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Case Report

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Indoor air quality audit and evaluation on thermal comfort in a school in Portugal

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Abstract

Given the Portuguese national programme for rehabilitation of school buildings and the new regulations for thermal comfort and air quality in Portugal, whose demands contribute to increase energy costs, it became relevant to study a case before any refurbishment intervention, in order to assess the potential of different methods of actions and to improve results. It was also intended with this study to evaluate the indoor thermal quality and the indoor air quality experienced by the school occupants. From a practical case, a school in Coimbra, the procedure passed through the measurement of some environmental physical parameters [dry bulb temperature and relative humidity and the concentrations of chemical indicators, such as carbon monoxide and carbon dioxide]. Contributing to the indoor environment characterization, it was developed a survey directed to the occupants, in parallel with the measurements taken inside a classroom during a period in the heating season and another period in the 'pre-cooling' season. An estimation of the predicted percentage of dissatisfied and predicted mean vote comfort indices was done based on the school measured data. The results were compared with those obtained from the questionnaire. In the end, an analysis was also done based on CO_2 concentration values.

Keywords

Indoor air quality, Thermal comfort, Indoor carbon dioxide, School, PMV/PPD indices

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Introduction

Before the implementation of the recent programme for the rehabilitation of school buildings in Portugal, in Portuguese schools, in a general way, the annual energy consumption per m^2 was relatively low: this did not necessarily mean they were efficient, but reflected both the effect of the Portuguese climate which is relatively mild and, the lack of comfort in the classrooms.[1] In general, those schools were not equipped with central heating systems; the case next presented is not an exception.

1 ~~The necessity to stop the increase of~~ energy consumption for heating and cooling, ~~balance~~ simultaneously ~~with~~ the needs of comfort in the use of spaces~~;~~ ~~has made~~ the 'energy rehabilitation' of a building envelope ~~a great opportunity~~. The main interventions are usually related to the outer walls and openings – improving their thermal behaviour would necessarily lead to a reduction in energy consumption/costs needed for obtaining the reference comfort conditions. The current EU legislative system makes this a mandatory condition. In the Portuguese case in particular, the *2015 Efficiency Program*[2] provides incentives to the isolation of the existing buildings' envelope. Similar to other studies,[3,4] the authors performed an assessment of the conditions of indoor air quality (IAQ) and thermal comfort

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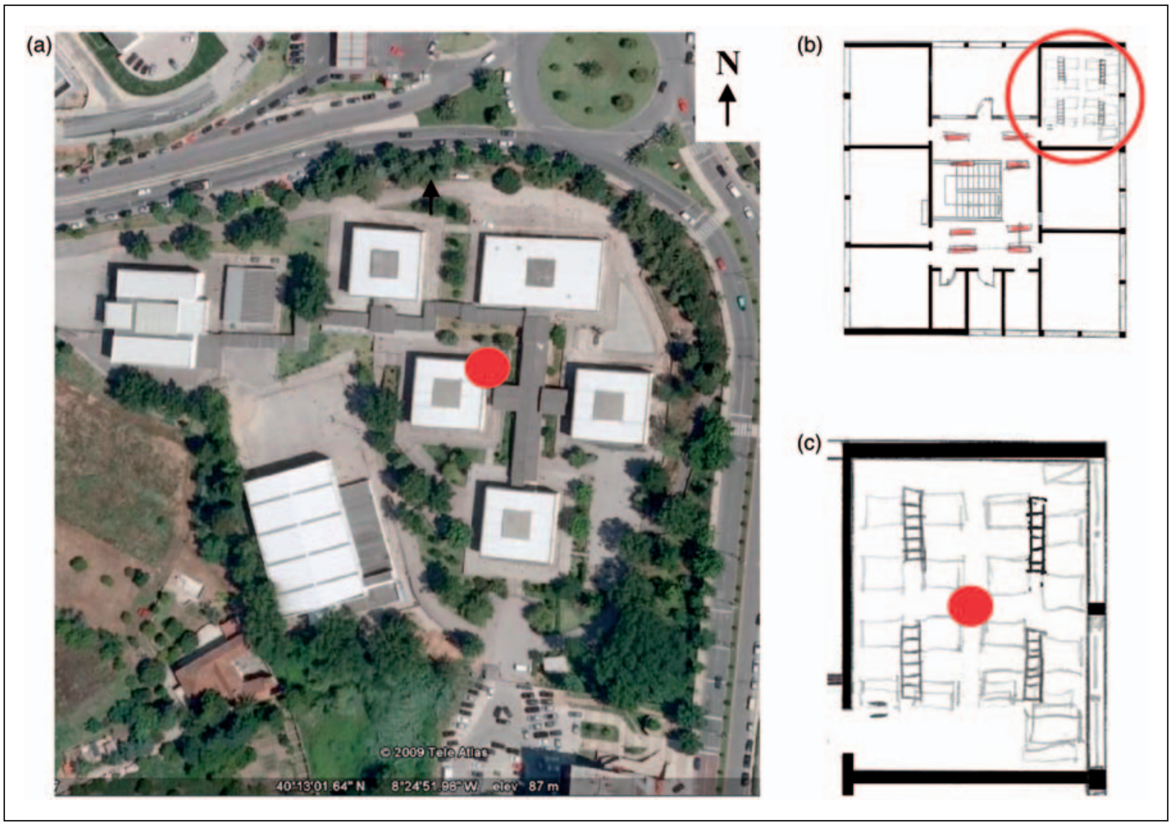

