annual sum of EC must be quantified and also the thermal discomfort indicators (that must be low or inexistent, once the comfort requirements were almost fulfilled during the occupation period).

The characterization of each refurbishment scenario will allow a comparative study of the solutions. The best scenario in a *minimizing discomfort* approach can be different from the *comfort* approach.

Additionally, it was made a mid-season assessment of the refurbishment strategies by the adaptive comfort model of EN 15251 in different locations.

5.3.2. RESULTS FROM PORTO

The results here presented were obtained by simulation from Wufi Plus model with TRY-Porto climatic data [174]. In this section, the discussion is focused on the optimization of the envelope insulation thickness and window system in *Brandão* schools for different heating strategies (H1, H2 and H3) and building orientations.

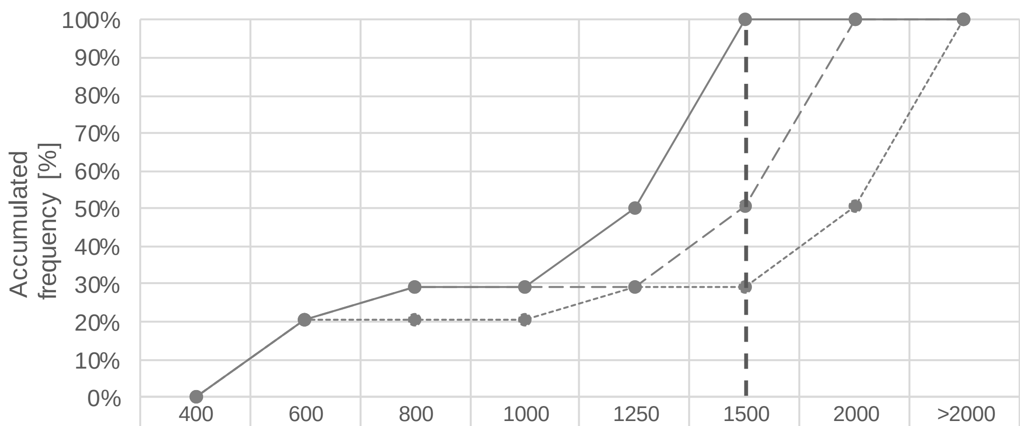
5.3.2.1. Ventilation strategy

The first important result from the simulation study is related to the ventilation rate.

As referred previously (chapters 3 and 4), in pre-existing conditions, there was a natural ventilation strategy and the opening of windows and doors was the only way to change the ventilation rate. Moreover, the classroom layout resulted in variable renovation air rates that were difficult to calculate and predict. The occupants had the opportunity to open or close windows whenever they wanted. By a calibration process, the ventilation rate considered before the refurbishment was 1 h^{-1} in classrooms and the infiltration was 0,5 h^{-1} during winter and mid-season/summer.

Once there was no partition wall in pre-existing conditions, it was expected an increase of CO_2 after the refurbishment. The Portuguese legislation defines for classrooms a minimum airflow of 24 m^3/(hour.person) [20] and the ventilation system in the prototype after refurbishment was prepared to 570/430 m^3/h (theoretical airflow). However, the real ventilation (after an adaptation period where the ventilation rate was 260 m^3/h) was 380 m^3/h, corresponding to 2.9 h^{-1}. Although the mean CO_2 after the refurbishment was below the reference value of 1500 ppm (a relaxed restriction in accordance with some international legislation, Table 1), there was indeed an increase of CO_2 inside the classroom, for the corresponding months before and after refurbishment.
During the experimental period, the ventilation system was operated by the school workers, starting in the morning and shutting down in the afternoon, from Monday to Friday. After the first year, the strategy has changed, and the ventilation was always on in order to reduce the unexpected faults on the manual starting and shutting down. The opening of the windows as a natural ventilation strategy persisted even after the installation of the ventilation system.

The simulation enables a controlled ventilation strategy, without failures or incidental changes in the ventilation operation. The three ventilation strategies studied after refurbishment (V1, V2 and V3) are the 260 m^3/h (V1), the 400 m^3/h (V2), which is an approximate value of the real ventilation rate in the prototype after refurbishment and 500 m^3/h (V3), that fulfils the requirement of 1500 ppm defined in this work. The accumulated frequency of CO_2 for the referred ventilation strategies is presented in Figure 69.



	400	600	800	1000	1250	1500	2000	>2000
V1	0%	21%	21%	21%	29%	29%	51%	100%
V2	0%	21%	29%	29%	29%	51%	100%	100%
V3	0%	21%	29%	29%	50%	100%	100%	100%

Figure 69 – Accumulated frequency of CO_2 from V1, V2 and V3 strategies.

Figure 69 results from Porto simulations in a west-sided *Brandão* school but the same conclusion can be obtained from other cities and building orientations since the CO_2 production is a result from the metabolism and depends mainly on the occupation.

From this first important conclusion, the remaining simulations were prepared for V3 strategy (500 m^3/h). Before the prototype refurbishment and when there was not a partition wall, the ventilation rate was variable and unpredictable, with higher values during class breaks and even when a student or a school worker enter or leave the classroom during classes. Regarding the in-service conditions, IAQ was an uncontrolled variable but not generally a problem before the refurbishment. After the refurbishment and the partition wall installation, the ventilation rate was quantified and the IAQ became a controlled variable. The sensitivity analysis confirmed the importance of increasing the ventilation rate to 500 m^3/h.

5.3.2.2. Energy consumption of each heating strategy

The winter energy consumption (EC) related to each refurbishment scenario is presented in Figure 70. It was quantified the EC from the 1st of November until the 30th of April, defined as the period when there are heating needs in Portuguese schools (winter analysis).

Some relevant conclusions about the global behaviour of Porto schools in winter (756 simulations), considering three heating strategies (3 h, 5 h and 9 h) are presented in Figure 70:

- ❖ There are three main groups of solutions. The solutions with lower EC are the ones with roof, walls and floor insulation, followed by the ones with roof and walls insulation, and finally the ones with only roof, only walls, only floor or walls and floor insulation with higher EC.
- ❖ The floor insulation always benefits the EC in winter.
- ❖ The south orientation promotes lower EC but the orientation importance is greater in higher heating strategies.
- ❖ For each heating strategy, the solution with absolute lower EC is R10-W8-F3 – W0SP0 for a south-sided classroom (roof: 10 cm, walls: 8 cm, floor: 3 cm, window: single-glazing without solar protection).
- ❖ Considering windows and solar protections, the solutions with lower EC are the ones with single glazing and without solar protection, due to solar gains. However, solar protection devices must be considered due to illumination reasons and to control solar gains during mid-season. The solutions with higher EC are the ones with single glazing with solar protection. When the window is replaced by a double-glazing system the EC decreases and when the g-value decreases there is a slight increase in EC.

- ❖ Globally, when the heating strategy is lower (3 h heating), the envelope solution is less important than when the heating strategy is higher (5 h and 9 h heating). This is a very relevant conclusion. It indicates that the investment in better envelope solutions (roof, walls, floor and solar protection) has little impact on EC when the adopted heating strategy is weak.

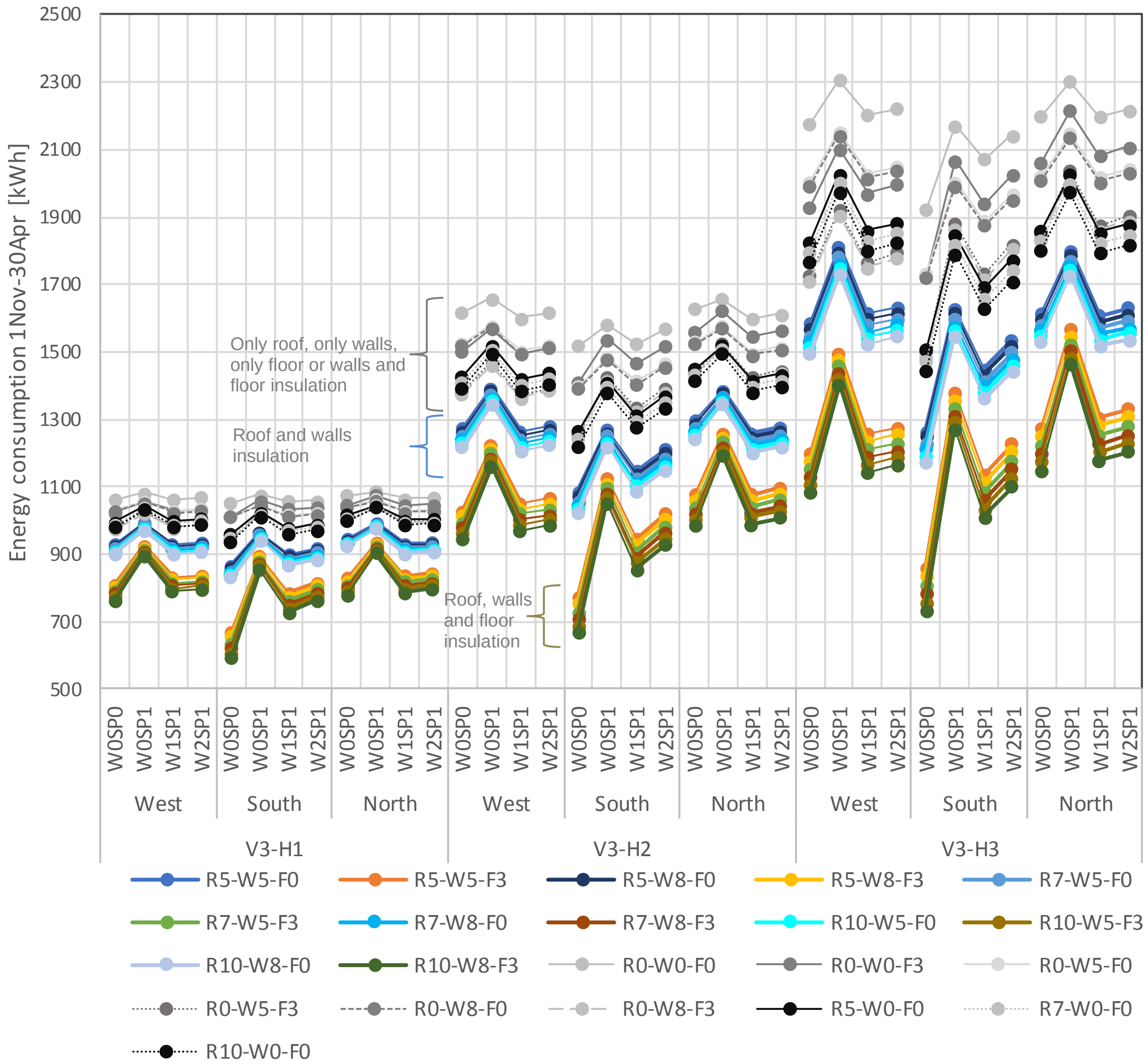


Figure 70 – EC related to each refurbishment scenario in Porto.

5.3.2.3. Global thermal discomfort assessment

5.3.2.3.1. Envelope analysis

The thermal discomfort assessment must be quantified by winter and mid-season discomfort indicators. In this section, the refurbishment solutions will be divided into three main groups: the *roof* insulation solutions, the *walls* and *floor* insulation solutions and finally the combined *roof*, *walls* and *floor* insulation solutions. An additional analysis of the window system and the *floor* insulation will be made, considering the chosen *roof* and *wall* solution. Regarding the previous Figure 70, the envelope analysis (roof, walls and floor insulation) considers the W1SP1 window solution. The solar protection has an important role in the illumination control and mid-season comfort and the double glazing improves an important reduction of energy consumption when compared to the single glazing, whatever is the chosen heating strategy.

5.3.2.3.2. Roof insulation

Figure 71 and Figure 72 present the DI_{20}, DI_{25}, $\%TD_{20}$ and $\%TD_{25}$ for each *roof* insulation solution in a *Brandão* building in Porto. It is possible to observe that the winter discomfort is much more important than the mid-season discomfort, which is a predictable result. On the one hand due to the temperate Porto climatic zone (V2, 20°C < Text,s ≤ 22°C) [74] and on the other hand due to the occupation calendar in schools (there is no occupation during the summer period but only during a mid-season period, here including spring and autumn period). Figure 72 also reveals that south orientation is the most advantageous in winter. The reduction of discomfort from R0 to R5, R7 and R10 of *roof* insulation is presented in Table 45.

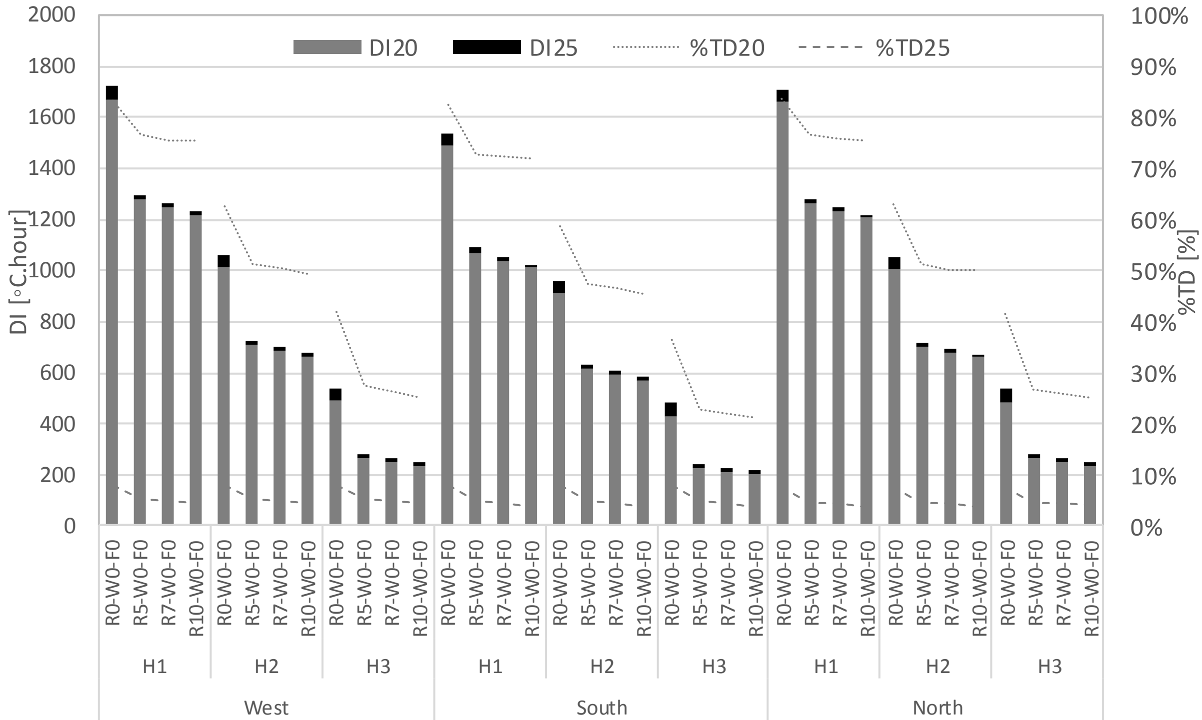


Figure 71 – DI_{20}, DI_{25}, $\%TD_{20}$ and $\%TD_{25}$ for each roof insulation solution, considering a W1SP1 system.

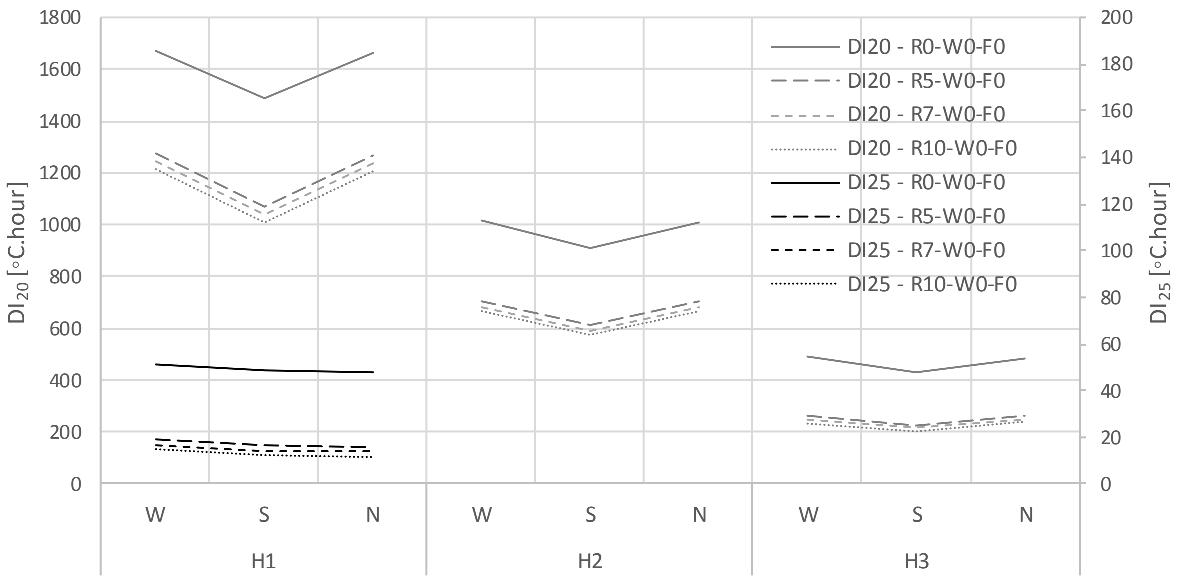


Figure 72 – DI_{20} and DI_{25} for each roof insulation solution, considering a W1SP1 system.

Table 45 – ΔDI_{20} and ΔDI_{25} achieved by each roof insulation solution.

			Δ DI_{20}	↓DI_{20} [%]	Δ DI_{25}	↓DI_{25} [%]
H1	West	Δ (R5-R0)	396	24%	32	64%
		Δ (R7-R0)	427	26%	35	68%
		Δ (R10-R0)	456	27%	37	72%
	South	Δ (R5-R0)	418	28%	32	67%
		Δ (R7-R0)	450	30%	35	71%
		Δ (R10-R0)	479	32%	36	74%
	North	Δ (R5-R0)	394	24%	32	67%
		Δ (R7-R0)	426	26%	34	72%
		Δ (R10-R0)	455	27%	36	75%
H2	West	Δ (R5-R0)	307	30%		
		Δ (R7-R0)	330	33%		
		Δ (R10-R0)	350	35%		
	South	Δ (R5-R0)	297	33%		
		Δ (R7-R0)	318	35%		
		Δ (R10-R0)	337	37%		
	North	Δ (R5-R0)	304	30%		
		Δ (R7-R0)	326	32%		
		Δ (R10-R0)	346	34%	(*1)	
H3	West	Δ (R5-R0)	228	47%		
		Δ (R7-R0)	242	49%		
		Δ (R10-R0)	254	52%		
	South	Δ (R5-R0)	205	48%		
		Δ (R7-R0)	217	50%		
		Δ (R10-R0)	228	53%		
	North	Δ (R5-R0)	224	46%		
		Δ (R7-R0)	238	49%		
		Δ (R10-R0)	251	52%		

(*1) The heating strategy does not have an influence on DI_{25}.

For the three orientations (west, south and north), the most important share of winter discomfort reduction is obtained from the first increment (Δ (R0-R5)). This conclusion was confirmed for 3 h, 5 h and 9 h heating. The higher the reduction in ºC.hour, the lower the heating strategy was but in percentage, the reduction was about 25% in H1, 30% in H2 and 45% in H3 heating strategy (for Δ

(R0-R5)). The percentage of discomfort reduction obtained from the same *roof* insulation solution is more relevant the higher the heating strategy is. The reduction of the winter discomfort (in percentage) is more relevant for south orientation than for the remaining orientations. Despite the important reduction of mid-season discomfort after the installation of *roof* insulation, the mid-season discomfort is not very relevant when compared with winter discomfort.

Regarding an EC analysis (winter), Figure 73 shows that the most important EC reduction was verified from the 0 cm solution (R0) to the 5 cm solution (R5), whatever the building orientation was. However, the additional investment in higher thicknesses of *roof* insulation did not have an important reduction on the EC.

Figure 74 shows the association between the winter thermal discomfort and the EC for the three main orientations. For H1 heating strategy, there was an important reduction of DI_{20} from R0 to R5 (400 ºC.hour in a west sided-school) but when the heating strategy increases, the DI_{20} reduction has a lower relevance (230 ºC.hour) and the reduction of EC increased (from 65 to 340 kWh). The higher the heating strategy was, the more relevant was the EC reduction (in kWh) associated with the *roof* insulation thickness increase. The investment in higher insulation thicknesses (R7 and R10) does not show a relevant reduction in DI_{20} or EC.

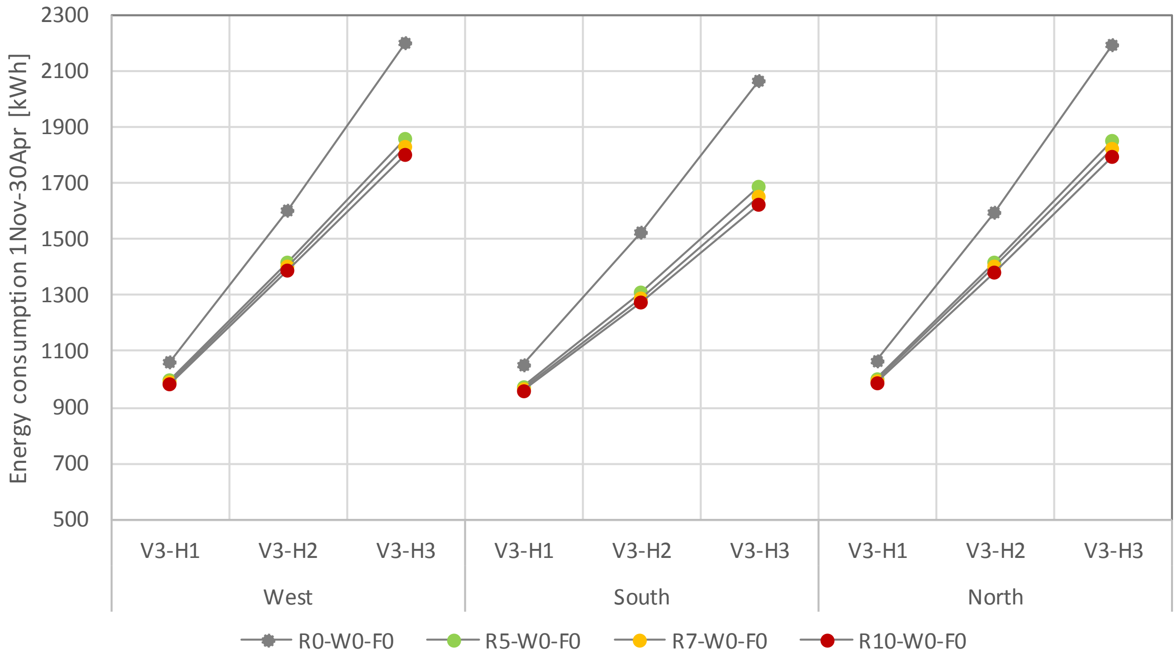


Figure 73 – Energy consumption in a Brandão school in Porto for different roof insulation solutions.

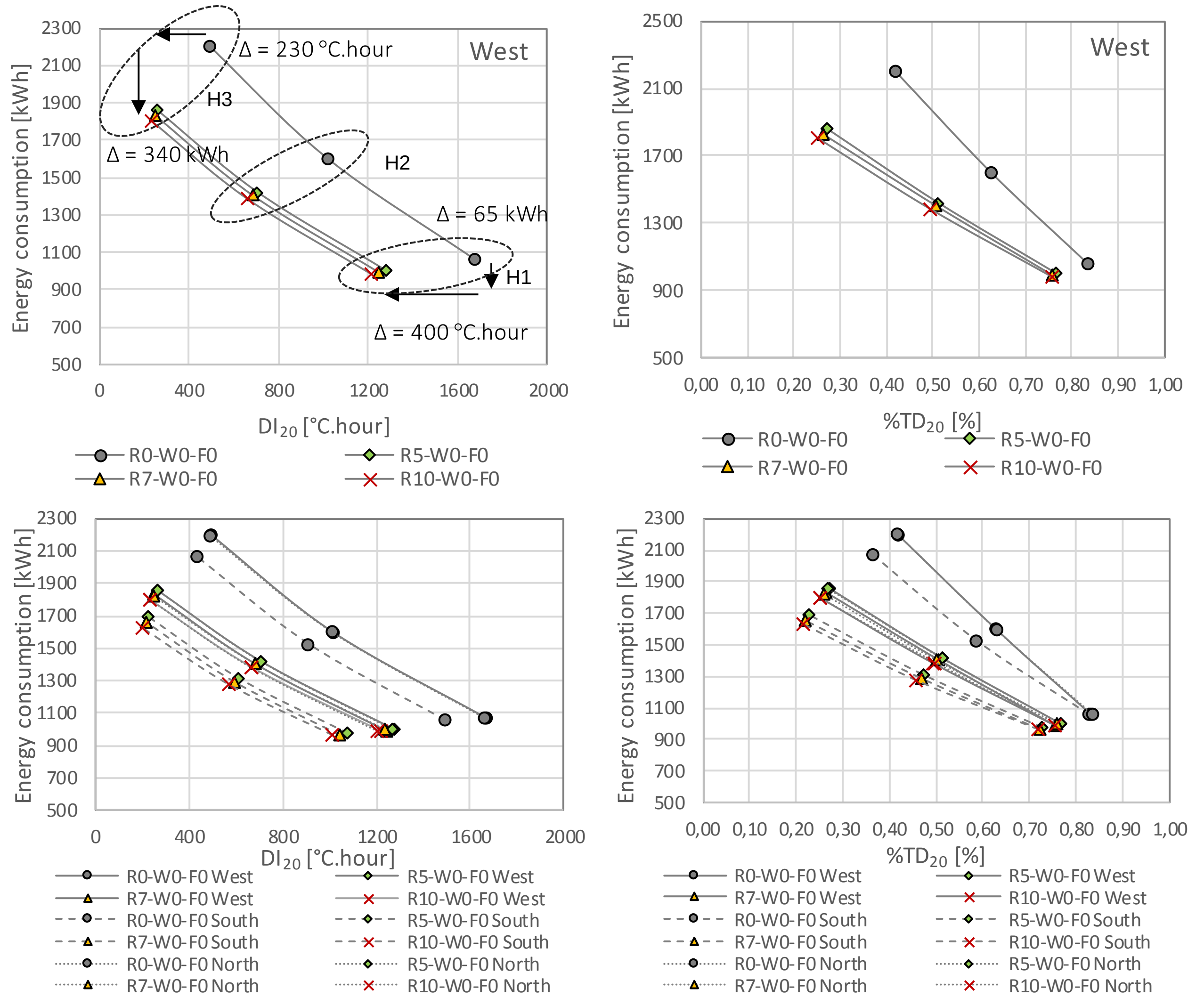


Figure 74 – Association between the winter thermal discomfort and energy consumption in a Brandão school in Porto for different roof insulation solutions.

In conclusion:

- ❖ The first increment in *roof* insulation thickness is quite relevant for the three heating strategies and for both considered approaches (*minimizing discomfort* and *comfort*), but neither the winter discomfort nor the EC had an important reduction resulting from the additional insulation thicknesses.
- ❖ The winter discomfort is much more important than the mid-season discomfort.

5.3.2.3.3. Walls and floor insulation

Figure 75 and Figure 76 present the DI_{20}, DI_{25}, $\%TD_{20}$ and $\%TD_{25}$ for each *wall* and *floor* insulation solution in a *Brandão* building in Porto. The winter discomfort is also much more important than mid-season discomfort, although the *floor* insulation has a bigger impact on mid-season discomfort than the *roof* or *wall* insulation. The impact of each *wall* (W5 and W8) and *floor* (F3) insulation thickness is presented in Table 46 and Table 47.

Considering *wall* insulation, the most important share of winter discomfort reduction is obtained from the first insulation thickness increment (Δ (W0-W5)). The percentage of winter discomfort reduction obtained from the same *wall* insulation solution is more relevant the greater the heating strategy is. There is a general slight decrease in mid-season comfort due to the *wall* insulation (without *roof* insulation), whatever the thickness of the solution is. Considering *floor* insulation, there is a very small reduction of the winter discomfort, with the exception of a small increase in H1 heating strategy for west and north orientations. There is an important increase (about 150%) in mid-season discomfort after the installation of *floor* insulation. However, the DI_{25} is still low when compared with DI_{20}.

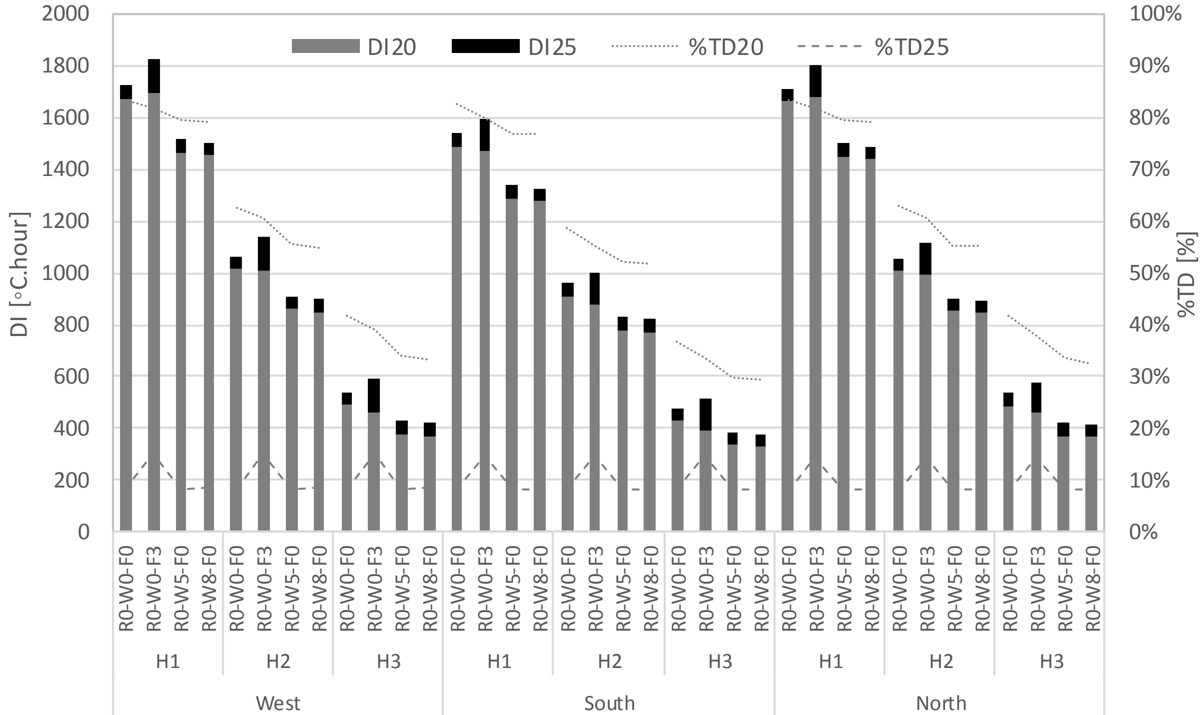


Figure 75 – DI_{20}, DI_{25}, $\%TD_{20}$ and $\%TD_{25}$ for each wall and floor insulation solution, considering a W1SP1 system.

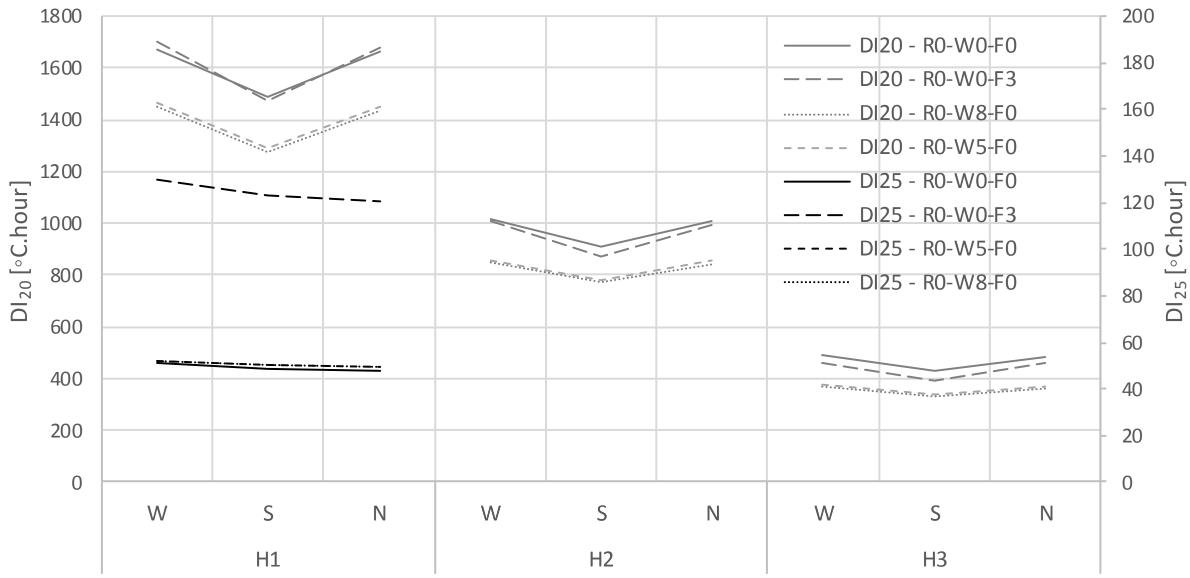


Figure 76 – DI_{20} and DI_{25} for each wall and floor insulation solution, considering a W1SP1 system.

Table 46 – ΔDI_{20} and ΔDI_{25} achieved by each wall insulation solution.

			Δ DI20	↓DI20 [%]	Δ DI25	↓DI25 [%]
H1	West	Δ(W5-W0)	206	12%	-1.1	-2%
	West	Δ(W8-W0)	220	13%	-0.8	-2%
	South	Δ(W5-W0)	200	13%	-1.4	-3%
	South	Δ(W8-W0)	213	14%	-1.2	-2%
	North	Δ(W5-W0)	209	13%	-1.8	-4%
	North	Δ(W8-W0)	224	13%	-1.6	-3%
H2	West	Δ(W5-W0)	155	15%	(*1)	
	West	Δ(W8-W0)	165	16%		
	South	Δ(W5-W0)	132	14%		
	South	Δ(W8-W0)	140	15%		
	North	Δ(W5-W0)	156	15%		
	North	Δ(W8-W0)	166	16%		
H3	West	Δ(W5-W0)	115	24%		
	West	Δ(W8-W0)	122	25%		
	South	Δ(W5-W0)	96	22%		
	South	Δ(W8-W0)	102	24%		
	North	Δ(W5-W0)	115	24%		
	North	Δ(W8-W0)	122	25%		

(*1) The heating strategy does not have an influence on DI_{25}.

Table 47 – ΔDI_{20} and ΔDI_{25} achieved by each floor insulation solution.

			Δ DI20	↓DI20 [%]	Δ DI25	↓DI25 [%]
H1	West	Δ(F3-F0)	-26	-2%	-78	-154%
	South	Δ(F3-F0)	18	1%	-75	-153%
	North	Δ(F3-F0)	-19	-1%	-73	-152%
H2	West	Δ(F3-F0)	6	1%	(*1)	
	South	Δ(F3-F0)	34	4%		
	North	Δ(F3-F0)	12	1%		
H3	West	Δ(F3-F0)	26	5%		
	South	Δ(F3-F0)	39	9%		
	North	Δ(F3-F0)	29	6%		

(*1) The heating strategy does not have an influence on DI_{25}.

Regarding an EC analysis (winter), Figure 77 shows that the most important EC reduction was verified for the first investment in insulation (*wall* or *floor*). As happened for *roof* insulation, the additional investment in strong *wall* insulation solutions did not have an important reduction in the EC.

Figure 78 presents the association between the winter thermal discomfort and the EC for the three main orientations. For H1 heating strategy, there was not a reduction of DI_{20} (in ºC.hour) from F0 to F3 but there was a reduction of EC when the heating strategy increases. For *wall* insulation solutions the behaviour was similar to the *roof* insulation. For H1 heating strategy, there was an important reduction of DI_{20} from W0 to W5 but when the heating strategy increases, the DI_{20} reduction has a lower relevance (in ºC.hour) and the reduction of EC increased. The higher the heating strategy was, the more relevant the EC reduction associated with the *wall* insulation increasing was. The investment in greater insulation solutions (W8) does not traduce a relevant reduction in DI_{20} or EC.

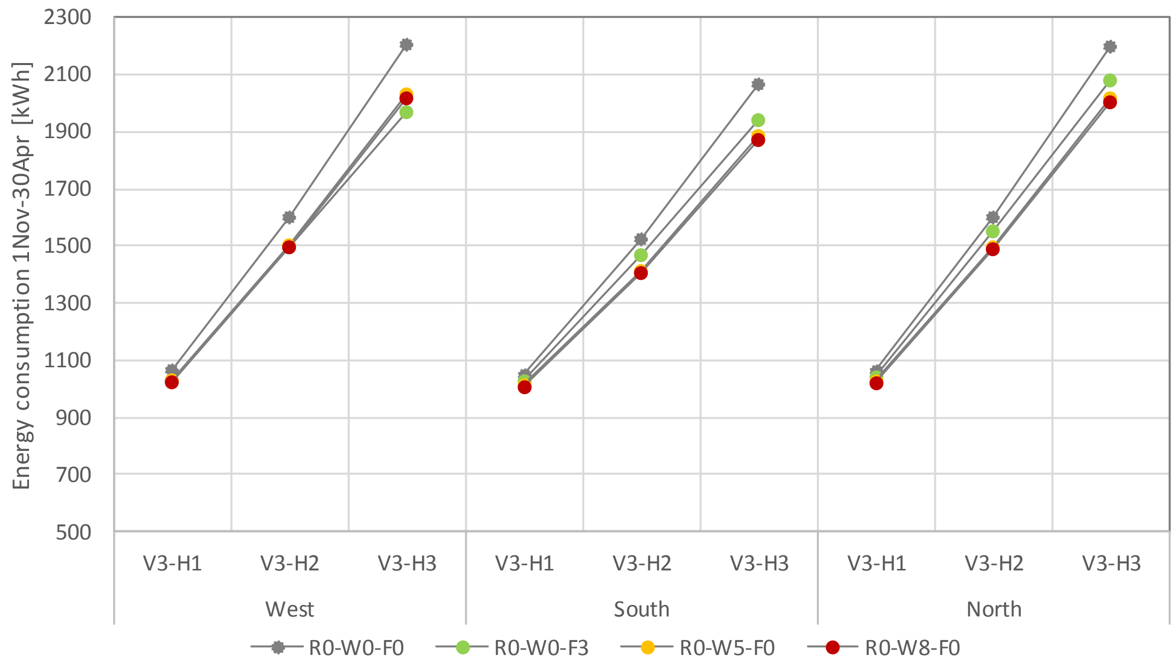


Figure 77 – Energy consumption in a Brandão school in Porto for different wall and floor insulation solutions.

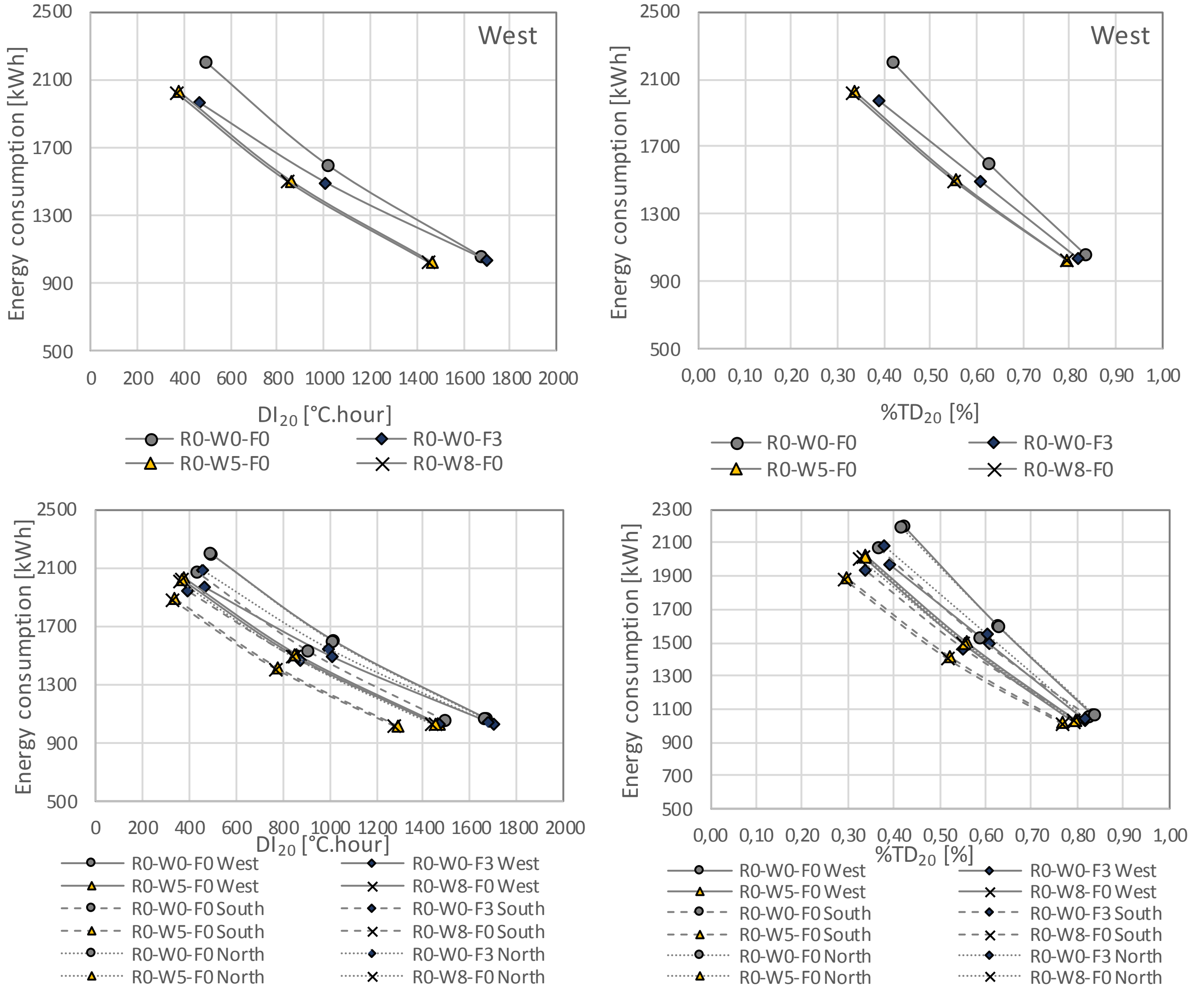


Figure 78 – Association between the winter thermal discomfort and energy consumption in a Brandão school in Porto for different wall and roof insulation solutions.

