Experimental characterization of the thermal performance of a school building prototype before and after refurbishment

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Abstract. Portuguese school buildings are generally characterized by an in service thermal discomfort. The refurbishments that the schools have recently undergone, have not fully considered the climatic diversity and the economic reality of the country and, for that reason, there are still some discomfort in these schools. This work studies the Portuguese *Brandão* schools model (from the 70's), which comprises about 100 non-refurbished basic schools. A prototype classroom was prepared in a *Brandão* school, in Porto. The in situ experimental campaign consisted in temperature, relative humidity, CO₂ concentration and energy consumption measurements. With this prototype, some studies were carried out regarding the thermal behavior before and after a refurbishment process, by experimental monitoring. The prototype construction has included the improvement of the envelope (roof insulation and solar protection) and of the technical systems (ventilation and heating). The main goal was the assessment of the discomfort in this prototype before and after the refurbishment in free-running conditions or with some intermittent heating strategies. Discomfort indexes 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 behavior of the environment after the refurbishment.

1 Introduction

Portugal is located in southwestern Europe, mostly defined by a temperate Mediterranean climate, with rainy winters and dry and hot summers, although it presents a considerable climatic diversity. The selection of the best intervention measures for a building should consider its climatic situation and the economic reality of the country.

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 [1]. For that reason, the so relevant international studies on schools

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energy consumption and potential savings referred in bibliography [2] do not traduce the Portuguese reality.

The constructive records of the past describe the existence of typified projects for school buildings replicated throughout the country, without the necessary adaptations to the particular climatic situation. Likewise, the replication of solutions in refurbishment projects, without taking into account the climatic reality, will have repercussions on the hygrothermal environment inside the classrooms.

The physical environment affects teaching and learning and this justifies the investment in users comfort and indoor air quality (IAQ). The low ventilation rates in classrooms reduce students' attention and vigilance and negatively affect memory and concentration [3, 4].

In the recent past (from 2007 to 2011), 175 Portuguese schools were refurbished. The investment reached 2400 million euros and focused mainly on high schools [5]. Despite the important investment and the high quality of the intervention, these refurbishments have not fully considered our climatic diversity and economic reality. For the future the challenge will be the refurbishment of the remaining schools taking into account their typology, the climate features and the actual capacity to support the operating costs.

2 Methodology

2.1 Case study

The object of this study is the Portuguese *Brandão* model, which comprises 100 basic schools replicated throughout the country in the 70s. This is a pavilion type project, composed by quadrangular single floor blocks of classrooms with a central courtyard (Fig. 1). Classrooms can be accessed around the building (outdoor circulation) or through the neighbor classrooms (indoor circulation).

A prototype classroom (Fig. 1) has been studied in a *Brandão* school, in Porto. The experimental campaign consisted in the continuous monitoring of temperature (T), relative humidity (RH), CO₂ concentration (CO₂) and energy consumption (EC).

Fig. 1. (left) *Brandão* school pavilion. (right) Prototype classroom.

The monitoring of hygrothermal parameters is done by a *Wireless Aptinov* system composed by a 3G router with GSM, a *GW357-2* gateway, 11 *Aptinov WLS-05* dataloggers (T and RH) and 2 *Telaire7001* sensors coupled to 2 *Aptinov WLS-07* dataloggers (CO₂). T_{ext} and RH_{ext} values were provided by LFC-FEUP Meteorological Station. The monitoring of EC is 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 EC monitoring and 3 smart plugs for the equipment connected to electrical plugs (including the heating system 2 + 2 kW).

2.2 Prototype classroom

The main goal of the prototype construction is the assessment of the classroom behavior before and after the intervention and the calibration of an advanced hygrothermal numerical model. This refurbishment pretended to minimize the discomfort in this classroom, regarding the typical in service conditions in these kind of schools.

The implementation of a partition wall and the upgrading of the enclosure allowed the improvement of the hygrothermal behavior and the introduction of heating strategies. Likewise, the partition wall allowed the control of the ventilation in order to ensure IAQ. The following interventions were implemented (Fig. 2.): electric heating system; partition wall between the classroom and the circulation zone; ventilation system with naturally filtered inflow and forced airflow to the circulation zone; exterior blinds; roof insulation.

Fig. 2. Prototype interventions.

2.4 Discomfort indicators

Discomfort indicators 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.

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 (equation 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 percentage of time ($\%DT_b$) represents the proportion of the discomfort periods during the analyzed occupation period (equation 2).

$$\%DT_b = \frac{\sum t_{i \text{ discomfort}}}{\sum t_{i \text{ occupation}}} \quad (2)$$

3 Results and discussion

The in service conditions before intervention were the free-running T, RH and CO₂. After the refurbishment the prototype was analyzed in three situations: (a) free-running T and RH; (b) reduced heating strategy (3h per day) and (c) regular heating strategy (10 hours per day), always with a controlled ventilation system.

3.1 Before the prototype refurbishment

The left side of Fig. 3. presents the $ID_{w,20}$ in 2016 and shows discomfort in 100% of the occupation period. Table 1 presents a detailed analysis of the weekly and mean daily $DI_{w,20}$ before refurbishment and the exterior mean T ($T_{m,ext}$) in each analyzed week.