Figure 1. (a) and (b) School coordinates 40°13'1"N 8°24'53"W [Google Maps (2009)] and Room A.11 location in the school. (c) Measurement equipment location inside room A.11.

(TC) of a school ~~none~~ embraced by the rehabilitation programme, similar to a simple audit for the Portuguese energetic certification system. Data about the building construction characteristics (not presented in the present text) were collected and several parameters were measured during different occupation periods in a typical classroom (A.11) – first in the heating season (February 2010) and secondly in a 'pre-cooling' season (May 2010). In addition, the obtained results were compared with a subjective assessment based upon a questionnaire applied to the students of the class who had most lessons in the room.

After this, the evolutions of the predicted mean vote (PMV) and of the predicted percentage of dissatisfied (PPD) TC indices were calculated based upon the data collected about the measured environmental indoor parameters and the values assumed for others.

The study presented next, based on a real case-study, intends to demonstrate the indoor environmental conditions in non-intervened Portuguese schools.

Case study presentation

The studied school is located near the main hospital of Coimbra, a city in the centre of Portugal. The main group of buildings (buildings A, B, C and R) dates approximately from 1983, the D building dates 1986 and the E building is the most recent of the classroom buildings, constructed in 1992. Although the E building is the 'youngest', oil heaters are still found in this building as the regular heating system. The School has 55 classrooms and an average of 25 students per class (Figure 1(a)).

Characteristics of the buildings

Most of the buildings in this school are ca. 25 years old. Given its construction period, it was inferred that like the majority of similar buildings, the school walls do not have thermal insulation. Assuming the relatively recent intervention on the coverage/roofs, the issue of lack of insulation was only considered in the vertical envelope.

After exterior walls, ~~openings correct isolation is one of the most important things to assure – reducing the air infiltration through watertight and trims frames in windows and doors~~. In this school, windows have single glass and aluminium frames without thermal cutting. The installation of double-paned or low-emissivity coating glasses could be an opportunity to reduce cooling/heating costs and to maintain TC conditions. 2

Space cooling/space heating

The most common equipment for the heating of spaces, in this school, are oil heaters, which are not recommended – besides high-energy consumption they are inefficient in large spaces, since they only heat their surrounding area. Even in the most recent building – E, there are two heaters in each 'typical' classroom.

Most spaces are naturally ventilated. In some rooms – as in the library, the teacher's room and the ITC (information technology communication) classrooms, there are individual heating, ventilation, and air conditioning (HVAC) split units. Once there is no global controlled system, all system performance and efficiency would depend strongly on human behaviour.

Measurements in the school

Once TC influences the efficiency/performance of the study and work,[5] it was important to measure some physical parameters such as relative humidity (RH) and air temperature. For this, simple equipment used in thermal environment and IAQ system audits of energy certification of buildings were used. The assessment of IAQ was based primarily on values of CO_2 concentrations. Measurements were performed in February and May, 2010.

All the meteorological information used in this study, were obtained from www.meteo.pt (Coimbra weather station – Aeródromo).

Room A.11 – spatial description and methodology

Measurements were carried out in room 11 whose characteristics are shown in Table 1. The room is located on the first floor in the N/NE corner of building A and the exterior openings of the room are NE oriented, as shown in Figure 1(a), (b) and (c).

The ~~used~~ measuring equipments – Fluke 975 Air Meter and SENSOTRON PS32 – were kept inside the room during the whole measuring interval, positioned in a 'representative' location, at the centre of the space, 1.10 m above the floor, in the breathing zone of occupants.[6]

The first monitoring period started on 10 February at 17:10 and ended at 18:10 on the 11, over a 24-h measurement period. The second collecting data phase started on 26 May at 8:00 and ended on 28 May at 08:20, over a 48 h measuring period, as detailed in Table 2.