In conclusion:

- The first increment in *wall* insulation thickness is relevant for the three heating strategies and for both considered approaches (*minimizing discomfort* and *comfort*), but the additional insulation thicknesses do not represent an important reduction of winter discomfort nor EC.
- Although the winter discomfort is much more important than the mid-season discomfort, there is a general slight decrease in mid-season comfort due to the *wall* insulation system (without an associated *roof* insulation).
- The *floor* insulation, when assessed as a separate intervention, promotes a general small reduction (or even a small increase) on the winter discomfort. It also increases the mid-season discomfort, although the absolute value of DI_{25} is still low when compared with DI_{20}.

5.3.2.3.4. Combined roof, walls and floor insulation

Figure 79 and Figure 80 present the DI_{20}, DI_{25}, $\%TD_{20}$ and $\%TD_{25}$ for each combined *roof*, *wall* and *floor* insulation solution in a *Brandão* building in Porto. The winter discomfort is also much more important than mid-season discomfort. The impact of the additional *roof* (R5), *wall* (W5) and *floor* (F3) insulation is presented in Table 48.

The percentage of winter discomfort reduction obtained from the same combined *roof*, *wall* and *floor* insulation solution is more relevant the higher the heating strategy is. The insulation of *walls* and *floor* without *roof* insulation is not a good solution, once it represents the lower decrease in winter discomfort and the higher increase in mid-summer discomfort. A complete insulation of the envelope (*roof*, *walls* and *floor*) reduces the winter discomfort. However, the investment in *floor* insulation must be carefully analysed in winter and mid-season conditions, considering an additional adaptive model application.

There is a general decrease in mid-season comfort due to the *floor* insulation system, whatever are the remaining combined *roof* and *wall* solutions. However, the absolute value of DI_{25} is still low when compared with DI_{20}.

Regarding an EC analysis (winter), Figure 81 shows that the most important EC reduction was verified for the higher investment in insulation (*roof*, *wall* and *floor* – R5-W5-F3), followed by the *roof* and *wall* insulation (R5-W5-F0) and the *wall* and *floor* insulation (R0-W5-F3). The same conclusion was verified from the three studied orientations.

Figure 82 presents the association between the winter thermal discomfort and the EC for the three main orientations. For H1 heating strategy, there was an important reduction of DI_{20} for each additional insulation solution but when the heating strategy increased, the DI_{20} reduction had a lower relevance (in ºC.hour) and the reduction of EC increased. The higher was the heating strategy, the more relevant was the EC reduction. West and north orientation have similar behaviour, but south orientation has a better global behaviour considering the association between DI_{20} and EC.

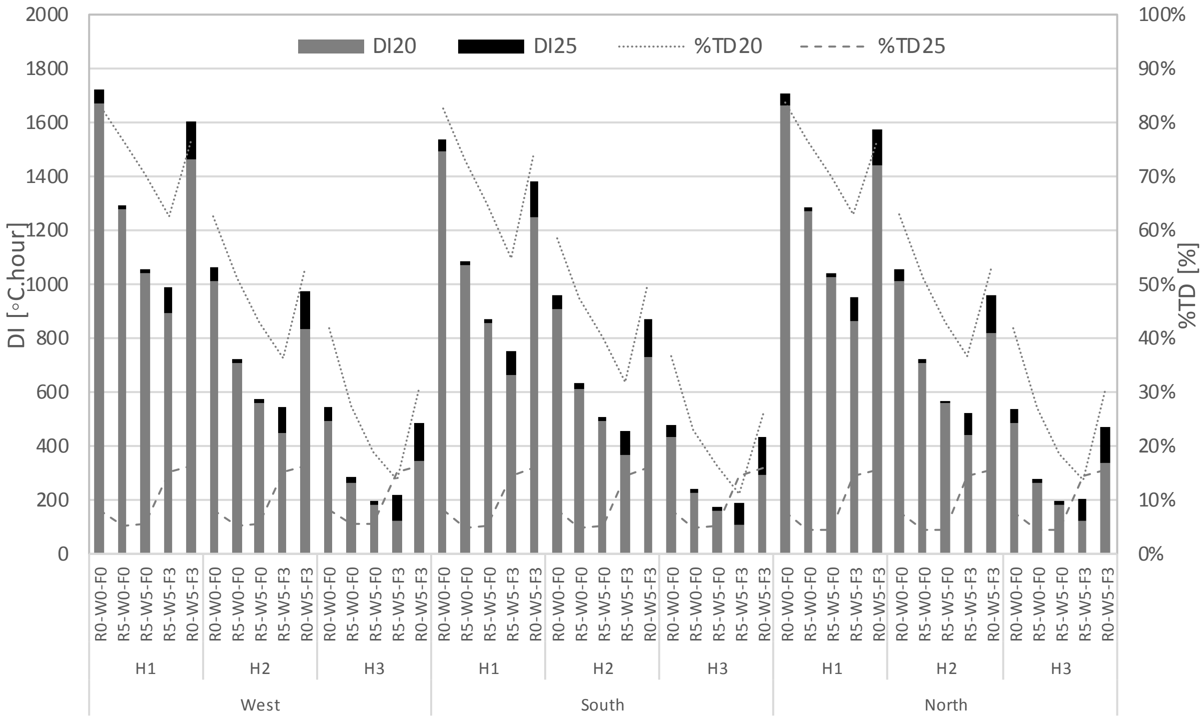


Figure 79 – DI_{20}, DI_{25}, $\%TD_{20}$ and $\%TD_{25}$ for each combined roof, wall and floor insulation solution, considering a W1SP1 system.

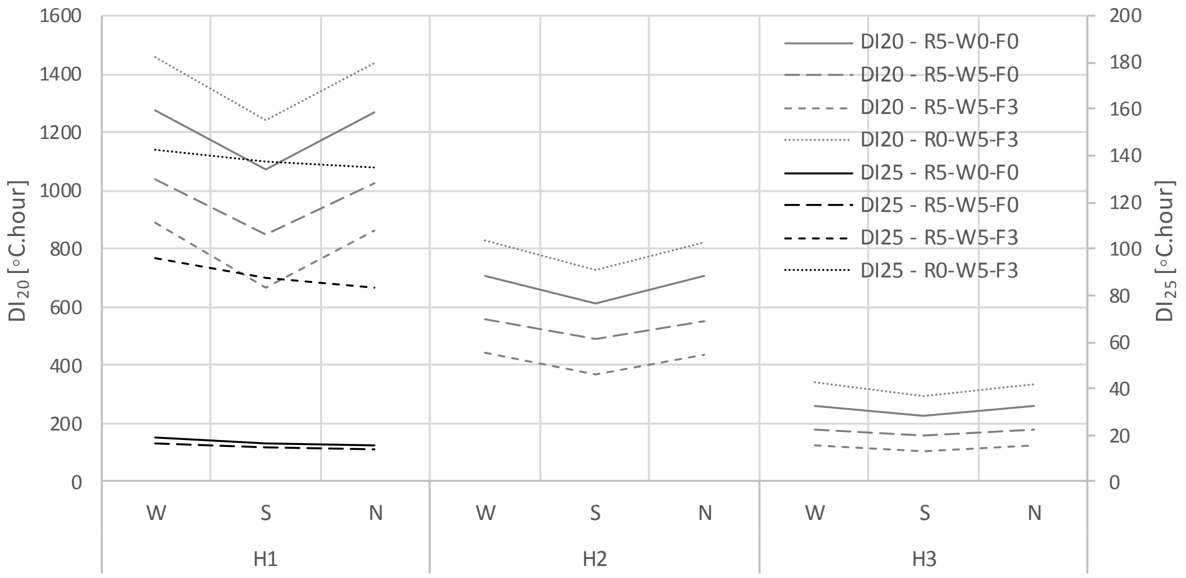


Figure 80 – DI_{20} and DI_{25} for each combined roof, wall and floor insulation solution, considering a W1SP1 system.

Table 48 – ΔDI₂₀ and ΔDI₂₅ achieved by the additional roof, wall and floor insulation solution.

			Δ DI20	↓DI20 [%]	Δ DI25	↓DI25 [%]
H1	West	Δ(R5-R0)	396	24%	32	64%
		Δ((R5-W5) - (R0-W0))	633	38%	34	67%
		Δ((R5-W5-F3) - (R0-W0-F0))	781	47%	-45	-88%
		Δ((W5-F3) - (W0-F0))	211	13%	-92	-180%
	South	Δ(R5-R0)	418	28%	32	67%
		Δ((R5-W5) - (R0-W0))	638	43%	34	70%
		Δ((R5-W5-F3) - (R0-W0-F0))	825	55%	-38	-79%
		Δ((W5-F3) - (W0-F0))	245	16%	-89	-182%
	North	Δ(R5-R0)	394	24%	32	67%
		Δ((R5-W5) - (R0-W0))	637	38%	33	70%
		Δ((R5-W5-F3) - (R0-W0-F0))	797	48%	-36	-75%
		Δ((W5-F3) - (W0-F0))	223	13%	-87	-183%
H2	West	Δ(R5-R0)	307	30%	(*1)	
		Δ((R5-W5) - (R0-W0))	456	45%		
		Δ((R5-W5-F3) - (R0-W0-F0))	568	56%		
		Δ((W5-F3) - (W0-F0))	182	18%		
	South	Δ(R5-R0)	297	33%		
		Δ((R5-W5) - (R0-W0))	420	46%		
		Δ((R5-W5-F3) - (R0-W0-F0))	541	60%		
		Δ((W5-F3) - (W0-F0))	181	20%		
	North	Δ(R5-R0)	304	30%		
		Δ((R5-W5) - (R0-W0))	454	45%		
		Δ((R5-W5-F3) - (R0-W0-F0))	572	57%		
		Δ((W5-F3) - (W0-F0))	187	19%		
H3	West	Δ(R5-R0)	228	47%		
		Δ((R5-W5) - (R0-W0))	311	63%		
		Δ((R5-W5-F3) - (R0-W0-F0))	366	75%		
		Δ((W5-F3) - (W0-F0))	150	31%		
	South	Δ(R5-R0)	205	48%		
		Δ((R5-W5) - (R0-W0))	273	63%		
		Δ((R5-W5-F3) - (R0-W0-F0))	327	76%		
		Δ((W5-F3) - (W0-F0))	140	33%		
	North	Δ(R5-R0)	224	46%		
		Δ((R5-W5) - (R0-W0))	308	63%		
		Δ((R5-W5-F3) - (R0-W0-F0))	365	75%		
		Δ((W5-F3) - (W0-F0))	151	31%		

(*1) The heating strategy does not have an influence on DI_{25}.

In conclusion:

- ❖ A complete insulation of the envelope (*roof*, *walls* and *floor*) has an important role in the reduction of winter discomfort.
- ❖ There is a general decrease in mid-season comfort due to the *floor* insulation system, whatever is the remaining combined *roof* and *wall* solution, although the absolute value of DI_{25} is still low when compared with DI_{20}. The investment in *floor* insulation must be carefully analysed in mid-season conditions (with an additional application of the adaptive model).

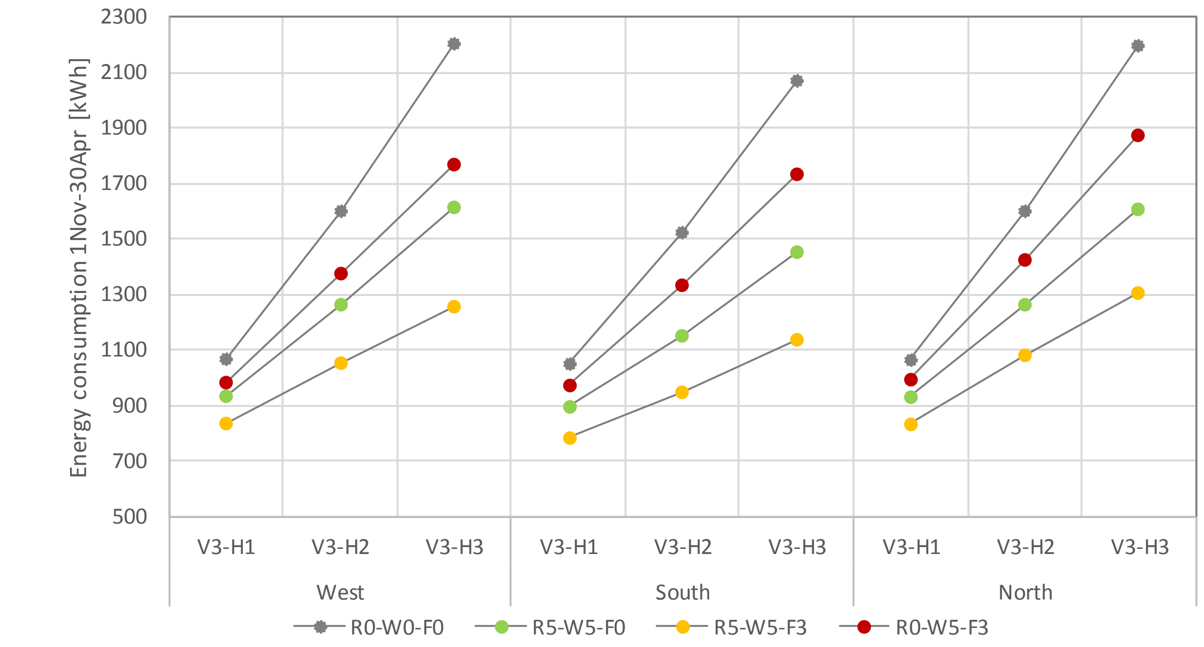


Figure 81 – Energy consumption in a Brandão school in Porto for the different combined roof, wall and floor insulation solutions.

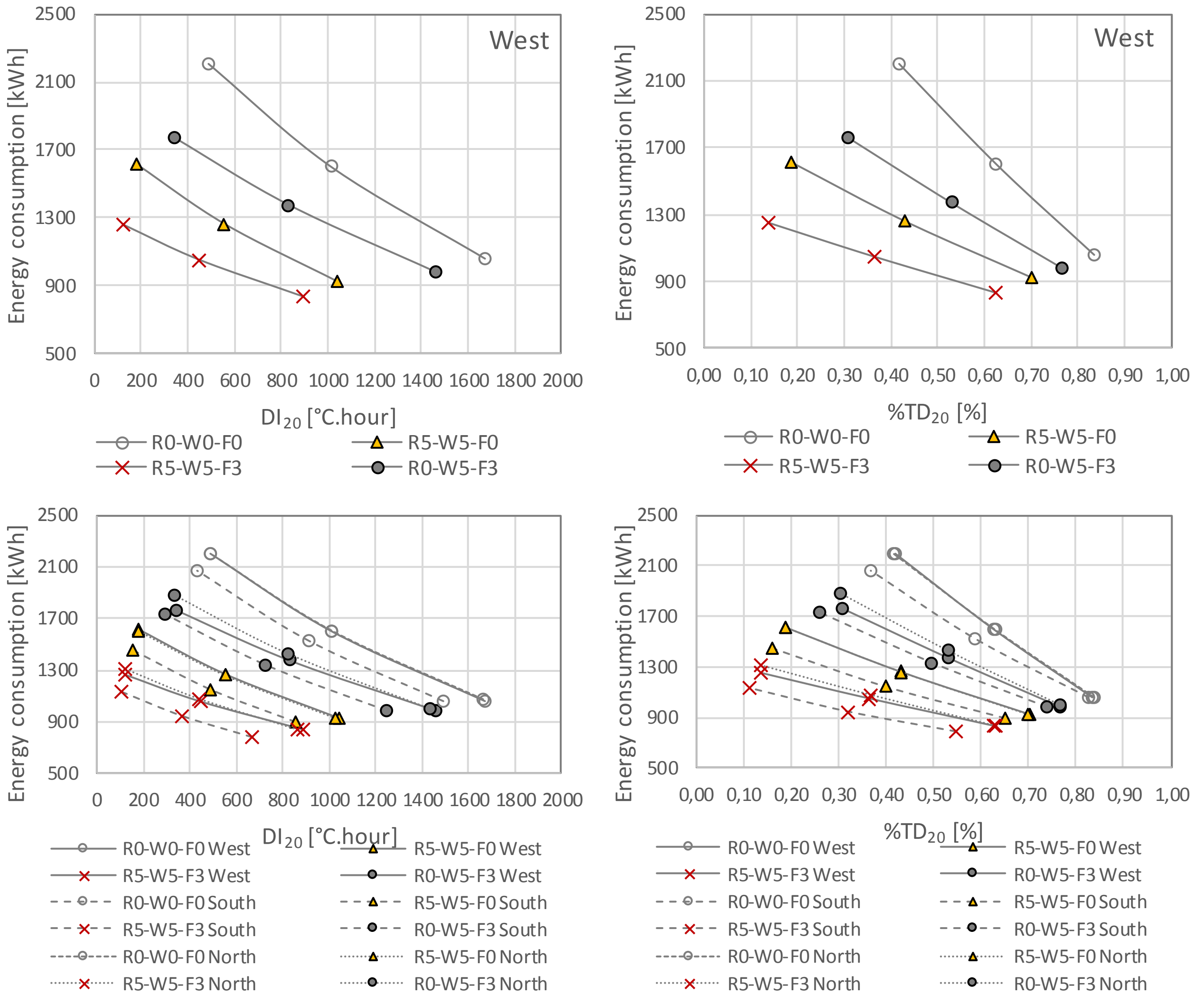


Figure 82 – Association between the winter thermal discomfort and energy consumption in a Brandão school in Porto for the different combined roof, wall and floor insulation solutions.

5.3.2.3.5. Windows and solar protection

Regarding the previous Figure 70, the analysis of the envelope insulation considered the W1SP1 window solution. The solar protection has an important role in the illumination control and mid-season comfort and the double glazing improves an important reduction of energy consumption when compared with the single glazing, whatever is the chosen heating strategy.

Figure 83, Figure 84 and Figure 85 present the winter EC of each window and solar protection solution (W0SP0, W0SP1, W1SP1 and W2SP1) for the three heating strategies (H1, H2 and H3) and for the three orientations, respectively west, south and north. Each line represents, for the same heating strategy, window and solar protection solution, different *roof* insulation thicknesses (R0, R5, R7 and R10).

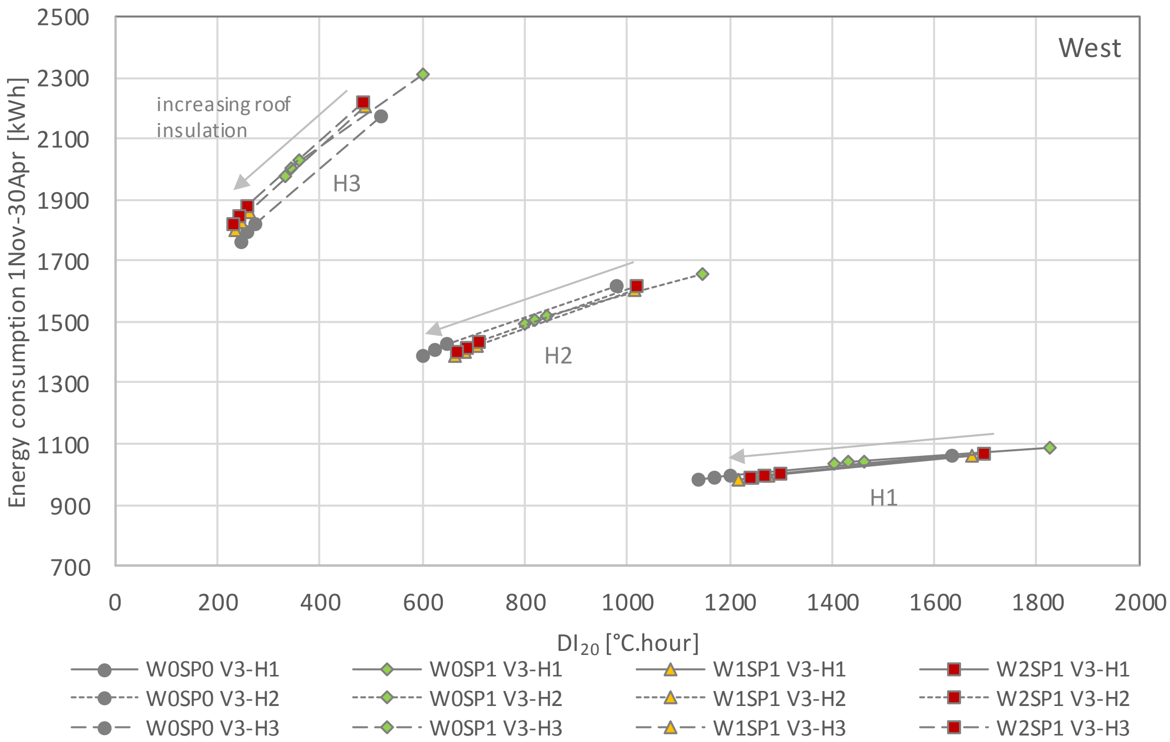


Figure 83 – Association between the winter thermal discomfort and energy consumption in a Brandão school in Porto for different window and solar protection and roof insulation solutions – west-sided building.

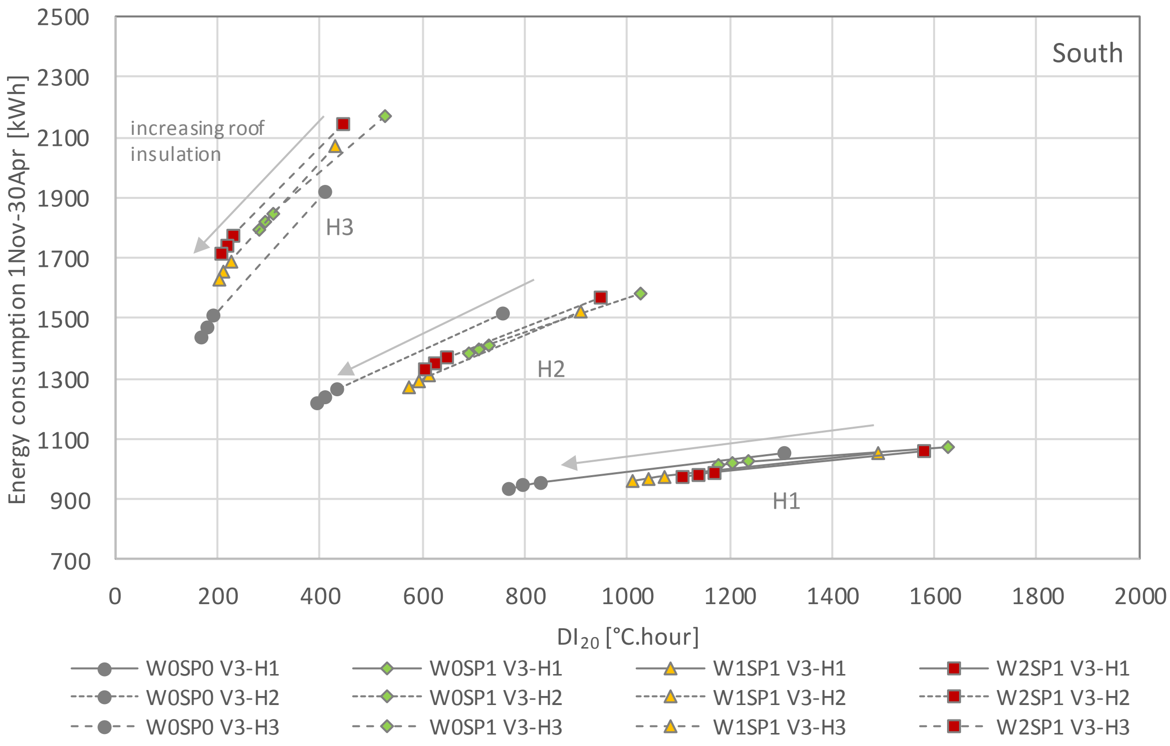


Figure 84 – Association between the winter thermal discomfort and energy consumption in a Brandão school in Porto for different window and solar protection and roof insulation solutions – south-sided building.

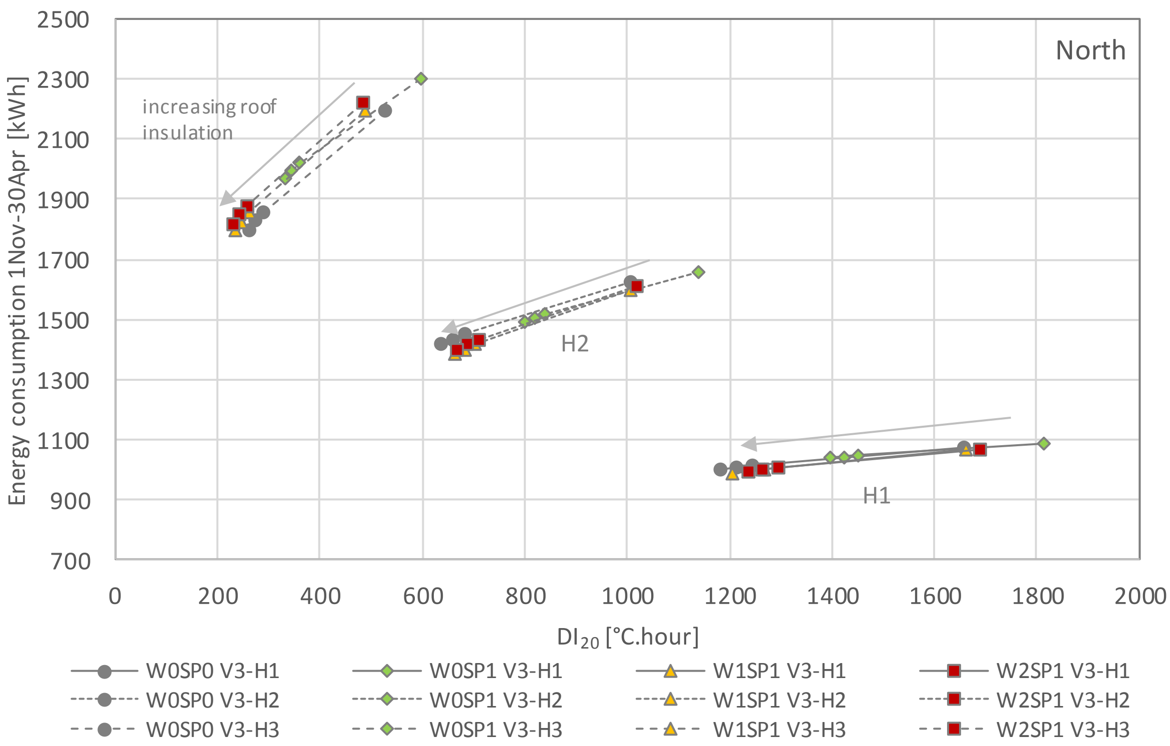


Figure 85 – Association between the winter thermal discomfort and energy consumption in a Brandão school in Porto for different window and solar protection and roof insulation solutions – north-sided building.

The main conclusions are:

- Considering the *roof* insulation, the first investment is the most important (from R0 to R5) and the additional investment does not traduce an important reduction of DI_{20} in lower heating strategies nor an important reduction in EC in higher heating strategies.
- In south orientation, the W0SP0 has a better thermal and energetic behaviour but for practical reasons (illumination) and mid-season comfort, this solution must be excluded.
- The W0SP1 solution presents the lower thermal performance and the higher EC, when compared with all the remain window and solar protection solutions.
- W1SP1 and W2SP1 have very similar behaviour in west and north orientations (Figure 83 and Figure 85, respectively).
- In south orientation, the global thermal discomfort reduction (for lower heating strategies) and the EC reduction (for higher heating strategies) due to roof insulation are generally greater than for the remaining orientations (west and north).

5.3.2.3.6. Floor insulation

This sub-chapter analyses two *floor* insulation solutions defined for Porto, F0 and F3, considering a chosen envelope (R5-W5-W1SP1), the V3 (500 m^3/h) ventilation strategy and regarding the global thermal discomfort (winter and mid-season). These two solutions were studied for the three main orientations and for the three defined heating strategies (H1, H2 and H3).

The statistical analysis was prepared with a sample of 80 results from Porto (TRY climate) (R0, R5, R7 and R10, W0, W5 and W8, F0 and F3, W0SP0, W0SP1, W1SP1 and W2SP1) per orientation and per heating strategy (Figure 86, Figure 87 and Figure 88).

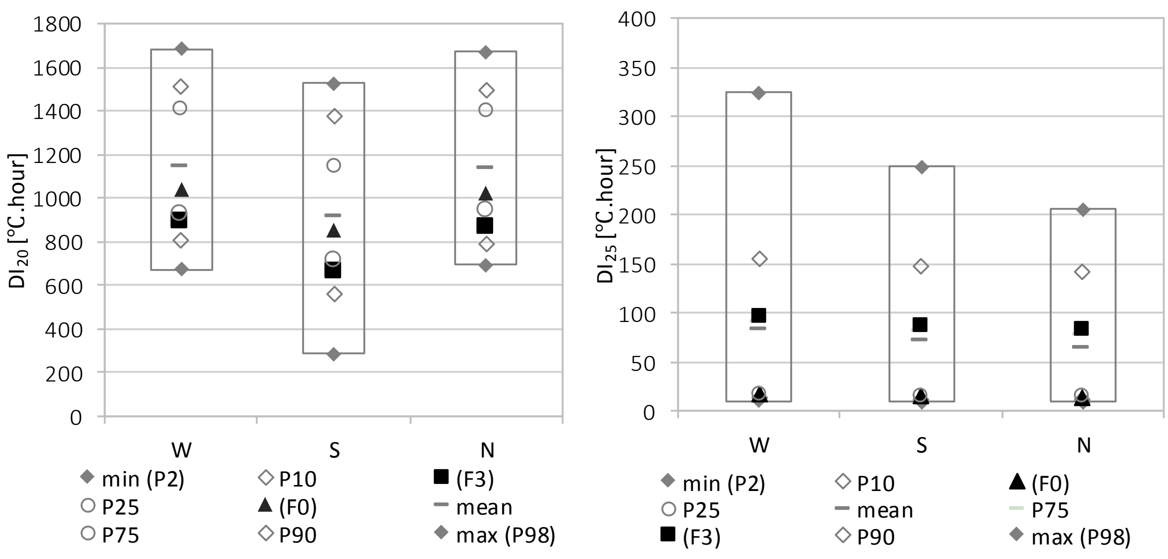


Figure 86 – Statistical analysis of H1 Porto discomfort (winter and mid-season), considering all the results and the two floor solutions.

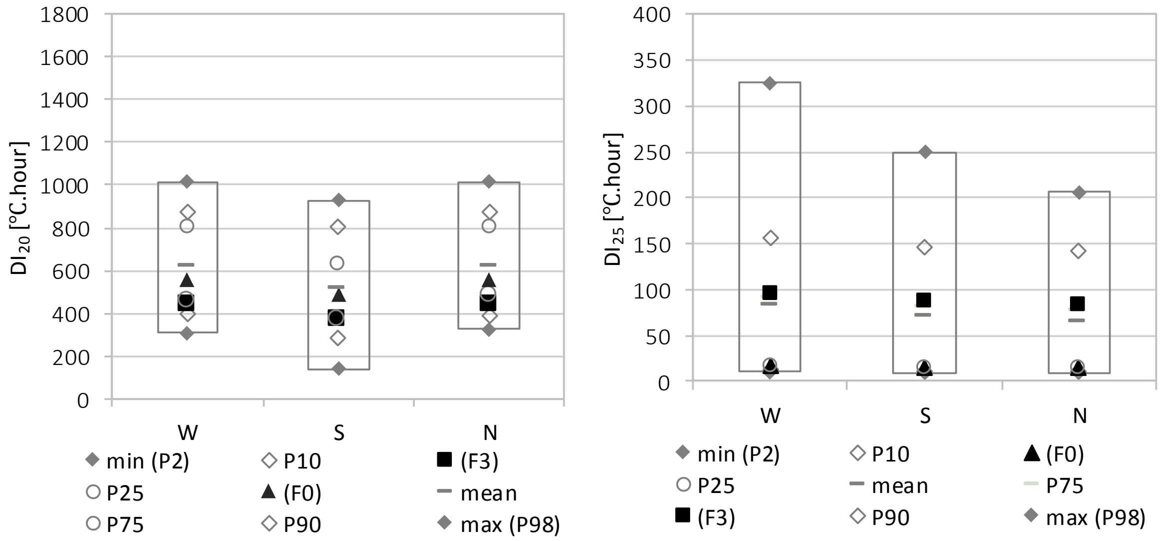


Figure 87 – Statistical analysis of H2 Porto discomfort (winter and mid-season), considering all the results and the two floor solutions.

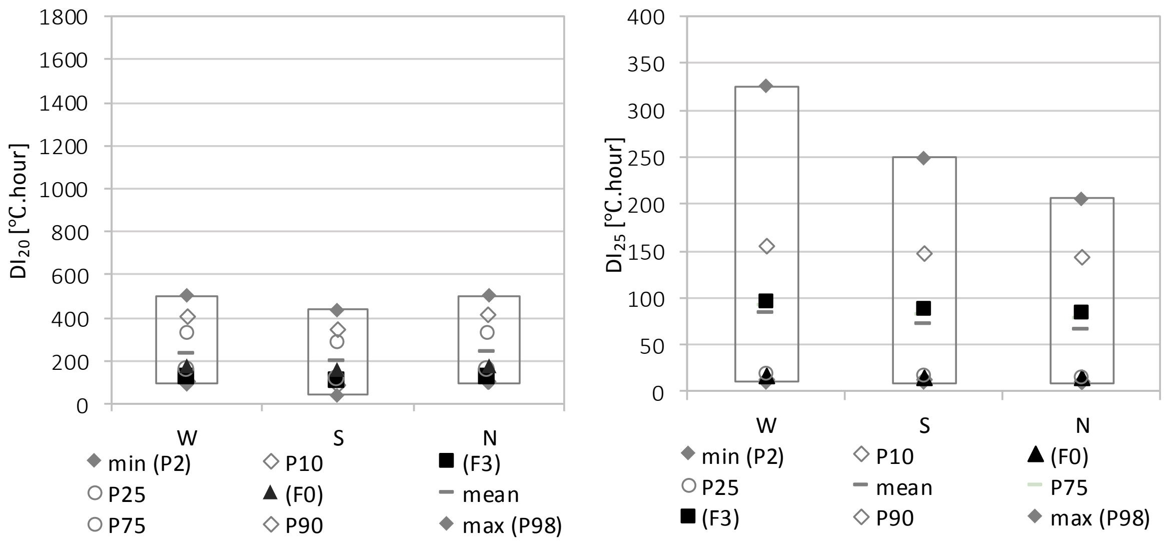


Figure 88 – Statistical analysis of H3 Porto discomfort (winter and mid-season), considering all the results and the two floor solutions.

Considering Figure 86, both *floor* solutions are below the average results during winter but, during mid-season, F3 solution is above the mean value and F0 is almost coincident with Percentile 25 and Percentile 2, suggesting its lower value. The same conclusion can be drawn from Figure 87 and Figure 88 (H2 and H3 heating strategies), although the DI_{20} reveals a lower difference between the two solutions when considering higher heating strategies, once the discomfort (in ºC.hour) is globally lower.

In fact, the following main conclusions can be referred:

- The *floor* insulation (together with *roof* and *walls* insulation) decreases winter discomfort but increases mid-season discomfort.

- The two analysed solutions have better winter performance than the average solution.
- The *floor* insulation decreases the mid-season performance but the DI_{25} values are lower than DI_{20} values when considering H1 and H2 heating strategies. However, considering a higher heating strategy with lower winter discomfort (H3), the mid-season discomfort becomes more important.

5.3.2.3.7. EN 15251 application during mid-season

During the mid-season period, there are no cooling systems and the application of an adaptive model must be done in order to confirm the non-importance of mid-season discomfort in these schools. The reference of *mid-season* instead of *summer* is due to the school calendar. In fact, in schools, there is no occupation during summer (classes start about the 15th of September and end about the 15th of June). An application of EN 15251 is presented in Figure 89, for a chosen envelope solution and two *floor* insulation solutions (R5-W5-F0-W1SP1 and R5-W5-F3-W1SP1). The difference between these two solutions is the *floor* insulation, which has a major relevance during summer.

The Porto TRY climatic data was used as an input in Wufi Plus simulation and for the calculation of θ_{rm} (outdoor running mean temperature from EN 15251). It was considered that the differences between mean radiant temperature and indoor air temperature were low and, for that reason, the indoor air temperature was used as operative temperature (θ_0). This was concluded by Jerónimo [190] for *roof* and *floor* insulated buildings.

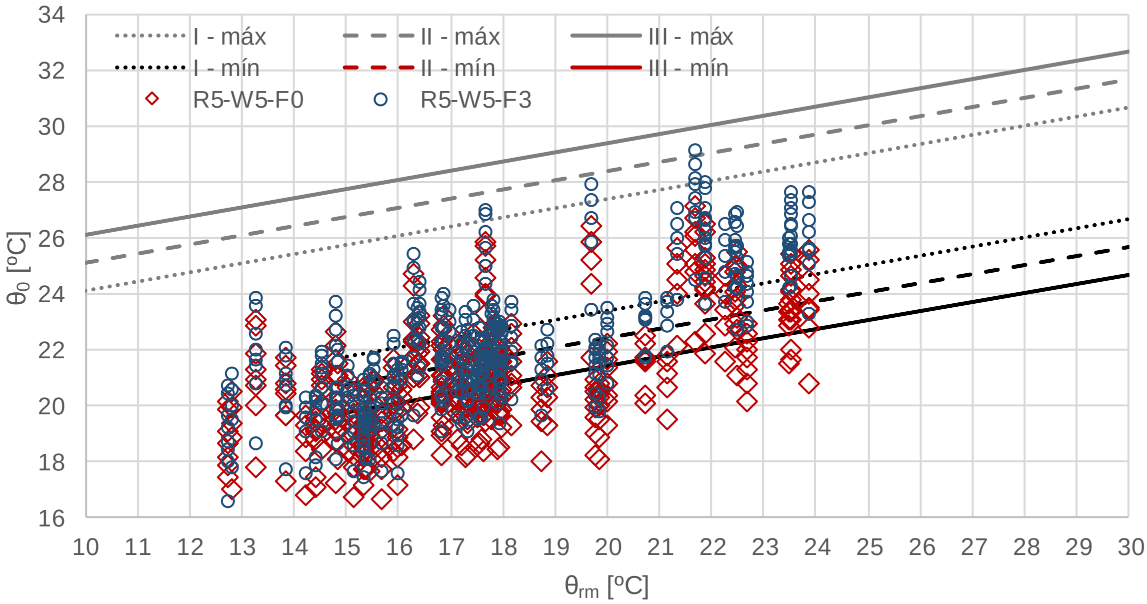


Figure 89 – EN 15251 application during mid-season in Porto (west-sided building and V3 ventilation strategy).

Observing Figure 89 and regarding the EN 15251 application, it can be concluded:

- Only 21% of the occurrences during the considered mid-season period were associated to θ_{rm} above 20 ºC. In fact, there is not a relevant summer period with occupation in these schools.
- During the mid-season period, there is not any occurrence of the first solution above EN 15251 limits and the second solution has only 1.5% of the occurrences above category I, 0.2% of the occurrences above category II and no occurrence above category III. This means that even the second solution (with *floor* insulation) has a reasonable mid-season behaviour without a cooling system and considering an adaptive model.
- The DI_{25} analysis is more demanding than the adaptive EN 15251 model for mid-season conditions.

