Temperature validation of an advanced hygrothermal model: statistical analysis

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ABSTRACT

Portuguese school buildings are generally characterized by an in-service thermal discomfort, due to the poor envelope thermal properties and the lack of resources for paying energy consumption. Portuguese schools are free-running buildings in a Mediterranean temperate climate, with a natural ventilation strategy.
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 rehabilitation projects, without taking into account the climatic reality, will have repercussions on the hygrothermal environment inside the classrooms.
This work studies the Portuguese *Brandão* basic schools (from the ’70s). About 100 non-refurbished *Brandão* schools will require some interventions in the near future. A prototype classroom was prepared in a *Brandão* school, in Porto. With this prototype, some studies were carried out regarding the thermal behavior before and after a refurbishment process, by experimental monitoring. The in situ experimental campaign consisted of temperature, relative humidity, CO_2 concentration and energy consumption measurements.
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 calibration process consisted of comparing and minoring differences between experimental and numerical results of temperature. 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 replies the *in situ* conditions and allows the studying of the other Portuguese *Brandão* buildings.
This paper presents the temperature 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 output was the temperature.

KEYWORDS: School buildings; Prototype; Experimental measurement; Numerical simulation; Validation.

1. FRAMEWORK

Portuguese school buildings are generally characterized by an in-service thermal discomfort, due to the poor envelope thermal properties and the lack of resources for paying energy consumption. In the past, there were some typified projects for school buildings that were implemented and replicated throughout the country, without the necessary adaptations to the specific climatic features. Likewise, the replication of refurbishment solutions, without considering the climatic features, may possibly result in distinct hygrothermal behavior patterns inside the classrooms.

The main goal of this work is the validation of a model to describe the thermal and energy performance of the *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 buildings' models to find the best refurbishment strategies for specific schools [1, 2] and there are also some studies about model validation (for distinct buildings) in Wufi Plus, but it is important to validate each numerical model attending the building typology and its specificities.

The hygrothermal model chosen in this work was the Wufi Plus software ("Wärme- und Feuchtetransport instationär", that is "Transient Heat and Moisture Transport"), developed by Fraunhofer IBP, regarding Kunzel [3] calculation model fundamentals.

2. CASE STUDY

This work studies the Portuguese *Brandão* basic schools (from the 70's). About 100 non-refurbished *Brandão* schools will require some interventions in the near future. This is a pavilion type project, composed by quadrangular single floor blocks of classrooms with a central courtyard [4]. 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 (Figure 1).

A prototype classroom has been studied in a *Brandão* school, in Porto (Figure 1). The experimental campaign consisted of the continuous monitoring of temperature (T), relative humidity (RH), CO_2 concentration (CO_2) and energy consumption (EC).

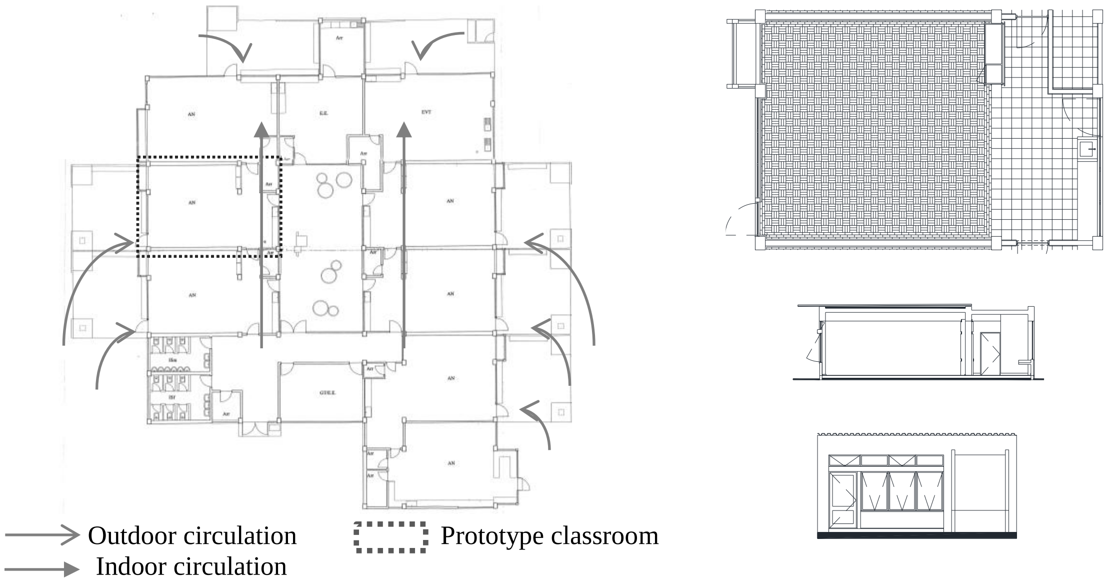

Figure 1: (left) Classrooms block. (right) Prototype classroom.

