Hygrothermal Performance of Portuguese Classrooms: measurement and computer simulation

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ABSTRACT: The rehabilitation of school buildings is an imperative in Portugal. The current buildings do not guarantee adequate conditions of habitability. So, a very ambitious public plan for rehabilitation of school buildings which involves substantial investments is being carried. It is essential to support this investment plan with a thorough investigation that could help and sustain the technical decisions to be taken. To that end a research project has started with two main objectives: to evaluate the suitability of the legal requirements currently in use in Portuguese codes regarding comfort conditions and ventilation rates through the measurement of temperature, relative humidity and carbon dioxide concentration in classrooms of different schools; and make an optimization of constructive solutions to be used in retrofitting of school buildings using computer simulations, artificial neural networks and genetic algorithms. This paper presents the initial results of this project, from the measured values starts a preliminary discussion and launches the future works of the research project.

1 INTRODUCTION

A major program of refurbishment of school buildings is starting in Portugal. It is an exceptional opportunity, not only to increase the energy efficiency of the buildings, but also to improve the indoor learning environment in terms of thermal comfort and indoor air quality. This intervention must be prepared carefully and the technical decisions must be scientifically supported to guarantee the sustainability of the exploration costs of the building, often neglected during the design process (Freitas, 2009).

To technically support the retrofit decisions the Laboratory of Building Physics (LFC) of Faculty of Engineering of University of Porto (FEUP) is conducting a research with two main purposes: (1) assess the indoor environmental quality conditions within classrooms of different school buildings by the measurement of temperature, relative humidity and carbon dioxide concentration, and from the results understand the comfort conditions that should be used in the design process and check the viability of some of the solutions that are being used, mainly in terms of ventilation systems, regarding the economic reality of Portugal and the high maintenance costs associated with those systems; (2) the development of a methodology for optimization of constructive solutions to use in the rehabilitation of school buildings, by means of multi-objective optimization with genetic algorithms. It is intended that the constructive solutions should ensure adequate conditions of comfort, low energy costs and sustainability in the operating costs of the buildings.

The aim of this paper is to show the initial results of this research and to launch a preliminary discussion. Therefore, this paper presents the results of the first experimental campaign of measurements in classrooms and the first models for computer simulation of hygrothermal and energy performance of school buildings.

2 EXPERIMENTAL CAMPAIGN SETUP

A key component of this work is the on-site assessment of the comfort conditions, measured by the temperature and relative humidity, and the indoor air quality, measured by the carbon dioxide concentration and the ventilation rate, of classrooms under service conditions. A total of eight classrooms, two in each of the four school buildings studied, were monitored. Two of the schools were recently retrofitted and the other two maintain the original conditions. The experimental campaign took place during the winter of 2009.

The campaign included continuous measurements and spot measurements: continuous measures included the monitoring through one week of the temperature, relative humidity and carbon dioxide concentration with equipment placed in the classrooms and spot measures include the evaluation of the ventilation rates by means of the tracer gas method - decay technique, with different conditions of envelope (door open/closed and interior windows open/closed).

2.1 *Retrofitted schools*

Measurements were taken at two schools in the city of Porto, Portugal, in this paper designated as R1 and R2. In each of the schools two classrooms considered representative of the environment within the school where chosen for the measurements. Both schools were recently retrofitted.

R1 school was built in the 80's and underwent a rehabilitation process during the year of 2008. The classrooms are now prepared with heating equipment and hybrid ventilation. The ventilation consists of mechanical air extraction with natural supply inlets. The air admission is obtained from pressure-controlled ventilators that guarantee a constant flow and the mechanical air extraction has a maximum capacity of 400 m^3/h. The occupants of the classrooms have the possibility to operate both the heating equipment and the mechanical air extraction.

The school building R2 date of 1930 and was retrofitted during 2008. The classrooms were equipped with openings in the facades for air intake and mechanical equipment for the extraction of air that allow a maximum flow of 600 m^3/h. Heating systems were built and the occupants have the possibility to regulate it.

2.2 *Non-retrofitted schools*

Two non-retrofitted schools were chosen to evaluate the indoor environmental quality, both in the city of Porto, designated in this paper as NR1 and NR2.

The school NR1 was built in 1997 while the NR2 in 1993. The schools were monitored for a week and have no heating system or air intake devices. The classrooms ventilation is achieved only by window opening.