5.3.3. Results from Portuguese cities

The results here presented were obtained by simulation from Wufi Plus model with IPMA climatic data (Portuguese Institute for Sea and Atmosphere). In this chapter, the optimization of the envelope insulation thickness and window systems for different heating strategies (H1,H2 and H3) is discussed for five Portuguese cities with distinct climatic conditions.

5.3.3.1. Global thermal discomfort assessment

5.3.3.1.1. Envelope analysis

The thermal discomfort assessment is quantified by winter and mid-season discomfort indicators. In this section, the refurbishment solutions will be also divided into three main groups: the *roof* insulation solutions, the *walls* and *floor* insulation solutions and finally the combined *roof*, *walls* and *floor* insulation solutions. The envelope analysis (*roof*, *walls* and *floor*) considers the W1SP1 window and solar protection solution. A west-sided *Brandão* building was considered, except for the window and solar protection analysis, for which the three main orientations (west, south and north) were considered.

5.3.3.1.2. Roof insulation

The insulation thicknesses (R0, R5 and R7) are compared considering the pre-existing envelope scenario (without walls insulation - W0 and without floor insulation - F0) and for W1SP1 window solution (double glazing with exterior solar protection).

Figure 90 presents the discomfort indicators (DI_{20} and $\%TD_{20}$) and Figure 91 presents the EC for a west-sided *Brandão* school.

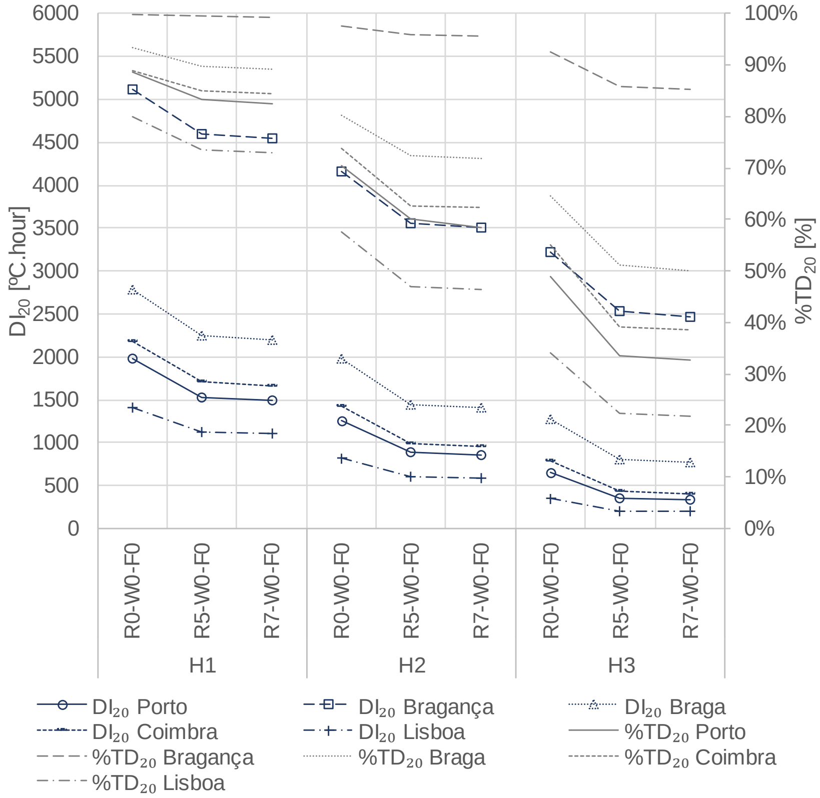


Figure 90 – Discomfort indicators (DI_{20} and %TD) for a west-sided Brandão school for different climatic locations.

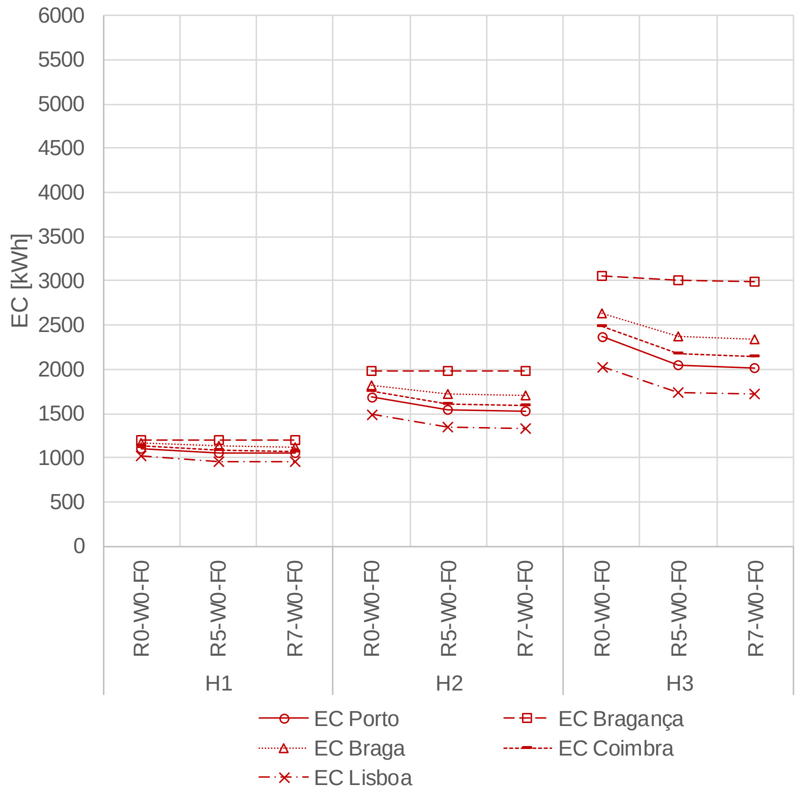


Figure 91 – Energy consumption (EC) for a west-sided Brandão school for different climatic locations.

The city with the higher winter thermal discomfort is Bragança, followed by Braga, Coimbra, Porto and Lisboa. There is an important reduction of the winter thermal discomfort from H1 to H2 and from H2 to H3 heating strategy. However, in Bragança (and with *roof* insulation) there is an important discomfort (about 80% of the occupied hours), even considering the higher heating strategy (9 h heating).

The *roof* insulation thickness has an important role from R0 to R5 but the investment in stronger solutions does not represent a relevant reduction in thermal discomfort or in EC in any location.

For a 9 h heating strategy (H3), and considering the R5 *roof* insulation thickness, the discomfort during the occupied hours is below 500 ºC.hour and below 40% of the occupied hours in Coimbra, Porto and Lisboa.

For a 5 h heating strategy (H2), the EC is between 1500 and 2000 kWh but the thermal discomfort increases about 1000, 650, 550, 500 and 400 ºC.hour for Bragança, Braga, Coimbra, Porto and Lisboa, when comparing with the H3 heating strategy.

For a 3 h heating strategy (H1), the EC is about 1000 kWh for all the studied cities but the %TD is above 70% of the occupied hours for all the studied cities and *roof* insulation solutions.

Considering mid-season, the *roof* insulation (R5) also promotes an important reduction of DI_{25} (Figure 92). As it was verified during winter, the additional investment in roof insulation thickness does not show a relevant decrease in mid-season discomfort.

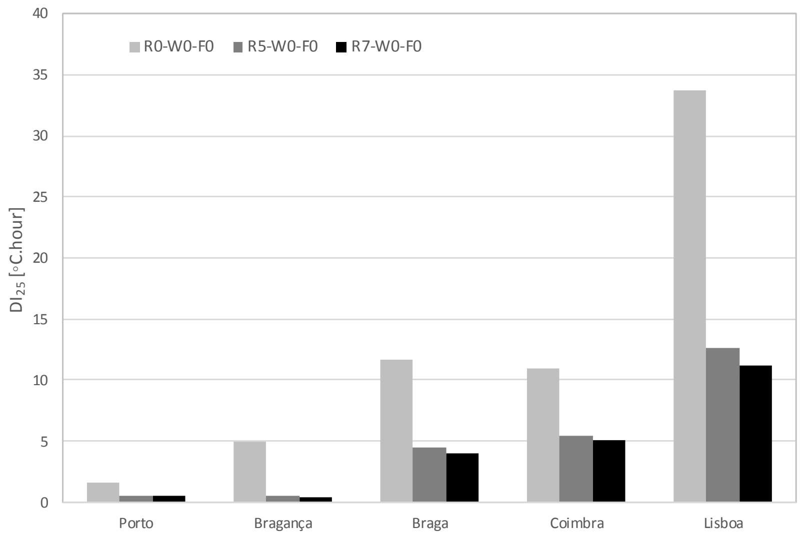


Figure 92 – DI_{25} in a west-sided Brandão school for different roof insulation thicknesses and distinct climatic locations.

5.3.3.1.3. Walls and floor insulation

The benefits of increasing insulation thickness of *wall* and *floor* (W5 and F3 solutions) are compared with the pre-existing envelope scenario (without walls insulation - W0 and without floor insulation - F0) and for W1SP1 window solution (double glazing with exterior solar protection).

Figure 93 shows the discomfort indicators (DI_{20} and $\%TD_{20}$) and Figure 94 presents the EC for a west-sided *Brandão* school. There is an important reduction of the winter thermal discomfort from H1 to H2 and from H2 to H3 heating strategy. However, in Bragança there is always an important discomfort, even considering the higher heating strategy.

The *wall* insulation thickness has a relevant role in all the analysed scenarios, but it promotes a lower reduction in the winter thermal discomfort than the *roof* insulation, previously analysed.

The *wall* insulation reduces winter thermal discomfort in all the analysed scenarios, but the additional *floor* insulation implementation (together with *wall* insulation and without *roof* insulation) only has a favorable winter behaviour (in ºC.hour) in Bragança and Lisboa. In the remaining cities (Porto, Braga and Coimbra) the additional *floor* insulation decreases the $\%TD_{20}$ but does not represent a reduction in DI_{20} (in ºC.hour). Despite the previous conclusion, it is known that the *floor* insulation would be beneficial for the reduction of local discomfort near the floor.

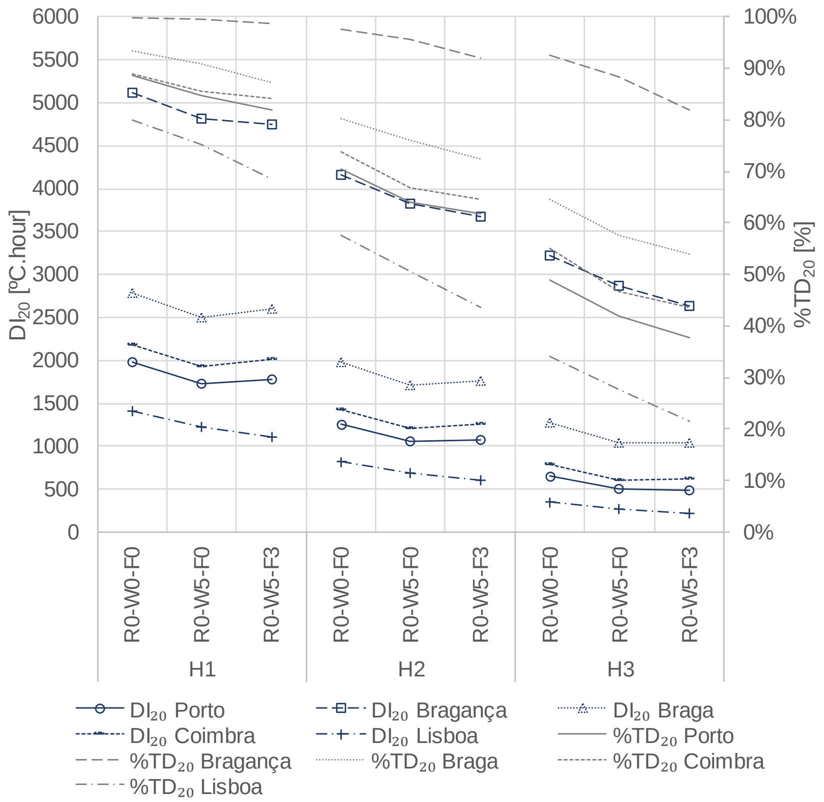


Figure 93 – Discomfort indicators (DI_{20} and %TD) for a west-sided Brandão school for different climatic locations.

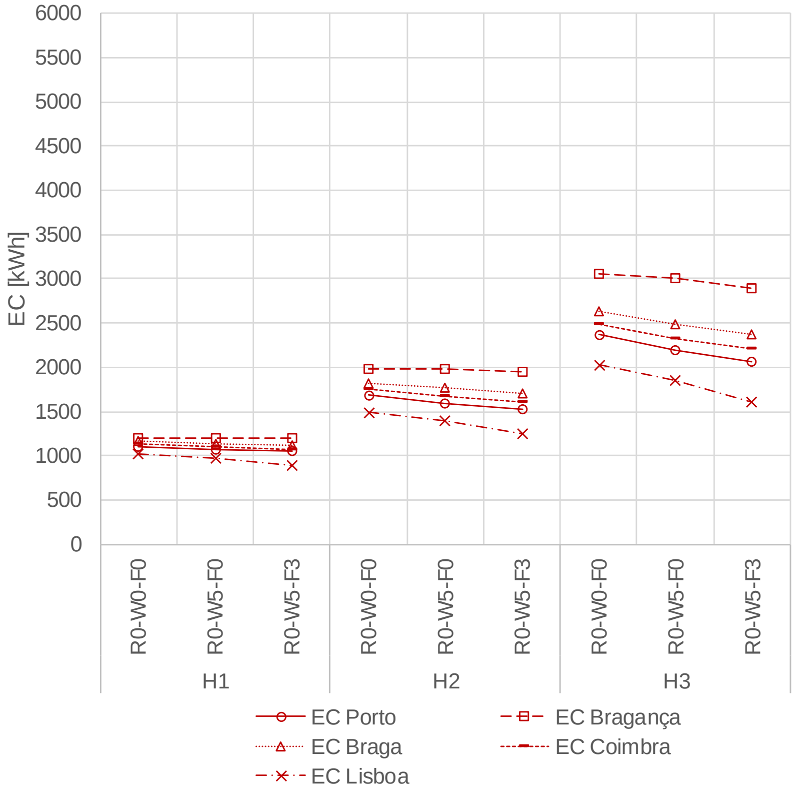


Figure 94 – Energy consumption (EC) for a west-sided Brandão school for different climatic locations.

Considering mid-season, the *walls* insulation (W5) increases DI_{25}, but the major increment in DI_{25} is promoted by the additional *floor* insulation (Figure 95).

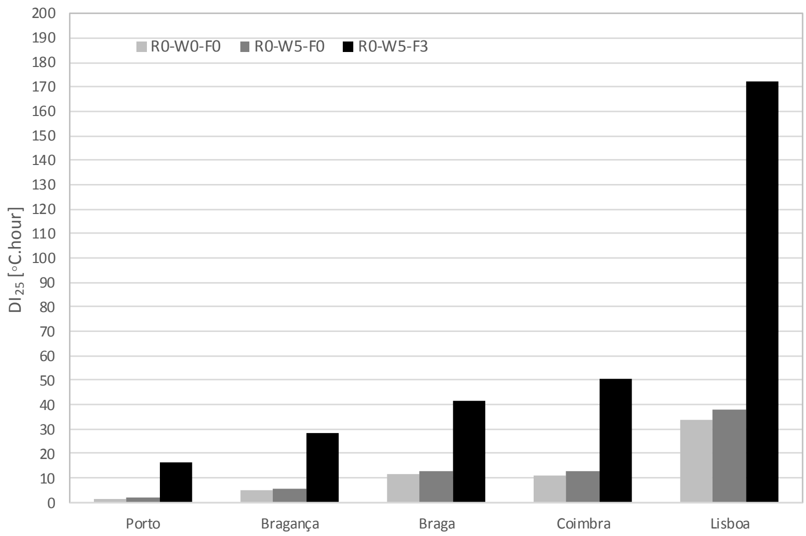


Figure 95 – DI_{25} in a west-sided Brandão school for wall and floor insulation solutions and distinct climatic locations.

5.3.3.1.4. Combined roof, walls and floor insulation

Figure 96 and Figure 97 show the DI_{20}, $\%TD_{20}$ and EC for each combined *roof*, *wall* and *floor* insulation solution in a *Brandão* building in the five studied Portuguese cities. Figure 97 shows that the most important EC reduction was verified for the complete investment in insulation (*roof*, *wall* and *floor* – R5-W5-F3), followed by the *roof* and *wall* insulation (R5-W5-F0). However, the EC reduction represents a winter analysis and the solution with *floor* insulation must be carefully analysed in mid-season conditions.

The impact of the additional *roof* (R5), *wall* (W5) and *floor* (F3) insulation is presented in Table 49. Table 49 confirms the importance of the *roof* insulation in all cities and for all heating strategies. The importance of *roof* insulation (in percentage) is more relevant the greater is the heating strategy. The impact of *roof* insulation when comparing H1 with H3 strategy is 22% to 46%, 10% to 22%, 20% to 38%, 22% to 46% and 20% to 41% for Porto, Bragança, Braga, Coimbra and Lisboa, respectively.

The additional investment in *walls* insulation (R5-W5-F0) has also an important role in winter discomfort reduction, with a higher benefic impact considering higher heating strategies. The impact of the additional *wall* insulation when comparing H1 with H3 strategy is 37% to 64%, 18% to 35%, 33% to 56%, 36% to 65% and 35% to 59% for Porto, Bragança, Braga, Coimbra and Lisboa, respectively.

In Porto, Braga and Coimbra, the additional *floor* insulation has a lower positive effect when compared with the before situation (R5-W5-F0) (the differences between the two referred situations are: 6%, 8% and 3% in H1 strategy; 8%, 9% and 6% in H3 strategy, for Porto, Braga and Coimbra, respectively). In Lisboa and Bragança the effect of winter discomfort reduction is higher. But the implementation of this solution in all cities must be carefully balanced by the disadvantages during the mid-season period (Figure 98).

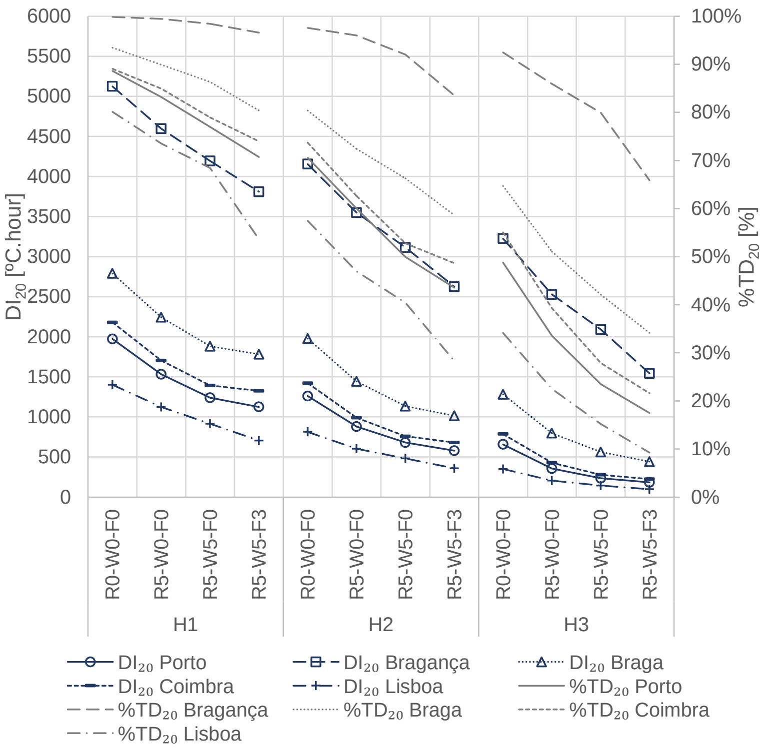


Figure 96 – Discomfort indicators (DI_{20} and %TD) for a west-sided Brandão school for different climatic locations.

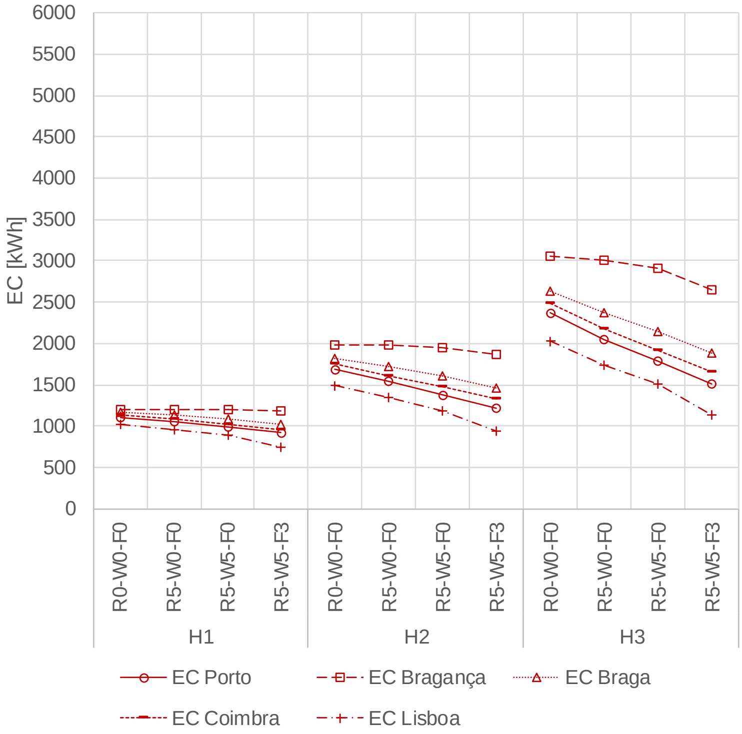


Figure 97 – Energy consumption (EC) for a west-sided Brandão school for different climatic locations.

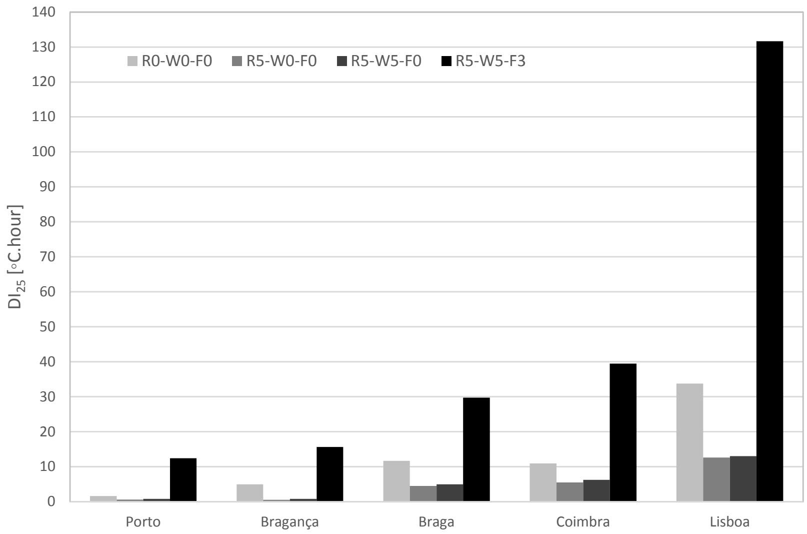


Figure 98 – DI_{25} in a west-sided Brandão school for the additional roof, wall and floor insulation and distinct climatic locations.

An important conclusion is that the *walls* and *floor* insulation by their own (previous sub-chapter) do not have a relevant benefic impact on winter and mid-season discomfort and that the *roof* insulation promotes the benefic impact of *walls* and *floor* insulation in winter and decreases the mid-season discomfort impact, when are implemented together (*roof*, *wall* and *floor*).

Table 49 – ΔDI_{20} and ΔDI_{25} achieved by the additional roof, wall and floor insulation for different Portuguese cities.

			ΔDI_{20}	$\downarrow DI_{20}$ [%]	ΔDI_{25}	$\downarrow DI_{25}$ [%]
H1	Porto (*2)	Δ(R5-R0)	439	22%	1.0	65%
		Δ((R5-W5) - (R0-W0))	731	37%	0.8	51%
		Δ((R5-W5-F3) - (R0-W0-F0))	848	43%	-10.8	-677%
	Bragança	Δ(R5-R0)	528	10%	4.5	90%
		Δ((R5-W5) - (R0-W0))	930	18%	4.2	84%
		Δ((R5-W5-F3) - (R0-W0-F0))	1315	26%	-10.6	-214%
	Braga	Δ(R5-R0)	546	20%	7.2	62%
		Δ((R5-W5) - (R0-W0))	909	33%	6.7	58%
		Δ((R5-W5-F3) - (R0-W0-F0))	1007	36%	-18.1	-155%
	Coimbra	Δ(R5-R0)	474	22%	5.5	50%
		Δ((R5-W5) - (R0-W0))	787	36%	4.7	43%
		Δ((R5-W5-F3) - (R0-W0-F0))	854	39%	-28.5	-261%
	Lisboa	Δ(R5-R0)	279	20%	21.1	63%
		Δ((R5-W5) - (R0-W0))	487	35%	20.8	61%
		Δ((R5-W5-F3) - (R0-W0-F0))	696	50%	-97.9	-290%
H2	Porto (*2)	Δ(R5-R0)	379	30%		
		Δ((R5-W5) - (R0-W0))	579	46%		
		Δ((R5-W5-F3) - (R0-W0-F0))	680	54%		
	Bragança	Δ(R5-R0)	605	15%		
		Δ((R5-W5) - (R0-W0))	1040	25%		
		Δ((R5-W5-F3) - (R0-W0-F0))	1529	37%		
	Braga	Δ(R5-R0)	532	27%		
		Δ((R5-W5) - (R0-W0))	843	43%		
		Δ((R5-W5-F3) - (R0-W0-F0))	964	49%		
	Coimbra	Δ(R5-R0)	431	30%		
		Δ((R5-W5) - (R0-W0))	665	47%		
		Δ((R5-W5-F3) - (R0-W0-F0))	741	52%		
	Lisboa	Δ(R5-R0)	210	26%		
		Δ((R5-W5) - (R0-W0))	331	41%		
		Δ((R5-W5-F3) - (R0-W0-F0))	455	56%		(*1)
H3	Porto (*2)	Δ(R5-R0)	301	46%		
		Δ((R5-W5) - (R0-W0))	422	64%		
		Δ((R5-W5-F3) - (R0-W0-F0))	474	72%		
	Bragança	Δ(R5-R0)	697	22%		
		Δ((R5-W5) - (R0-W0))	1134	35%		
		Δ((R5-W5-F3) - (R0-W0-F0))	1682	52%		
	Braga	Δ(R5-R0)	484	38%		
		Δ((R5-W5) - (R0-W0))	720	56%		
		Δ((R5-W5-F3) - (R0-W0-F0))	839	65%		
	Coimbra	Δ(R5-R0)	358	46%		
		Δ((R5-W5) - (R0-W0))	509	65%		
		Δ((R5-W5-F3) - (R0-W0-F0))	561	71%		
	Lisboa	Δ(R5-R0)	145	41%		
		Δ((R5-W5) - (R0-W0))	206	59%		
		Δ((R5-W5-F3) - (R0-W0-F0))	250	72%		

(*1) The heating strategy does not have an influence on DI_{25}.

(*2) For Porto sensitivity studies (5.3.2), the TRY was preferably used, although for the comparison amongst different cities the option was a specific climatic year from IPMA, in order to ensure the same climatic year for each location. For that reason, the results from Porto may differ from 5.3.2. and 5.3.3. section.

5.3.3.1.5. Windows and solar protection

It was previously concluded for Porto that when the single glazing window system (W0SP1) is replaced by a double-glazing window system (W1SP1) the EC decreases and when the g-value decreases (W2SP1) there is a slight increase in EC.

This sub-chapter aims to assess if a lower g-value has any advantage in different climatic conditions, regarding thermal comfort and EC in winter and thermal comfort in mid-season (Figure 99). The studied solutions in this chapter are W1SP1 and W2SP1, characterized in previous Table 42.

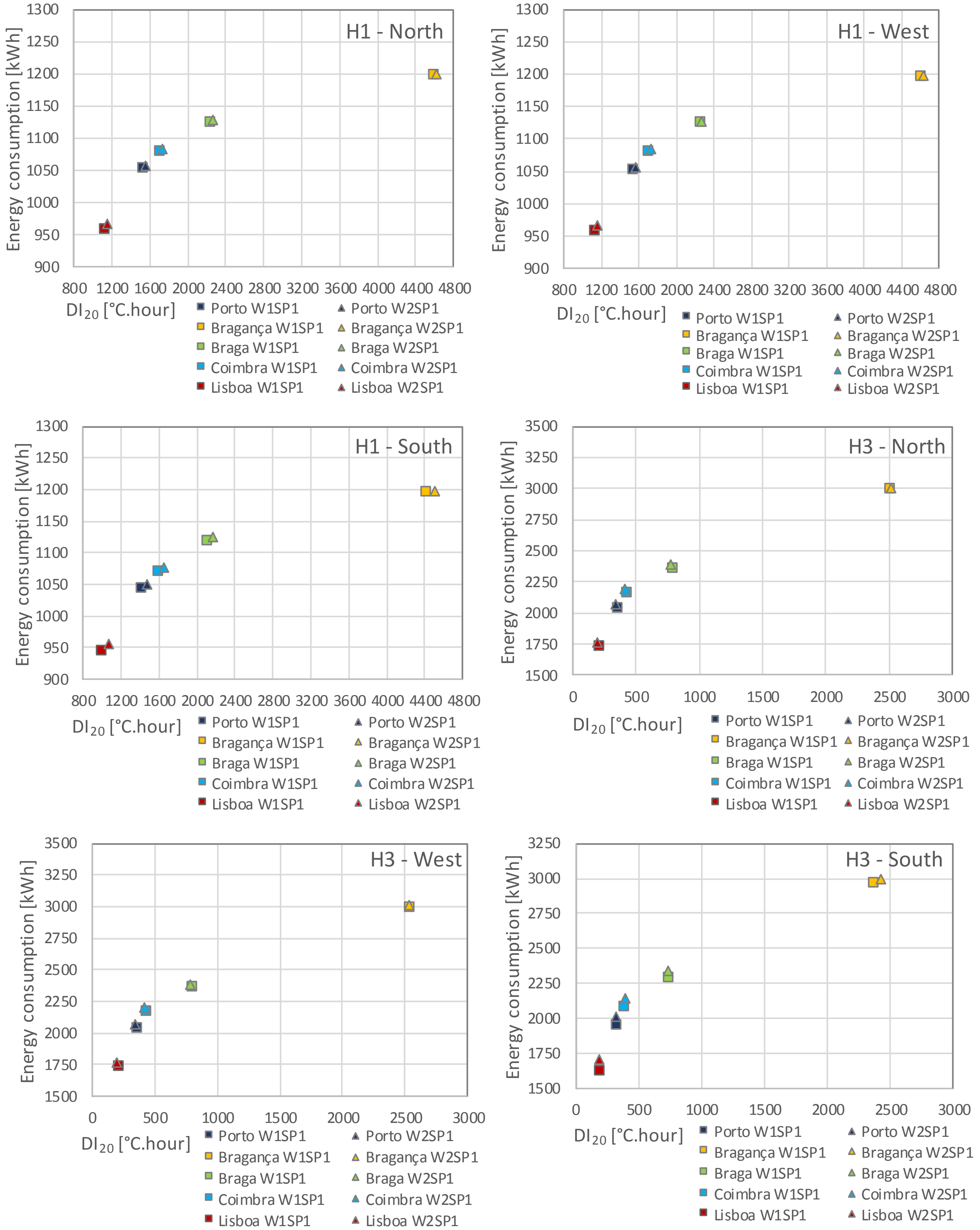


Figure 99 – Association between the winter thermal discomfort and energy consumption for two window solutions for different Portuguese cities – H1 and H3 (north, west and south).

Once each orientation has distinct solar gains, this analysis was prepared for the three studied orientations and for H1 and H3 heating strategies. The envelope conditions are R5-W0-F0.
Figure 99 shows the association between the winter thermal discomfort and the EC for the two window glazing solutions.

It can be observed that, for all orientations, and considering the defined operation mode of the solar protections, there are not important differences between the two solutions in winter thermal discomfort or in EC.

Figure 100 presents the mid-season discomfort for the two studied window glazing solutions in different climatic conditions. It can be concluded that the mid-season discomfort in Porto and Bragança is low and the investment in improved windows with lower g-value (W2SP1) is not relevant. In Braga, Coimbra and Lisboa, the lower g-value window (W2SP1) has a benefic impact on mid-season comfort. However, as previously referred, an adaptive analysis of mid-season discomfort must be considered in order to understand the intensity of the mid-season discomfort and the relevance of this refurbishment.

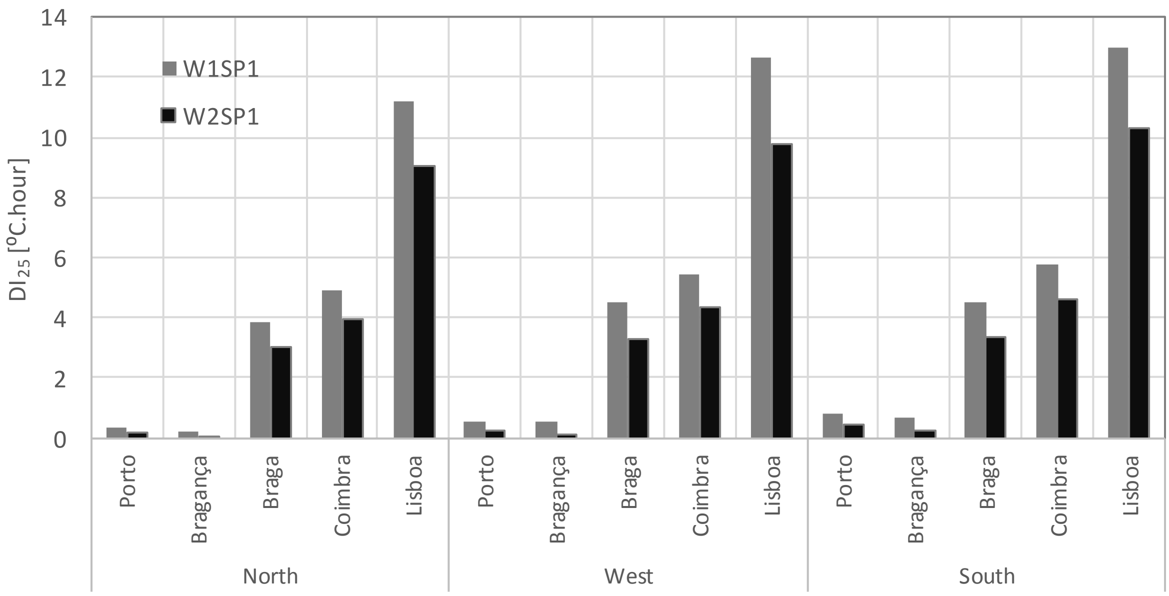


Figure 100 – DI_{25} in a west-sided Brandão school for the two studied window glazing solutions and distinct climatic locations.

5.3.3.1.6. Floor insulation

Considering the five Portuguese climatic locations studied and the three heating strategies, Figure 101, Figure 102 and Figure 103 present the winter and mid-season DI and %TD for the two *floor* insulation solutions (F0 and F3), for an optimized envelope (R5-W5-W1SP1), a V3 (500 m^3/h) ventilation strategy and considering the global thermal discomfort (winter and mid-season).

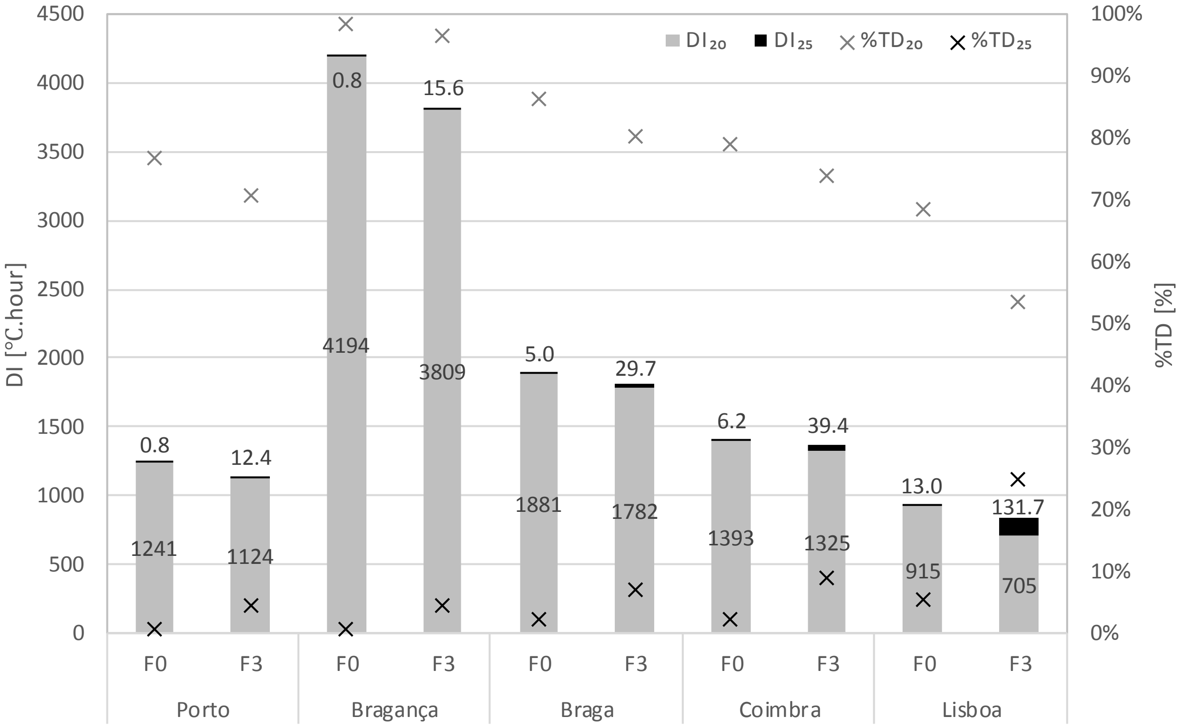


Figure 101 – DI and %TD for the two floor solutions – 5 Portuguese locations - west-H1.

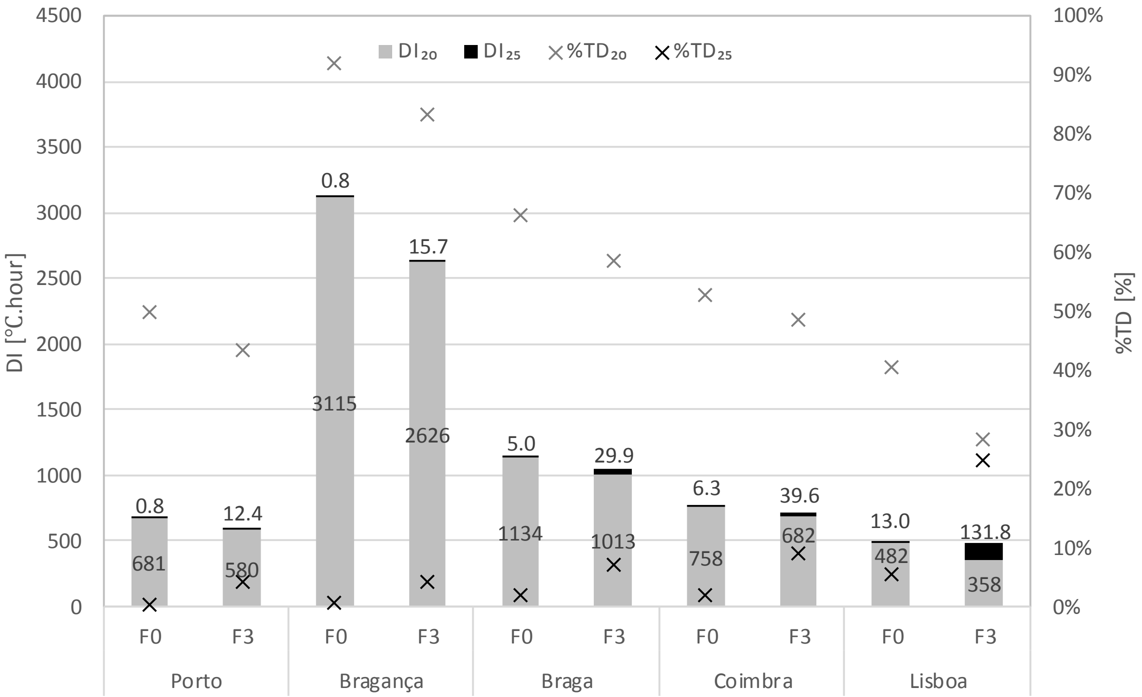


Figure 102 – DI and %TD for the two floor solutions – 5 Portuguese locations - west-H2.