According to the provided time schedule information, on Wednesdays there were classes on room A.11 during the morning between 8:30 and 13:30 (26 May 2010), but on Thursday there were lessons all day long – from 8:30 until 18:00. Exceptionally, on 11 February room A.11 was empty between 10:20 and 11:50 and on 27 May room A.11 was unoccupied between 15:20 and 16:20.

Table 1. A.11 room characteristics and openings dimension.

Area (m^2)	Ceiling (m)	Volume (m^3)	Number of occupants
46.24	3.10	143.34	25 (medium)
	Height (m)	Width (m)	Area (m^2)
Window	1.90	1.55	2.95
Window (opening)	1.28	0.78	0.99
Door	2.60	0.90	2.34
Door (opening)	1.94	0.90	1.75

Audit results and discussion

Heating season evaluation

The recorded values of air temperature, RH and concentration of carbon dioxide in room A.11 on 11 February 2010 are presented next. On this day, according to the available meteorological information, exterior temperature varied in Coimbra approximately between 4°C and 10.5°C. Occupancy periods are represented by the grey shadowed areas (Table 2).

Air temperature. The time evolutions of air temperatures on 11 February are depicted in Figure 2. It is possible to verify that the air temperature values were always out of the reference interval (20–24°C),[7,8] reaching values lower than 15°C during the occupation period. The average air temperature (class time period) was 16.2°C.

The uncomfortable conditions in terms of the thermal environment are due to:

a. the building envelope is poorly insulated (or absent);
b. the heating power is low in each room and was off on the day of the monitoring. Since the idea was to assess the indoor comfort without influencing the normal routine of the building, the conditions were kept as they were.

CO_2 levels. The time history evolution of CO_2 concentration in room A.11 is presented in Figure 3. It was verified that the CO_2 concentrations were in an interval range, during the occupancy period, from 374–4640 ppm. The maximum value was reached at about

Table 2. Monitoring planning schedule 2010.

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
First monitoring (February 2010)	–	–	10th Start: 17:10	11th End: 18:10	–	–	–
Second monitoring (May 2010)	–	–	26th Start: 8:00	27th	28th End: 8:20	–	–

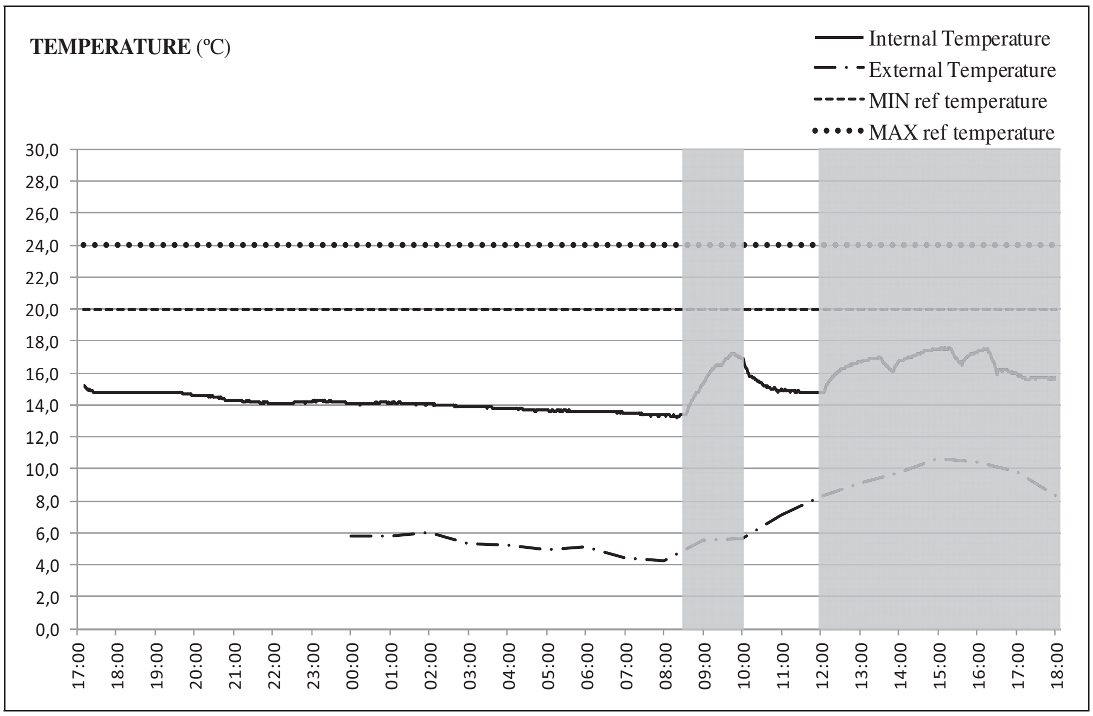

Figure 2. Temperature values in room A.11 on 11 February 2010.