2.3 *Techniques and equipment*

The continuum monitoring of temperature and relative humidity was carried with data loggers *HOBO-H08-007-02* (±0,7ºC and ±5%, resolution of 0.4°C) and the carbon dioxide concentration was measured with the *TelAire 7001* associated to a data logger *HOBO-H08-007-02* (0 to 2500ppm, errors of ±50 ppm).

The determination of ventilation flows was performed using a tracer gas and the decay technique. For the typical situation inside a classroom (temperature and wind steady - almost constant flow) and when the tracer gas concentration outside is null and there is no emission or absorption of gas inside, the mass balance of the tracer gas can be expressed by the following differential equation:

$$V \cdot \frac{\partial c(t)}{\partial t} = -q \cdot c(t) \quad (1)$$

where V = volume; t = time; c = concentration of the tracer gas; q = flow.

The solution for Equation 1 is:

$$c(t) = c_0 \cdot e^{-\frac{q}{V} \cdot t} \quad (2)$$

where c_0 = initial concentration of the tracer gas.

Rearranging this last equation, we can obtain:

$$\frac{q}{V} = ACH = \frac{\ln\left(\frac{c_0}{c(t)}\right)}{t} \quad (3)$$

where ACH = air changes per hour.

Thus, for calculating the leakage flow or ventilation in spaces that can be considered as a single zone is necessary to introduce the tracer gas in the space until a uniform initial concentration, c_0, is achieved. Then record the evolution of concentration with time in a graph ln (c) versus time, which by Equation 3, is a straight line. The module of its slope, q/V is the unknown that allows the calculation of the air changes per hour, ACH. This test is regulated by ISO 12569 (2000) and ASTM E741-00 (2000).

To perform this measurements the *Innova* analyzer *reference 1312* was used. The tracer gas was the sulfur hexafluoride (SF6) and the equipment recorded its concentration during the test.

3 RESULTS

The continuous measurements of temperature, relative humidity and carbon dioxide concentration began on a saturday and held for a week.

3.1 *Temperature and relative humidity*

The following Figures illustrate the results obtained for the temperature and relative humidity in the classrooms studied. Tables 1 and 2 summarize the results.

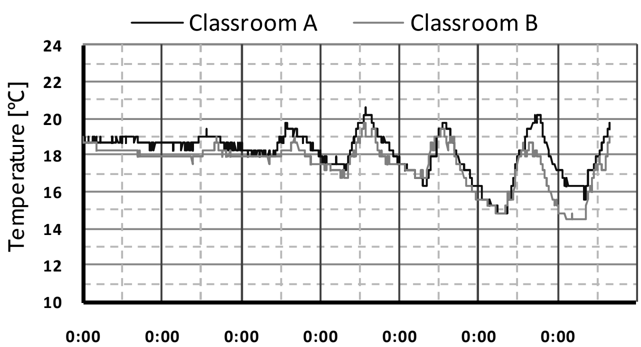

Figure 1. Temperature variation in school R1.

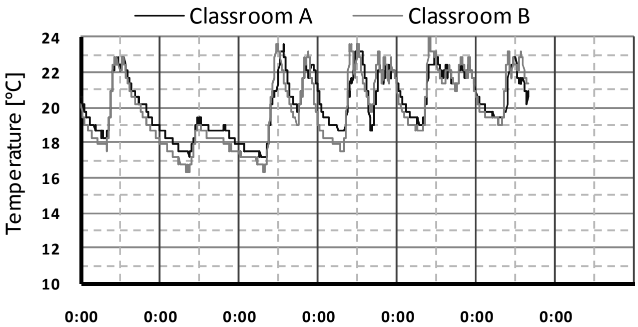

Figure 2. Temperature variation in school R2.

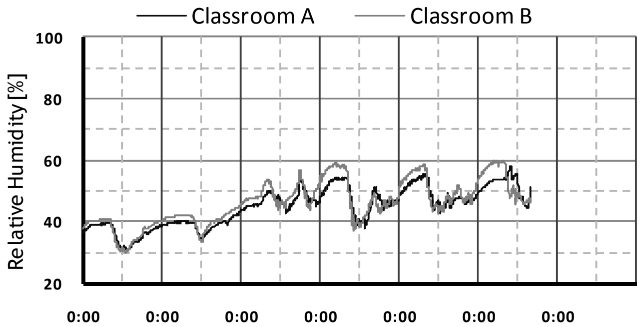

Figure 6. Relative humidity variation in school R2.