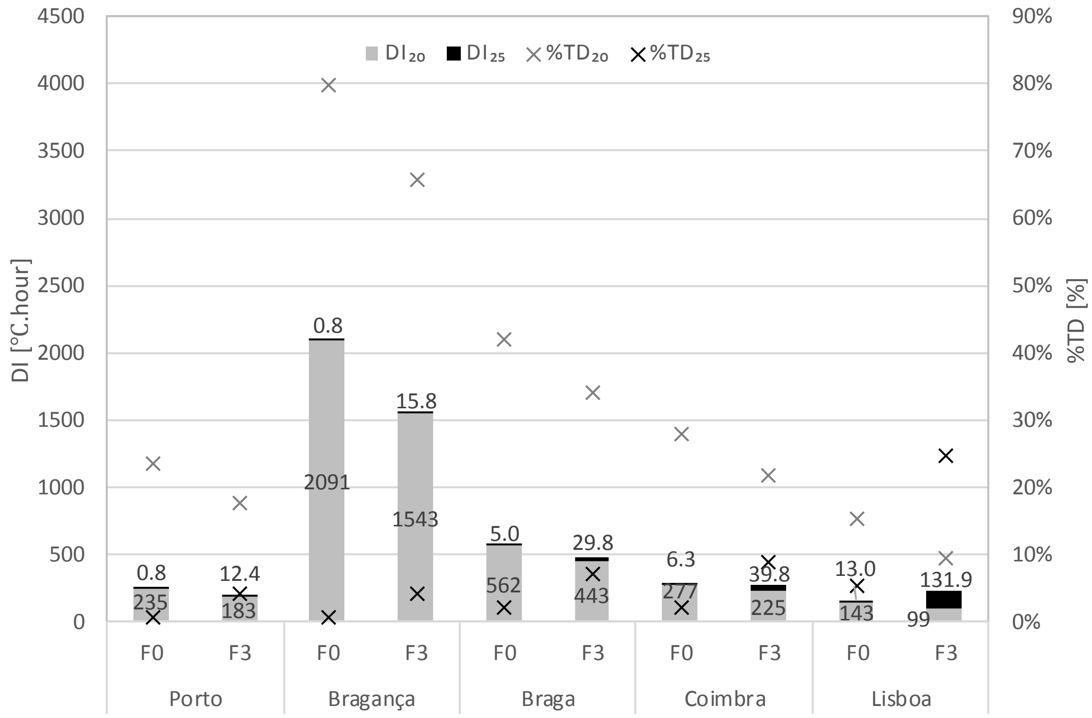


Figure 103 – DI and %TD for the two floor solutions – 5 Portuguese locations - west-H3.

The additional *floor* insulation has a positive effect on winter discomfort and $\%TD_{20}$ (when associated with *roof* and *walls* insulation) and a negative effect on mid-season discomfort and $\%TD_{25}$. However, it is not clear yet if the *floor* insulation represents an important benefit in the global discomfort reduction.

Nevertheless, in winter, F3 solution assumes higher importance in Bragança. The major benefit results from the higher heating strategies (H2 and H3). In fact, the 3 h heating strategy is not adequate in Bragança and the stronger envelope solutions are not enough to minimize the winter discomfort.

5.3.3.1.7. EN 15251 application during mid-season

The application of EN 15251 confirmed the non-importance of mid-season discomfort in Porto schools. However, and in order to define some *Guidelines*/*recommendations* for the refurbishment of *Brandão* schools, this adaptive model must be applied to other Portuguese climatic conditions. Moreover, the adaptive model may also confirm that some specific refurbishment scenario that decreases winter comfort does not have a harmful effect on mid-season comfort.

An application of EN 15251 for the *floor* insulation analysis in mid-season is presented in Figure 104, Figure 105, Figure 106, Figure 107 and Figure 108 (comparison between the solutions R5-W5-F0 and R5-W5-F3, without and with floor insulation, respectively), for a west-sided *Brandão* building and V3 ventilation strategy.

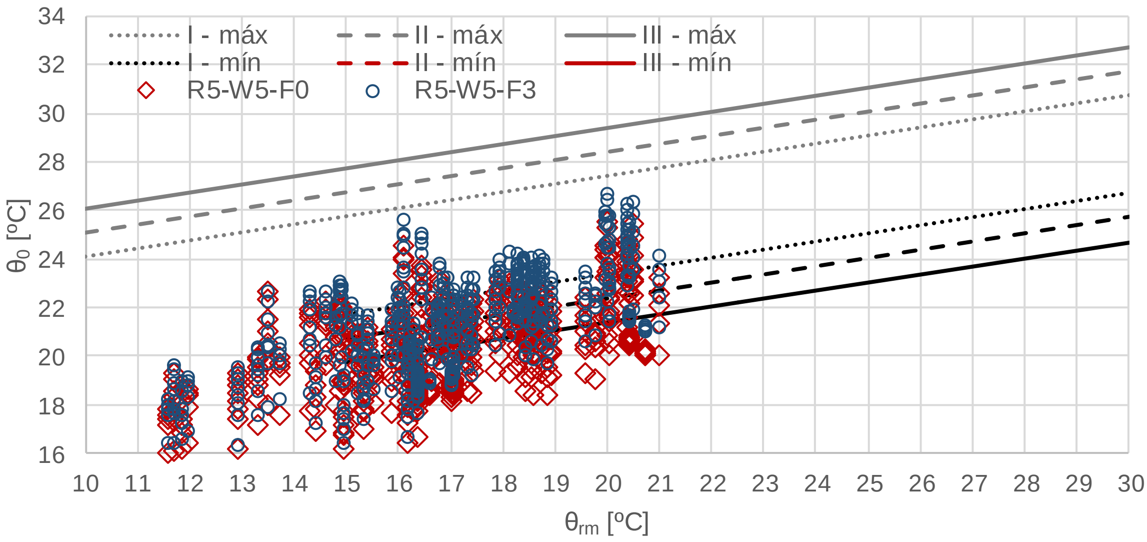


Figure 104 – EN 15251 application during mid-season in Porto.

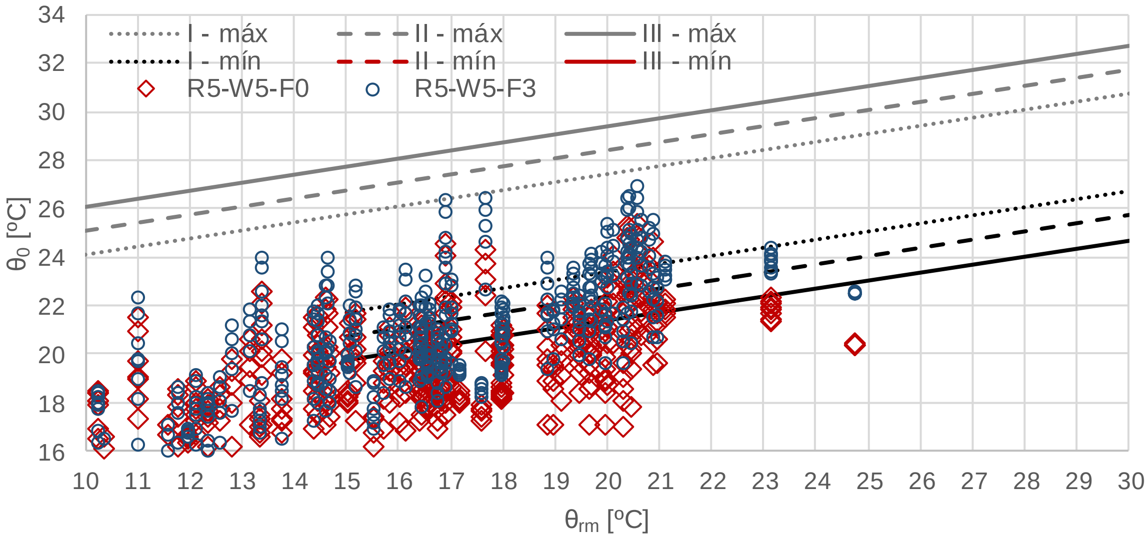


Figure 105 – EN 15251 application during mid-season in Bragança.

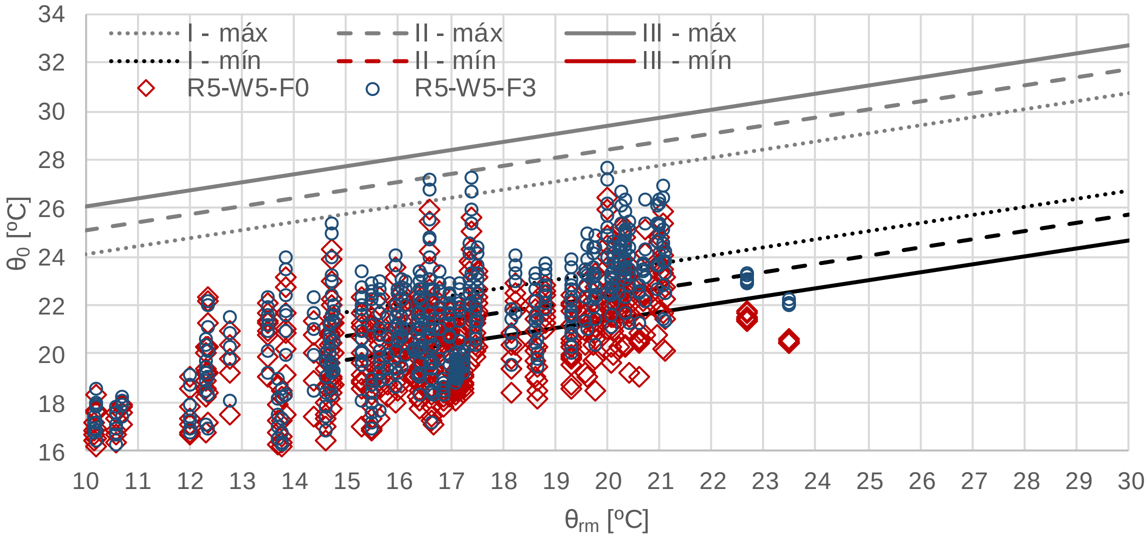


Figure 106 – EN 15251 application during mid-season in Braga.

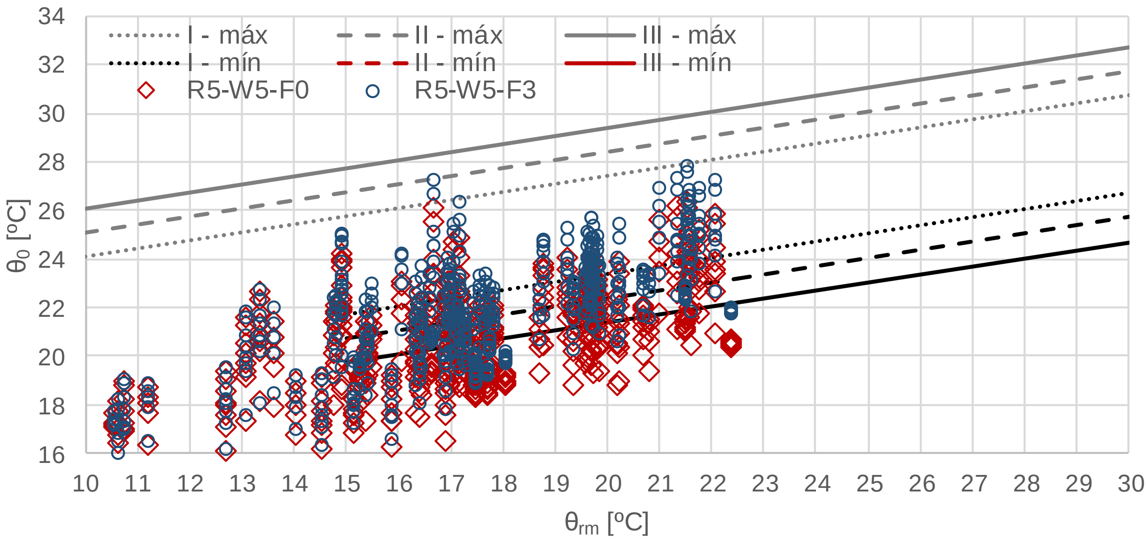


Figure 107 – EN 15251 application during mid-season in Coimbra.

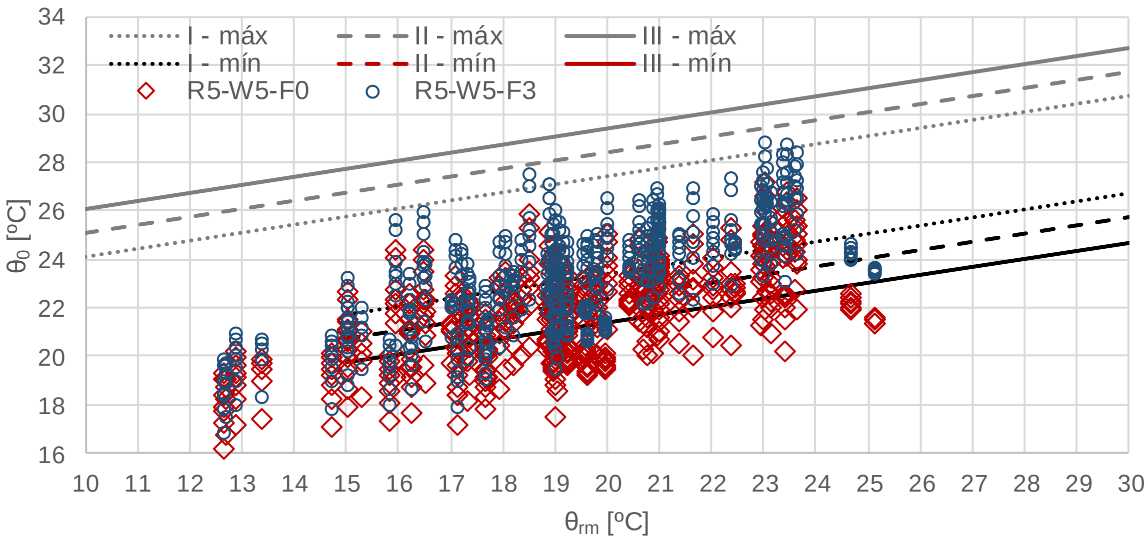


Figure 108 – EN 15251 application during mid-season in Lisboa.

The IPMA climatic data (from Porto, Bragança, Braga, Coimbra and Lisboa) was used as an input in Wufi Plus simulation and for the calculation of θ_{rm} (outdoor running mean temperature from EN 15251). As referred before, it was considered that the differences between mean radiant temperature and indoor air temperature were low and, for that reason, the indoor air temperature was used as operative temperature (θ_0) [190].

It can be observed that only 8%, 13%, 16%, 15% and 34% of the occurrences during the considered mid-season period were associated to θ_{rm} above 20 ºC (for Porto, Bragança, Braga, Coimbra and Lisboa, respectively).

It can be also concluded that for the mid-season period, there is not any occurrence of the two solutions above EN 15251 limits for Porto and Bragança.

Considering the solution R5-W5-F3, in Braga, Coimbra and Lisboa there are only 1.1%, 0.4% and 1.1% of occurrences above category I, respectively, and no occurrence above categories II and III. In conclusion, all the studied climatic conditions, the *floor* insulation does not represent an important mid-season discomfort (considering the adaptive analysis of EN 15251).

Moreover, once the mid-season discomfort is very low, the implementation of a window solution with lower g-value seems not to be relevant for the reduction of mid-season discomfort.

The previous DI_{25} analysis is more demanding than the adaptive EN 15251 model for mid-season conditions.

5.4. FINAL CONSIDERATIONS

The sensitivity study was an important tool to prepare the *Guidelines*/*recommendations* for the refurbishment of Portuguese *Brandão* schools, regarding thermal comfort, IAQ and EC during the occupation period and considering the two defined approaches (*minimizing discomfort* and *comfort*). The main conclusions of this chapter are:

- The simulation enables a controlled ventilation strategy, without failures or incidental changes in the ventilation operation. The three ventilation strategies studied after refurbishment (V1, V2 and V3) are the 260 m^3/h (V1), the 400 m^3/h (V2), which is an approximate value of the real ventilation rate in the prototype after refurbishment and 500 m^3/h (V3) (a little below the legislation), that fulfils the requirement of 1500 ppm defined in this work (a relaxed restriction in accordance with some international legislation).
- The insulation of the envelope has an important role in the reduction of winter discomfort in lower heating strategies and in EC in stronger heating strategies.
- The first increment in *roof* insulation thickness (R5) is very relevant for the three heating strategies and for both considered approaches (*minimizing discomfort* and *comfort*), but the additional investment in *roof* insulation thicknesses does not represent an important reduction in winter discomfort and in EC.
- For lower heating strategies, there is an important reduction of DI_{20} from R0 to R5 but when the heating strategy increases, there is also an important reduction of EC.
- Considering mid-season, the *roof* insulation (R5) also promotes an important reduction of DI_{25}. Such as in winter discomfort, the additional investment in *roof* insulation thicknesses does not traduce a relevant decrease in mid-season discomfort.

- Considering *wall* insulation, the most important share of winter discomfort reduction and EC reduction is obtained from the first increment (W5) for the three heating strategies and for both considered approaches.
- The *wall* insulation has a relevant role in all the analysed scenarios, but it promotes a lower reduction in the winter thermal discomfort than the *roof* insulation.
- There is a general slight decrease in mid-season comfort due to the *wall* insulation system (without *roof* insulation), whatever the thickness of the solution is.
- The *floor* insulation, when assessed as a separate intervention, promotes a general small reduction of the winter discomfort in Porto (or a small increase in lower heating strategies). Despite the previous conclusion, it is known that the *floor* insulation would be benefic for the reduction of local discomfort near the floor. The *floor* insulation also increases the mid-season discomfort, although the absolute value of DI_{25} is still low when compared with DI_{20}.
- The *floor* insulation has a positive effect on winter discomfort and $\%TD_{20}$ (when associated with *roof* and *walls* insulation) and a negative effect on mid-season discomfort and $\%TD_{25}$. However, it is not already clear if the *floor* insulation represents an important benefit in the global discomfort reduction.
- The window must be double-glazed (W1SP1) in order to minimize the discomfort and the EC in lower and higher heating strategies, respectively. The exterior solar protection is an important element due to the illumination strategy inside classrooms.
- The installation of a lower g-value window (W2SP1) was not a beneficial winter solution in any studied Portuguese climatic location. Moreover, the mid-season discomfort is low and the investment in improved windows with lower g-value must be carefully analysed.
- The winter discomfort is much more important than mid-season discomfort. An adaptive analysis of mid-season discomfort (EN 15251 application) showed that even with *floor* insulation (the solution with lower mid-season performance), the mid-season discomfort is very low. The DI_{25} analysis is more demanding than the adaptive EN 15251 model for mid-season conditions.

6
Guidelines for refurbishment

6.1. MAIN GOALS AND MOTIVATION

The main goal of this Thesis is the proposal of refurbishment strategies for *Brandão* schools that decrease the thermal discomfort, considering intermittent heating strategies, or ensure thermal comfort, considering a regular (although non-continuous) heating strategy. The proposal must consider not only a lower global investment but also an appropriate distribution of the investment (envelope and technical systems), regarding the present in-service conditions (free-running T and natural ventilation strategy). The refurbishment of the remaining non-refurbished schools must consider their typology, the local climate features and the actual capacity to support the operating costs.

The *Guidelines/recommendations* must take into account the approach to be privileged: a *minimizing discomfort* approach or a *comfort* approach. The best scenarios defined for free-running temperature or low intermittent heating strategies can be different from comfort scenarios under a regular (although non-continuous) heating strategy (Figure 109). The *Guidelines/recommendations* may support the decision process on the rehabilitation of school buildings.

Guidelines development considered experimental and numerical results. The experimental work confirmed the *in-situ* thermal discomfort before the refurbishment and was important to validate the numerical model. The prototype was an important tool to assess the users' discomfort before and after the intervention and, along with the experimental monitoring, to validate the numerical model in both circumstances. The sensitivity analysis included a combination of different envelope scenarios and ventilation and heating strategies. The refurbishment *Guidelines* for *Brandão* school are a natural output of this work. Figure 109 presents the tools and the strategy for the preparation of the *Guidelines/recommendations*.

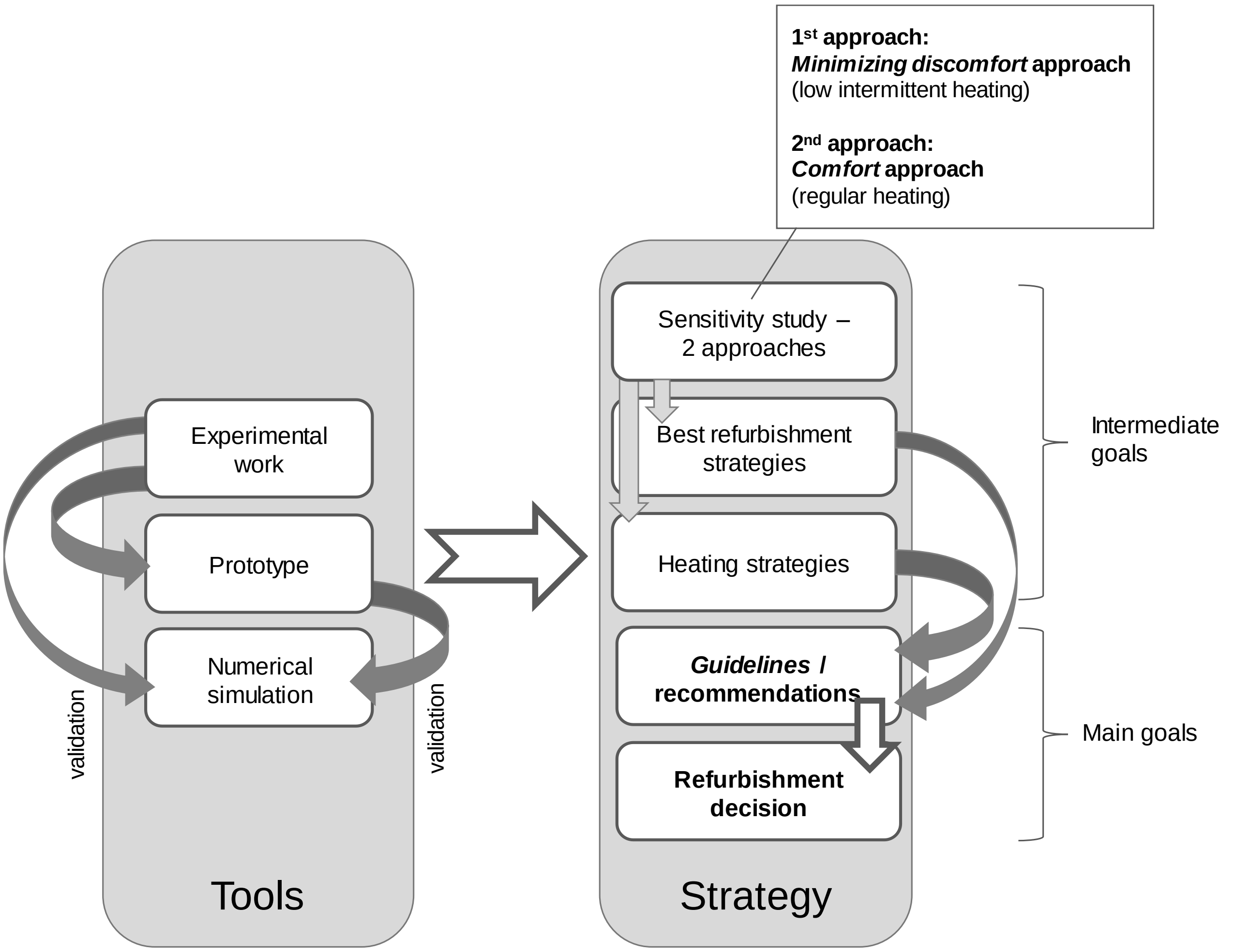


Figure 109 – Tools and strategy for the preparation of the Guidelines/recommendations.

Different refurbishment scenarios are characterized by distinct levels of intervention in the insulation of the envelope (roof, exterior walls, floor, windows and solar protections) and in technical systems (ventilation and heating strategies), presented in the previous Table 42.

The refurbishment scenarios characterization is made considering the two possible approaches previously defined:

- ❖ For the *minimizing discomfort* approach (considering low intermittent heating strategies) the analysis includes the thermal comfort performance (T), the IAQ performance (CO_2) and the EC (predictably low in this approach, respecting the present strategy in these schools with low EC). The particular situation of free-running conditions excludes the last variable (EC), once there is not an associated heating strategy.

- For the *comfort* approach (considering a regular, although non-continuous, heating strategy during the occupation period), the analysis includes the EC, once the comfort requirements were almost fulfilled during the occupation period.

Figure 110 presents the decision variables considered for each defined approach.

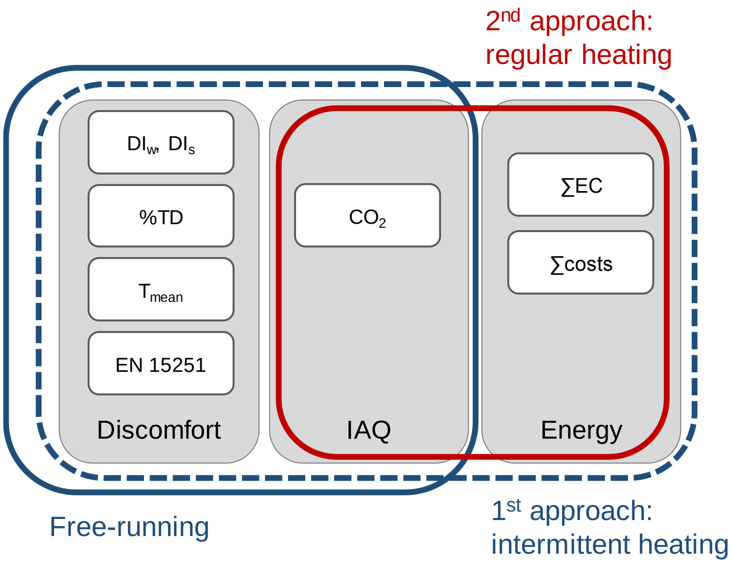


Figure 110 – Thermal comfort, IAQ and EC – minimizing discomfort and comfort approach.

6.2. REFURBISHMENT STRATEGIES FOR *BRANDÃO* SCHOOL BUILDINGS

6.2.1. REFURBISHMENT STRATEGIES – PRELIMINARY SOLUTIONS

The previous chapters (3, 4 and 5) had the purpose of preparing the *Guidelines* for the refurbishment of *Brandão* schools. Some steps have been followed and it is now possible to summarize, step by step, the selection of the refurbishment strategies. Figure 111, Figure 112, Figure 113, Figure 114 and Figure 115 present steps 0 to 4.

The experimental work performed a pre-analysis of *in-situ* heating strategies, roof insulation and ventilation control benefits (step 0).

One important conclusion resulting from chapter 3 is that free-running conditions are not adequate in winter and an intermittent or regular heating strategy to minimize the discomfort must be considered (3 h and 10 h were the experimental heating strategies studied) (step 1).

Another important conclusion was that the ventilation rate *in-situ* (380 m^3/h or 2.9 h^{-1}) was not enough to fulfil all the time the 1250 ppm requirement nor the 1500 ppm defined in this work, although the mean CO_2 was below 1500 ppm (Table 1). At the same time, numerical simulation studies showed that it was necessary to upgrade the real ventilation to 500 m^3/h (V3 ventilation strategy) to satisfy the 1500 ppm requirement for 100% of the occupation period and that the CO_2 did not have a direct relationship with the heating strategy and the mean values were similar for the three strategies (step 2).

The sensitivity study developed for Porto climatic conditions (TRY) confirmed the importance of *roof* insulation and the relevance of exterior *walls* insulation (step 3). It also revealed that the additional insulation thickness of *roof* and *walls* insulation did not have an important reduction in winter discomfort or EC. The result of step 3 was the exclusion of R0, R10, W0 and W8 solutions (0 cm and 10 cm of roof insulation and 0 cm and 8 cm of walls insulation, respectively). It also excluded W0SP0 window and solar protection solution (single-glazing window without solar protection), due to illumination needs inside classrooms and W0SP1 (single-glazing window with solar protection) due to its lower thermal performance and higher EC when compared with the remain solutions.

The analysis of envelope and heating strategies for 5 Portuguese cities (IPMA WS 2012) resulted in the exclusion of R7 (7 cm of roof insulation) in all the studied climatic locations (step 4).

The preliminary solutions (presented in Figure 116) are analysed in this chapter, regarding the winter thermal discomfort and EC and also the mid-season thermal discomfort. The roof, wall and ventilation strategy had already been decided (R5, W5 and V3 - 5 cm of roof insulation, 5 cm of exterior walls insulation and 500 m^3/h for the ventilation strategy, respectively). The heating strategy (and related costs) have a strict connection with the economic conditions that must be considered at the moment of the refurbishment and estimated in a future perspective. Finally, the *floor* insulation and the window system were not clearly defined in previous steps and are assessed in this chapter.

Step 0		
Main goal:	Pre-analysis of *in-situ* heating strategies, roof insulation and ventilation control benefits	
Procedure:	Experimental	
Decision variables:	T, CO_2 and EC	
Approach:	*Minimizing discomfort* and *comfort*	R0 | R5 V2 Free running | 3 h | 10 h Legend: R0: 0 cm of roof insulation; R5: 5 cm of roof insulation; V2: 400 m^3/h (≈380 m^3/h experimental)
Result:	Importance of roof insulation and ventilation control	

Figure 111 – Pre-analysis of in-situ heating strategies, roof insulation and ventilation control benefits – Step 0.

Step 1		
Main goal:	Analysis of free-running conditions	
Procedure:	Experimental	
Decision variables:	T	
Approach:	*Minimizing discomfort*	~~Free running~~ | 3 h | 10 h
Result:	Exclusion of free-running conditions	

Figure 112 – Analysis of free-running conditions – Step 1.

Step 2

Main goal:	Analysis of IAQ
Procedure:	Experimental and numerical
Decision variables:	CO_2
Approach:	*Minimizing discomfort* and *comfort*

~~V1~~	~~V2~~	V3

Legend:

V1: 260 m^3/h; V2: 400 m^3/h; V3: 500 m^3/h.

Result:	Exclusion of V1 and V2 ventilation strategies

Figure 113 – Analysis of IAQ – Step 2.

Step 3

Main goal:	Analysis of envelope and heating strategies
Procedure:	Numerical (TRY climatic data)
Decision variables:	T and EC
Approach:	*Minimizing discomfort* and *comfort*

~~R0~~(*)	R5	R7	~~R10~~
~~W0~~(*)	W5	~~W8~~	
F0	F3		
~~W0SP0~~	~~W0SP1~~(*)	W1SP1	W2SP1
West	South	North	
H1	H2	H3	

Legend:

R0: 0 cm of roof insulation; R5: 5 cm of roof insulation; R7: 7 cm of roof insulation; R10: 10 cm of roof insulation; W0: 0 cm of walls insulation; W5: 5 cm of walls insulation; W8: 8 cm of walls insulation; F0: 0 cm of floor insulation; F3: 3 cm of floor insulation; W0SP0: single glazing without solar protection; W0SP1: single glazing with solar protection; W1SP1: double glazing with solar protection; W2SP1: lower g-value double glazing with solar protection; H1: 3 h heating; H2: 5 h heating; H3: 9 h heating.

Result:	Exclusion of R0 (*), R10, W0 (*), W8, W0SP0 and W0SP1 (*) These options were maintained during the sensitivity analysis in order to compare with the pre-existing situation

Figure 114 – Analysis of envelope and heating strategies – Step 3.

Step 4		
Main goal:	Analysis of envelope and heating strategies	
Procedure:	Numerical (IPMA WS)	
Decision variables:	T and EC	
Approach:	*Minimizing discomfort* and *comfort*	

~~R0(*)~~	R5	~~R7~~
~~W0(*)~~	W5	
F0	F3	
W1SP1	W2SP1	
West	South	North
H1	H2	H3

Legend:

R0: 0 cm of roof insulation; R5: 5 cm of roof insulation; R7: 7 cm of roof insulation; W0: 0 cm of walls insulation; W5: 5 cm of walls insulation; F0: 0 cm of floor insulation; F3: 3 cm of floor insulation; W1SP1: double glazing with solar protection; W2SP1: lower g-value double glazing with solar protection; H1: 3 h heating; H2: 5 h heating; H3: 9 h heating.

Result: Exclusion of R7 in all the studied climatic locations

(*) These options were maintained during the sensitivity analysis in order to compare with the pre-existing situation

Figure 115 – Analysis of envelope and heating strategies – Step 4.

R5		
W5		
F0	F3	
W1SP1	W2SP1	
West	South	North
H1	H2	H3

Legend:

R5: 5 cm of roof insulation; W5: 5 cm of walls insulation; F0: 0 cm of floor insulation; F3: 3 cm of floor insulation; W1SP1: double glazing with solar protection; W2SP1: lower g-value double glazing with solar protection; H1: 3 h heating; H2: 5 h heating; H3: 9 h heating.

Preliminary solutions:

R5-W5-F0-W1SP1

R5-W5-F0-W2SP1

R5-W5-F3-W1SP1

R5-W5-F3-W2SP1

Figure 116 – Preliminary solutions.

6.2.2. ASSESSMENT OF WINTER AND MID-SEASON THERMAL DISCOMFORT IN DIFFERENT CLIMATIC CONDITIONS

This section discusses the assessment of winter and mid-season thermal discomfort in different climatic conditions, regarding the previous discussion about the thermal discomfort of all refurbishment scenarios. The envelope solution defined is the R5-W5 and the envelope solutions that must be discussed are the *floor* insulation (F0 and F3) and the window and solar protections systems (W1SP1 and W2SP1). These two envelope solutions are studied for the three main orientations and for the three defined heating strategies. The ventilation strategy had already been defined (V3).

Table 50 presents the $\%TD_{20}$, the DI_{20}, the EC (kWh) and its costs (€) (0,1409 €/kWh) [155] during the heating season (from the 1st of November until the 30th of April) and the $\%TD_{25}$ and the DI_{25} during the mid-season period (from the 15th of September until the 31st of October and from the 1st of May until the 15th of June) for all the preliminary solutions under study in Porto climatic location (GD 1250 ºC, where GD is the Portuguese number of degree days during heating season [74]). For one simulated year, there are 703 h of winter occupation and 455 h of mid-season occupation. The duration of each period (winter and mid-season) must be considered when analysing the results, once the same value of %TD corresponds to a lower number of discomfort hours in mid-season than in winter.

The selection of a final solution for Porto must take into account the available budget to pay energy consumption for heating. Between the range 130-140 €/year/classroom, a lower heating strategy must be adopted (H1, 3 h heating) but between the range 160-200 €/year/classroom a medium heating strategy can be adopted (H2, 5 h heating) while between the range 200-260 €/year/classroom a more comfortable heating strategy can be adopted (H3, 9 h heating). A higher number of heating hours promotes the reduction of thermal discomfort (number of discomfort hours and ºC.hour of discomfort) but the choice is limited by economic reasons. Whatever is the chosen heating strategy, the final solution for Porto is the R5-W5-F0-W1SP1 (roof, exterior walls and floor insulation with 5, 5 and 0 cm of thickness and double-glazing system with solar protection). The additional floor insulation (F3) promotes a reduction on winter discomfort and an increase on mid-season discomfort. Although the number of mid-season discomfort hours (18 h) is lower than the number of comfort hours in winter obtained by the implementation of F3 (42 h for a west-sided school and H1, H2 and H3 heating strategies), the mid-season discomfort is harder to control once the cooling is not a usual habit in Portuguese schools and was not considered in this intervention strategy. Moreover, the accurate assessment of ground climate conditions must be improved in future developments in order to consider a more realistic mid-season behaviour. The W2SP1 solution can be excluded once there is not an important mid-season discomfort. It was also observed that, for the adopted operation mode of solar protections, there is no need to analyse the three main orientations due to the similar results they show among them (although south orientation during winter has a little better behaviour).

A similar analysis was made in Braga (GD 1491 ºC [74]), Coimbra (GD 1304 ºC [74]) and Lisboa (GD 1071 ºC [74]) (Table 52, Table 53 and Table 54), with the same final solution R5-W5-F0-W1SP1, for the same previous referred reasons.

In Bragança (GD 2015 ºC [74]) (Table 51), the lower heating strategy (H1) do not represent an important reduction of winter discomfort due to its stricter winter climate. The indoor thermal discomfort is always near 100% and a higher investment in heating is required (H2 between the range 260-280 €/year/classroom and H3 between the range 360-410 €/year/classroom). If a non-continuous heating strategy (5 h or 10 h) has to be considered, the chosen solution is R5-W5-F3-W1SP1, with a higher insulated envelope (considering *floor* insulation for winter discomfort reduction). However, in Bragança climate and as future developments, it would be interesting to study the implementation of a continuous heating strategy instead of intermittent heating.

The chosen solution for *roof* is above the required U_{max} for all the studied cities in different winter climatic locations. For that reason, a lower roof insulation thickness was not studied. The chosen solution for *walls* is below the required U_{max} for all the studied cities, except for Bragança, where the chosen solution is a little above the Portuguese requirement for I3 winter climatic zone. The chosen solution for *windows* is below the required U_{max} for all the climatic locations.

Table 50 – $\%TD_{20}$, DI_{20}, EC, energy costs, $\%TD_{25}$ and DI_{25} of the preliminary solutions - Porto.

		Winter												Mid-season					
		W				S				N				W		S		N	
		$\%TD_{20}$	DI_{20}	EC	costs [€]	$\%TD_{20}$	DI_{20}	EC	costs [€]	$\%TD_{20}$	DI_{20}	EC	costs [€]	$\%TD_{25}$	DI_{25}	$\%TD_{25}$	DI_{25}	$\%TD_{25}$	DI_{25}
H1	R5-W5-F0-W1SP1	77%	1241	993	140	74%	1129	982	138	77%	1233	993	140	0%	0.8	0%	0.9	0%	0.6
	R5-W5-F0-W2SP1	77%	1270	996	140	76%	1203	989	139	77%	1265	995	140	0%	0.5	0%	0.6	0%	0.4
	R5-W5-F3-W1SP1	71%	1124	915	129	67%	975	890	125	70%	1106	912	129	4%	12.4	4%	13.4	4%	11
	R5-W5-F3-W2SP1	72%	1166	925	130	70%	1074	909	128	71%	1155	923	130	4%	9.2	4%	10	4%	8.6
H2	R5-W5-F0-W1SP1	50%	681	1381	195	48%	625	1329	187	50%	679	1377	194	0%	0.8	0%	0.9	0%	0.6
	R5-W5-F0-W2SP1	50%	684	1397	197	49%	651	1367	193	50%	683	1395	197	0%	0.5	0%	0.6	0%	0.4
	R5-W5-F3-W1SP1	44%	580	1219	172	41%	510	1148	162	43%	574	1211	171	4%	12.4	4%	13.4	4%	11
	R5-W5-F3-W2SP1	44%	589	1241	175	43%	545	1198	169	44%	584	1236	174	4%	9.2	4%	10	4%	8.6
H3	R5-W5-F0-W1SP1	23%	235	1789	252	21%	220	1699	239	23%	233	1785	252	0%	0.8	0%	0.9	0%	0.6
	R5-W5-F0-W2SP1	22%	227	1813	255	21%	217	1759	248	22%	226	1810	255	0%	0.5	0%	0.6	0%	0.4
	R5-W5-F3-W1SP1	17%	183	1504	212	16%	164	1396	197	17%	179	1493	210	4%	12.4	4%	13.4	4%	11
	R5-W5-F3-W2SP1	17%	178	1530	216	16%	166	1463	206	16%	176	1522	214	4%	9.2	4%	10	4%	8.6

Table 51 – %TD$_{20}$, DI$_{20}$, EC, energy costs, %TD$_{25}$ and DI$_{25}$ of the preliminary solutions - Bragança.