15 : 00 which is 4.5 times the maximum recommended value of 1000 ppm established in the Portuguese regulation Regulamento dos Sistemas Energéticos de Climatização de Edifícios (RSECE).[7]

The lowest value was recorded during the night, about 370 ppm (infiltration period – unoccupied room). The decay period registered between 10 : 20 and 12 : 00 was caused by window opening during room vacancy. The fitting of this decay period with an exponential function, as suggested by Asadi,[9] gives an infiltration rate of 1.9 air exchanges per h (272 m^3/h). After 15 : 40, the decay in CO_2 concentration was justified by room occupancy decrement, from 25 to 11 people. During class time period (from 8 h 30 until 18 h 00) the average CO_2 value was 1927 ppm, circa twice the recommended value, 72% of this time concentration levels were over 1000 ppm.

Relative humidity. The recorded RH values are presented in Figure 4. During the occupation period (shadowed area in the figure), the values were within the recommended interval (20–70%).[10] Only during a short period, in the beginning of the acquisition, the values were slightly exceeding 70%. Nevertheless, only during 30% of the occupation period the RH was below 50%.

Discussion. As exposed before, HVAC systems in this school are practically absent. Room A.11, as in the majority of classrooms, is naturally

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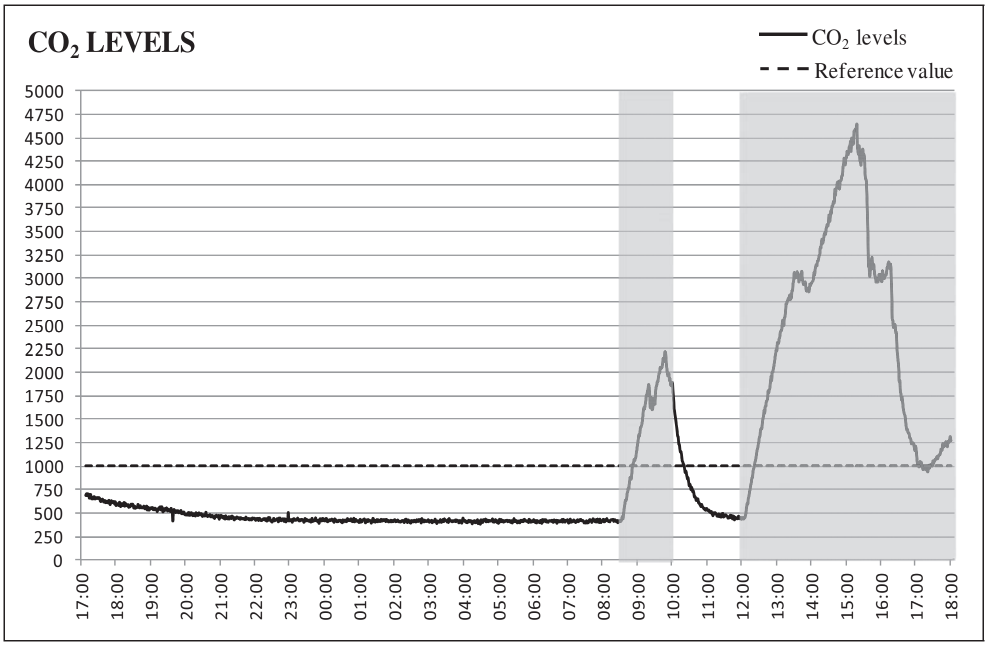

Figure 3. CO_2 concentration values in room A.11 on 11 February 2010.