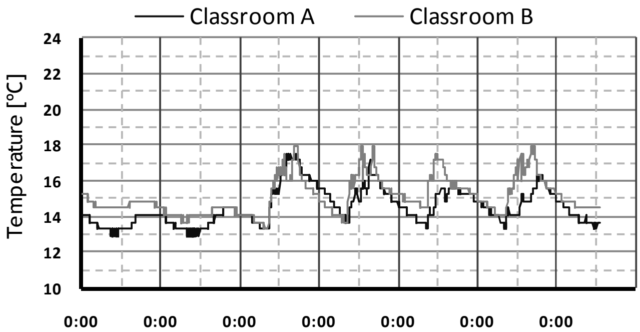

Figure 3. Temperature variation in school NR1.

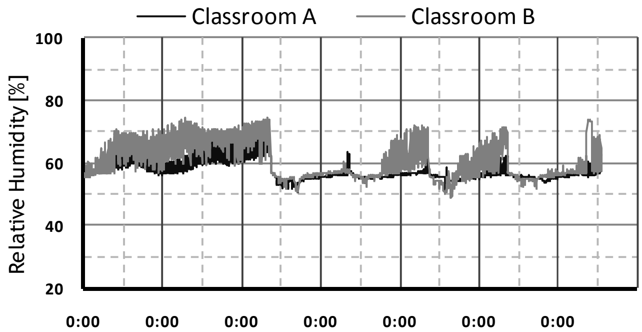

Figure 7. Relative humidity variation in school NR1.

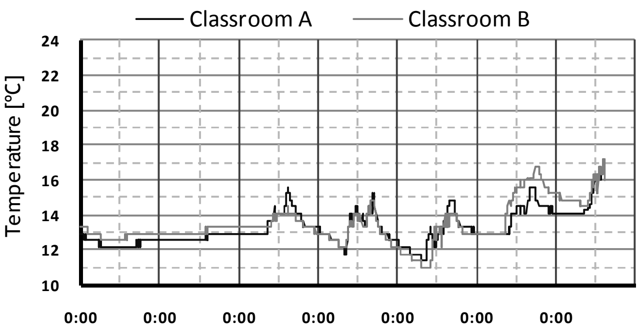

Figure 4. Temperature variation in school NR2.

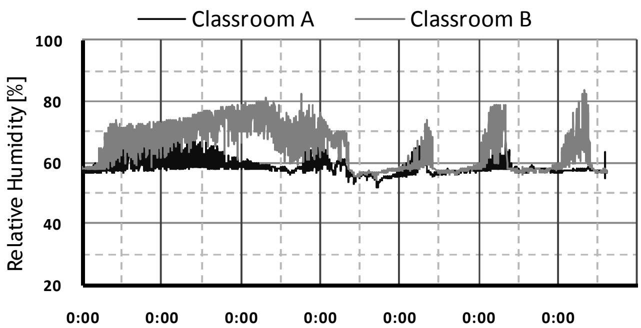

Figure 8. Relative humidity variation in school NR2

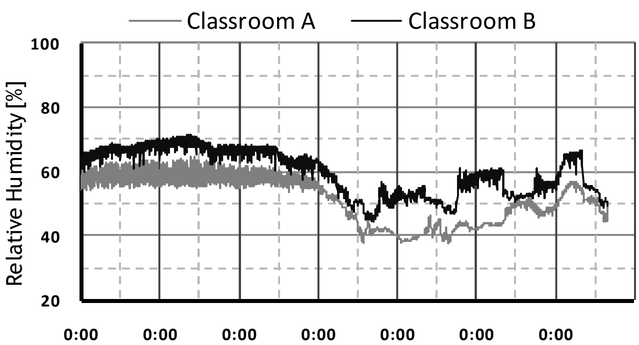

Figure 5. Relative humidity variation in school R1.

3.2 *Carbon dioxide concentration*

Figures 9 to 11 show the variation of the carbon dioxide concentration in the classrooms studied during the measurement period. Table 3 summarizes the results.