The right side of Fig. 3 presents the accumulated frequency of CO₂. In winter time, the CO₂ is below 1250 ppm [6] in 50-80% of the occupation period, below 1500 ppm [7] in 70-90% and below 2000 ppm in 90-100%, here defined as maximum acceptable value.

Fig. 3. (left) $DI_{w,20}$ and $\%DT$ – strategy (a). (right) Accumulated frequency of CO₂ before the intervention.

Table 1. Discomfort indicators in winter before the intervention.

week	Nb of days	strategy	T _{m,ext}	DI _{w,20}	%DT ₂₀
11-12 Feb	2	(a)	11.4	57.6	100%
15-19 Feb	5	(a)	11.9	251.9	100%
22-26 Feb	5	(a)	12.5	185.4	100%
29-4 Mar	4	(a)	10.4	122.0	100%
7-11 Mar	5	(a)	11.1	166.6	100%
14-18 Mar	5	(a)	13.7	117.7	95%
daily mean	---	(a)	---	34.7	99%

3.2 After the prototype refurbishment

Fig. 4. presents the $ID_{w,20}$ in 2018 for the referred three situations: (a) free-running T and RH (Fig.4., left); (b) reduced heating strategy (Fig.4., center) and (c) regular heating strategy (Fig.4., right), always with a controlled ventilation system.

In free-running winter weeks of 2018, the mean $\%TD_{20}$ remains 100% (Fig. 4, left), 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). The $\%TD_{20}$ decreases from 100% to 80% (mean values) for the adopted strategy (b) and to about 30% for the (c) heating strategy. $DI_{w,20}$ decreases 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. This reduction could be more noticeable if we had the same exterior conditions (which did not

happened since $T_{m,ext}$ is not a controlled variable). Table 2 presents a detailed analysis of the weekly and mean daily $DI_{w,20}$ after refurbishment and the exterior mean T ($T_{m,ext}$) in each analyzed week.

Fig. 5 shows the accumulated frequency of CO₂. Regardless the adopted heating strategy, in winter time the CO₂ is below 1250 ppm [6] in 30-40% of the occupation period, below 1500 ppm [7] in 50-60% and below 2000 ppm in 90%.

Fig. 4. (left) $DI_{w,20}$ and %DT - strategy (a). (center) $DI_{w,20}$ and %DT - strategy (b). (right) $DI_{w,20}$ and %DT - strategy (c).

Fig. 5. Accumulated frequency of CO₂ during (a), (b) and (c) heating strategies, after the intervention.

Table 2. Discomfort indicators in winter after the intervention.

week	Nb of days	strategy	$T_{m,ext}$	Energy [kWh]	$DI_{w,20}$	%DT ₂₀
3-5 Jan	3	(a)	12.6	0	61.9	100%
8-12 Jan	5	(b)	9.1	43	115.3	100%
15-19 Jan	5	(c)	9.3	170	19.7	38%
22-26 Jan	5	(a)	10.5	0	139.5	100%
29-2 Fev	5	(b)	11.2	59	43.9	83%
5-9 Fev	5	(c)	7.1	199	15.0	38%
12-16 Fev	2	(a)	12.7	0	49.5	100%
19-23 Fev	5	(b)	11.9	48	37.7	69%
26-2 Mar	5	(c)	11.0	197	0.02	3%
5-9 Mar	5	(a)	11.3	0	127.3	100%
12-16 Mar	5	(b)	11.6	52	41.4	69%
19-23 Mar	5	(c)	9.9	147	15.3	38%
daily mean	---	(a)	---	0	25.2	100%
	---	(b)	---	10	11.9	80%
	---	(c)	---	36	2.5	29%

4 Conclusions

The non-refurbished *Brandão* schools show very low comfort and inadequate hygrothermal conditions and will require some interventions in the near future. It is then important to

define some strategies for the refurbishment of these basic schools. The main purpose of this experimental work was the assessment of the discomfort in this prototype before and after the refurbishment in free-running conditions or with some intermittent heating strategies, regarding the typical in service conditions in these kind of schools.

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 hours per day. The comfort T (20°C) during all the occupation period was only possible with the (c) heating strategy, which represented an energy consumption of 36 kWh/day (experimental measurement) for this classroom, that is 5€/day (0,1381 €/kWh) [8]. Considering a typical *Brandão* school with four blocks (28 classrooms) the investment would represent about 12000 €/year for electric heating and, for an optional heating system with gas consumption, the investment would be less than 50% of this value.

The CO₂ is the main pollutant in school buildings and results from the metabolism. The ventilation system was an important intervention in this prototype in order to control the CO₂ after the installation of the partition wall. Before the intervention, the CO₂ was mostly under the reference values. After the prototype refurbishment CO₂ has worsen. This might be improved in the next months by the establishment of a regular ventilation schedule. Nevertheless, numerical simulation studies show that will be necessary to upgrade the ventilation to 500 m³/h (which corresponds to the 24 m³/(hour.person) defined for classrooms in Portuguese legislation [6]) to satisfy the 1500 ppm requirement.

This work pretended to give a contribution for 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.

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