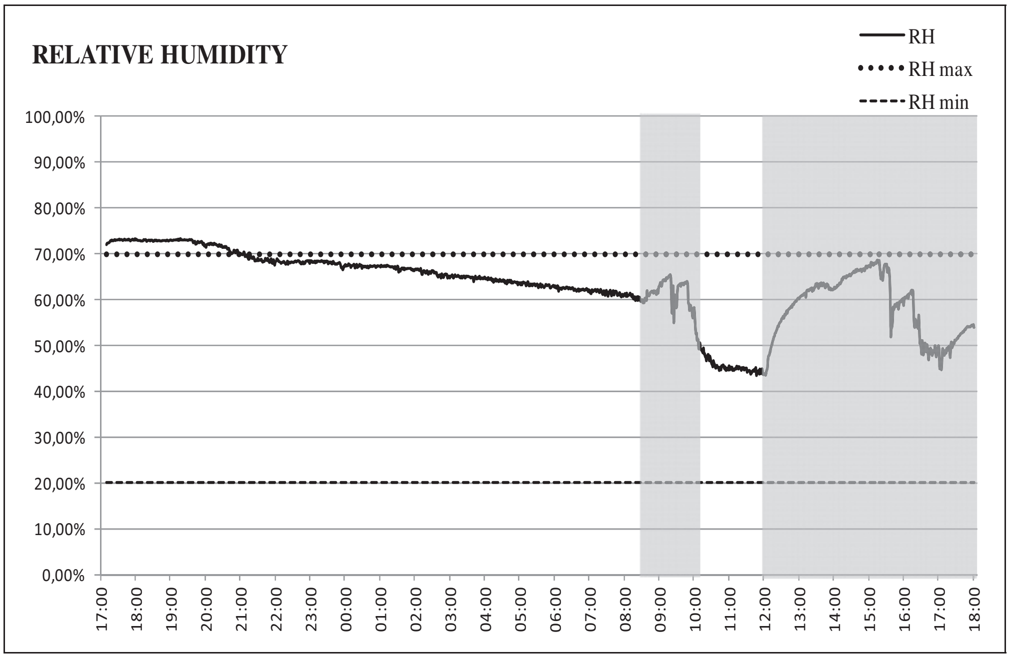

Figure 4. Relative humidity values in room A.11 on 11 February 2010.

ventilated and heated with electric heaters. This condition does not satisfy, in most of the time, the users' comfort requirements. From the results of the recorded measurements inside room A.11 (Table 3), it can be concluded that indoor thermal quality (ITQ) in the classrooms of this school has a problem: air temperature values were out of the TC interval during the entire occupation period and only in 28.5% of the time CO_2 levels were within the limit.

Intermediate season evaluation ('almost cooling season')

On 26 and 27 May 2010, during the intermediate (almost cooling) season another audit was carried out.

Table 3. Synthesis presentation table of the recorded values.

Parameter	Lowest record	Highest record	Reference value	Percentage of compliance
Room temperature	13.2°C	17.6°C	20°C–24°C	0
Relative humidity	43.4%	73.3%	30–70%	85.9
Carbon dioxide (CO_2)	374 ppm	4640 ppm	≤1000 ppm	28.5
Carbon monoxide (CO)	0 ppm	0 ppm	0 ppm	100

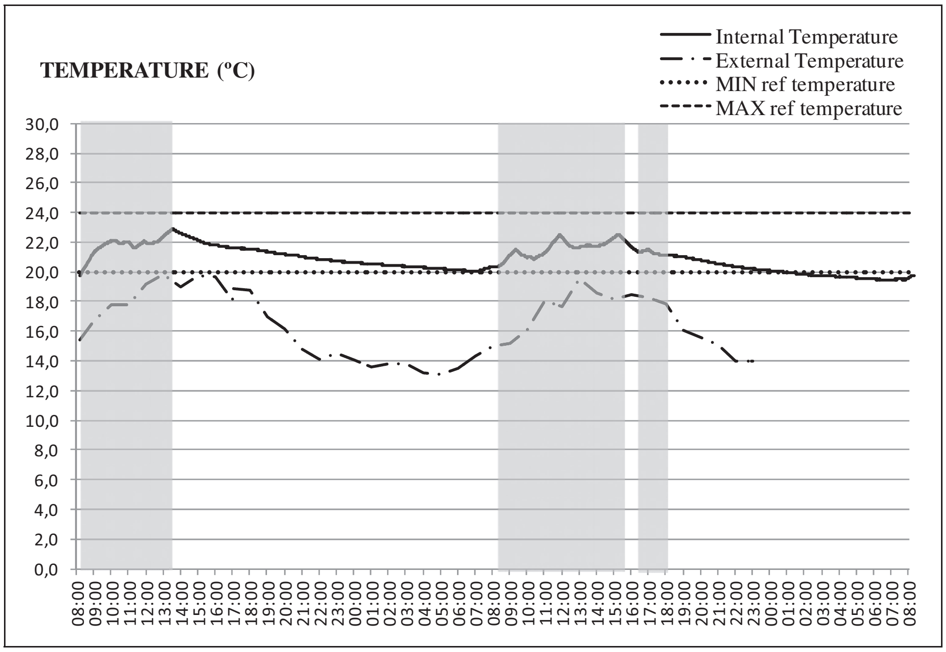

Figure 5. Temperature values in room A.11 on 26 and 27 May 2010.