Table 1. Statistical analysis of temperature

		R1		R2		NR1		NR2	
		Classroom A	Classroom B	Classroom A	Classroom B	Classroom A	Classroom B	Classroom A	Classroom B
T_{indoor}	*Mean*	18,5	17,9	21,3	21,6	16,3	15,3	14,7	14,2
	Standard deviation	1,32	1,22	1,43	1,46	0,99	1,08	3,76	1,33
	Maximum	20,6	19,8	23,6	24,0	17,9	17,5	21,0	17,1
	Minimum	14,9	14,5	17,1	16,4	13,3	13,3	4,0	11,0
$T_{outdoor}$	*Mean*	10,2		14,5		14,7		11,0	
	Standard deviation	2,24		1,35		3,76		2,69	
	Maximum	13,0		17,0		21,0		17,0	
	Minimum	4,0		11,0		4,0		4,0	

Table 2. Statistical analysis of relative humidity

		R1		R2		NR1		NR2	
		Classroom A	Classroom B	Classroom A	Classroom B	Classroom A	Classroom B	Classroom A	Classroom B
HR_{indoor}	*Mean*	46	51	46	47	56	55	57	61
	Standard deviation	4,2	3,0	3,7	4,1	3,3	1,8	1,6	6,4
	Maximum	55	67	55	59	74	69	67	84
	Minimum	38	45	38	37	49	50	52	55
$HR_{outdoor}$	*Mean*	78		82		69		81	
	Standard deviation	13,5		9,2		15,0		13,5	
	Maximum	100		100		100		100	
	Minimum	58		63		40		58	

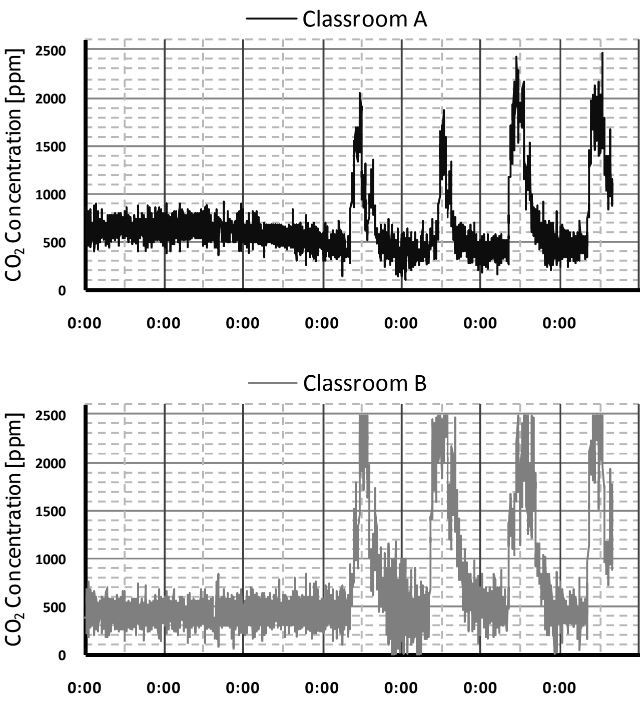

Figure 9. Carbon dioxide concentration variation in school R1.

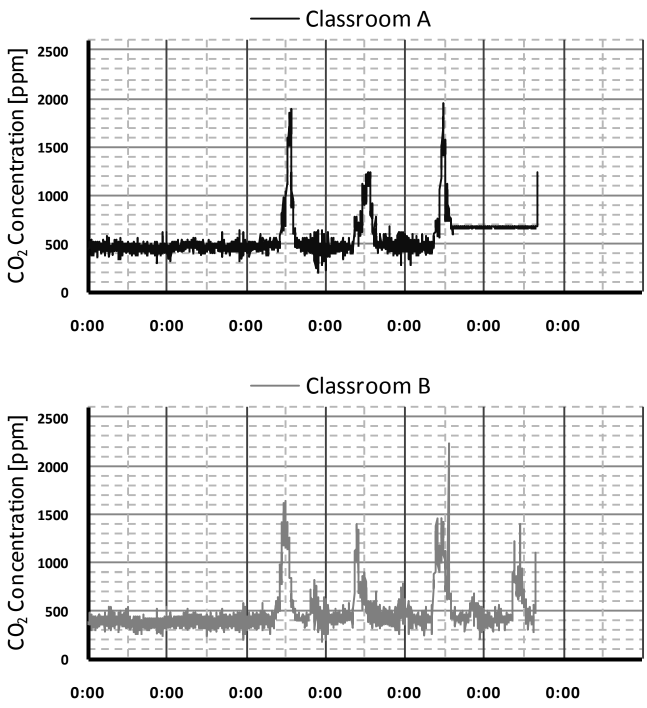

Figure 10. Carbon dioxide concentration variation in school R2.