3. INPUTS FOR CALIBRATION

3.1. Climatic data

The validation of this model considered the hourly data from Meteorological Station (MS) of LFC-FEUP [5] from 2016, 2017 and 2018, since the prototype is in Paranhos, near the MS.

The sinusoidal of the Porto ground climate was defined with a mean value of 17ºC and an amplitude of 3ºC. To the RH definition, it was accepted the 99% value [6]. Some measurements of ground temperature were made in different countries [7, 8] but Portuguese reality was studied by Pinto, Rodrigues and Mota [9]. The Porto ground climate was defined considering the previous results in Aveiro and the mean exterior air temperature of Porto.

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 validate the model after the refurbishment.

3.2. Prototype refurbishment and envelope conditions

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

The implementation of a partition wall and the upgrade of the envelope allowed the introduction of heating strategies and the improvement of the hygrothermal behavior. The partition wall also allowed the control of the ventilation in order to ensure IAQ. The following interventions were implemented (Figure 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.

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

Figure 2: Prototype interventions: (a) partition wall; (b) ventilation system; (c) exterior blinds; (d) roof insulation.

3.3. Internal loads

The school building's internal loads result from occupation and other sources such as lighting and equipment. A realistic calendar and schedule were defined in order to validate the model, once the occupation has an important role in the water vapor production, on the CO_2 production and in internal heat production.

The Wufi Plus database for occupation (considering 20 students and 1 teacher) was used to the model validation and also 15 W / m^2 for lighting for the studied classroom (Table 1) [10, 11].

Table 1: Internal loads in classrooms.

Source	Internal loads		Reference
	[W/m^2]	met	
Student 14-16 years occupation	50 (*)	1,2	Wufi Plus [10]
Adult (sitting, working)	67 (*)	1,2	Wufi Plus [10]
Illumination (mean heating-level)	15	---	Moret Rodrigues, Canha da Piedade and Braga [11]

(*) 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 área.

4. EXPERIMENTAL VS SIMULATION – DISCUSSION OF THE RESULTS

For the validation of the *Brandão* schools model, some calibration tests were done by comparing the indoor environmental measurements of T obtained from in situ monitoring with simulation results.
The validation was divided into three steps: (1) before the intervention in free-running conditions; (2) after the intervention in free-running conditions; (3) after the intervention with three heating strategies in a weekly schedule calendar.

Although the comparison has been made for the full-time period, the main goal is the validation of the model for the occupation period and, for that reason, it was not a concern to validate the model for the summer period (without classes).

Table 2 presents the statistical analysis of the weekly differences between experimental and numerical results for the same input conditions (envelope, solar gains, inner gains, ventilation, climate) for three winter weeks before refurbishment and three winter weeks after refurbishment. Figure 3 shows the T experimental and simulated development during these winter weeks.

Through a detailed weekly analysis (Figure 3), it is possible to observe that the occurrence of higher gaps between measured and simulated data is during the heating weeks. Figure 4 represents a statistical analysis of the T differences inside the prototype classroom for three distinct situations after refurbishment: (a) free-running condition, without heating; (b) 3 heating hours/day in early morning; (c) 10 heating hours/day. 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. Furthermore, the measured in-service conditions reveal an important temperature stratification in different classroom locations that justifies the differences between experimental data and simulation.

Table 2: Weekly statistical analysis of T differences before and after refurbishment.

	Before refurbishment			After refurbishment		
	22-26 Feb	7-11 Mar	14-18 Nov	6-10 Nov	5-9 Feb	5-9 Mar
Mean	**0.36**	**0.52**	**0.38**	**0.45**	**2.23**	**0.43**
Maximum	1.53	2.29	1.64	1.35	8.59	1.17
Percentile 25	0.26	0.43	0.29	0.25	0.62	0.28
Percentile 75	0.13	0.18	0.16	0.51	3.81	0.56
Percentile 95	0.54	0.68	0.49	0.99	6.21	0.91