According to the meteorological information, exterior temperature varied in Coimbra, during this period, between 13°C and 20°C.

Air temperature. The time evolutions of temperatures on 26 and 27 May are depicted in Figure 5. During occupancy period from the obtained data, relating indoor temperature, it was possible to verify that all the recorded values were within the reference interval (20–24°C, defined for indoor air temperature in RSECE[7]), and for the operative temperature in ISO Standard 7730 : 2005,[8] for a category B building.

CO_2 levels. The time history evolution of CO_2 concentration in room A.11on 26 and 27 May is presented in Figure 6. On the first day, the maximum CO_2 concentration recorded value was lower than 1750 ppm (about 13 : 00 – during the last class in the occupancy period measured). On the second day, the maximum value was higher, almost 2250 ppm – more than two times the maximum recommended value ($1800\ mg/m^3 \approx 1000$ ppm, according to RSECE[7]). The lowest value was recorded during the night, about 390 ppm (infiltration period – unoccupied room).

The large difference between the morning periods values on both days was justified by room occupancy, but most of all by openings manipulation. On 26 May, room occupancy decreased from 25 to 3 occupants between 10 : 00 and 10 : 20, and the room was empty from 11 : 00 to 11 : 15 and from 11 : 50 to 12 : 00. On this morning at 8 : 35 a window was opened. At 10 : 00, a second window was opened and at 12 : 00 a third one was opened (though blinds were down). Besides, during break periods, the door was kept open promoting cross ventilation.

On the next day, the decay period registered over 15 min after 9 : 20 was caused by cross ventilation – two windows and the door were opened. During the break from 11 : 50 to 12 : 00, the door was left opened and later at 12 : 15 two windows were opened, promoting again cross ventilation. During the afternoon, this was also verified over a half of an hour period, after

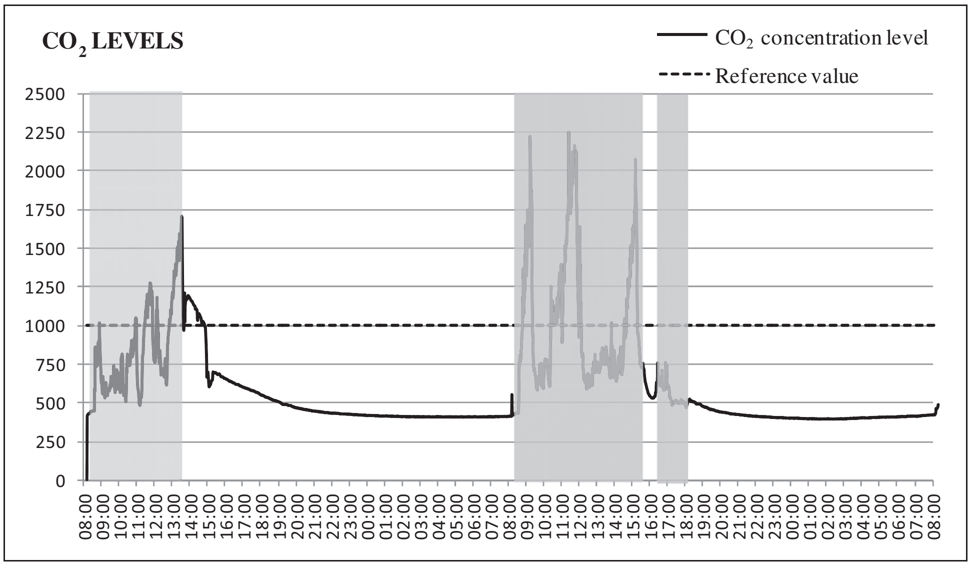

Figure 6. CO_2 concentration values in room A.11 on 26 and 27 May 2010.

15 : 15 – though the room was unoccupied, one window and the door were opened.

It has been verified that that the maximum recorded CO_2 concentration on this evaluation period was practically half of the maximum recorded on 11 February.

Relative humidity. The results of the recorded values on 26 and 27 May, demonstrate that during the occupation time of the room, RH values were within the recommended, though, only for short moments it was below 50%.

Discussion and analysis of the results. Since on Wednesday afternoons there were no classes in room A.11, and no measurements were performed on 10 February, it is reasonable to compare the values recorded on 11 February and 27 May, during the teaching periods.