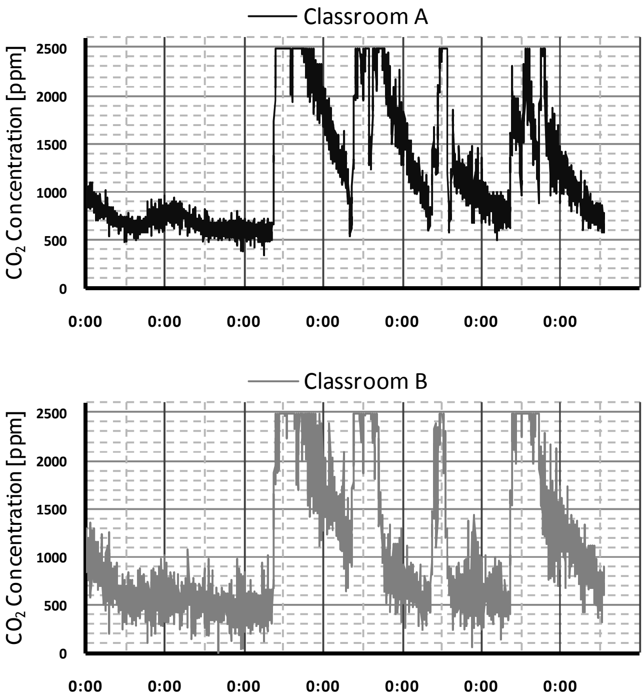

Figure 11. Carbon dioxide concentration variation in school NR1.

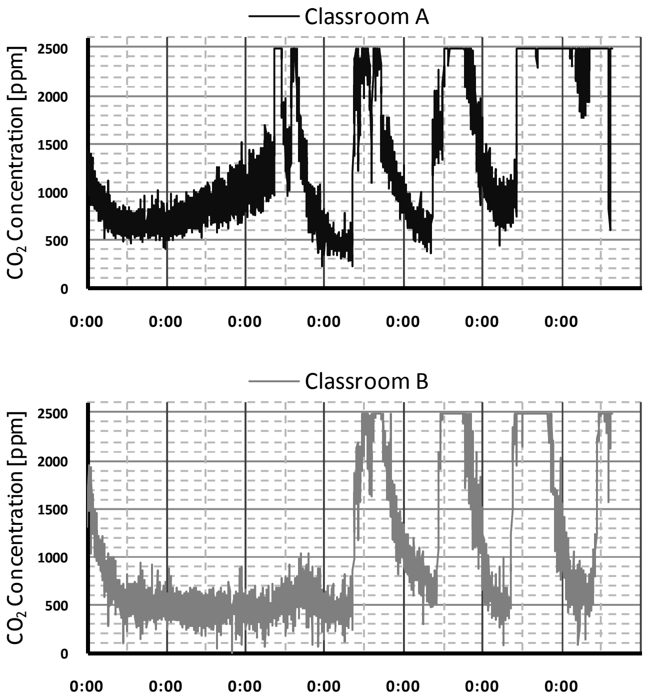

Figure 12. Carbon dioxide concentration variation in school NR2.

Table 3– Statistical analysis of carbon dioxide concentration

	R1		R2		NR1		NR2	
	Classroom A	Classroom B	Classroom A	Classroom B	Classroom A	Classroom B	Classroom A	Classroom B
Mean	1113	1597	732	667	1890	1964	2083	1730
Standard deviation	512	607	286	313	614	717	568	861
*Maximum**	2466	2500	1958	2231	2500	2500	2500	2500
Minimum	259	261	386	259	503	349	320	381

* data logger was limited to 2500 ppm.

3.3 *Ventilation*

The ventilation rates were determined using the tracer gas method – decay technique. Ventilation rates were measured in one classroom of R1 school and one classroom of NR1 school. In the classroom of school R1 two scenarios were measured: (a) mechanical air extraction off and (b) mechanical air extraction on. In both scenarios door and windows were closed. In the classroom of school NR1 three scenarios were measured: (a) the door and interior windows closed; (b) the door open and interior windows closed; (c) door closed and interior window open. Figures 13 and 14 show the results from the decay of tracer gas in the classrooms of schools R1 and NR1 respectively. Table 4 summarizes the ventilation rates measured.