Before refurbishment	After refurbishment

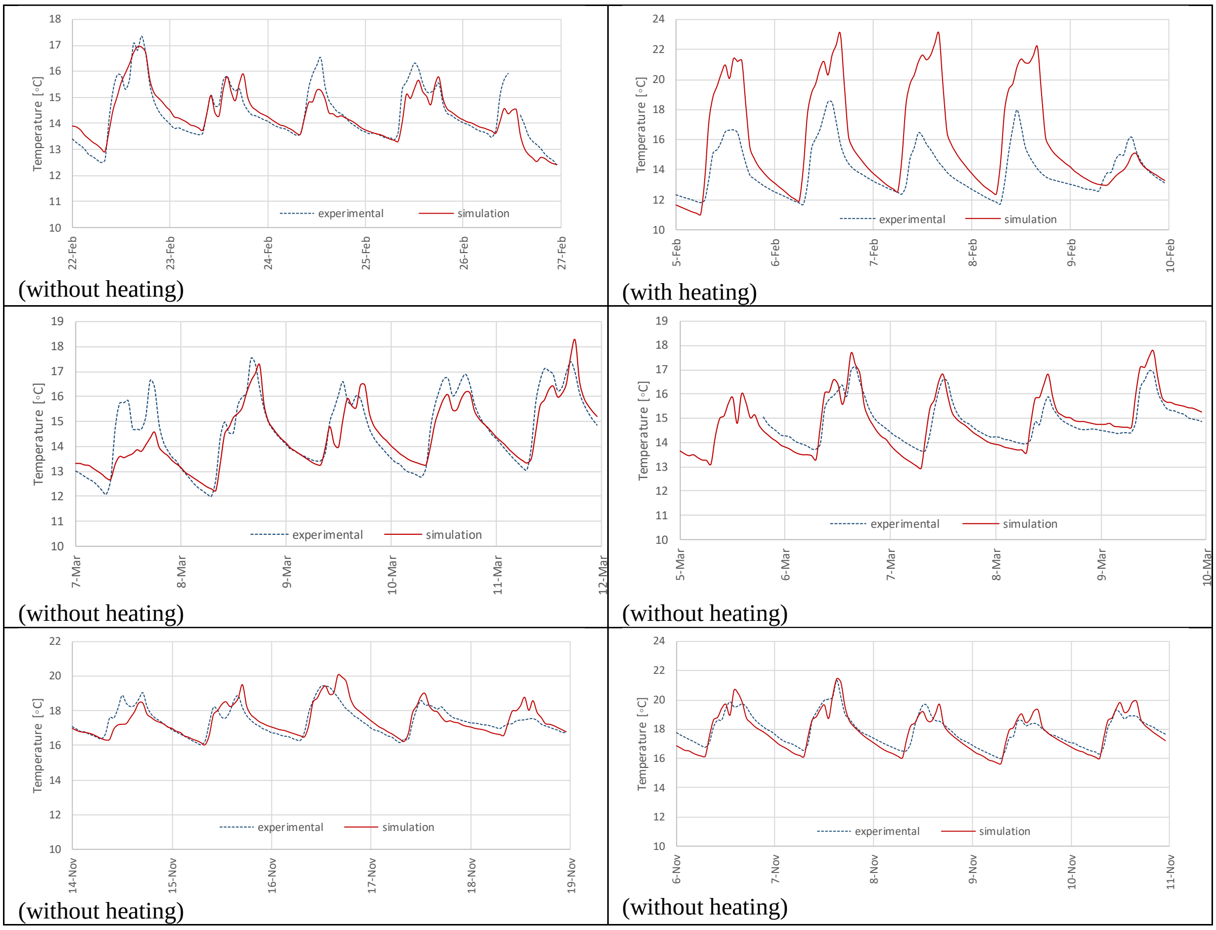

Figure 3: Weekly experimental and simulated development of T.

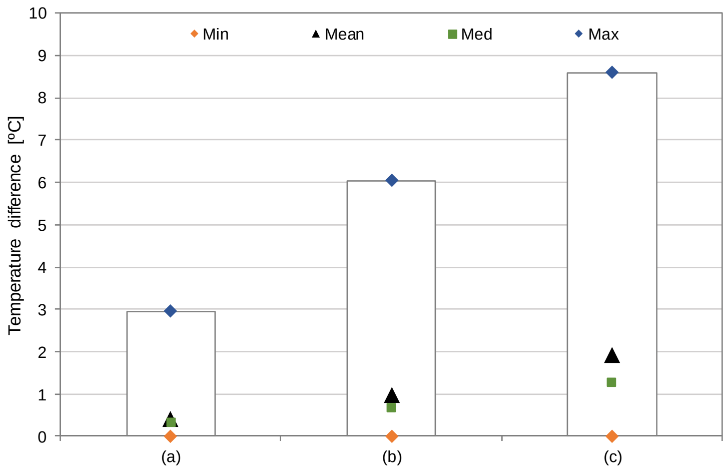

Figure 4: Statistical analysis of T differences after refurbishment for each heating strategy.

The R^2 statistical parameter describes the correlation between measured and simulated values. After refurbishment, the R^2 for the whole period and for the occupation period are 0.92 and 0.80 respectively, which fulfills the requirement of 0.75 [12]. The R^2 traduces a good correlation between measurements and simulation results.

5. CONCLUSIONS

The main conclusions of this paper are:

- The mean differences between measured and simulated T and the T statistical parameters traduce a good correlation between measurements and simulation results, which is a very important result (the R^2 between measured and simulated values are 0.92 and 0.80 for the whole period and for the occupation period, respectively).

- The higher gaps between measured and simulated data were verified during the heating weeks.

- 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.

6. ACKNOWLEDGMENTS

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