		Winter												Mid-season					
		W				S				N				W		S		N	
		%TD$_{20}$	DI$_{20}$	EC	costs [€]	%TD$_{20}$	DI$_{20}$	EC	costs [€]	%TD$_{20}$	DI$_{20}$	EC	costs [€]	%TD$_{25}$	DI$_{25}$	%TD$_{25}$	DI$_{25}$	%TD$_{25}$	DI$_{25}$
H1	R5-W5-F0-W1SP1	98%	4194	1195	168	98%	4016	1193	168	98%	4174	1194	168	1%	0.8	1%	0.8	1%	0.4
	R5-W5-F0-W2SP1	98%	4228	1194	168	98%	4122	1194	168	98%	4216	1194	168	0%	0.3	1%	0.2	0%	0.1
	R5-W5-F3-W1SP1	97%	3809	1182	167	96%	3544	1178	166	96%	3765	1181	166	4%	15.7	4%	16.2	4%	14.4
	R5-W5-F3-W2SP1	97%	3864	1185	167	97%	3703	1182	167	97%	3836	1184	167	4%	11.8	4%	12.2	3%	11.1
H2	R5-W5-F0-W1SP1	92%	3115	1952	275	90%	2951	1939	273	92%	3097	1951	275	1%	0.8	1%	0.8	1%	0.4
	R5-W5-F0-W2SP1	93%	3133	1956	276	92%	3033	1950	275	92%	3121	1956	276	0%	0.3	1%	0.2	0%	0.1
	R5-W5-F3-W1SP1	83%	2626	1861	262	80%	2407	1826	257	83%	2588	1857	262	4%	15.7	4%	16.2	4%	14.4
	R5-W5-F3-W2SP1	84%	2638	1846	260	83%	2502	1858	262	84%	2615	1873	264	4%	11.8	4%	12.2	3%	11.1
H3	R5-W5-F0-W1SP1	80%	2091	2913	410	77%	1951	2876	405	80%	2073	2910	410	1%	0.8	1%	0.8	1%	0.4
	R5-W5-F0-W2SP1	80%	2086	2925	412	79%	2000	2905	409	80%	2075	2924	412	0%	0.3	1%	0.2	0%	0.1
	R5-W5-F3-W1SP1	66%	1543	2643	372	63%	1380	2567	362	65%	1512	2634	371	4%	15.7	4%	16.2	4%	14.4
	R5-W5-F3-W2SP1	67%	1522	2665	375	63%	1420	2622	369	66%	1503	2659	375	4%	11.8	4%	12.2	3%	11.1

Table 52 – %TD$_{20}$, DI$_{20}$, EC, energy costs, %TD$_{25}$ and DI$_{25}$ of the preliminary solutions - Braga.

		Winter												Mid-season					
		W				S				N				W		S		N	
		%TD$_{20}$	DI$_{20}$	EC	costs [€]	%TD$_{20}$	DI$_{20}$	EC	costs [€]	%TD$_{20}$	DI$_{20}$	EC	costs [€]	%TD$_{25}$	DI$_{25}$	%TD$_{25}$	DI$_{25}$	%TD$_{25}$	DI$_{25}$
H1	R5-W5-F0-W1SP1	86%	1881	1086	153	84%	1754	1080	152	86%	1869	1086	153	2%	5.0	2%	5.1	2%	4.4
	R5-W5-F0-W2SP1	87%	1900	1088	153	86%	1825	1084	153	87%	1893	1088	153	2%	3.5	2%	3.6	1%	3.3
	R5-W5-F3-W1SP1	80%	1783	1024	144	77%	1605	1009	142	80%	1758	1023	144	7%	29.7	7%	30.5	7%	27.9
	R5-W5-F3-W2SP1	81%	1815	1031	145	79%	1706	1022	144	81%	1798	1031	145	6%	24.3	6%	24.9	6%	23.2
H2	R5-W5-F0-W1SP1	66%	1134	1609	227	63%	1051	1573	222	66%	1127	1607	226	2%	5.0	2%	5.1	2%	4.4
	R5-W5-F0-W2SP1	67%	1130	1622	229	65%	1078	1601	226	67%	1125	1620	228	2%	3.5	2%	3.6	1%	3.3
	R5-W5-F3-W1SP1	59%	1013	1465	206	55%	897	1413	199	58%	995	1459	206	7%	29.7	7%	30.5	7%	27.9
	R5-W5-F3-W2SP1	59%	1013	1482	209	57%	941	1451	204	58%	1001	1479	208	6%	24.3	6%	24.9	6%	23.2
H3	R5-W5-F0-W1SP1	42%	562	2149	303	40%	519	2073	292	42%	556	2144	302	2%	5.0	2%	5.1	2%	4.4
	R5-W5-F0-W2SP1	42%	544	2167	305	40%	517	2123	299	41%	539	2164	305	2%	3.5	2%	3.6	1%	3.3
	R5-W5-F3-W1SP1	34%	443	1877	264	31%	390	1778	251	34%	432	1866	263	7%	29.7	7%	30.5	7%	27.9
	R5-W5-F3-W2SP1	34%	427	1897	267	32%	392	1838	259	34%	419	1891	266	6%	24.3	6%	24.9	6%	23.2

Table 53 – %TD_{20}, DI_{20}, EC, energy costs, %TD_{25} and DI_{25} of the preliminary solutions - Coimbra.

		Winter												Mid-season					
		W				S				N				W		S		N	
		%TD_{20}	DI_{20}	EC	costs [€]	%TD_{20}	DI_{20}	EC	costs [€]	%TD_{20}	DI_{20}	EC	costs [€]	%TD_{25}	DI_{25}	%TD_{25}	DI_{25}	%TD_{25}	DI_{25}
H1	R5-W5-F0-W1SP1	79%	1393	1025	144	77%	1279	1016	143	79%	1381	1025	144	2%	6.2	2%	6.5	2%	5.6
	R5-W5-F0-W2SP1	80%	1417	1027	145	78%	1348	1022	144	80%	1410	1027	145	2%	4.8	2%	4.9	2%	4.4
	R5-W5-F3-W1SP1	74%	1325	956	135	71%	1167	935	132	73%	1301	953	134	9%	39.4	9%	41.2	8%	37.3
	R5-W5-F3-W2SP1	75%	1365	965	136	73%	1268	952	134	75%	1349	963	136	7%	32.9	8%	33.9	7%	31.7
H2	R5-W5-F0-W1SP1	53%	758	1470	207	50%	696	1422	200	53%	752	1466	207	2%	6.2	2%	6.5	2%	5.6
	R5-W5-F0-W2SP1	53%	758	1485	209	51%	721	1456	205	52%	754	1482	209	2%	4.8	2%	4.9	2%	4.4
	R5-W5-F3-W1SP1	49%	682	1322	186	44%	601	1254	177	48%	669	1313	185	9%	39.4	9%	41.2	8%	37.3
	R5-W5-F3-W2SP1	48%	688	1343	189	46%	638	1303	184	48%	681	1337	188	7%	32.9	8%	33.9	7%	31.7
H3	R5-W5-F0-W1SP1	28%	277	1923	271	25%	255	1835	259	28%	274	1916	270	2%	6.2	2%	6.5	2%	5.6
	R5-W5-F0-W2SP1	27%	267	1942	274	25%	253	1891	266	27%	264	1938	273	2%	4.8	2%	4.9	2%	4.4
	R5-W5-F3-W1SP1	22%	225	1655	233	19%	199	1546	218	21%	220	1641	231	9%	39.4	9%	41.2	8%	37.3
	R5-W5-F3-W2SP1	21%	219	1679	237	19%	202	1613	227	20%	215	1669	235	7%	32.9	8%	33.9	7%	31.7

Table 54 – %TD$_{20}$, DI$_{20}$, EC, energy costs, %TD$_{25}$ and DI$_{25}$ of the preliminary solutions - Lisboa.

		Winter												Mid-season					
		W				S				N				W		S		N	
		%TD$_{20}$	DI$_{20}$	EC	costs [€]	%TD$_{20}$	DI$_{20}$	EC	costs [€]	%TD$_{20}$	DI$_{20}$	EC	costs [€]	%TD$_{25}$	DI$_{25}$	%TD$_{25}$	DI$_{25}$	%TD$_{25}$	DI$_{25}$
H1	R5-W5-F0-W1SP1	68%	915	890	125	65%	800	874	123	68%	904	889	125	5%	13.0	5%	13.2	5%	11.8
	R5-W5-F0-W2SP1	70%	956	896	126	68%	887	887	125	70%	950	896	126	4%	9.9	4%	10.1	4%	9.3
	R5-W5-F3-W1SP1	54%	705	742	105	48%	570	704	99	54%	685	736	104	24%	131.7	24%	131.7	24%	124
	R5-W5-F3-W2SP1	56%	750	757	107	54%	665	733	103	56%	737	753	106	21%	113.2	22%	113.5	21%	109.3
H2	R5-W5-F0-W1SP1	40%	482	1190	168	38%	435	1126	159	40%	479	1185	167	5%	13.0	5%	13.2	5%	11.8
	R5-W5-F0-W2SP1	41%	493	1215	171	39%	464	1176	166	40%	491	1212	171	4%	9.9	4%	10.1	4%	9.3
	R5-W5-F3-W1SP1	28%	358	937	132	26%	305	851	120	28%	350	925	130	24%	131.7	24%	131.7	24%	124
	R5-W5-F3-W2SP1	30%	373	963	136	28%	340	911	128	30%	368	956	135	21%	113.2	22%	113.5	21%	109.3
H3	R5-W5-F0-W1SP1	15%	143	1509	213	13%	132	1406	198	15%	142	1500	211	5%	13.0	5%	13.2	5%	11.8
	R5-W5-F0-W2SP1	15%	141	1542	217	13%	134	1481	209	15%	140	1537	217	4%	9.9	4%	10.1	4%	9.3
	R5-W5-F3-W1SP1	9%	99	1134	160	8%	89	1015	143	9%	97	1117	157	24%	131.7	24%	131.7	24%	124.0
	R5-W5-F3-W2SP1	9%	101	1166	164	8%	94	1093	154	9%	100	1156	163	21%	113.2	22%	113.5	21%	109.3

The proposed solutions for each heating strategy (H1, H2 and H3) are evidenced in Figure 117, Figure 118 and Figure 119.

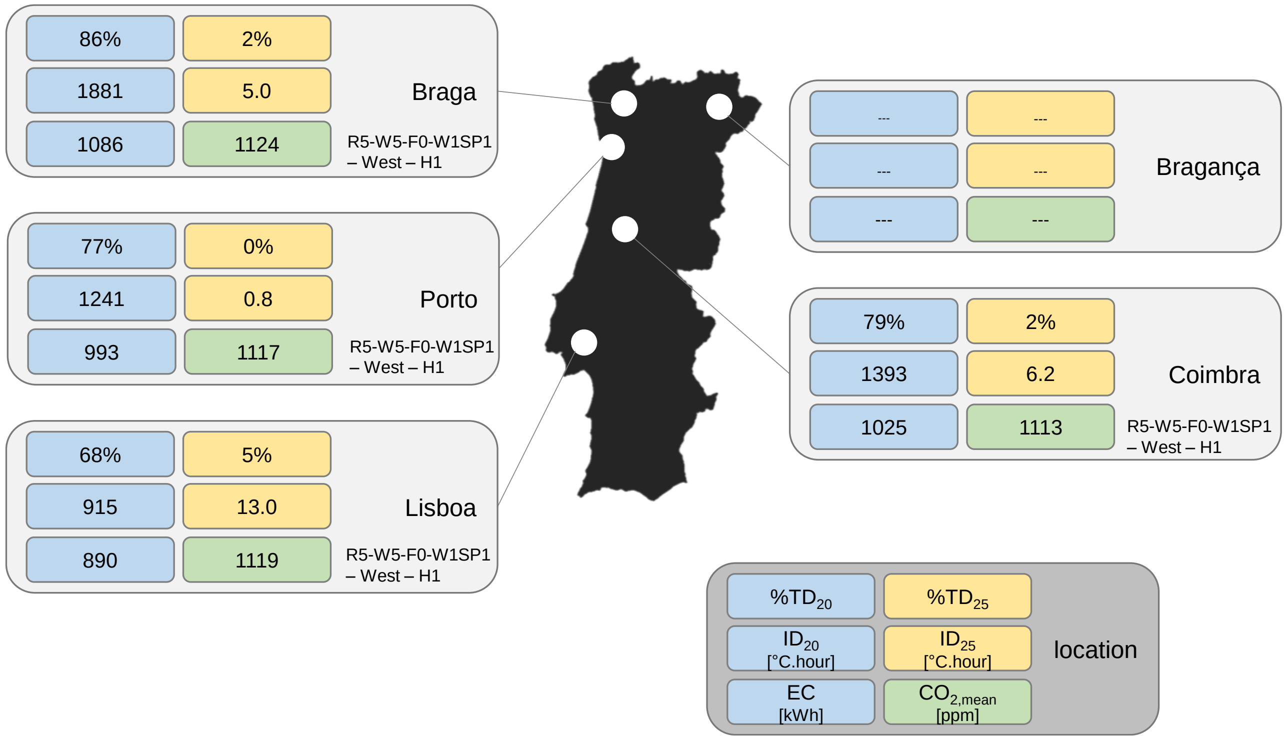


Figure 117 – Global analysis: winter and mid-season discomfort, IAQ and EC – 5 Portuguese locations - west-H1.

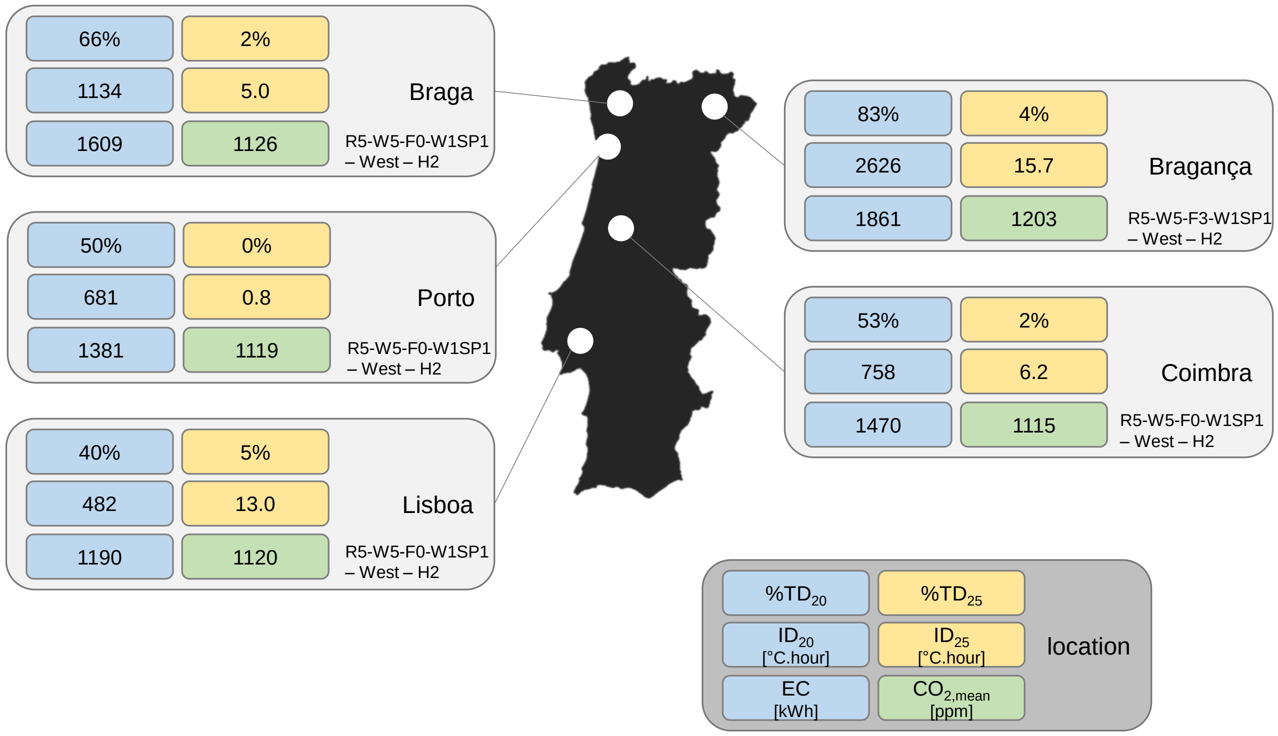


Figure 118 - Global analysis: winter and mid-season discomfort, IAQ and EC – 5 Portuguese locations - west-H2.

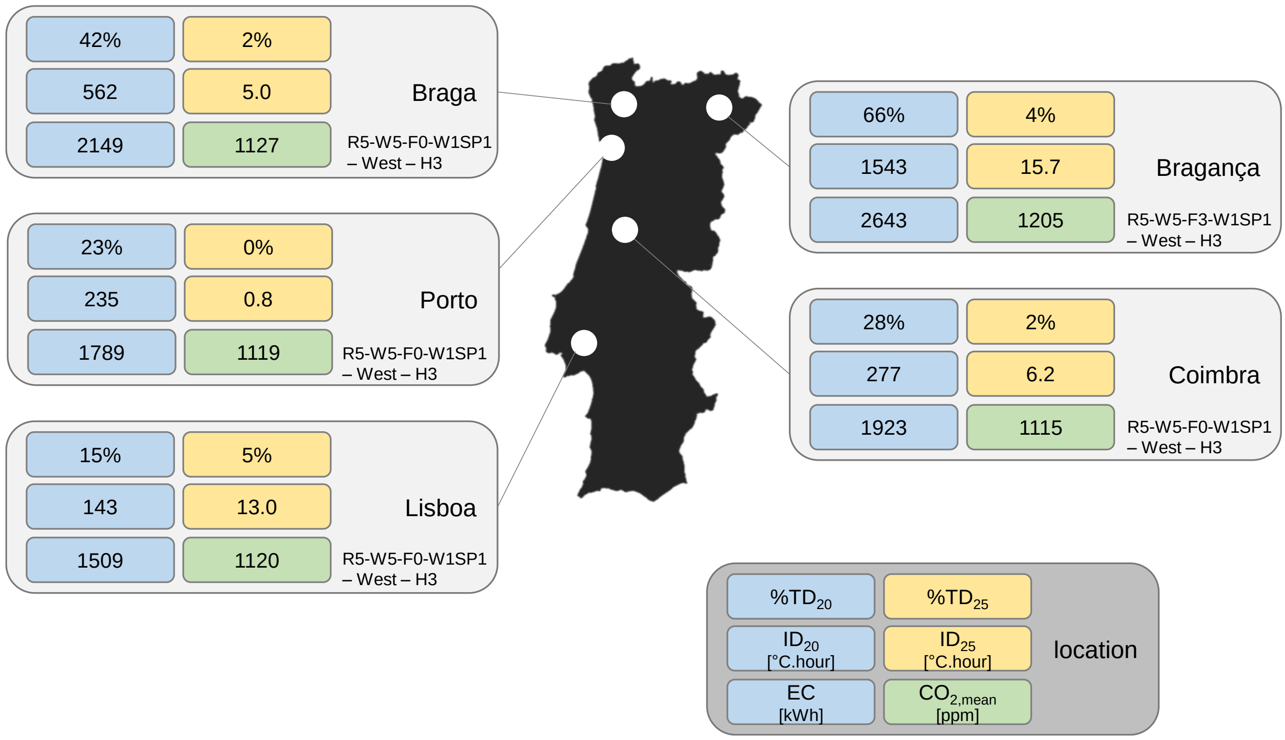


Figure 119 - Global analysis: winter and mid-season discomfort, IAQ and EC – 5 Portuguese locations - west-H3.

6.3. FINAL CONSIDERATIONS

Guidelines/recommendations were developed for *Brandão* schools in different Portuguese cities and with different orientations.

The main conclusions of this chapter are:

- ❖ A heating strategy must be considered in order to minimize the discomfort or to achieve comfort conditions. The selection of a final solution must take into account the available budget to pay energy consumption for heating. A higher number of heating hours promotes the reduction of thermal discomfort (number of discomfort hours and ºC.hour of discomfort) but the choice is limited by economic reasons.
- ❖ Whatever is the chosen heating strategy, the final solution for Porto is the R5-W5-F0-W1SP1 (roof, exterior walls and floor insulation with 5, 5 and 0 cm of thickness and double-glazing system with solar protection). The same final solution (R5-W5-F0-W1SP1) was considered for Braga, Coimbra and Lisboa.
- ❖ The additional *floor* insulation (F3) would have promoted, in some situations, a reduction in winter discomfort and an increase in mid-season discomfort. However, the winter discomfort can be minimized with heating strategies, but the mid-season discomfort is harder to control in free-running conditions.

- In Bragança, the lower heating strategy (H1) must be excluded and, as future developments, it would be interesting to study the implementation of a continuous heating strategy instead of intermittent heating.
- In Bragança, the final solution for H2 and H3 heating strategies is the R5-W5-F3-W1SP1 (*roof*, *walls* and *floor* insulation with 5, 5 and 3 cm of thickness and double-glazing system with solar protection). The high winter discomfort in Bragança justifies the *floor* insulation solution.

7
Conclusion

7.1. MAIN CONSIDERATIONS

This work has contributed to the refurbishment of *Brandão* school buildings in different climatic conditions and in free-running conditions or with a strategy of intermittent heating, considering the actual capacity to support the operating costs.

The intermittent and irregular heating in Portuguese schools turns these schools into a particular situation between the analytical and adaptive models. The *minimizing discomfort* and *comfort* approach were important strategies to assess thermal comfort in *Brandão* schools. The IAQ and the energy consumption were not a concern in *Brandão* schools in pre-existing conditions. The refurbishment proposal for these schools must improve the in-service thermal comfort conditions and ensure acceptable CO_2 levels and low energy consumption.

The main conclusions of this Thesis are:

Pre-existing situation

- There is an important in-service thermal discomfort inside the *Brandão* classrooms in Porto in the present free-running conditions. The thermal discomfort was quantified by discomfort indicators in ºC.hour and in percentage of time of discomfort (DI_{20} and $\%TD_{20}$) and also by mean values of T and RH. The discomfort assessment was made during the occupation period.
- The summer was not an actual concern in the pre-existing situation in Porto. In fact, the summer in schools should be called "mid-season", once there is not occupation during the

summer period. The mid-season starts in the middle of September until the end of October and re-starts in May until the middle of June. The mid-season period is shorter than the winter period, which also justifies its lower impact on the thermal discomfort.

- ❖ The IAQ was not a concern in *Brandão* schools in pre-existing conditions. In the winter before the refurbishment of the prototype, the CO_2 was below 1250 ppm (national requirement) [20] during 50-80% of the occupation period and below 1500 ppm (international requirement) [23] during 70-90%.

Indoor Air Quality

- ❖ The partition wall between the classroom and the circulation zone allowed the control of the ventilation and of IAQ in the prototype. The ventilation system consisted in a naturally filtered inflow through the envelope and forced airflow to the circulation zone. There was an expected increase of CO_2 inside the classroom for the corresponding months before and after the refurbishment of the prototype, although the mean CO_2 remained below the defined 1500 ppm international requirement, with 60% of the occurrences below 1500 ppm after the refurbishment.
- ❖ The higher ventilation rate studied by numerical simulation (500 m^3/h) fulfils the CO_2 international standards requirement of 1500 ppm. Since the CO_2 production is a result of the metabolism and depends mainly on the occupation, this conclusion was also reached for different cities, building orientations and heating strategies.

Prototype and refurbishment strategies

- ❖ The prototype in a *Brandão* school in Porto was developed within the scope of this work and had an important role in the proposal of a low-cost refurbishment strategy to improve the hygrothermal conditions of these schools (with a controlled increase of EC). This refurbishment can be replicated to other *Brandão* schools and the methodology can be applied to other typologies. The prototype refurbishment was suitable and useful in winter. The increased *roof* insulation thickness was the main improvement in the prototype. Although the mean $\%TD_{20}$ remained 100%, there was an important reduction of the discomfort after the refurbishment in free-running conditions.
- ❖ After the refurbishment of the prototype, it was found that the mid-season performance of the west-sided *Brandão* classroom depended on the climate severity in each year and location. The results of the survey confirmed the users' satisfaction after the refurbishment but it was not found any correspondence between the users' perception and the hygrothermal and IAQ conditions inside the classroom.

- ❖ The sensitivity analysis revealed that the insulation of the envelope has an important role in the reduction of winter discomfort in lower heating strategies and in EC in higher heating strategies (in all the studied cities). The *roof* insulation is very relevant for both situations, but the additional insulation thicknesses do not represent an important reduction of winter discomfort nor EC.
- ❖ Considering winter energy consumption, when the heating strategy is lower (3 h heating), the envelope solution is less important than when the heating strategy is higher (5 h and 9 h heating). This indicates that the investment in better envelope solutions (*roof*, *walls*, *floor* and solar protection) has little impact on EC when the adopted heating strategy is weak. The higher is the heating strategy, the more relevant the envelope insulation solution is, once it minimizes the EC.
- ❖ The window must be double-glazed in order to minimize the winter discomfort and the EC in lower and higher heating strategies, respectively. The exterior solar protection is an important element due to the illumination strategy inside classrooms.
- ❖ The installation of a lower-g window (in a window system with solar protections) is not important in any studied Portuguese climatic location. The mid-season discomfort in Porto, Bragança, Braga, Coimbra and Lisboa is low and the investment in improved windows with lower g-value is not relevant for mid-season conditions.
- ❖ The additional *floor* insulation represents a reduction of winter discomfort in all the studied cities, but it also represents an increased mid-season discomfort. It is also important to notice that the winter discomfort can be controlled by heating strategies and the mid-season discomfort is harder to control once the cooling is not a usual habit in Portuguese schools and was not considered in this intervention strategy.
- ❖ The analysis of *floor* insulation performance was defined for *Brandão* schools with a ground floor and depends on the climatic ground conditions defined and also on Wufi inputs definition. The assessment of ground climatic conditions will be referred in future developments.
- ❖ The building orientation affected the winter and mid-season thermal comfort results but the solutions to adopt are not affected by the building orientation. This was concluded for the solar protection operation mode strategy defined.

<u>*Heating strategies*</u>

- ❖ In spite of the benefits of the low-cost refurbishment of the prototype even in free-running conditions, heating has an important role in the reduction of the discomfort. In the prototype (Porto), the first three hours of heating (from free-running strategy to 3 h heating) represented the most important share of discomfort decrease (in ºC.hour) with a low increase in energy consumption.

- The sensitivity analysis also revealed the importance of considering a heating strategy in all the five Portuguese studied cities (Porto, Bragança, Braga, Coimbra and Lisboa). An intermittent heating strategy benefits the thermal comfort conditions inside the classroom in Porto, Braga, Coimbra and Lisboa climatic locations. The selection of a heating strategy must take into account the available budget to pay energy consumption for heating.
- In Bragança, a lower heating strategy does not represent a relevant reduction of winter discomfort due to its stricter winter climate. Neither are the higher intermittent heating strategies (H2 and H3) enough to minimize the discomfort. A higher investment in heating is required and it would be interesting to study the implementation of a continuous heating strategy in Bragança, considering heating systems and strategies currently adopted in Nordic countries and the applicable legislation.

Energy costs

- The experimental analysis of free-running conditions confirmed the *in-situ* winter thermal discomfort in Porto. The 10 h heating strategy was the most appropriate for reaching the 20 ºC comfort T and represented an energy consumption of 36 kWh/day (experimental measurement) for this classroom, which is 5€/day (0.1409 €/kWh) [155]. Considering a typical *Brandão* school with four blocks (28 classrooms) and four heating months, the investment would represent about 12 000 €/year for electric heating.
- Numerical simulation studies showed that a 3 h heating strategy in a refurbished *Brandão* school represents 130-140 €/year/classroom in Porto, 170 €/year/classroom in Bragança, 140-160 €/year/classroom in Braga, 130-150 €/year/classroom in Coimbra and 100-130 €/year/classroom in Lisboa, which means 4000, 5000, 4500, 4200 and 3600 €/year/school (28 classrooms) in Porto, Bragança, Braga, Coimbra and Lisboa, respectively. For a 5 h heating strategy, the energy costs for heating are 5500, 7500, 6500, 6000 and 5000 €/year/school for the referred cities. For a 9 h heating strategy, the energy costs for heating are 7000, 11000, 8500, 7500 and 6000 €/year/school for the same referred cities, taking into account the winter heating calendar and schedule considered during simulation. The differences between Porto experimental and numerical results are explained by the difference between the number of heating hours (10 h/day during experimental analysis, whatever was the daily schedule or a maximum of 9 h/day during simulation regarding the daily schedule) and also the unpredictable ventilation strategy during experimental monitoring.

Guidelines/recommendations

- *Guidelines/recommendations* were developed for *Brandão* schools in different Portuguese cities and with different orientations. A heating strategy must be considered in order to minimize the discomfort or to achieve comfort conditions. With an optimized envelope, it is possible to decrease discomfort conditions with a low EC investment. An optimized envelope for intermittent heating strategies consists of the insulation of the *roof* and of the exterior *walls*. It is not necessary to install high insulation thicknesses. Considering the intermittent heating, the *roof* thermal transmittance of 0.56 W/(m^2.ºC) was the chosen *roof* solution for all the studied cities. The exterior wall thermal transmittance of 0.53 W/(m^2.ºC) was the chosen exterior *wall* solution. The double-glazing window with thermal transmittance of 3.3 W/(m^2.ºC) and g-value 0.75 was the one chosen for the current situations. In Bragança, the high winter discomfort justifies the *floor* insulation solution.
- In *minimizing discomfort* approach (low intermittent heating strategies) the best envelope refurbishment strategies satisfy the proposed reduction of winter discomfort (in all the studied cities, except for Bragança).
- The mid-season discomfort was also minimized considering the discomfort indicators (DI_{25} and $\%TD_{25}$) but the EN 15251 adaptive approach revealed that there was not important mid-season discomfort for all the studied climatic conditions. The DI_{25} and $\%TD_{25}$ analysis is more demanding than the adaptive EN 15251 model for mid-season conditions.

7.2. FUTURE DEVELOPMENTS

The following topics can be suggested as future or complementary developments:

- An additional improvement of the prototype refurbishment. The installation of photovoltaic modules could be interesting to assess, by experimental monitoring, the importance of renewable energies on comfort and EC.
- The improvement of the ventilation system. It could be interesting to improve the real in-service ventilation rate to the 500 m^3/h studied by numerical simulation, or even to 600 m^3/h [20] (24 m^3/(hour.person) and 25 students). It could be also interesting to prepare a sensitivity analysis regarding a free-night cooling strategy during mid-season.
- An assessment of ground climatic conditions for each studied Portuguese city. A more complete study about temperature amplitude should be done and also a clarification about the Wufi Plus input data (temperature), namely the ground depth to which it refers.
- An assessment of the T stratification effect. The study and mitigation of the stratification effect could be considered in future experimental and simulation works.

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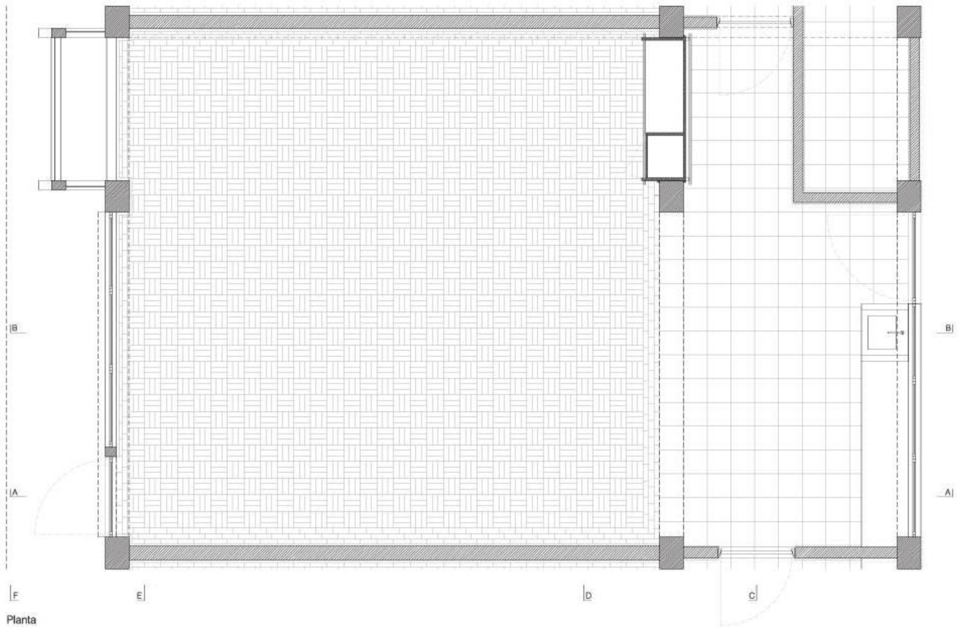
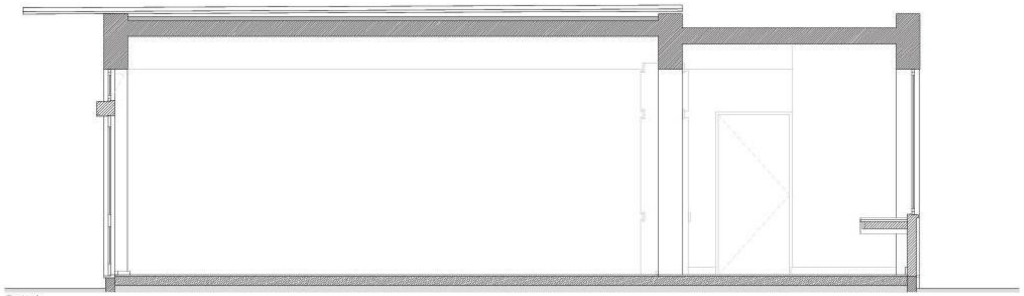
APPENDIX A – REFURBISHMENT PROCESS OF ESCOLA EB 2,3 DE PARANHOS, PORTO - DRAWING COMPONENTS (WITHOUT SCALE)

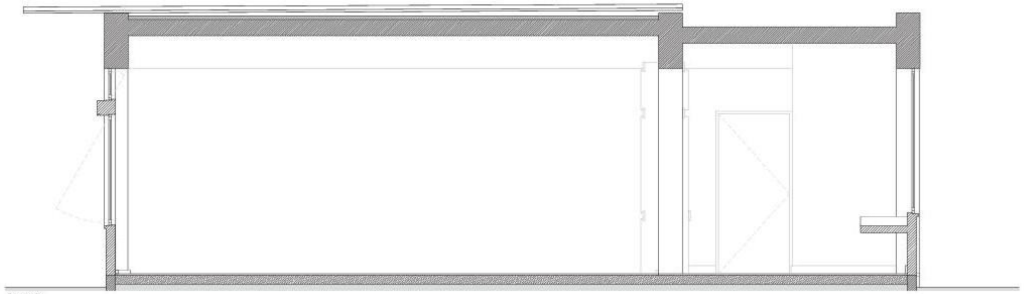


Planta

Arquitectura:	Notas:	Designação:	N.º de desenho:
André Freire de Almeida, Arquitecto e: andrefreirealmeida@gmail.com t: 911 936 504	Nos desenhos prevalecem as medidas cotadas. As medidas cotadas devem ser previamente confirmadas em obra. Em caso de incoerência entre os desenhos, prevalece a escala de maior ampliação.	ESTUDO PRÉVIO ESCOLA DE PARANHOS - SALA PROTÓTIPO EXISTENTE - PLANTA	EP.001.03 Data: 22 Mar 2016 Escala: 1/50

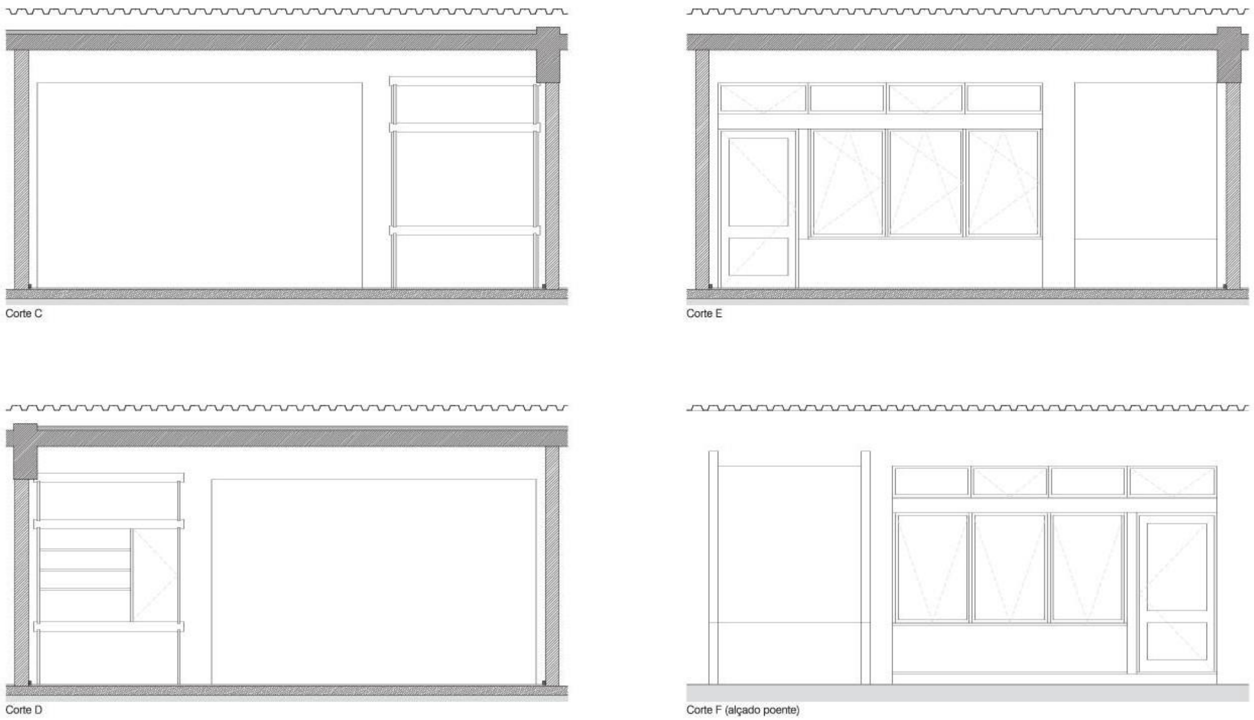


Corte A

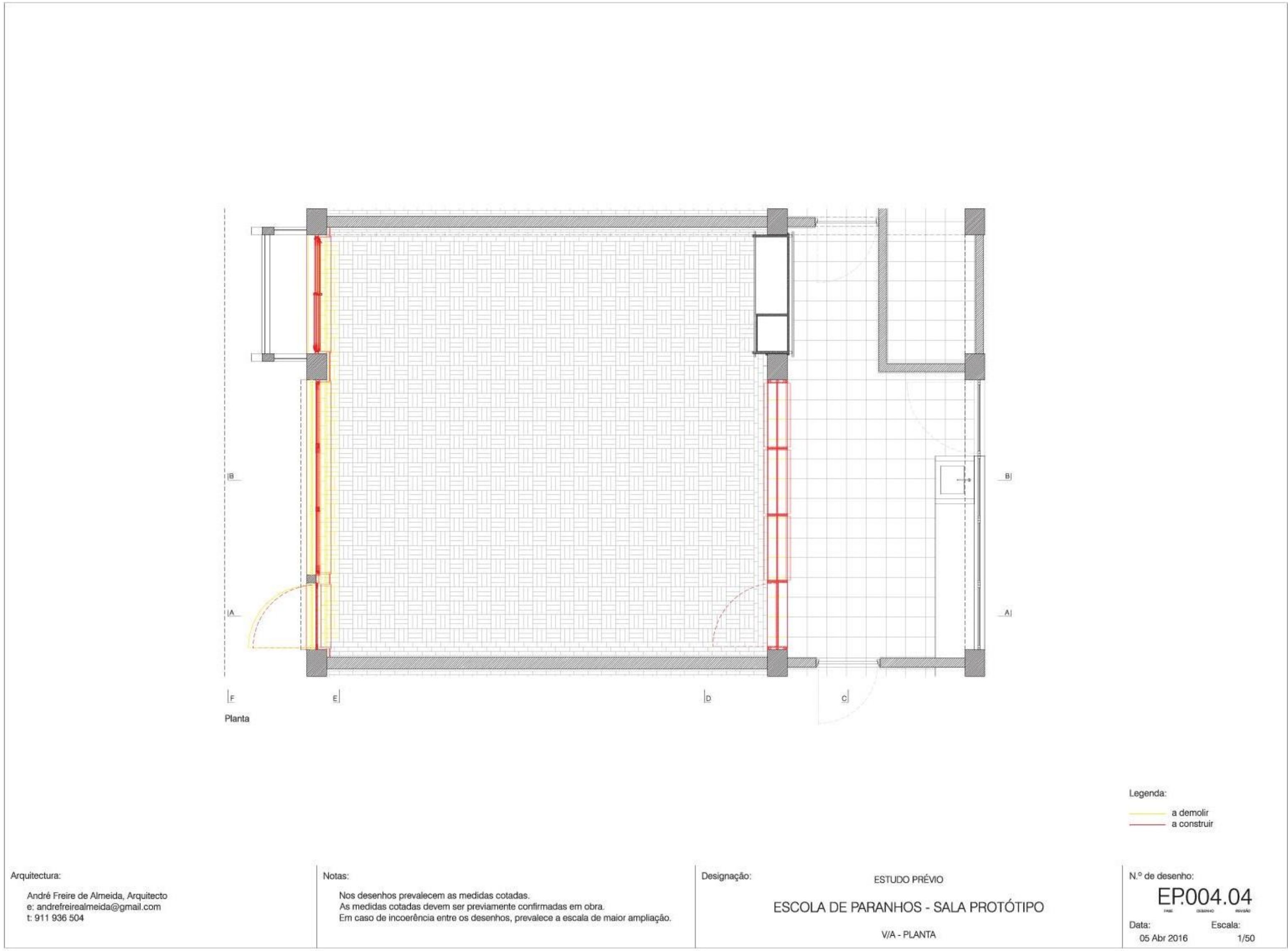


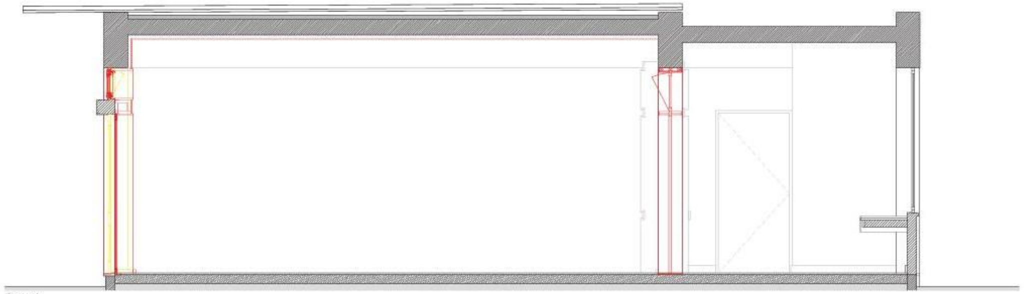
Corte B

Arquitectura:	Notas:	Designação:	N.º de desenho:
André Freire de Almeida, Arquitecto e: andrefreirealmeida@gmail.com t: 911 936 504	Nos desenhos prevalecem as medidas cotadas. As medidas cotadas devem ser previamente confirmadas em obra. Em caso de incoerência entre os desenhos, prevalece a escala de maior ampliação.	ESTUDO PRÉVIO ESCOLA DE PARANHOS - SALA PROTÓTIPO EXISTENTE - CORTES A e B	EP.002.03 Data: 23 Mar 2016 Escala: 1/50

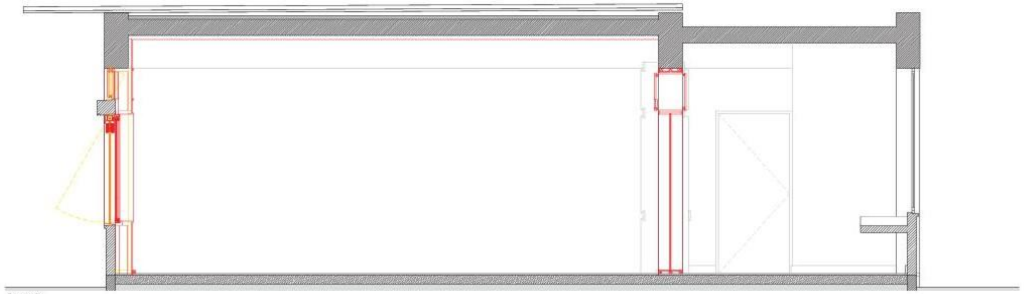


Arquitectura: André Freire de Almeida, Arquitecto e: andrefreirealmeida@gmail.com t: 911 936 504	Notas: Nos desenhos prevalecem as medidas cotadas. As medidas cotadas devem ser previamente confirmadas em obra. Em caso de incoerência entre os desenhos, prevalece a escala de maior ampliação.	Designação: ESTUDO PRÉVIO ESCOLA DE PARANHOS - SALA PROTÓTIPO EXISTENTE - CORTES C, D, E e F	N.º de desenho: EP.003.03 Data: 23 Mar 2016 Escala: 1/50


B
A
B
A
F
E
D
C
Planta
Legenda:
a demolir
a construir
Arquitectura:
André Freire de Almeida, Arquitecto
e: andrefreirealmeida@gmail.com
t: 911 936 504
Notas:
Nos desenhos prevalecem as medidas cotadas.
As medidas cotadas devem ser previamente confirmadas em obra.
Em caso de incoerência entre os desenhos, prevalece a escala de maior ampliação.
Designação:
ESTUDO PRÉVIO
ESCOLA DE PARANHOS - SALA PROTÓTIPO
V/A - PLANTA
N.º de desenho:
EP.004.04
Data:
05 Abr 2016
Escala:
1/50



Corte A



Corte B

Legenda:

- a demolir
- a construir

Arquitectura:

André Freire de Almeida, Arquitecto
e: andrefreirealmeida@gmail.com
t: 911 936 504

Notas:

Nos desenhos prevalecem as medidas cotadas.
As medidas cotadas devem ser previamente confirmadas em obra.
Em caso de incoerência entre os desenhos, prevalece a escala de maior ampliação.