In both days, it was verified that CO_2 concentrations increased during room occupation and decayed either in vacancy periods (more significantly) or when a door or window was opened. Break time periods between classes can be clearly identified, corresponding to small decays in the graphics (Figures 3 and 6), caused by door opening. The difference between values recorded in February and those in May could be explained by cross ventilation verified during almost the entire day on 27 May – main door and two windows were opened during most of the teaching period.

With regard to indoor air temperature, the conclusions are quite objective: if during 'almost cooling season' room A.11 had a comfortable temperature, mainly because of crossed ventilation induced by its occupants – teacher and students, between 20–24°C, during winter, temperatures inside the room were very low, even with closed windows.

Relating this information with CO_2 concentrations, it can be assumed that during summer, lower levels of CO_2 could be achieved by the effect of cross ventilation inside the spaces. This could be significant when evaluating TC – considering air speeds of 0.2 m/s,[11] higher temperatures could be tolerated indoors – this represents immediate cooling energy savings.

The same reasoning cannot be applied for winter, especially because of occupants' comfort – window opening would increase even more their discomfort. Even so, the values recorded have demonstrated that there could be problem of IAQ and that CO_2 recorded values in February must be reduced.

IEQ questionnaire

For a more complete study on TC of the school, students of the same classroom were asked to fill in a questionnaire, which took place on 25 February 2010, at 9 : 15 a.m., two weeks after IAQ measurements. This survey was used to assess how well the school building was performing from the viewpoint of its main occupants – students. The external temperature in Coimbra varied between 9.5°C and 15°C during the questionnaire day.

Students' answers to the questionnaire relating TC and IAQ are presented on the next three figures (Figures 7–9). All the individuals responding to the questionnaire were less than 20 years old – sixth-grade students. In terms of clothing, 83% of students were insulated with trousers and a sweater, while the rest had a raincoat or an overcoat on.

Of all the students seated near the window, 66% affirmed being *cold*, while the rest in this position declared feeling *comfortable*. Generally, most of the students felt *cold or a slightly cold* and only 29% were feeling *comfortable or slightly warm*. This particular subject reveals the asymmetry of the thermal radiation caused by a *cold window* or door opening – the more 'comfortable' students were those seated in the middle of the room or near an interior wall. Vertical air temperature difference and floor temperature were not considered in this study.

In terms of IAQ (polluted air–clean air), around 30% of students did not even considered it slightly good, almost 30% considered the air *slightly good* and the remaining votes were good or better.

In a global IAQ observation (also regarding smells and odours), opinions varied from *bad with positives aspects* to *good with positive aspects*. Over 60% considered the air, at least, as *good with negative aspects*.

The survey confirms the first impression obtained from the measured values on the 11 February – in terms of comfort, it was not expected that individuals seated in the classroom with temperatures below 20°C would feel thermally neutral (comfort).

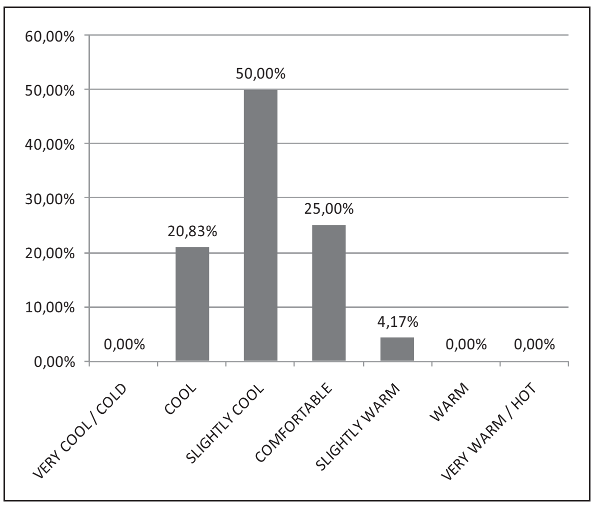

Figure 7. Thermal comfort.

Estimation of PMV and PPD indices based on the school data collection

From Fanger's[12] method and ISO Standard 7730 : 2005;[8] adaptation based on PMV index calculation, Gameiro da Silva[13,14] developed a set of spreadsheets to calculate TC indices. For the present study, the tool used to determine PMV and PPD indices is a variation from this author's first version, which directly applies the method recommended by ISO Standard 7730 : 2005.[8] In the presented case-study, data input for which convergence is included within the limits defined in ISO Standard 7730 : 2005,[8] relating to environmental conditions are air temperature, mean radiant temperature, air velocity and RH – instead of partial vapour pressure. The other determinant parameters are: metabolic rate, effective mechanical power and clothing insulation.