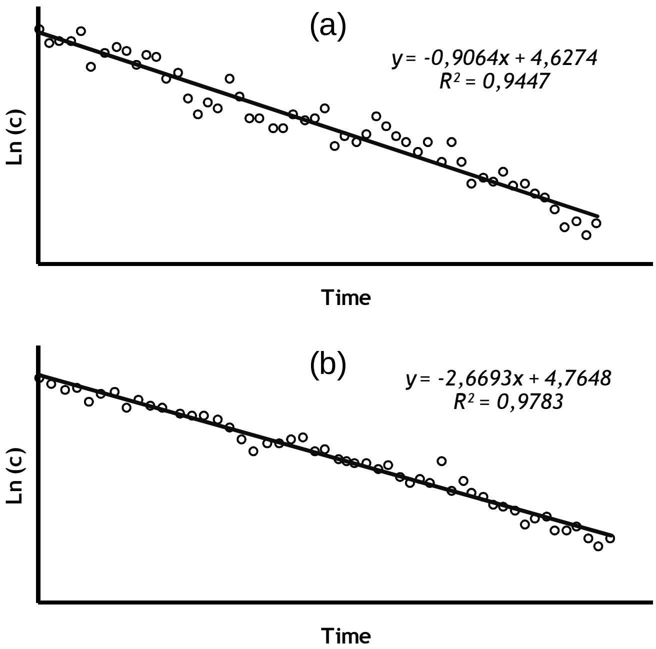

Figure 13. Tracer gas decay – school R1.

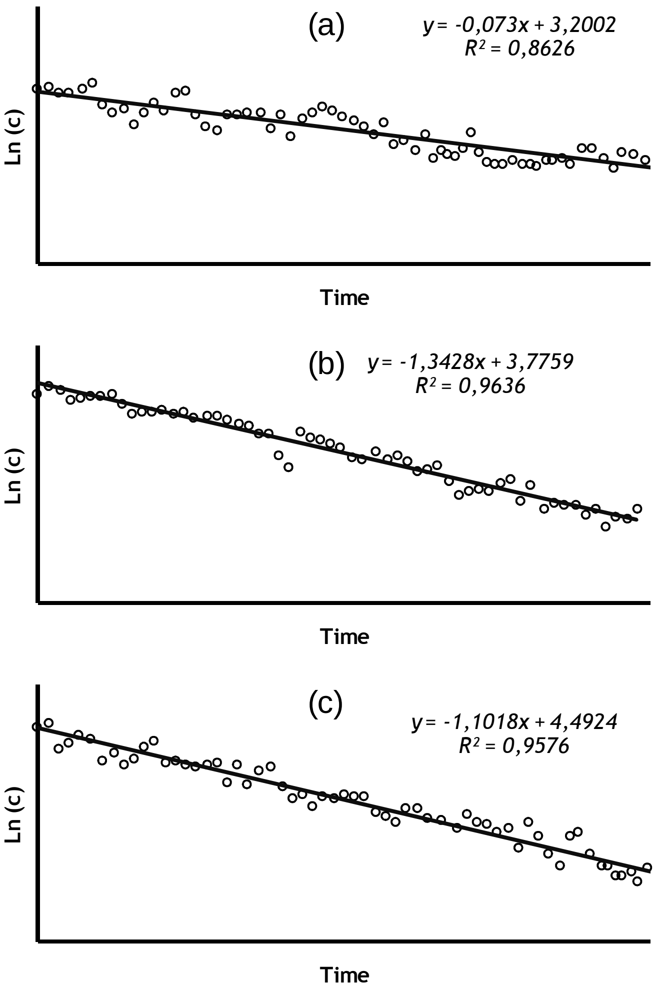

Figure 14. Tracer gas decay – school NR1.

Table 4 summarizes the results.

Table 4 – Ventilation rates

	R1		NR1		
	(a)	(b)	(a)	(b)	(c)
Ventilation rate (m^3/h)	137	405	11	201	165

4 SIMULATION

The parameters and physical processes involved in the phenomena of heat, air and moisture transfer in buildings and, in many situations, the complicated geometry of the building, mean that more detailed analysis of the hygrothermal performance of buildings must make use of modeling and computer simulations.

The use of simulation tools has increased significantly and is universally acknowledged its contribution to finding solutions that enhance energy efficiency in buildings, notably the choice of the ventilation system, constructive solutions to the building envelope, heating system, more efficient lighting equipment, solar protection systems...

Since the hygrothermal phenomena that occur inside a building affect its ventilation system (such as the buoyancy effects in naturally ventilated buildings where the ventilation flow rates depend on temperature differences between indoor air and the exterior) and it has a strong impact on the energy performance of the building, it is clear that the best way to simulate the performance of a building is using models that combine the phenomena of heat transfer phenomena associated with ventilation.