Designação:

ESTUDO PRÉVIO

ESCOLA DE PARANHOS - SALA PROTÓTIPO

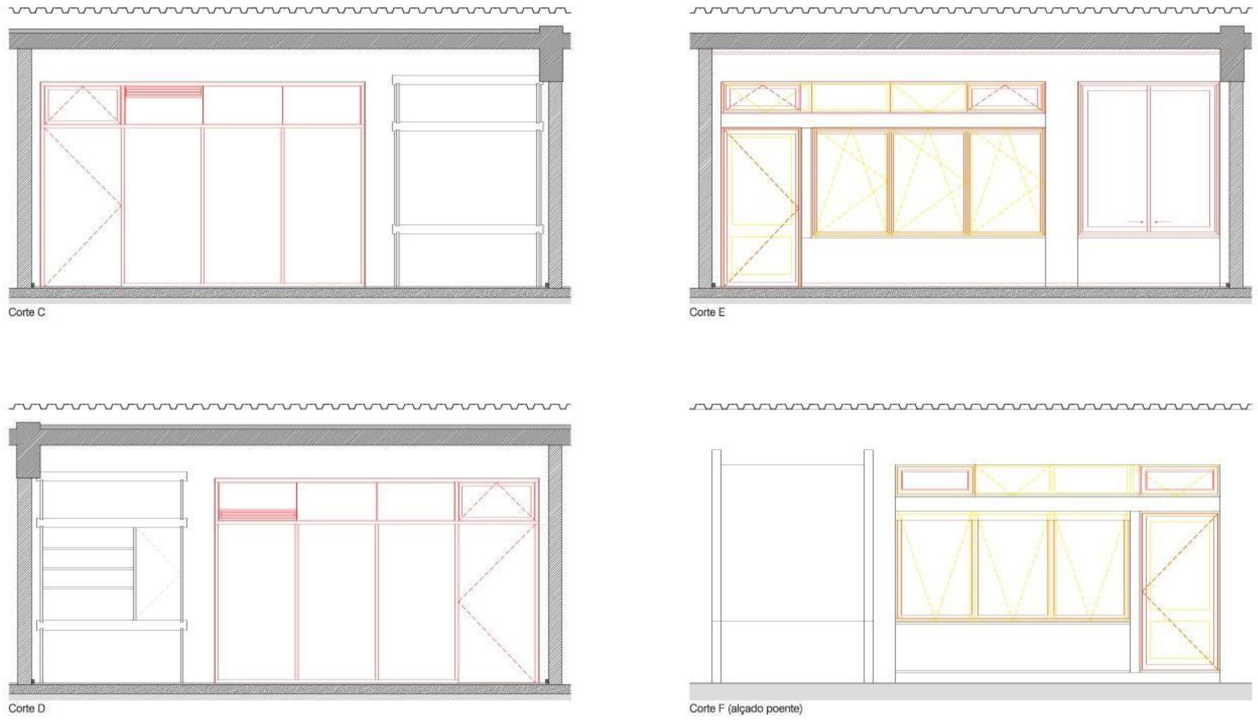
V/A - CORTES A e B

N.º de desenho:

EP.005.04

Data: 05 Abr 2016

Escala: 1/50



Arquitectura:

André Freire de Almeida, Arquitecto
e: andrefreirealmeida@gmail.com
t: 911 936 504

Notas:

Nos desenhos prevalecem as medidas cotadas.
As medidas cotadas devem ser previamente confirmadas em obra.
Em caso de incoerência entre os desenhos, prevalece a escala de maior ampliação.

Designação:

ESTUDO PRÉVIO

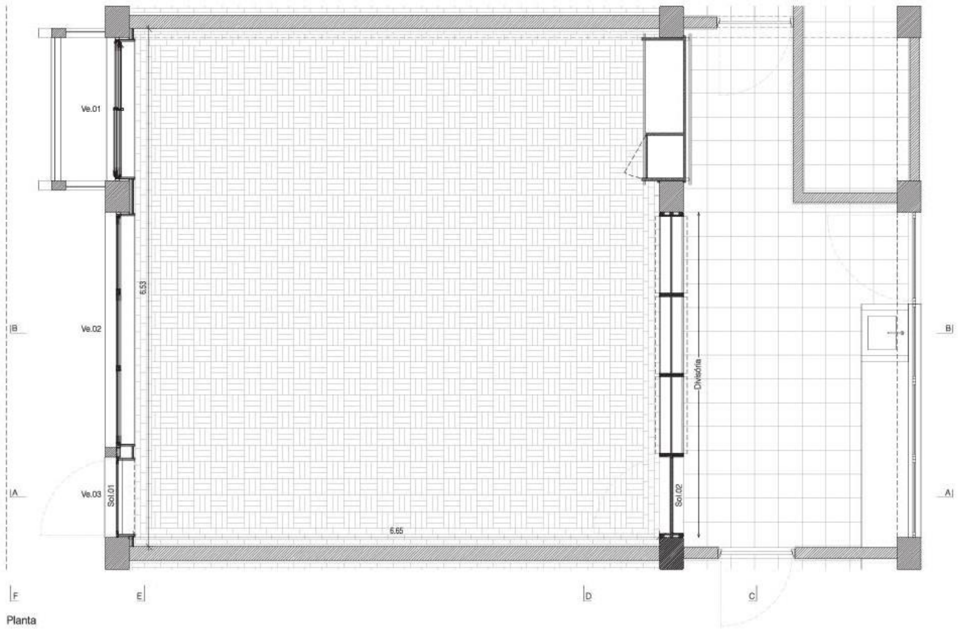
ESCOLA DE PARANHOS - SALA PROTÓTIPO

V/A - CORTES C, D, E e F

N.º de desenho: EP.006.04

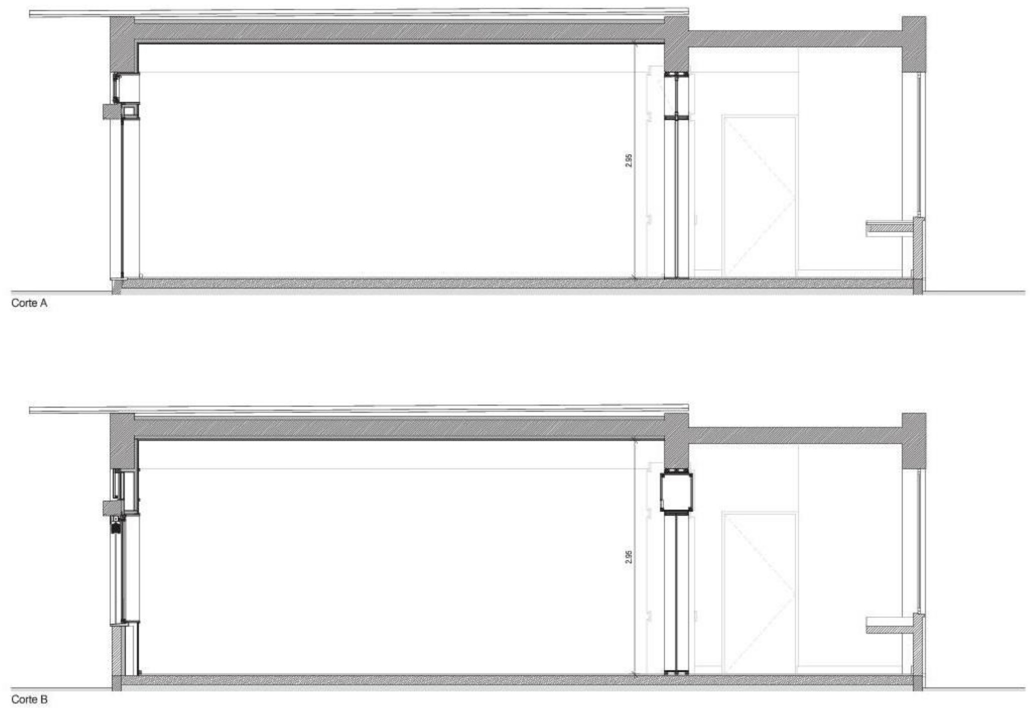
Data: 05 Abr 2016

Escala: 1/50



Planta

Arquitectura:	Notas:	Designação:	N.º de desenho:
André Freire de Almeida, Arquitecto e: andrefreirealmeida@gmail.com t: 911 936 504	Nos desenhos prevalecem as medidas cotadas. As medidas cotadas devem ser previamente confirmadas em obra. Em caso de incoerência entre os desenhos, prevalece a escala de maior ampliação.	ESTUDO PRÉVIO ESCOLA DE PARANHOS - SALA PROTÓTIPO PROPOSTO - PLANTA	EP.007.04 Data: 05 Abr 2016 Escala: 1/50



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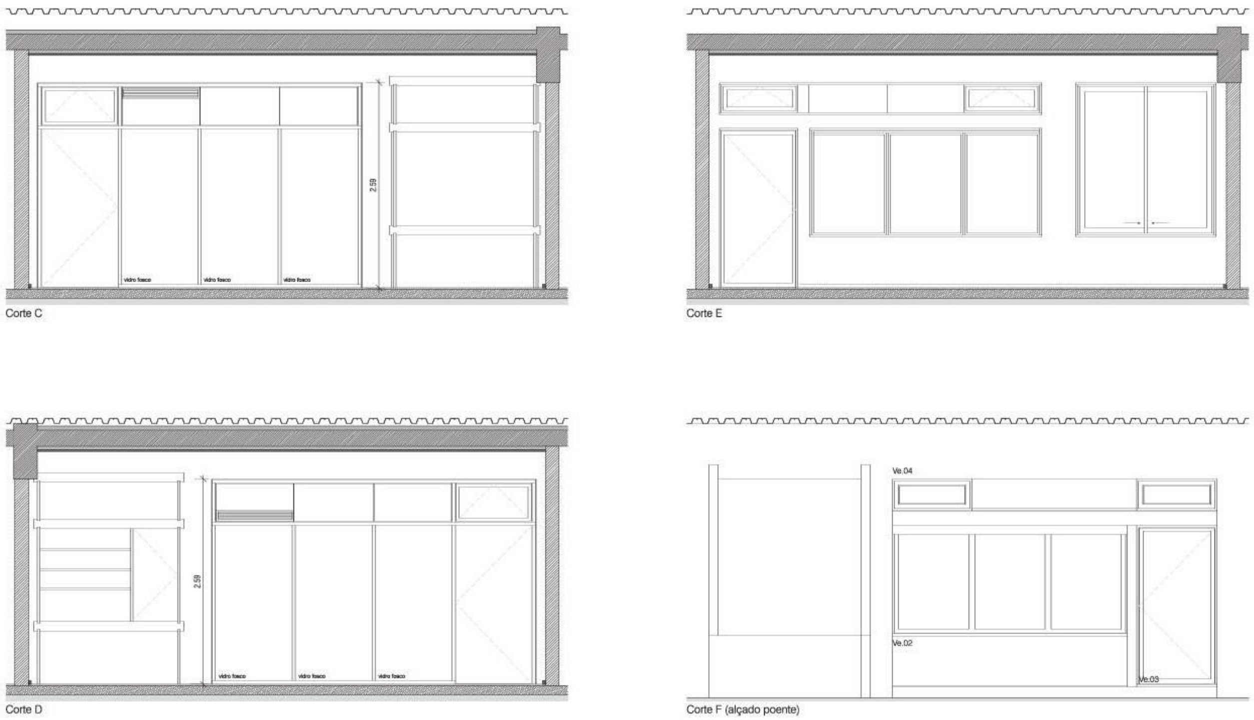

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ESTUDO PRÉVIO

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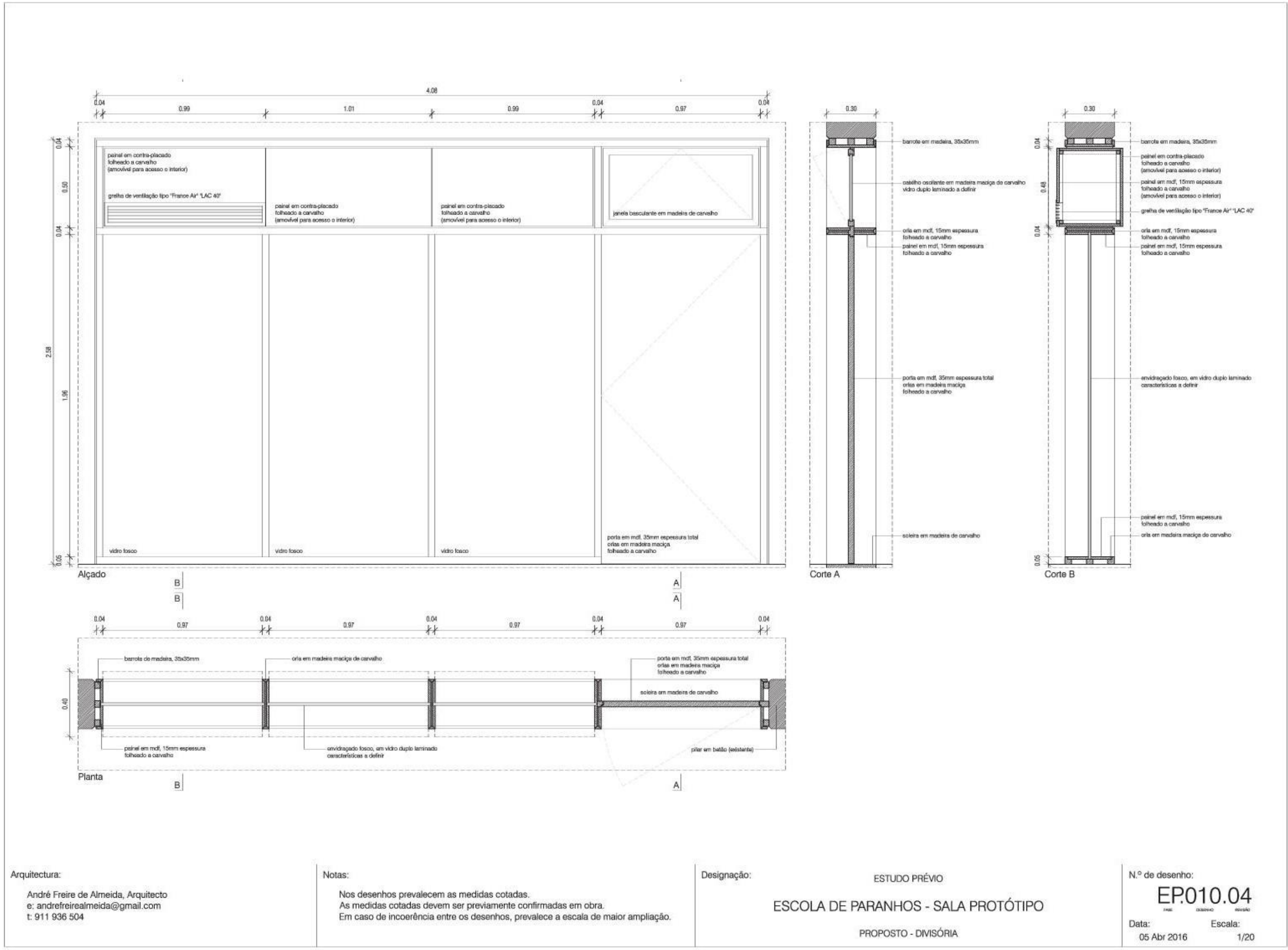
PROPOSTO - CORTES C, D, E e F

N.º de desenho:

EP.009.04

Data: 05 Abr 2016

Escala: 1/50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folheado a carvalho
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vidro fosco
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Alçado
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barrote em madeira, 35x35mm
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orla em mdf, 15mm espessura
folheado a carvalho
painel em mdf, 15mm espessura
folheado a carvalho
porta em mdf, 35mm espessura total
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folheado a carvalho
soleira em madeira de carvalho
Corte A
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painel em contra-placado
folheado a carvalho
(amovível para acesso o interior)
painel em mdf, 15mm espessura
folheado a carvalho
(amovível para acesso o interior)
grelha de ventilação tipo "France Air" "LAC 40"
orla em mdf, 15mm espessura
folheado a carvalho
painel em mdf, 15mm espessura
folheado a carvalho
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Arquitectura:
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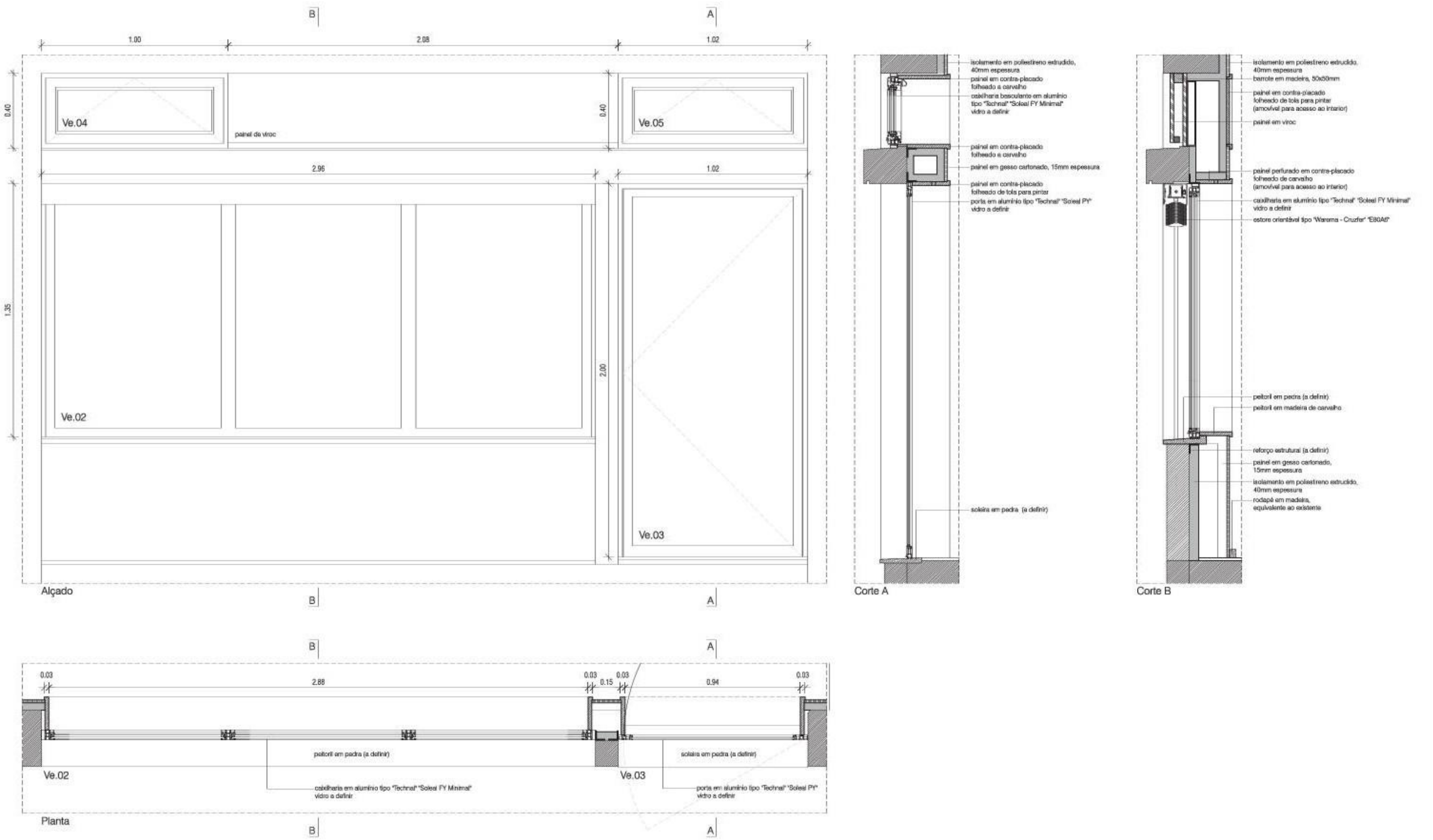

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Designação:

ESTUDO PRÉVIO

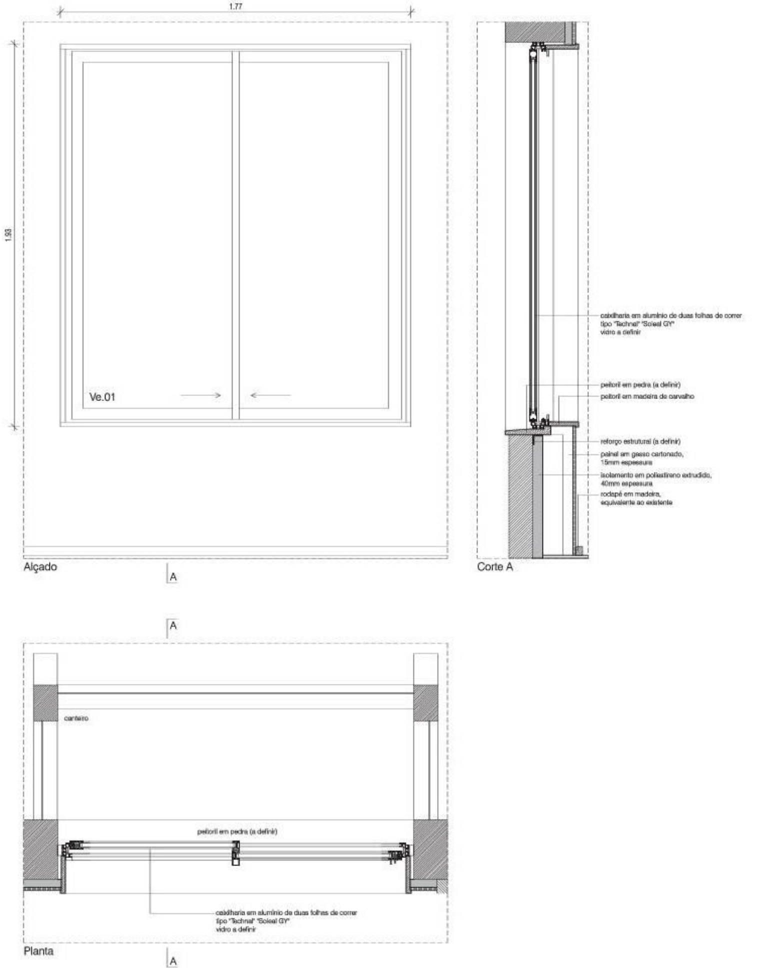
ESCOLA DE PARANHOS - SALA PROTÓTIPO

PROPOSTO - VÃOS Ve.02, Ve.03, Ve.04 e Ve.05

N.º de desenho: EP.011.04

Data: 05 Abr 2016

Escala: 1/20



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André Freire de Almeida, Arquitecto e: andrefreirealmeida@gmail.com t: 911 936 504	Nos desenhos prevalecem as medidas cotadas. As medidas cotadas devem ser previamente confirmadas em obra. Em caso de incoerência entre os desenhos, prevalece a escala de maior ampliação.	ESTUDO PRÉVIO ESCOLA DE PARANHOS - SALA PROTÓTIPO PROPOSTO - Vão Ve.01	EP.012.04 Data: 05 Abr 2016 Escala: 1/20

APPENDIX B – CALIBRATION OF TEMPERATURE AND RELATIVE HUMIDITY DATALOGGERS

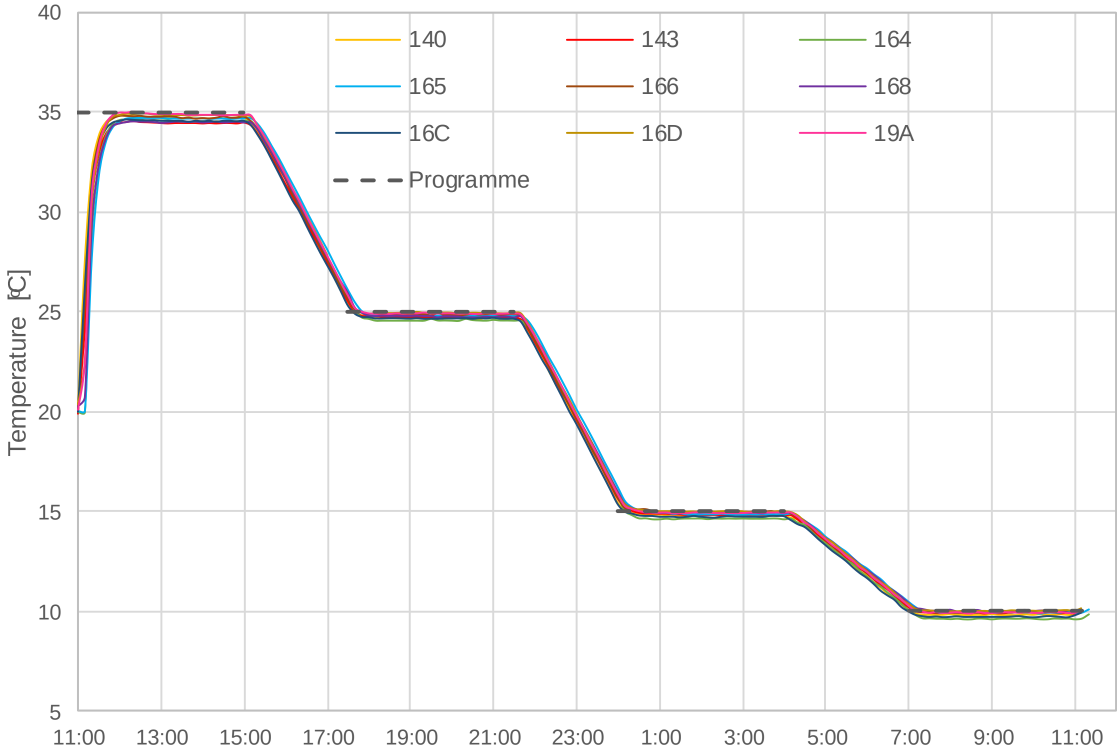

Figure B.1 – Dataloggers temperature calibration.

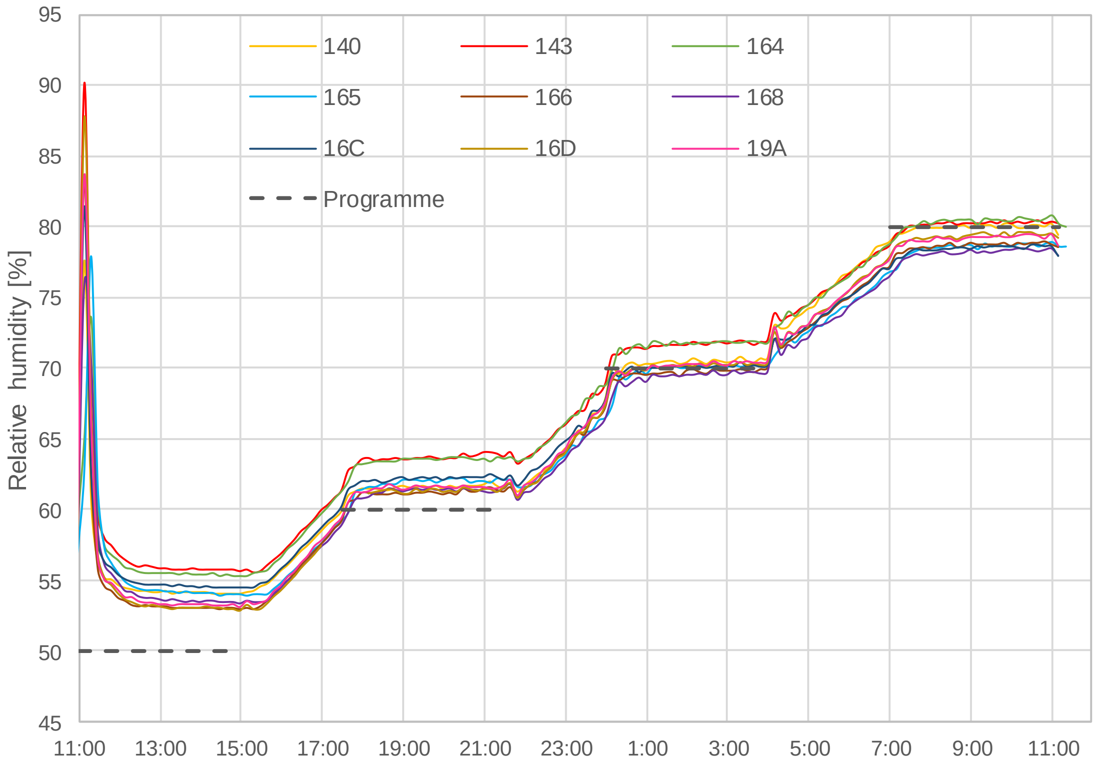

Figure B.2 – Dataloggers relative humidity calibration.

APPENDIX C – CLASSROOM'S WEEKLY SCHEDULE

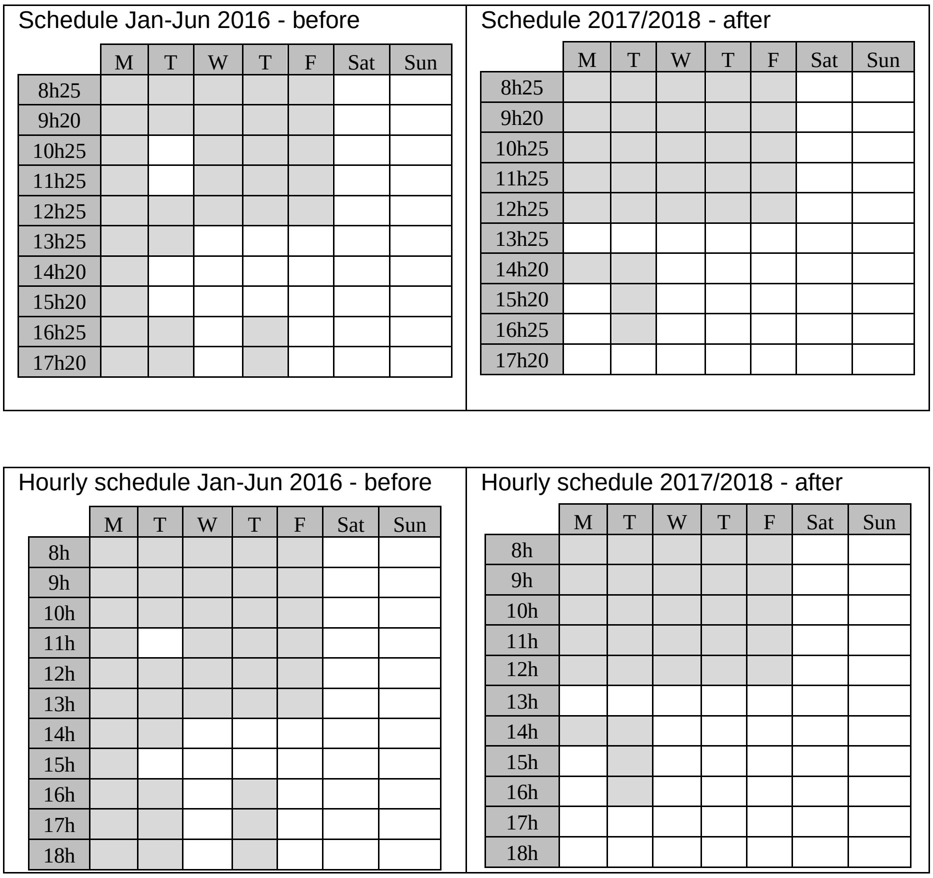

Figure C.1 – Schedule of the studied classroom before and after refurbishment.

APPENDIX D – SURVEY

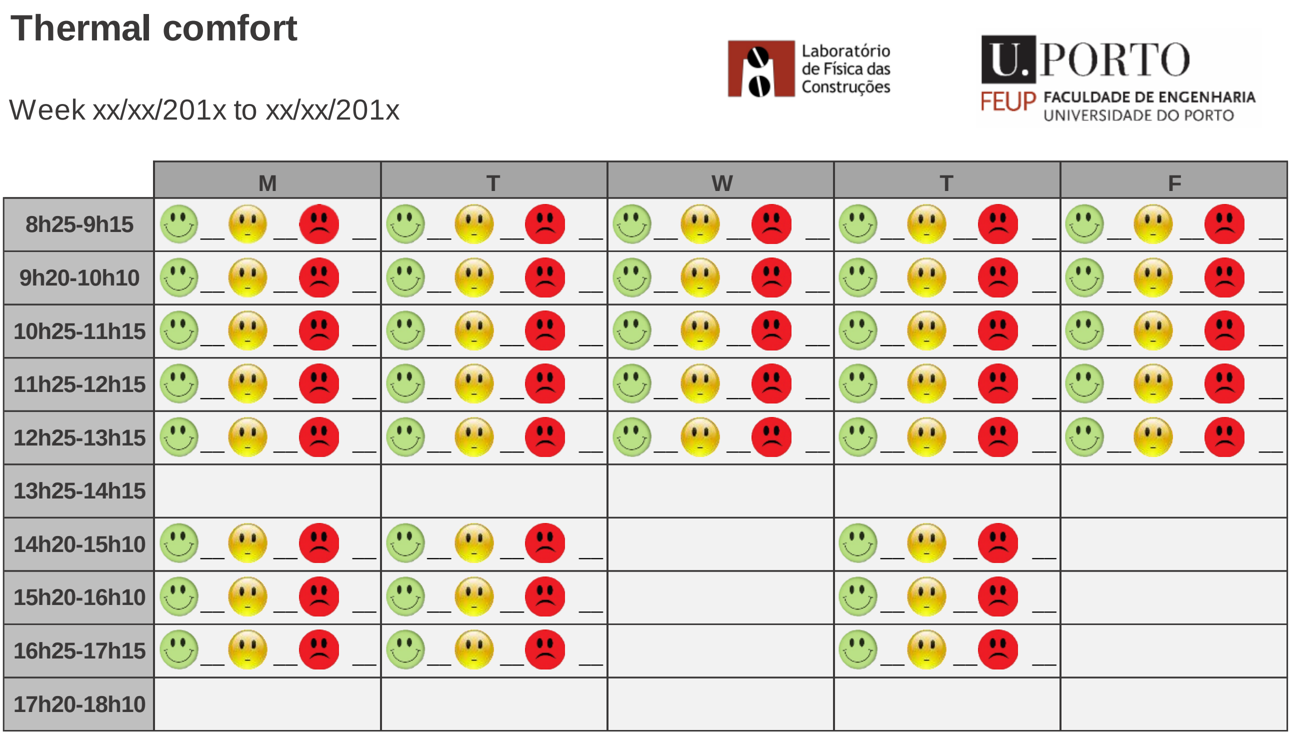

Figure D.1 – Students' survey.

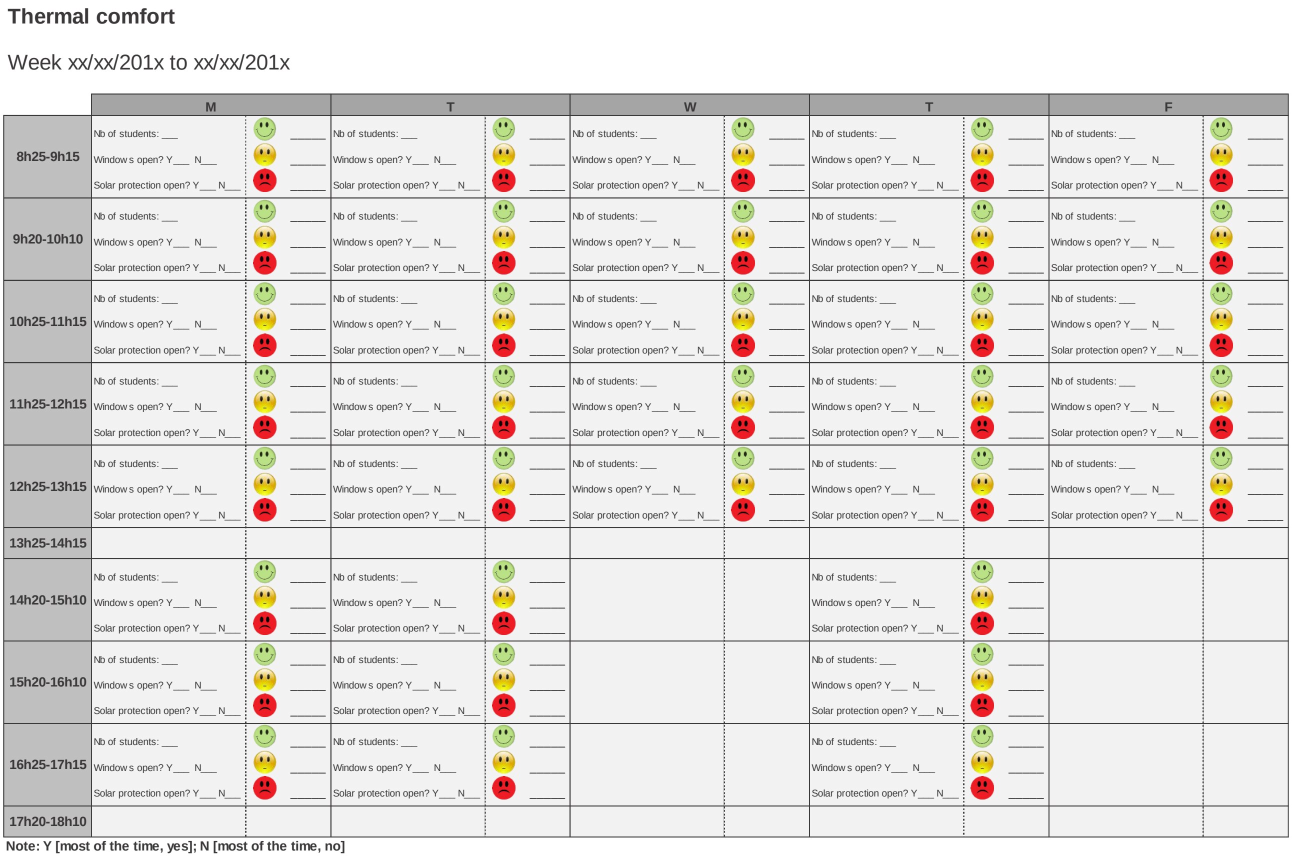

Figure D.2 – Teacher's survey.