Given the objectives of this study, *EnergyPlus* (Crawley et al. 2001a, b) software was chosen for the simulation of the school buildings hygrothermal end energetic performance. The software *DesignBuilder* (2009) was used to create the models.

4.1 *Models*

The two non-retrofitted schools, NR1 and NR2, were modeled with *DesignBuilder* (2009), Figures 15 and 16.

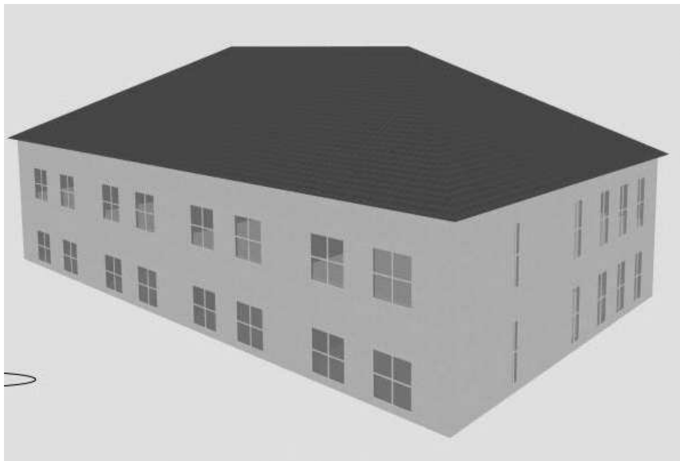
Figure 15. Simulation model of NR1 school.

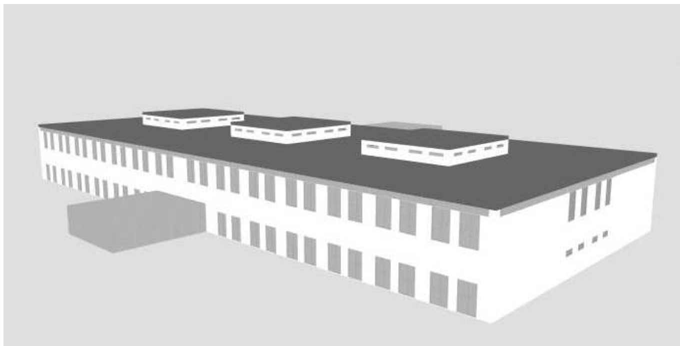
Figure 16. Simulation model of NR2 school.

4.2 *Models validation*

The simulation results were compared with the on-site measurements to allow a validation of the model used. The results obtained for the temperature on a typical day of occupation are shown in Figures 17 and 18, for school NR1 and NR2 respectively.

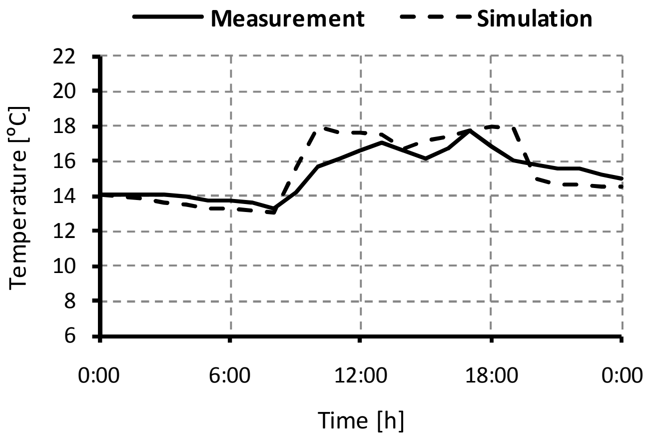

Figure 17. Measurement and simulation in NR1 school.

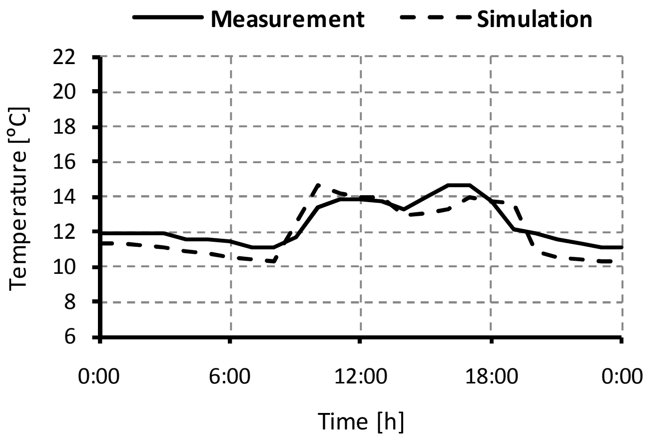

Figure 18. Measurement and simulation in NR2 school.

The differences found between the simulated and measured values can be mainly explained by two reasons: it was considered a daily profile of occupancy of the classrooms constant, different from the real situation where the number of students varies from class to class and the classroom does not hold the same occupation every day, and the climatic data used was not from the exact location of the school but from a meteorological station nearby.

5 DISCUSSION AND CONCLUSIONS

The rehabilitation of school buildings involves huge investments and, as such, the associated decisions should be taken carefully seeking the optimization of the available resources.

Since these buildings present unique characteristics in terms of occupancy rates and consequently high internal gains, concerns about comfort, indoor air quality and energy performance must be decisive when choosing the best constructive solutions and techniques, which must be economically sustainable throughout the life cycle of the building.

To help and support the necessary decisions the LFC of FEUP is undertaking a research project that, by means of measurement of temperature, relative humidity and carbon dioxide concentration, intends to verify the suitability of the actual legislation in terms of hygrothermal conditions and ventilation rates. The Portuguese codes impose a maximum value of 1000 ppm for carbon dioxide concentration inside the classrooms which corresponds to a value between 600 and 700 m^3/h of fresh air (30 m^3/h/person). These values make almost impossible the use of natural ventilation. This way all schools that are being retrofitted are mechanically ventilated. The applied systems have high operational and maintenance costs which, in authors opinion, are quite inadequate for the typical school budgets.

From the results of the first measurement campaign can be concluded the following:

- non-retrofitted schools do not have suitable conditions of comfort and indoor air quality, thus it is imperative to improve it by means of retrofitting the building envelope;

- the reference design temperatures in the Portuguese codes are 20ºC and 25ºC for winter and summer season, respectively. The mean air temperature in schools NR1 and NR2 was significantly less than the 20ºC value of reference. These schools do not have heating systems and the walls, roofs and windows have a high U value which help to explain the results. The ventilation rates were very low and, consequently, the carbon dioxide concentration very high. So the indoor air quality must be improved with higher values of fresh air, even if this action involves an increase of the energy losses due to ventilation;

- so in authors opinion these schools hygrothermal performance must be increased to guarantee adequate comfort conditions by means of improving the thermal behavior of walls, roofs and windows and applying adequate heating systems with low maintenance costs; the indoor air quality must be assured with adequate ventilation systems, mainly natural ventilation due to the costs associated with mechanical systems;

- temperature and relative humidity in retrofitted schools are within the usually considered comfort conditions; this fact show that simple heating systems and improving insulation of the building envelope can guarantee adequate indoor environmental quality;

- the carbon dioxide concentration in the retrofitted schools is higher than the maximum value of 1000 ppm but within the ranges considered enough in some European countries (mean values of 1100 to 1600 ppm in school R1 and 667 to 732 in school R2);

- the ventilation rates were lower than the legislation values but during the measurement period the occupants of the classrooms in the retrofitted schools, although having that possibility, chose not to put in operation the mechanical exhaust ventilation, meaning that the values obtained for the carbon dioxide concentration correspond to a situation of natural ventilation. It is imperative to question the need for so significant investments in the mechanical systems for ventilation.

6 FUTURE WORK

The research project also intends to seek optimized construction solutions to be used in the retrofit of school buildings. The search for the best constructive solutions is a multi objective optimization problem, since it seeks to ensure adequate conditions of comfort and indoor air quality, minimizing energy consumption and costs, both initial and operational throughout the life cycle of the building. The parameters that will be optimized are the heat transfer coefficient of external walls, roof, and windows, the total solar energy transmittance of windows and the air change rate. The cost functions for optimization are related to heating energy consumption, indoor relative humidity and overheating discomfort in summer season.

The optimization of the design solutions will be achieved through the use of computational simulation of the energy and hygrothermal annual performance of the buildings. Since numerical simulation of buildings is a very time consuming procedure, and the goal is to perform a multi-objective optimization, it is virtually impossible to employ it directly for the optimization of the solutions. So, it will be used artificial neural networks that, after being properly trained, allow estimating the results of the simulations on a simple and quick manner. The final optimization of the solutions will be achieved with genetic algorithms.

ACKNOWLEDGEMENT

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