APPENDIX E – JOURNAL PAPER

F.C. Barbosa, V.P. de Freitas, M. Almeida, School building experimental characterization in Mediterranean climate regarding comfort, indoor air quality and energy consumption, Energy and Buildings, 212 (2020) 109782. https://doi.org/10.1016/j.enbuild.2020.109782

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School building experimental characterization in Mediterranean climate regarding comfort, indoor air quality and energy consumption

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ABSTRACT

Public school buildings represent an important share of public buildings in Europe, some of them built several decades ago. In Portugal, there are about 5800 public schools, many of them in free-running conditions, with significant thermal discomfort and without any heating strategy due to economic restrictions. This work studies the Portuguese *Brandão* school model (from the '70 s), which comprises about 100 non-refurbished basic schools. This paper suggests the passive refurbishment of these public schools with some affordable interventions, regarding the climate features and the reduced capacity to support the operating costs. A prototype classroom was prepared in a *Brandão* school, in Porto. The in situ experimental campaign consisted of temperature, relative humidity, CO_2 concentration and energy consumption measurements. The prototype construction included the improvement of the envelope and of the technical systems. The main goals of this work are: (1) the comparison of the prototype in-service thermal performance in pre-existing conditions and the improvement after the refurbishment in free-running conditions or with some intermittent heating strategies; (2) the establishment of discomfort indexes for the assessment of the discomfort for Mediterranean temperate climate; (3) the quantification of the energy consumption vs discomfort regarding the passive refurbishment strategy and the intermittent heating strategies. When comparing the before and after refurbishment results, the mean daily discomfort indicator has decreased from 34.7 °C.hour to 25.2 °C.hour in free-running conditions and after the refurbishment has decreased from 25.2 °C.hour to 11.9 °C.hour for 3 heating hours strategy and to 2.5 °C.hour for 10 heating hours strategy. There was an expected increase of CO_2 inside the classroom for the corresponding months before and after refurbishment, although the mean CO_2 was below the required 1500 ppm.

Introduction

The impact of school buildings on the education quality

Portuguese school buildings are generally characterized by an in-service hygrothermal discomfort, due to the poor envelope thermal properties and the lack of resources for paying energy consumption. Most Portuguese schools are free-running buildings with a natural ventilation strategy [1]. For that reason, the so relevant international studies on schools' energy consumption and potential savings mentioned in bibliography [2–6] do not reflect the Portuguese reality.

In Portugal, children spend most of their time in school, just after their own home. Furthermore, the physical environment affects teaching and learning which justifies the investment in comfort and indoor air quality (IAQ).

The low ventilation rates in classrooms reduce students' attention and vigilance thus negatively affecting memory and concentration [7,8]. In fact, the low ventilation rates and high temperature fluctuations can reduce 30% of students' performance [9]. Some studies also report that a healthy school environment and an adequate ventilation system reduces the prevalence of asthma symptoms [10]. The investment in appropriate hygrothermal behavior and IAQ of classrooms to promote a healthy learning environment is therefore justified [11].

One of the main challenges in this kind of buildings is the occupation, that can reach up to four times the occupation of an office building [12] and focuses, in general, within five working days of

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0378-7788/

Table 1
CO_2 concentration and airflow requirements in school buildings [17–26].

		CO_2 concentration [ppm]	Airflow [m^3/h] Winter	Airflow [m^3/h] Summer
Standards	ASHRAE 62.1	700[a]	5 l/(s.occupant) + 0.6 l/(s.m^2) = 486 m^3/h[b]	
	EN 15251	Category II[c] – 500[a] Category III[c] – 800[a]	Very low-polluting buildings: Category II[c] – 3.8 l/(s.m^2) = 684 m^3/h[b] Category III[c] – 2.2 l/(s.m^2) = 396 m^3/h[b]	
	ASTM D6245-12	1000 ppm	7.5 l/(s.occupant) = 567 m^3/h[b]	
Portuguese legislation	RSECE (until 2006)	1800 mg/m^3 ≈ 1000 ppm	30 m^3/(h.occupant) = 630 m^3/h[b]	
	RECS	1250 ppm[d]	24 m^3/(h.occupant) = 504 m^3/h[b]	
	DL n.° 243/86 (office buildings)	–	30 m^3/(h.occupant)[e] = 630 m^3/h[b]	
	Portaria n.° 987/93 (work spaces)	–	30–50 m^3/(h.occupant) = 630–1050 m^3/h[b]	
International legislation	Building Bulletin 101 (United Kingdom)	1500[f]	378 m^3/h[f]	
	DIN 4108 and 4701 (Germany)	1500	315 a 420 m^3/h[f]	

[a] Above outdoor air CO_2 concentration - [20] indicates 390 ppm at normal atmospheric pressure and for 25 °C.
[b] For a 50 m^2 classroom with 20 students and a teacher.
[c] Category II – new buildings and renovations; category III – existing building.
[d] Mean value during the occupation period.
[e] Or until 50 m^3, when environmental conditions require an increase.
[f] Mean daily value. The legislation requires the possibility of achieving 1000 ppm and 600m^3/h respectively, by opening windows, for example.

the week and through September to June. CO_2 is the main pollutant and can reach high values in occupied classrooms [13], once it results from the metabolism. Some auhors have performed CO_2 in-situ measurements in classrooms with natural ventilation [14–16]. International legislation defines the maximum acceptable level of CO_2 concentration and the minimum airflow in office buildings and particularly in school buildings (Table 1). In this paper the reference value considered is 1500 ppm.

Nevertheless, in the non-refurbished Portuguese school buildings, IAQ is not a concerning matter once there is generally a high permeability of the envelope. In refurbished schools, despite the demanding air-tightness standard values [20,27], it is important to consider a reasonable air-tightness increase that does not compromise the IAQ, once the active ventilation systems installed in the refurbished Portuguese buildings are sometimes disabled for economic reasons.

Geographic location of public Portuguese school buildings

Portuguese school buildings represent 12% of non-exclusively residential buildings, which means an important investment in construction, conservation and in the implementation of the educational system. Public spending on education (5^{th} to 12^{th} grade) was 2.3% of the Gross National Product (GNP) in 2011 [28]. Since 2009 Portuguese public spending on education is above the European Union (EU) mean value and also above Spain and Italy, but below France and United Kingdom. There are about 6000 public schools in Portugal, of which 1000 are basic schools from 7^{th} to 9^{th} grade and 300 are high schools (geographic location in Fig. 1) [29,30].

In the recent past (from 2007 to 2011), 175 Portuguese public schools were refurbished. The investment reached 2400 million euros and focused mainly on high schools [31], with an average investment of 13 million euros per school (about 840 euros per square meter according to *Parque Escolar* program and 877 euros per square meter according to the *General Inspection of Finance*) [31,32]. Despite the important investment and the high quality of the intervention, these refurbishments have not fully considered

Fig. 1. (left) Portuguese public schools, (center) Basic schools from 7^{th} to 9^{th} grade (right) High schools.

the Portuguese climatic diversity and economic reality. Almeida and de Freitas [1] studied some refurbished and non-refurbished schools and concluded that, although the IAQ is worse in non-refurbished schools, the results in the refurbished ones are different from the expected since mechanical ventilation and air conditioning are frequently turned off. For these reasons, the refurbished buildings do not always have the required in-service comfort conditions.

The *Parque Escolar* modernization program has not fully concluded the rehabilitation process of Portuguese school buildings. Hundreds of high and basic schools have not been refurbished and still have problems or anomalies and inadequate in-service conditions and need to be rehabilitated in the near future. It will be, therefore, an opportunity to apply the acquired knowledge of comfort, habits, energy consumption and costs that have been studied since these refurbishments, by experimental and monitoring processes.

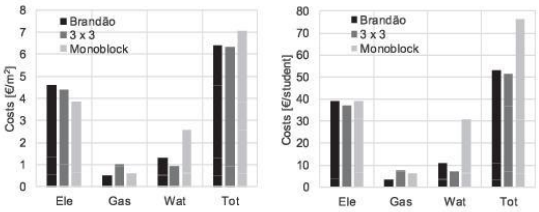

Fig. 2. Operating costs, per square meter and per student (electricity, gas and water).

Operating costs

Portugal, in southwestern Europe, is mostly defined by a temperate Mediterranean climate, with rainy winters and dry and hot summers (although it may present a considerable climatic diversity). It is possible to find monthly average minimum temperatures of 0.3 °C (Bragança), 5.0 °C (Porto) and 8.1 °C (Lisbon) in January and monthly average maximum temperatures of 28.5 °C (Bragança), 25.0 °C (Porto) and 27.8 °C (Lisbon) in August [33]. Relative humidity ranges from 80 to 90% in the winter months and may decrease to 50 to 60% in the summer months [34]. The Koppen-Geiger Classification system classifies the Portuguese territory as mainly temperate climate – type C, with two variations, Csa and Csb [33]. It is also possible to find the sub-type BSk in a small region of the Baixo Alentejo.

Portugal's climatic pattern is similar to some other southern European countries, namely Spain, southern France, southwest Italy and Greece. However, even with similar climatic conditions and sometimes similar ventilation or heating strategies [35], local preferences and cultural habits have an important role in energy performance, thermal comfort and IAQ in schools [36]. In Portugal, the cultural habits, the non-insulated buildings envelope and the economic restrictions lead to an absence of heating and cooling strategies, which is not expected to change in the near future. Previous studies carried out in Portuguese schools indicate no significant differences between the average profile of electricity consumption for schools with or without heating system, suggesting their reduced use [37].

Fig. 2 represents the electricity, gas and water operating costs, per square meter and per student, referring to 14 public Portuguese schools of three different typologies defined in Fig. 3 (*Brandão* - 70 s; *3 × 3* - 80 s; *Monoblock* - 90 s) [38–51].

In Portugal, the school building operating costs are generally low, resulting from the irregular use (or absence) of heating and cooling strategies. Fig. 4 presents the electricity consumption for one year (2007/2008 or 2008/2009) of four *Brandão* schools from the north of Portugal. From October to May (months with higher occupancy), electricity costs are on average 2400 €/month. The annual average electricity consumption in *Brandão* schools is 4.6 €/m² and 39.1 €/student.

Although its absence or irregular use, heating is an important strategy for reaching comfort in some Portuguese regions. And for that reason, the adaptive models in schools (developed for exclusive free-running behavior) may also not be a solution for a country with a climatic diversity like Portugal. The intermittent and irregular heating in Portuguese schools makes these schools a particular situation between the analytical and adaptive models. In Portuguese and Italian free-running schools, no agreement was found between the Fanger method (PMV Index) and the thermal perception [1,52,53]. International legislation defines the acceptable hygrothermal parameters (T and RH) in office buildings and particularly in school buildings (Table 2). In this paper, the T reference values considered are 20 °C (EN 15251 – category II) [18] and 25 °C (Portuguese Energy Regulation of Buildings – service buildings) [20] for winter and summer respectively.

Refurbishment strategy

In the past, there were some typified projects for the refurbishment of school buildings replicated throughout the country, without the necessary adaptations to the specific climatic features. Likewise, and considering the typical free-running situation or intermittent heating strategy, the replication of the same solution in distinct refurbishment projects will have different repercussions on the hygrothermal environment inside the classrooms.

In addition, Mitterer, Künzel, Herkel and Holm [57] reported that the absence of climate location adjustments and the use of foreign standards by countries with no specific legislation can result in low-comfort buildings. The simplest way to compensate this is the use of mechanical equipment, with an increasing need of energy consumption (which is not a possibility in the Portuguese situation). The updating of thermal legislation that requires greater insulation of the enclosure and air-tightness and the demanding construction techniques and trends, with reduced thermal capacity and larger glazed area also contribute to the increasing need of active heating, cooling and ventilation systems. Some studies have been recently prepared in order to choose the best refurbishment strategies for specific school buildings in different countries, regarding their particular needs and legislation [58–60]. The optimization of the opaque envelope of *Brandão* schools for the present free-running conditions or some intermittent heating strategies is the main feature of this study.

Portuguese schools users do not heat as much as they want, due to economic restrictions. In general, Portuguese schools are free-running buildings with a natural cooling operation mode in the warmer months. The future challenge will be the refurbishment of the remaining schools taking into account their typology, the local climate features and the actual capacity to support the operating costs.

Fig. 3. Three school building typologies: *Brandão* - 70 s; *3 × 3* - 80 s; *Monoblock* - 90 s.

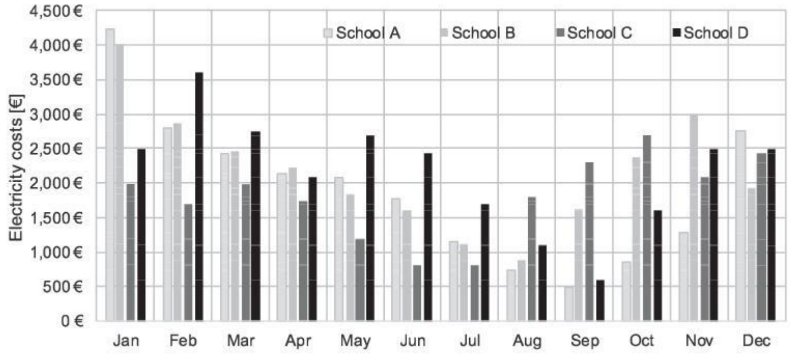

Fig. 4. Monthly electricity consumption (*Brandão* schools).

Table 2
Hygrothermal requirements for school buildings [1,18,19,23,26,54,55,56].

		Temperature [°C]		Relative Humidity [%]	
		Winter	Summer	Winter	Summer
Standards	ISO 7730:2005[a]	22.0 ± 2.0	24.5 ± 2.5	40	60
	EN 15251 (2007)[b]	Category I - 21 Category II - 20 Category III - 19	Category I - 25 Category II - 26 Category III - 27	–	
Portuguese lesgislation	RCCTE (until 2006)	20	25	–	50
	REH	18	25	–	
	RECS	20–25 ou 19–27[c]		–	
	DL n.° 243/86 (office buildings)	18–22[d]		50–70	
International legislation	Building Bulletin 87 and 101 (United Kingdom)	18	<28[e]	–	<70[f]
	DIN 4108 and 4701 (Germany)	20–23	<26	40–60	

[a] Classrooms – C category.
[b] Temperature interval for mechanically heated and/or cooled buildings for each level of expectation – non-adaptative methodology.
[c] 20–25 °C for IEEref calculation and 19–27 °C for IEEpr calculation through the simplified dynamic calculation for hybrid or passive buildings.
[d] Or until 25 °C for specific climatic features.
[e] It can be exceeded for 80 h/year.
[f] It can be exceeded for 2 h in 12 h period.

Methodology

Case study

The object of this study is the Portuguese *Brandão* model, which comprises 100 basic schools replicated throughout the country in the 70s [61]. This is a pavilion type project, composed by quadrangular single floor blocks of classrooms with a central courtyard (Fig. 5) [38]. Classrooms can be accessed around the building (outdoor circulation) or through the neighboring classrooms (indoor circulation), once they are clustered by a common circulation zone. This layout results in variable renovation air rates that are difficult to calculate and predict. Although the potentially high natural ventilation rate, the high occupation rate deserves special attention. The occupants have the opportunity to open or close windows whenever they want but during classes in winter it may not be, in some cases, a usual behavior, in order to prevent the internal heat loss.

It is assumed that these non-refurbished schools have very low comfort and inadequate hygrothermal conditions and will possibly require some interventions in the near future. It is thus important to define some strategies for the refurbishment of these basic schools, considering passive low-cost interventions and the appropriate use of affordable intermittent heating strategies.

A prototype west-sided classroom (Fig. 5) has been studied in a *Brandão* school in Porto. The experimental campaign consisted of temperature (T), relative humidity (RH), CO_2 concentration (CO_2) and energy consumption (EC) measurements, before and after the prototype refurbishment.

Prototype classroom

The main goal of the prototype construction is the assessment of the classroom behavior before and after the intervention. This refurbishment pretended to minimize the discomfort in this classroom with some affordable interventions, regarding the typical in-service conditions in this type of schools.

The following interventions were implemented (Fig. 6): construction of a partition wall between the classroom and the circulation zone, resulting in an enclosed classroom (which was not the case before the renovation); application of a ventilation system with naturally filtered inflow through the envelope and forced airflow to the circulation zone; application of roof insulation (6 cm, rock wool 70 kg/m^3); application of mobile exterior blinds; application of an electric convective heating system (2 + 2 kW) with thermostat. The theoretical airflow (570/430 m^3/h) [20] and the final coefficient of thermal transmission of the roof was 0.43 W/(m^2.°C) [62] complied with Portuguese legislation

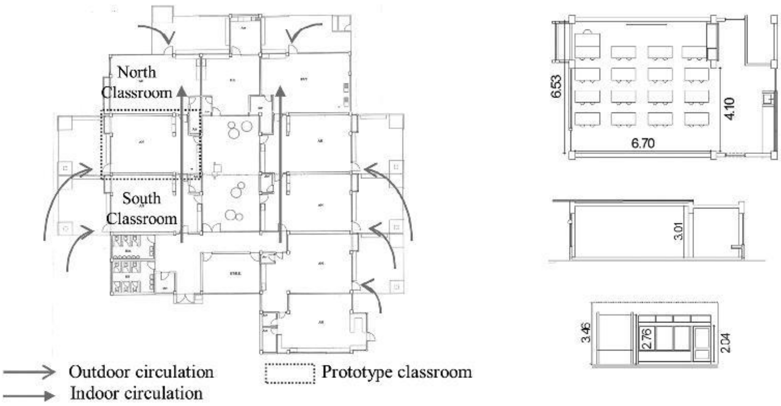

Fig. 5. (left) Classrooms block. (right) Prototype classroom.

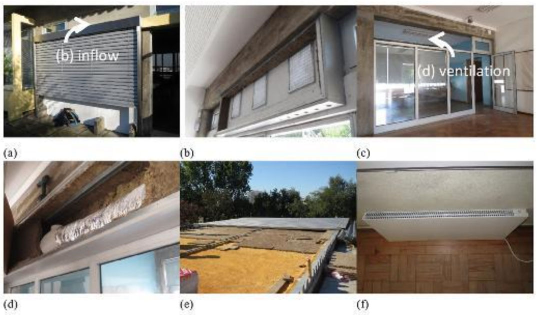

Fig. 6. Prototype interventions: (a) exterior blinds; (b) naturally filtered inflow through the envelope; (c) partition wall; (d) ventilation system - forced airflow to the circulation zone; (e) roof insulation; (f) electric heating system.

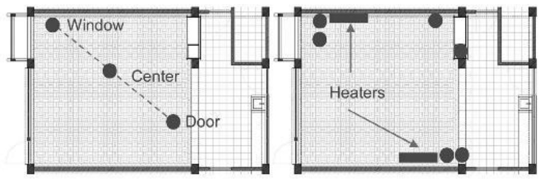

Fig. 7. (left) Hygrothermal monitoring sensors; (right) Energy consumption sensors and heaters.

for school buildings. Both the implementation of a partition wall to enclosure the classroom and the upgrade of the envelope, allowed the introduction of heating strategies and the improvement of hygrothermal behavior. Additionally, the partition wall allowed the control of the ventilation in order to ensure IAQ. The ventilation system was operated by the school workers, starting in the morning and shutting down in the afternoon, from Monday to Friday. After the first year, the strategy has changed and the ventilation was always on in order to reduce the unexpected failures in operating the ventilation. The opening of the windows as a natural ventilation strategy persisted even after the installation of the ventilation system.

Measurements

The hygrothermal and IAQ monitoring included the continuous measurement of *T, RH* and CO_2 before and after the refurbishment. ISO 7726 [63] defines some general indications for minimum requirements and localization for air temperature and air absolute humidity sensors. Some authors [64] have also registered the challenges of indoor residential sensing and some manufacturers have defined practical indications for the installation of the sensors [65].

In this prototype, the *T* and *RH* dataloggers were in an oblique profile (*window, center* and *door*), with the configuration presented in Fig. 7, and at two levels (*ceiling* and *desk* level), in order to analyze the *T* stratification. The CO_2 dataloggers were near the *window*, at *ceiling* level. The dataloggers were protected inside aluminum boxes (10 cm apart from the nearest surface) and weren't easily reached by students. *T* and *RH* dataloggers were installed in the neighboring classrooms in order to assess the boundary conditions. Exterior *T* and *RH* were measured by LFC-FEUP Meteorological Station.

The energy consumption (EC) monitoring system (Fig. 7) included the EC measurement of illumination, PC device, interactive board, ventilation and heating system. One heater was installed near the professor desk (*window*) and the other near the classroom door (*door*).

The hygrothermal monitoring was done by a Wireless *Aptinov* system composed by a 3G router with GSM, a *GW357-2* gateway, 11 *Aptinov WLS-05* dataloggers for *T* and *RH* and 2 Telaire7001 sensors coupled to 2 *Aptinov WLS-07* dataloggers for CO_2 (Fig. 8). The communication between the sensors and the system was performed through electromagnetic transmission of radio waves. The specifications are presented in Table 3.

The EC monitoring was done by a *Wireless Cloogy Smart Living* connected to a 3G router with GSM, a *Cloogy Hub* concentration, 2 mini-transmitters coupled to ammeter clamps for lighting and ventilation monitoring and 4 smart plugs for the equipment connected to electrical plugs (Fig. 8). The specifications of each sensor are presented in Table 4.

Both monitoring systems were a long-distance acquisition of data systems. In addition, the energy consumption system was linked to a web management platform which facilitated the data real-time processing.

Discomfort indexes

The in-service conditions before intervention were the free-running *T, RH* and CO_2. After the refurbishment, the prototype was

(a) (b) (c) (d) (c)

Fig. 8. (a) T and RH datalogger, (b) T and CO_2 datalogger, (c) CO_2 sensor, (d) smart plug and (e) mini-transmitter.

Table 3
Temperature, relative humidity and CO_2 concentration sensors specification.

	Sensor *WLS-05*		Sensor *Telaire 7001* and *WLS-07*	
	Temperature	Relative Humidity	Temperature	CO_2 concentration
Operation range	−30 to 60 °C	0 to 100%	−30 to 60 °C	0 to 4000 ppm
Precision	0.01 °C	0.1%	0.01 °C	10 ppm
Accuracy	0.5 °C*	3%**	0.5 °C*	50 ppm (below 1000 ppm) and 5% (above 1000 ppm)
Distance between measurements			10 min	

* From 0 to 60 °C.
** From 20% to 80% HR, at 25 °C.

Table 4
Energy consumption sensors specification.

	Smart plugs	Plug and mini-transmitter
Maximum current	16A	50A*
Accuracy	±1% ± 0.5W**	±3% ± 15W***
Distance between measurements	15 min	

* 50A per phase, for three-phase installations.
** Test conditions: V = 230AC 50 Hz, electrical resistance≤70 kΩ.
*** Test conditions: V = 230AC 50 Hz, electrical resistance≤530 Ω.

analyzed in three situations: (a) free-running T and RH; (b) reduced heating strategy (3 h per day during winter) and (c) regular heating strategy (10 h per day during winter), always with a controlled ventilation system.

Discomfort indicators defined in this paper quantify, on average, how long occupants are experiencing discomfort (above or below reference) and the effort required to achieve reference comfort conditions. The indicators of discomfort (for the period of occupation) compare preexisting discomfort and discomfort after refurbishment. EN 15251 [18] also defines an hourly-criteria (% of the time when the criterion is met or not) and a degree-hour criterion (degree hours outside the upper or lower boundary that can be used as a performance indicator of building for the warm or cold season). Previous works have also considered discomfort indicators based on EN 15251 [66–68].

The discomfort index for winter ($DI_{w,b}$) is the sum of positive differences between comfort temperature (20 °C) and real temperature, in °C.hour (Eq. (1)). When the reference temperature of comfort is 20 °C, $DI_{w,b}$ is classified as $DI_{w,20}$.

$$DI_{w,b} = \sum_{t_i}^{t_n} (\theta_b - \theta_i), \text{ When } \theta_i < \theta_b \quad (1)$$

where $DI_{w,b}$ is the discomfort index in °C.hour, θ_b is the reference temperature of comfort (20 °C) and θ_i is the experimental hourly temperature in each period t_i.

The discomfort index for summer ($DI_{s,b}$) is the sum of positive differences between real temperature and comfort temperature (25 °C), in °C.hour (Eq. (2)). When the reference temperature of comfort is 25 °C, $DI_{s,b}$ is classified as $DI_{s,25}$.

$$DI_{s,b} = \sum_{t_i}^{t_n} (\theta_i - \theta_b), \text{ When } \theta_i > \theta_b \quad (2)$$

where $DI_{s,b}$ is the discomfort index in °C.hour, θ_b is the reference temperature of comfort (25 °C) and θ_i is the experimental hourly temperature in each period t_i.

The discomfort percentage of time ($\%TD_b$) represents the proportion of the discomfort periods during the analyzed occupation period (Eq. (3)).

$$\%TD_b = \frac{\sum t_{i\,discomfort}}{\sum t_{i\,occupation}} \quad (3)$$

Strategy and main goals

This experimental campaign (three and a half academic years) has started in February 2016 and finished in June 2019. The refurbishment was during the summer of 2017. The in-service conditions before intervention were the free-running T, RH and CO_2. After the refurbishment the prototype was analyzed in three situations implemented in a weekly based calendar: (a) free-running T and RH, without climatization; (b) reduced heating strategy with 4 kW power (3 h per day at early morning during winter, from 7h30 am to 10h30 am) and (c) regular heating strategy with the same heating power (10 h per day during winter, from 7h30 am to 5h30 pm), always with a controlled ventilation system. After the refurbishment, the scheduled heating strategies started in January of 2018. The winter and mid-season periods analyzed in this paper before and after refurbishment are presented in Table 5.

The main goal of this work is the assessment of the thermal discomfort in this prototype before and after the refurbishment in free-running conditions or with the defined heating strategies, without compromising IAQ. The discomfort indicators have been developed for the assessment of the discomfort. This work presents the prototype thermal performance in pre-existing in-service con-

Table 5
Calendar of measurements analysis.

		Statistical analysis	DI_{20}/%TD_{20} or DI_{25}/%TD_{25} analysis
Winter	Before refurbishment	Feb, Mar, Apr, Nov, Dec 2016	11 Feb – 18 Mar 2016
	After refurbishment	3 Jan – 23 Mar 2018	3 Jan – 23 Mar 2018
Mid-season	Before refurbishment	19 Sep - 23 Oct 2016	19 Sep - 23 Oct 2016
	After refurbishment	13 Sep – 27 Oct 2017 and 18 Sep – 26 Oct 2018	13 Sep – 27 Oct 2017 and 18 Sep – 26 Oct 2018

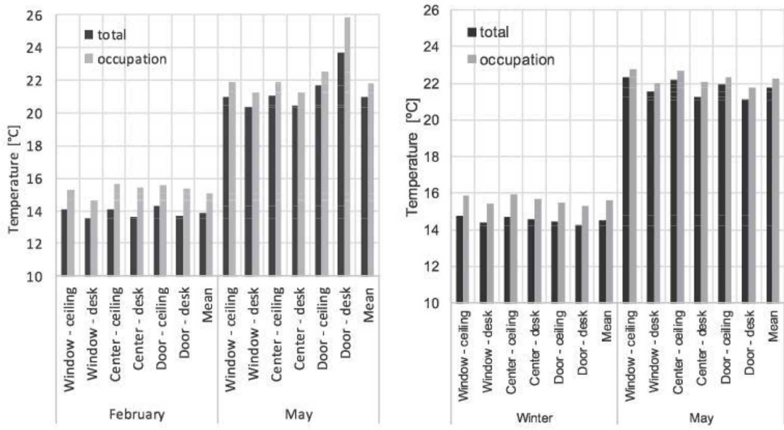

Fig. 9. Mean *T* during the occupation and the total period: (left) before refurbishment: Feb and May 2016; (right) after refurbishment: winter (without heating) and May 2018. * After refurbishment, different heating strategies were adopted in a weekly schedule. Therefore, and in order to have comparable results, *Winter* refers to free-running weeks, which were the previous conditions before refurbishment.

ditions and the improvement in the thermal behavior of the environment after the refurbishment. It also discusses the hygrothermal performance of the passive low-cost refurbishment and the energy consumption resulting from the heating strategies. It is performed a winter and mid-season analysis of the discomfort.

Results and discussion

Occupation period

In school buildings, hygrothermal conditions assessment is restricted to the occupation period that reflects the real users' discomfort. Simanic, Nordquist, Bagge and Johansson [69] have also discussed the importance of considering only weekdays and working hours.

The occupation period considered was the real in-service schedule (complete mornings from Monday to Friday and two or three afternoons before and after refurbishment, respectively). There were on average 20 to 25 occupants before and after refurbishment.

Fig. 9 shows the mean temperature of the occupation period and the total period before and after the intervention in free-running conditions. The differences observed were as expected: the mean temperature was higher when considering the occupation period, due to internal and solar gains once the night period is not included. There are not important differences amongst different localization inside the classroom. The mean differences between the occupation period and the total period before refurbishment were 1.4 °C in a winter month (February) and 1.1 °C in a mid-season month (May); after the refurbishment, the differences were 1.1 °C in winter weeks and 0.5 °C in a mid-season month (May). The CO_2 concentration was also higher during the occupation period once the CO_2 is an important evidence of human metabolism and is produced mainly during the occupation (Fig. 10). The partition wall and the fact that the ventilation system was not in full working capacity justify the increase in CO_2 after refurbishment. However,

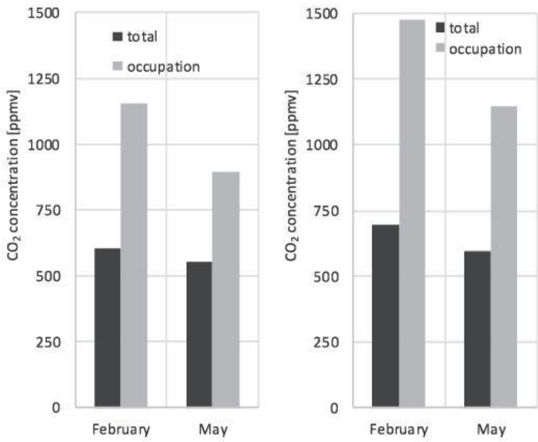

Fig. 10. Mean CO_2 during the occupation and the total period: (left) before refurbishment: Feb and May 2016; (right) after refurbishment: Feb and May 2018.

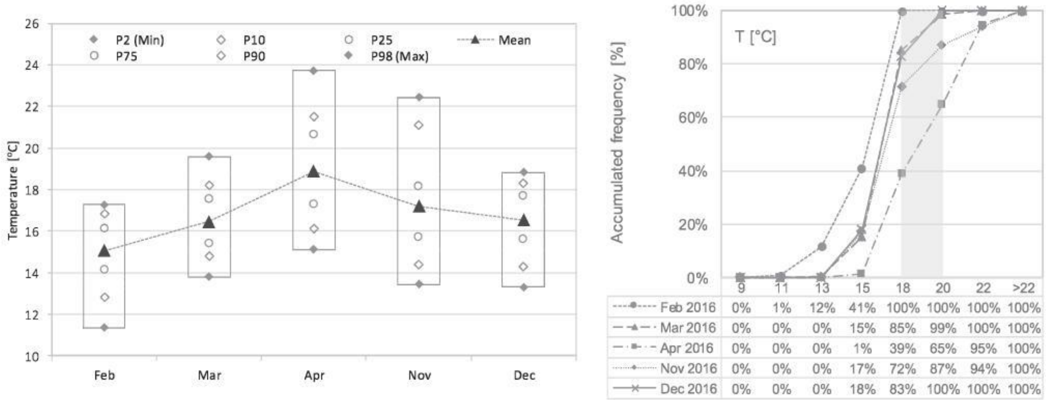

Fig. 11. *T* distribution in the winter before the refurbishment of the prototype.

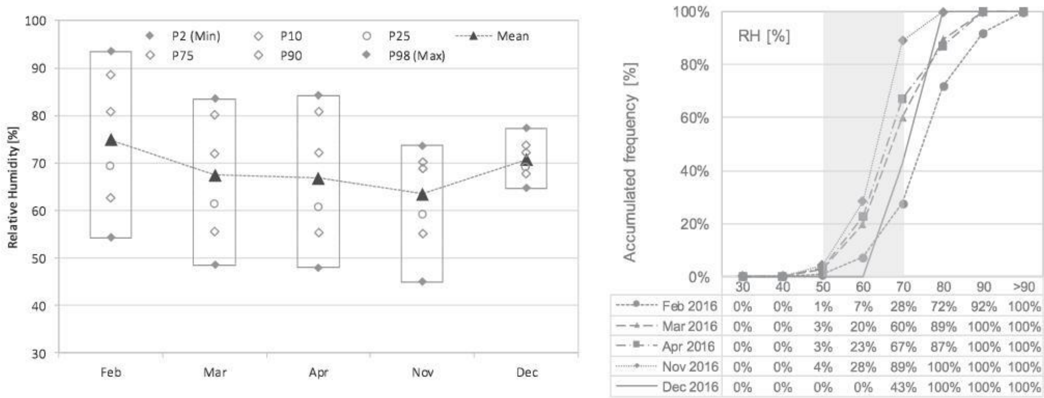

Fig. 12. *RH* distribution in the winter before the refurbishment of the prototype.

its mean concentration is below the reference value of 1500 ppm and around the 1250 ppm, even during winter when the windows were closed.

Winter analysis before the prototype refurbishment

The free-running temperature development in winter before the refurbishment clearly reveals a temperature increase during each day, due to internal gains and also solar gains. There was also a clear discomfort most of the time, with temperatures below 18 °C. Fig. 11 shows the temperature in winter during the occupation period, before the intervention and any heating strategy. It also presents the statistical distribution of temperature during the occupation period on 2016 winter, through a probabilistic analysis of the results by temperature ranges. It confirms that the temperature in the prototype was not adequate, considering the reference values of *T*. In February, the temperature was below 18 °C during 100% of the occupation period, in March during 85%, in December during 83%, in November during 72% and in April during 39%. An increasing requirement of 20 °C would enhance this analysis. The *RH* inside the classroom followed the *T* evolution (Fig. 12). In winter, the CO_2 was below 1250 ppm [20] during 50–80% of the occupation period, below 1500 ppm [23] during 70–90% and below 2000 ppm during 90–100%, here defined as the maximum acceptable value (Fig. 13).

The discomfort indicators of the winter before the refurbishment (2016) were calculated for each week. Before the refurbishment, there was no heating system available, which is a common situation in these Portuguese buildings, as previously mentioned. In a normal five-day week, the $DI_{w,20}$ were above 120 °C.hour and the discomfort represented 100% of the occupation period (Fig. 14). Table 6 presents a detailed analysis of the $DI_{w,20}$, $\%TD_{20}$, $DI_{w,18}$ and $\%TD_{18}$ before refurbishment and the outdoor mean temperature in each winter week ($T_{m,ext}$), since $T_{m,ext}$ affects the inside thermal behavior and it is not a controlled variable in an in-situ experimental work developed in an in-service building. The daily mean values of $DI_{w,20}$ and $\%TD_{20}$ were 34.7 °C.hour and 99%, respectively.

Winter analysis after the prototype refurbishment

In the winter after the prototype refurbishment (2018), the (a), (b) and (c) heating strategies presented above were adopted in a weekly schedule. For that reason, the *T*, *RH* and CO_2 statistical analysis is not defined by month but by strategy. When comparing the (a) heating strategy after refurbishment with the previous conditions, the results reflect the improvement due to the envelope and ventilation. It is important to confirm that this refurbishment strategy was a good choice even without adding a heating strategy. It was previously mentioned that the passive refurbishment is an important goal of this work, as the economic restrictions define a

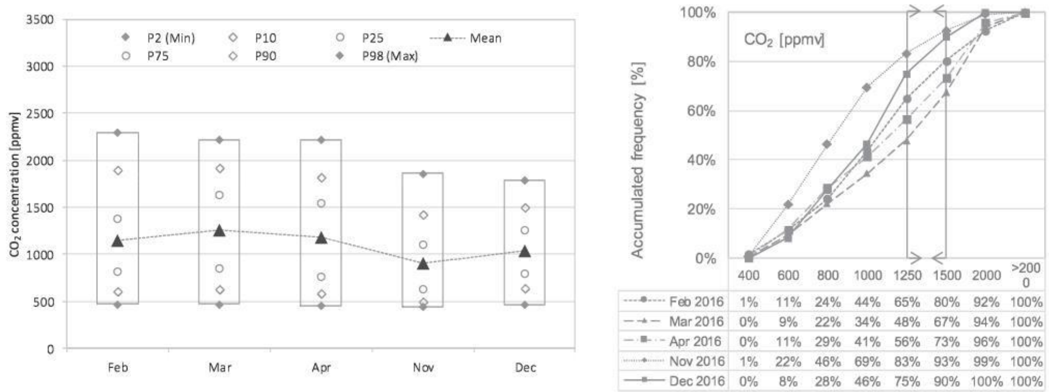

Fig. 13. CO_2 distribution in the winter before the refurbishment of the prototype.

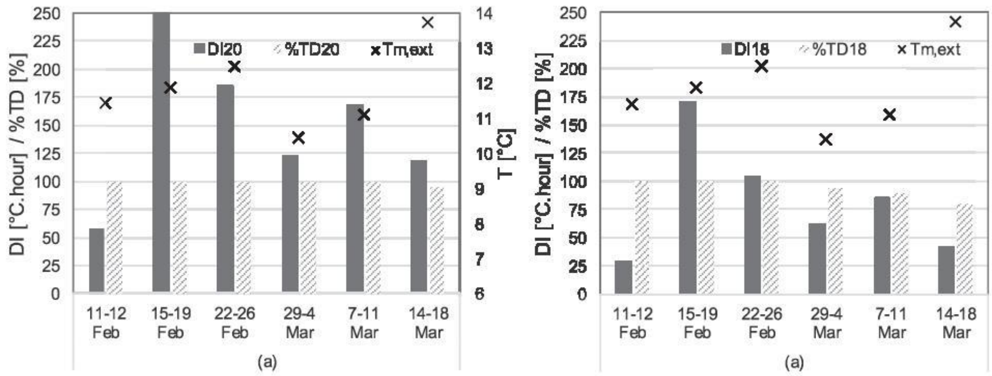

Fig. 14. Discomfort indicators for each winter week: (left) DI_{20} and $\%TD_{20}$; (right) DI_{18} and $\%TD_{18}$.

Table 6
Discomfort indicators in winter before refurbishment.

week	Nb of days	strategy	$T_{m,ext}$	$DI_{w,20}$	$\%TD_{20}$	$DI_{w,18}$	$\%TD_{18}$
11–12 Feb	2	(a)	11.4	57.6	100%	27.6	100%
15–19 Feb	5	(a)	11.9	251.9	100%	169.9	100%
22–26 Feb	5	(a)	12.5	185.4	100%	103.4	100%
29–4 Mar	4	(a)	10.4	122.0	100%	62.2	93%
7–11 Mar	5	(a)	11.1	166.6	100%	85.2	90%
14–18 Mar	5	(a)	13.7	117.7	95%	42.4	80%
daily mean	**–**	**(a)**	**–**	**34.7**	**99%**	**18.9**	**93%**

free-running behavior in so many cases. Through the (a) strategy, we expected to minimize the discomfort after the refurbishment, but it was unlikely to achieve the 18 or 20 °C of comfort during all the occupation period. However, the establishment of some affordable heating strategies was also an aim of this work. The (b) and (c) heating strategies were implemented to achieve the 18 or 20 °C of comfort during the occupation period. The Portuguese regional habits and the low use of heating systems (subject to each school management) determined the choice of a heating system with low initial investment, easy to operate and with a flexible schedule use. All the chosen refurbishment solutions of this prototype were required to be low-cost and adjustable to the 100 *Brandão* schools throughout the country.

The temperature inside the classroom in the winter after the refurbishment had a distinct behavior according to the heating strategy (Table 7). Fig. 15 shows the temperature in winter during the occupation after refurbishment. It also presents the statistical distribution of temperature on 2018 winter. In free-running conditions, the mean T remained below 18 °C. The increasing heating strategies (b) and (c) improved the mean indoor T for 18 °C and 21.5 °C, approximately. The T was below 18 °C during 100% of the occupation period for (a) strategy, 46% for (b) strategy and 5% for (c) strategy. An increasing requirement of 20 °C represented discomfort during 26% of the occupation period during (c) strategy. The RH inside the classroom followed the T evolution (Fig. 16) and was not a concern. The CO_2 did not have a direct relationship with the heating strategy and the mean values were similar for the three strategies (Fig. 17). Regardless the adopted heating strategy, in winter the CO_2 was below 1250 ppm [20] in 30–40% of the occupation period, below 1500 ppm [23] in 50–60% and below

Table 7
Statistical information of T, RH and CO_2 during the occupation, in winter.

	T [°C]			RH [%]			CO_2 [ppmv]		
	a(*)	b(*)	c(*)	a(*)	b(*)	c(*)	a(*)	b(*)	c(*)
Mean	15.6	18.1	21.4	78	62	51	1451	1378	1404
P2 (Min)	12.9	14.0	16.7	66	42	34	542	470	570
P10	14.4	15.4	18.7	68	50	40	810	700	750
P25	15.0	16.4	19.9	71	56	45	1140	1039	1040
P75	16.2	19.6	22.8	84	69	58	1800	1710	1770
P90	16.6	21.1	24.2	88	75	62	2040	1941	2022
P98 (Max)	17.5	22.7	25.7	90	79	65	2364	2258	2282
St Dev	0.7	1.7	1.6	6	8	7	371	374	388

(*) *a, b* and *c* refer to January to March.

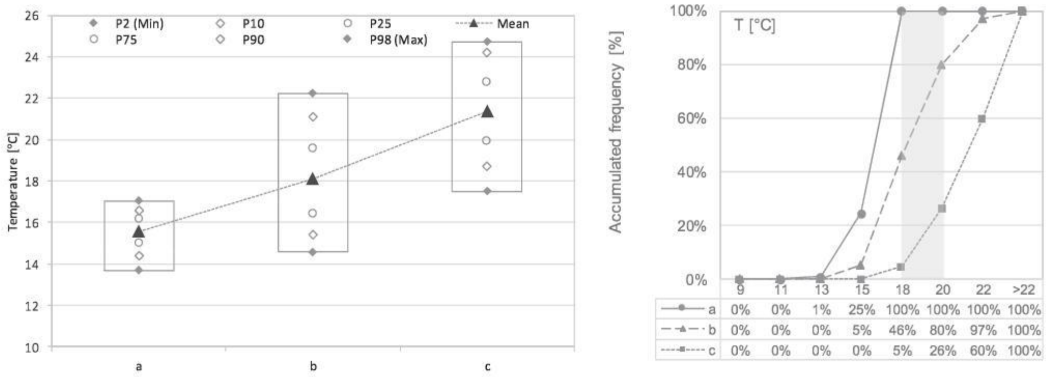

Fig. 15. *T* distribution in the winter after the refurbishment of the prototype.

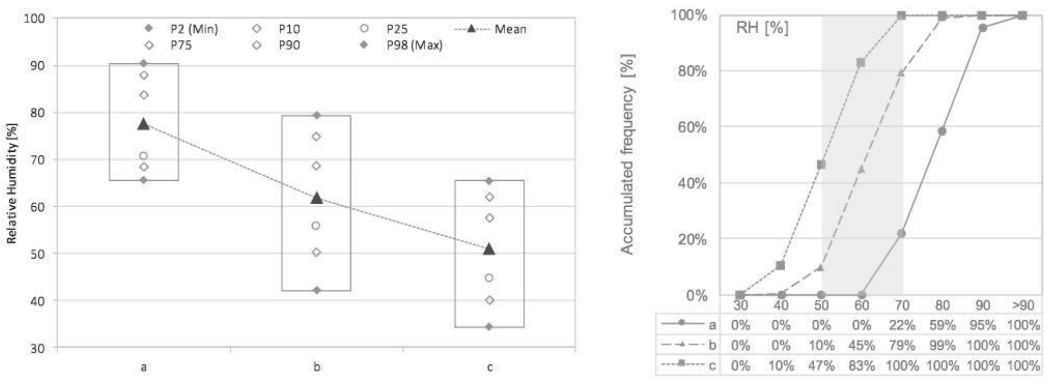

Fig. 16. *RH* distribution in the winter after the refurbishment of the prototype.

2000 ppm in 90%. Once there was no partition wall in pre-existing conditions, it was expected an increase of CO_2 after the refurbishment (Fig. 18). The Portuguese legislation defines for classrooms a minimum airflow of 28 m^3/(hour.person) and the ventilation system in the prototype was prepared to 570/430 m^3/h (theoretical airflow). However, the real ventilation was 380 m^3/h, corresponding to 2.9 h^{-1}. Although the CO_2 after the refurbishment was below the requirement of 1500 ppm (Table 1), there was indeed an increase of CO_2 inside the classroom, for the corresponding months before and after refurbishment.

Fig. 19 represents the evolution of inside and outside *T* in a winter week for each strategy, considering only the occupation period. The inside *T* had a growing pattern during each day in (a) strategy due to internal and solar gains and in (c) strategy also due to heating during the occupation but (b) strategy showed an inflection of *T* after early morning heating.

The $DI_{w,20}$, $\%TD_{20}$, $DI_{w,18}$ and $\%TD_{18}$ after refurbishment in 2018 were calculated in each winter week for (a), (b) and (c) regular heating strategies, always with a controlled ventilation system (Figs. 20 and 21).

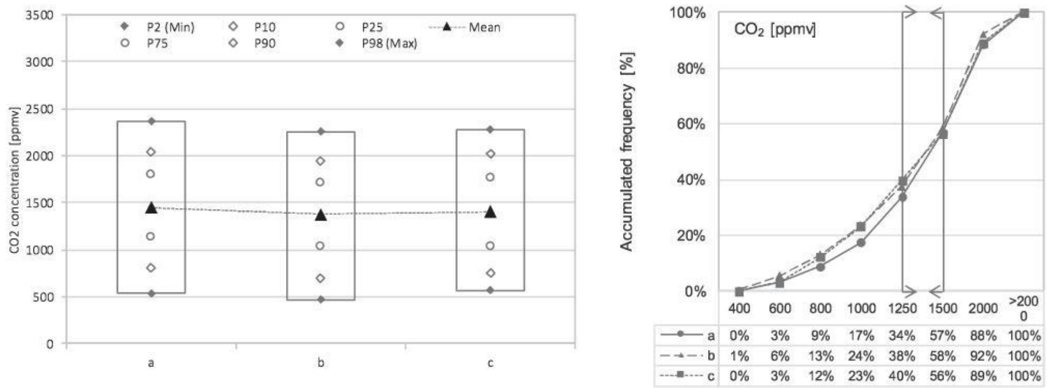

Fig. 17. CO_2 distribution in the winter after the refurbishment of the prototype.

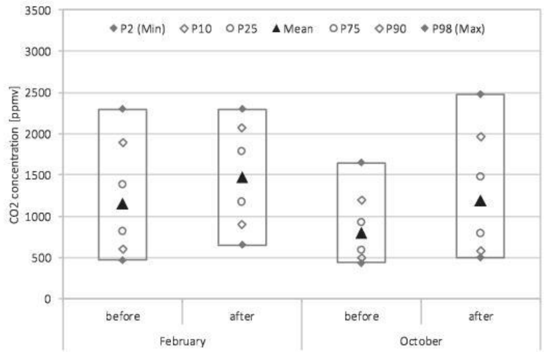

Fig. 18. CO_2 before and after the refurbishment of the prototype.

In free-running winter weeks of 2018, the mean $\%TD_{20}$ remained near 100%, although $DI_{w,20}$ values have decreased when compared with the pre-existing situation (from 34.7 °C.hour to 25.2 °C.hour, mean daily values) (Table 8), that confirms the success of the refurbishment strategy even without adding a heating strategy (regarding the passive refurbishment for reducing discomfort).

The $\%TD_{20}$ decreased from an average of 100% to 80% for the adopted strategy (b) and to about 30% for the (c) heating strategy. $DI_{w,20}$ decreased from 25.2 to 11.9 °C.hour when comparing free-running *T* and *RH* to 3 heating hours and from 11.9 to 2.5 °C.hour when comparing 3 with 10 heating hours (Table 8). This reduction could have been more noticeable if we had the same exterior conditions (which did not happen since $T_{m,ext}$ is not a controlled variable).

The lower EC/DI_w gradient resulted from the first three hours of heating (from (a) to (b) strategy). It represented an important decrease in discomfort with a reasonable increase in energy consumption (Fig. 22) and this was more noticeable in DI_{20} than in DI_{18}. The point between strategies (b) and (c) corresponds to the experimental results of some weeks with (c) heating strategy when the heating systems were not in full work (one heater on and the other off), and represents the behavior with nearly half of the heating capacity (EC between 19 and 25 kWh/day). Considering the EC/$\%TD$ gradient, the results revealed a linear relationship between energy consumption vs decreased discomfort (Fig. 22).

Temperature stratification before and after refurbishment

The *T* development before refurbishment during a winter day revealed discomfort (below 18 °C) in all locations (Fig. 23) and a mean stratification of 0.6 °C, 0.2 °C and 0.3 °C (respectively *window*, *center* and *door*), detailed for each month and location in

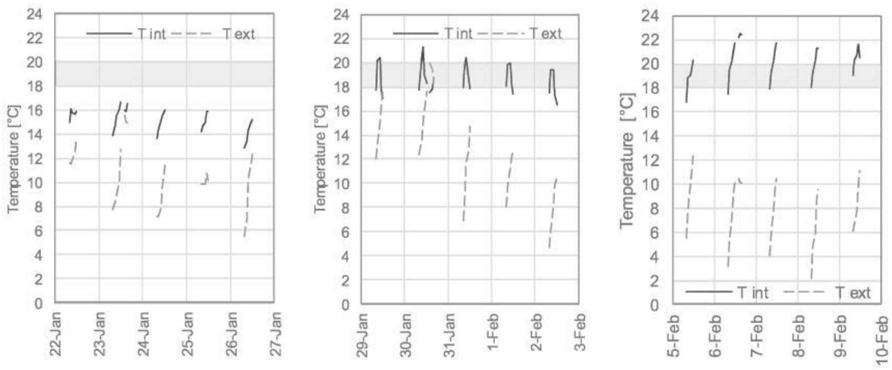

Fig. 19. Inside and outside *T* in a winter week, considering only the occupation period: (left) strategy (a); (center) strategy (b); (right) strategy (c).

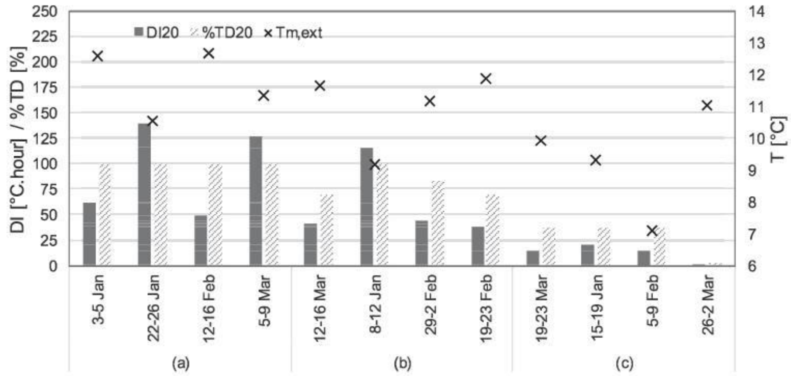

Fig. 20. DI_{20}, $\%TD_{20}$ and $T_{m,ext}$ for each winter week after refurbishment.

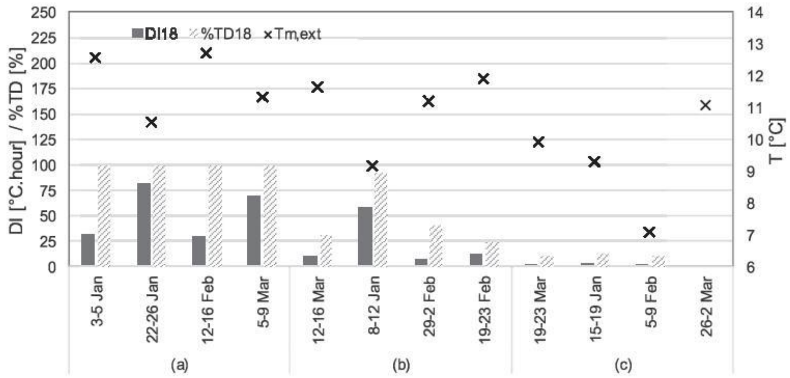

Fig. 21. DI_{18}, $\%TD_{18}$ and $T_{m,ext}$ for each winter week after refurbishment.

Table 8
Discomfort indicators in winter after refurbishment.

week	Nb of days	strategy	$T_{m,ext}$	Energy [kWh]	$DI_{w,20}$	$\%TD_{20}$	$DI_{w,18}$	$\%TD_{18}$
3–5 Jan	3	(a)	12.6	0	61.9	100%	31.9	100%
8–12 Jan	5	(b)	9.1	43	115.3	100%	58.9	93%
15–19 Jan	5	(c)	9.3	170	19.7	38%	3.3	14%
22–26 Jan	5	(a)	10.5	0	139.5	100%	81.5	100%
29–2 Fev	5	(b)	11.2	59	43.9	83%	7.1	41%
5–9 Fev	5	(c)	7.1	199	15.0	38%	1.7	10%
12–16 Fev	2	(a)	12.7	0	49.5	100%	29.5	100%
19–23 Fev	5	(b)	11.9	48	37.7	69%	12.8	24%
26–2 Mar	5	(c)	11.0	197	0.02	3%	0.0	0%
5–9 Mar	5	(a)	11.3	0	127.3	100%	69.3	100%
12–16 Mar	5	(b)	11.6	52	41.4	69%	9.7	31%
19–23 Mar	5	(c)	9.9	147	15.3	38%	2.1	10%
	–	**(a)**	–	0	25.2	100%	14.1	100%
daily mean	–	**(b)**	–	10	11.9	80%	4.4	47%
	–	**(c)**	–	36	2.5	29%	0.4	9%

Fig. 24 (left side). After the refurbishment, there was an important stratification of temperature, with higher values at the *ceiling* level and lower at the *desk* level, mostly during heating periods (Fig. 24, right side). The stratification was more relevant the greater the heating strategy was and was also more important near the heaters (*window* and *door* locations). The mean values during the winter months were 8.9 °C, 5.9 °C and 5.9 °C for (c) heating strategy, 3.6 °C, 2.3 °C and 2.3 °C for (b) heating strategy and 0.4 °C, 0.3 °C and 0.2 °C for (a) heating strategy (for each heating strategy, respectively *window, center* and *door*). The mitigation of the stratification effect, resulting from the chosen heating system, must be considered in future developments.

Mid-season comfort before and after the prototype refurbishment

The Portuguese temperate climate (type C) is characterized by an average temperature in the coldest months between 0 and 18 °C. It is possible to find the sub-type Cs with two variations, depending on whether the summer is hot (Csa - average temperature in the hottest month above 22 °C) and temperate (Csb - av-

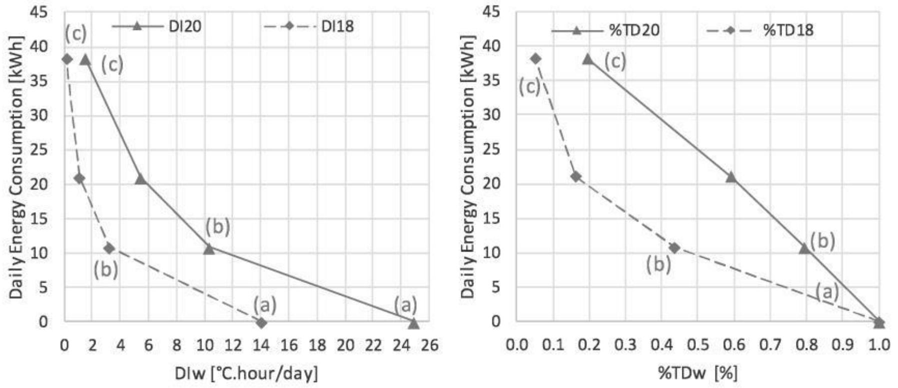

Fig. 22. (left): EC/DI_w in winter after refurbishment - strategies (a), (b) and (c); (right): EC/$\%TD_w$ in winter after refurbishment - strategies (a), (b) and (c).

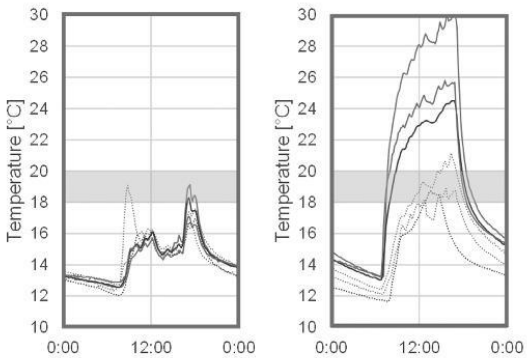

Fig. 23. *T* on a winter day in different measurement locations: (left) before refurbishment; (right) after refurbishment.

erage temperature in the hottest month below or equal to 22 °C, and with four months or more with average temperatures above 10 °C) [15]. The Csb Porto climate enables mid-season comfort in the prototype (Fig. 25) and that has been confirmed during monitoring before refurbishment. Although the refurbishment was not focused on summer comfort, it was necessary not to worsen the previous conditions (Figs. 26 and 27). After the refurbishment, the mean *T* in each mid-season week was between 22 °C and 25 °C, with the exception of a September week in 2018. The CO_2 was also below 1250 ppm, with the exception of an October week in 2018 (although it did not exceed 1500 ppm).

The DI_{25} and $\%TD_{25}$ for the mid-season weeks before the intervention were low and confirmed that the mid-season was not a real concern in the pre-existing scenario (Fig. 28). The mean daily DI_{25} was 0.7 °C.hour/day and the $\%TD_{25}$ was 13%. After the refurbishment, the DI_{25} and $\%TD_{25}$ for the mid-season weeks were also low and their mean daily values were 0.3 °C.hour/day and 7% for the 2017 mid-season and 2.3 °C.hour/day and 32% for the 2018 mid-season (Fig. 29). These mean values show a small reduction of $DI_{s,25}$ and $\%TD_{25}$ in 2017 mid-season weeks (after refurbishment) even though the exterior blinds were not installed in September and October and the ventilation system was not in full working capacity. However, the small increase in $DI_{s,25}$ and $\%TD_{25}$ in 2018 (when the exterior blinds and the ventilation system were in full operation) reveals the dependence on the weather conditions. While the enclosure classroom option would benefit conditions in the winter, it can complicate mid-season conditions depending on the weather severity.

The mid-season discomfort assessment was made through an analytical approach (non-adaptative) with a reference comfort *T* of 25 °C. The Csb Porto climate allows an analytical analysis once it is not a strict climate with special requirements, although an adaptative approach can be assessed in future developments.

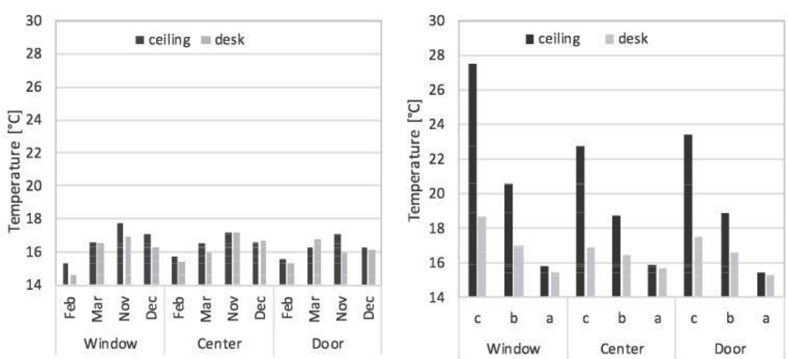

Fig. 24. Temperature stratification: (left) before refurbishment; (right) after refurbishment.

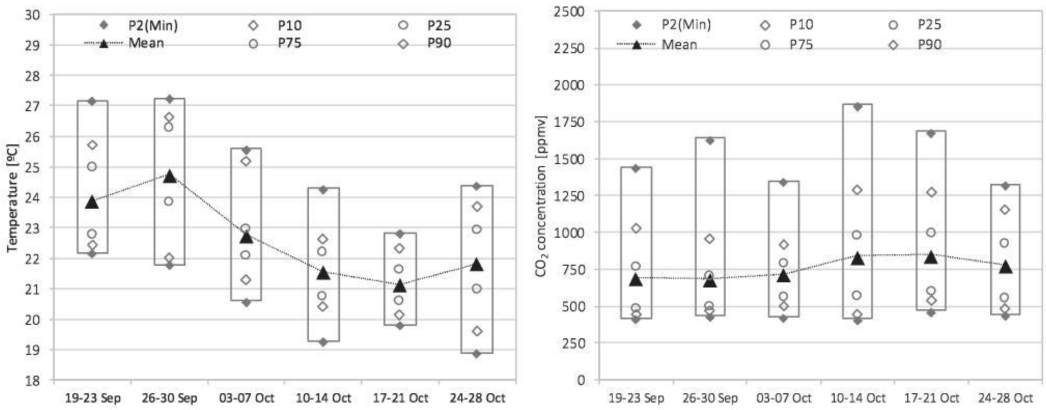

Fig. 25. *T* and CO_2 in mid-season weeks before refurbishment (2016).

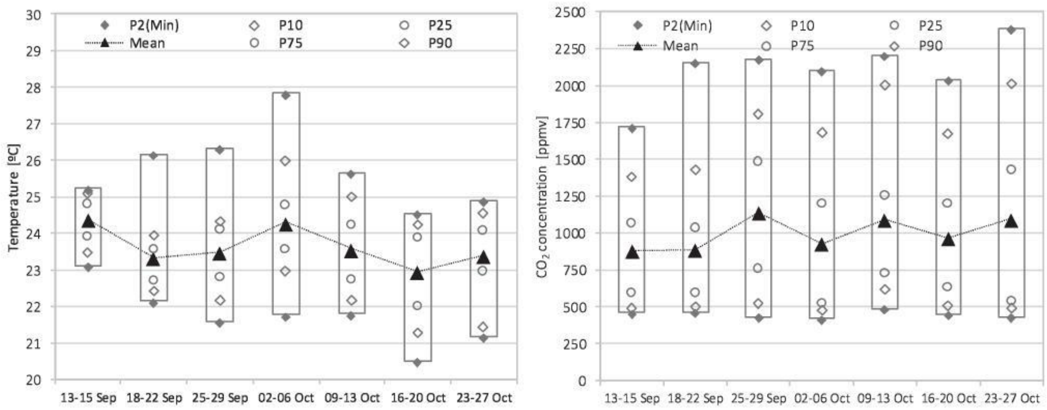

Fig. 26. *T* and CO_2 in mid-season weeks after refurbishment (2017).

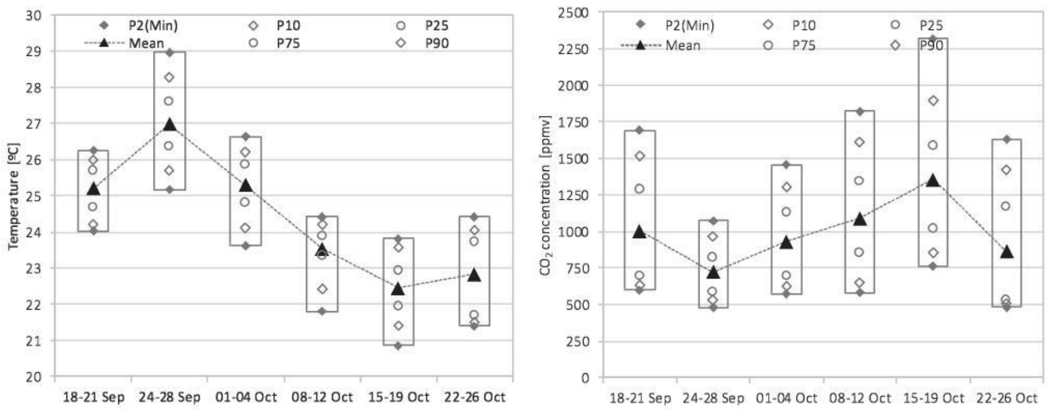

Fig. 27. *T* and CO_2 in mid-season weeks after refurbishment (2018).

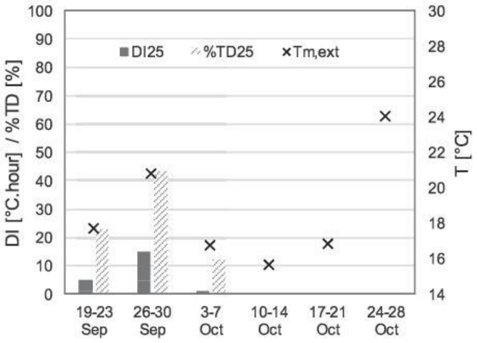

Fig. 28. DI_{25} and $\%TD_{25}$ in summer weeks before refurbishment (2016).

Nevertheless, classroom users were asked to fill in some written questions in order to qualify thermal comfort perception (green: good; yellow: medium; red: low) during the mid-season weeks. The data were collected through 6 autumn weeks with occupation in free-running hygrothermal conditions for all class-weeks (one answer per user per class). The questionnaires were a useful tool for gathering some information about the users' perception of comfort.

The results confirmed the users' satisfaction after the refurbishment. Fig. 30 shows a general satisfaction of the users (above 85% very satisfied – green answers; and about 10% medium satisfied – yellow answers).

The mean indoor *T* during occupation did not have important fluctuations. Two ventilation strategies were implemented (280 m^3/h and 380 m^3/h) but there was not found a direct correspondence between the ventilation rate and the CO_2 concentration. The users' answers did not reveal any discomfort related to CO_2 concentration, which is an expected result since the mean value during occupation remained always below 1500 ppm.

Conclusion

The non-refurbished *Brandão* schools show very low comfort and inadequate hygrothermal conditions and will require intervention in the near future. The opportunity to refurbish these schools must consider the acquired knowledge in this type of buildings by experimental monitoring of in-service free-running schools. The balance between hygrothermal comfort, IAQ, low energy consumption and affordable costs is a very strict commitment that must consider the climatic features, the users' habits, the economic restrictions and the requirements defined by international standards and also international/national legislation.

The main conclusions of this paper are:

- The experimental work of the *Brandão* school before and after refurbishment consisted of *T*, *RH*, CO_2 and EC monitoring of the prototype, developed in a west-sided classroom in Porto. The prototype was developed within the scope of this work and had an important role in the proposal of a low-cost refurbishment strategy to improve the hygrothermal conditions of these schools with a controlled increase of EC. This refurbishment can be replicated to other *Brandão* schools and the methodology can be applied to other typologies.
- The analysis of users' discomfort must consider the occupation period of classrooms. The differences between the occupation period and the total period were the expected: the mean *T* was higher when considering the occupation period, due to internal and solar gains, once the night period was not included. Before and after refurbishment, for the same free-running conditions, the mean differences between the occupation period and the total period were higher in winter than in mid-season.
- The refurbishment was suitable and useful in winter. There was an important reduction of the discomfort after the refurbishment in free-running conditions. Although the mean$\%TD_{20}$ remained 100%, $DI_{w,20}$ values have decreased from 34.7 °C.hour to 25.2 °C.hour, mean daily values.
- After the refurbishment, the $DI_{w,20}$ values decreased from 25.2 to 11.9 °C.hour when comparing free-running *T* and *RH* to 3 heating hours; and from 11.9 to 2.5 °C.hour when the heating period was increased to 10 h per day. The (c) heating strategy was the most appropriate for reaching the 20 °C comfort T and represented an energy consumption of 36 kWh/day (experimental measurement) for this classroom, which is 5€/day (0,1381 €/kWh) [58]. Considering a typical *Brandão* school with four blocks (28 classrooms) the investment would represent about 12000 €/year for electric heating.
- Although the benefits of the low-cost refurbishment even in free-running conditions, heating has an important role in the reduction of the discomfort. The lower EC/DI_w gradient resulted from the first three hours of heating (from (a) to (b) strategy). It represented an important decrease in discomfort with a reasonable increase in energy consumption. The daily energy con-

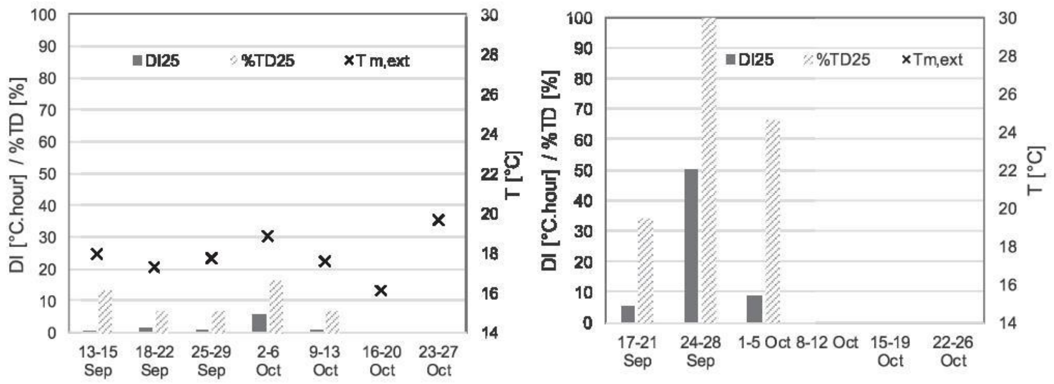

Fig. 29. DI_{25} and $\%TD_{25}$ in mid-season weeks after refurbishment: (left) 2017; (right): 2018.

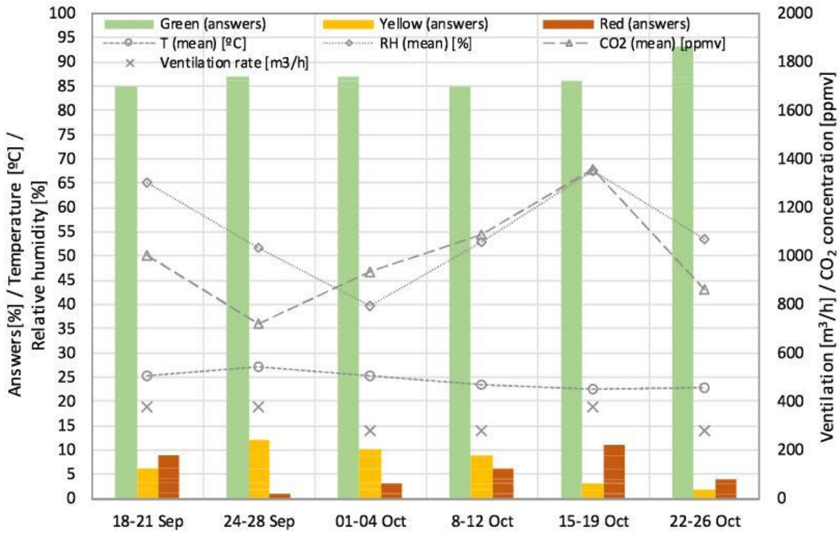

Fig. 30. Users' answers about comfort, mean *T*, *RH*, CO_2 and ventilation rates in autumn weeks after refurbishment.

sumption had an exponential behavior when moving towards the reduction of the discomfort (20 °C during the occupation period).

- The experimental monitoring of the prototype showed an important stratification of *T* during the winter. The stratification was increasingly relevant for greater heating strategies. It was also more important near the heaters. The mean difference values during the winter months in the center of the classroom were 5.9 °C for (c) heating strategy, 2.3 °C for (b) heating strategy and 0.3 °C for (a) heating strategy. The experimental monitoring contributed to understanding the real in-service conditions of these classrooms.
- There was an expected increase of CO_2 inside the classroom for the corresponding months before and after refurbishment, although the mean CO_2 was below the required 1500 ppm. Nevertheless, numerical simulation studies show that it will be necessary to upgrade the real ventilation to 500 m^3/h to satisfy the 1500 ppm requirement for 100% of the occupation period. The CO_2 did not have a direct relationship with the heating strategy and the mean values were similar for the three strategies. The IAQ was not a concerning matter in *Brandão* schools since in pre-existing conditions the CO_2 was below the requirement and remained acceptable after the refurbishment.
- The summer was not an actual concern in the pre-existing situation. After the refurbishment, it was found that the summer performance of the west-sided *Brandão* classroom depends on the climate severity in each year and location.
- The results of the survey confirmed the users' satisfaction after the refurbishment but it was not found any correspondence between the users' perception and the hygrothermal and IAQ conditions inside the classroom.

This work pretended to give a contribution to the refurbishment of school buildings in free-running conditions or with intermittent heating strategies, considering the temperate Mediterranean climate features and the actual capacity to support the operating costs.

Acknowledgements

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APPENDIX F – WUFI SOFTWARE INPUTS AND OUTPUTS

Table F.1 –Wufi software inputs.

Outdoor climate	Temperature	ºC
	Relative Humidity	%
	Counterradiation atmospheric horiz.	W/m^2
	Solar global horizontal radiation	W/m^2
	Solar diffuse horizontal radiation	W/m^2
	Wind direction	º
	Wind speed	m/s
	Atmospheric Pressure	hPa
	Rain	$l/(m^2.h)$
	Latitude	º
	Longitude	º
	Height MSL	m
	Time zone (hours from UTC)	---
	Ground reflectance (short)	---
	Ground reflectance (long)	---
	Emissividade do solo	---
	Cloud index	---
	CO_2 concentration	Ppmv
Building geometry	Height above ground	m
	Building height	m
	Visualized volume	m^3
	Gross volume	m^3
	Net volume	m^3
	Floor area	m^2
	Main orientation	---
	Attachment outside (zone, outer air, ground, space with same inner conditions)	---
	Attachment inside (zone, outer air, ground)	---
	Element type (opaque, transparent)	---

Indoor (each zone)	Ventilation (natural/ mechanical/ interzone)		---
	Mechanical ventilation control (temperature, relative humidity, CO_2)		---
	Rph		h^{-1}
	Ventilation periodic day profile		---
	Infiltration ACH		h^{-1}
	Moisture		g/h
	Heat convective		W
	Heat radiant		W
	Human activity		met
	CO_2 production		g/h
	Clothing		clo
	Air velocity		m/s
	Periodic day profile (year/week/day)		---
	AVAC system type		---
	Used for (space heating / DHW / space cooling / space ventilation / air humidification / air dehumidification)		---
	Share zones for each equipment		---
	Heating power day profile (year/week/day)		W
Envelope / element characterization	Type (opaque / transparent / opening)		---
	Assembly		---
	Material	Bulk density	kg/m^3
		Porosity	---
		Specific heat capacity	J/(kg.K)
		Thermal conductivity, dry, 10ºC	W/mK
		Typical built-in moisture	kg/m^3
		Reference water content	kg/m^3
		Free water saturation	kg/m^3
		Water absorption coefficient	$kg/(m^2.s^{1/2})$
		Thermal conductivity supplement	%/M. - %
	Superficial heat transfer resistance		$m^2.K/W$
	Sd-value – water vapour diffusion resistance		m
	Initial T and RH		º/%
	Calculation mode (Thermal/Hygrothermal)		---

Table F.2 – Wufi software outputs.

Climate	Outdoor		Outdoor temperature	ºC
			Outdoor relative humidity	%
	Indoor (each zone)		Indoor air temperature	ºC
			Operative temperature (interior)	ºC
			Dew point temperature of inner air	ºC
			Mean windows inner surface temperature	ºC
			Indoor relative humidity	%
			Absolute humidity of inner air	[-]
		Ventilation	Natural	m^3/h
			Mechanical	m^3/h
			Total	m^3/h
			Interzone	m^3/h
Energy	Indoor (each zone)		Heating power	kW
			Cooling power	kW
		Heat flow	Solar gains	kW
			Inner heat source convective	kW
			Inner heat source radiant	kW
			Heat exchange with opaque partitions	kW
			Heat exchange with windows	kW
			Ventilation	kW
			Interzone ventilation	kW
			Latent heat - humidification	kW
			Latent heat - dehumidification	kW
Comfort	Indoor (each zone)		Predicted Mean Vote	---
			Predicted Percentage of Dissatisfied	%
			Mean surface temperature (interior)	ºC
			Mean floor temperature	ºC
			Mean ceiling temperature	ºC
			Operative temperature	ºC
			CO_2 concentration	ppm
Moisture	Indoor (each zone)		Humidification	kg/h
			Dehumidification	kg/h
		Moisture flow	Moisture Exchange with partitions	kg/h
			Natural ventilation + infiltration	kg/h
			Mechanical ventilation	kg/h
			Interzone ventilation	kg/h
			Inner moisture source	kg/h

APPENDIX G – ENVELOPE ASSEMBLIES BEFORE THE REFURBISHMENT

West and east facade

	thickness	ρ	λ	c_p	μ	ε	R	U
	[m]	[kg/m³]	[W/(m.°C)]	[J/(kg.K)]	[-]	[-]	[(m².°C)/W]	[W/(m².°C)]
R_{se}							0,04	
Mortar plaster (exterior)	0,02	2000	1,3	1000	25	0,3		
Simple solid brick masonry	0,11	2060	0,85	920	19	0,28	0,160	3,03
Mortar plaster (interior)	0,02	2000	1,3	1000	25	0,3		
R_{si}							0,13	

Interior walls

	thickness	ρ	λ	c_p	μ	ε	R	U
	[m]	[kg/m³]	[W/(m.°C)]	[J/(kg.K)]	[-]	[-]	[(m².°C)/W]	[W/(m².°C)]
R_{si}							0,13	
Mortar plaster (interior)	0,02	2000	1,3	1000	25	0,3		
Simple solid brick masonry	0,11	2060	0,85	920	19	0,28	0,160	2,38
Mortar plaster (interior)	0,02	2000	1,3	1000	25	0,3		
R_{si}							0,13	

Aluminium roof

	thickness	ρ	λ	c_p	μ	ε	R	U
	[m]	[kg/m^3]	[W/(m.°C)]	[J/(kg.K)]	[-]	[-]	[(m^2.°C)/W]	[W/(m^2.°C)]
R_{se}							0,10 (*1)	0,85
Aluminium roof coating	0,0005	2800	160	880	0,73	0,999	0,973 (*2)	
Air layer	0,90	1,3	0,523	1000	0,17	0,999		
XPS surface skin	0,03	40	0,035	1500	450	0,95		
Concrete slab	0,2	2300	2	1000	130	0,16		
Mortar plaster	0,02	2000	1,3	1000	10	0,3		
R_{si}							0,10 (*1)	

(*1) Ascending flow; (*2) Calculated from indoor until the insulation.

Concrete tiles roof

	thickness	ρ	λ	c_p	μ	ε	R	U
	[m]	[kg/m^3]	[W/(m.°C)]	[J/(kg.K)]	[-]	[-]	[(m^2.°C)/W]	[W/(m^2.°C)]
R_{se}							0,04 (*1)	0,82
Concrete screed, bottom layer	0,03	2100	1,5	1000	100	0,175	1,079	
XPS surface skin	0,03	40	0,035	1500	450	0,95		
Lightweight concrete layer	0,1	1800	1,15	1000	110	0,16		
Concrete slab	0,2	2300	2	1000	130	0,16		
Mortar plaster	0,02	2000	1,3	1000	10	0,3		
R_{si}							0,10 (*1)	

(*1) Ascending flow.

Pine wood floor

	thickness	ρ	λ	c_p	μ	ε	U_{bf}
	[m]	[kg/m^3]	[W/(m.°C)]	[J/(kg.K)]	[-]	[-]	[W/(m^2.°C)]
Pine wood floor	0,02	600	0,18	1600	70	0,73	
Lightweight concrete layer	0,03	1800	1,15	1000	110	0,16	0,575 (*1)
Concrete slab	0,2	2300	2	1000	130	0,16	

(*1) U_{bf} [W/(m^2.ºC)], according with Diário da República [19].

Concrete screed floor

	thickness	ρ	λ	c_p	μ	ε	U_{bf}
	[m]	[kg/m^3]	[W/(m.°C)]	[J/(kg.K)]	[-]	[-]	[W/(m^2.°C)]
Concrete screed, bottom layer	0,02	1990	1,6	850	99	0,175	
Lightweight concrete layer	0,03	1800	1,15	1000	110	0,16	0,575 (*1)
Concrete slab	0,2	2300	2	1000	130	0,16	

(*1) U_{bf} [W/(m^2.ºC)], according with Diário da República [19].

Wood doors

	thickness	ρ	λ	c_p	μ	ε	R	U
	[m]	[kg/m^3]	[W/(m.°C)]	[J/(kg.K)]	[-]	[-]	[(m^2.°C)/W]	[W/(m^2.°C)]
R_{si}							0,13	
Plywood	0,04	600	0,14	1700	50	0,5	0,286	1,83
R_{si}							0,13	