Aiming at comparing PMV and PPD indices, with the results obtained from the questionnaire on

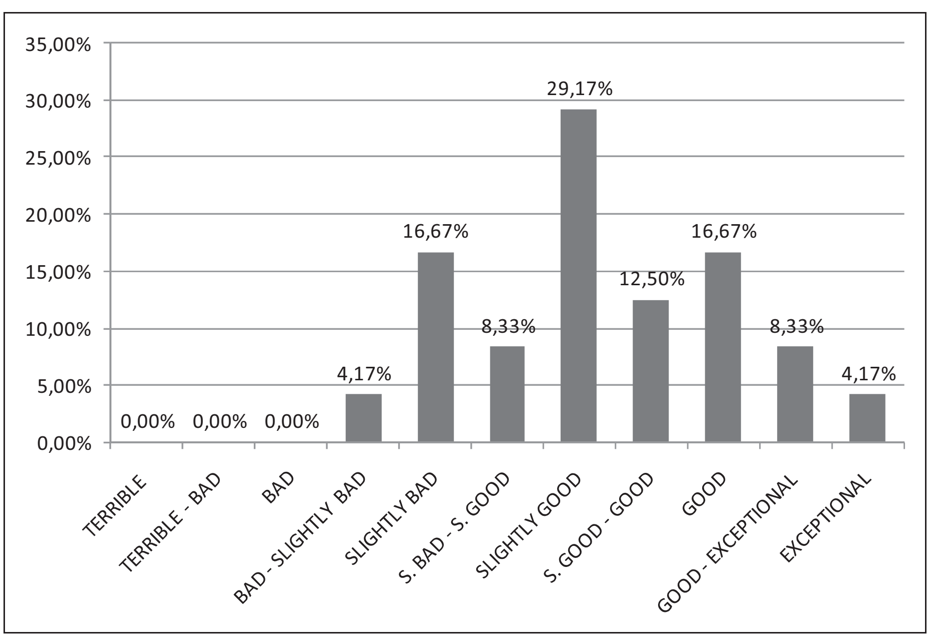

Figure 8. Polluted air/clean air.

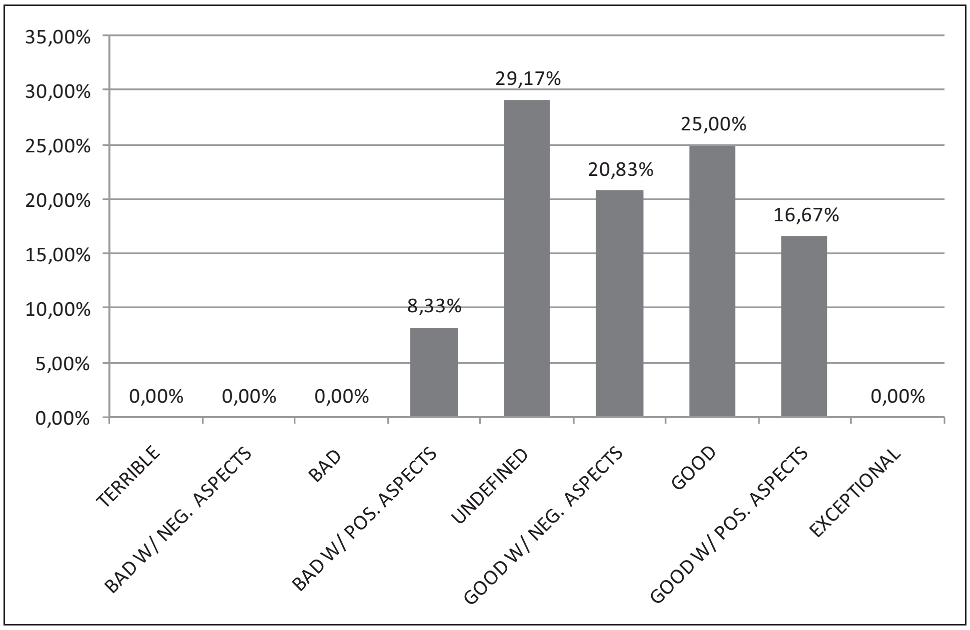

Figure 9. Global air quality.

Table 4. Synthesis table of data input in the simulation spreadsheet.

Parameters	Input value	Considerations
M (Metabolic heat production rate)	1.2 to 1.5 met	Varying from 1.2 met[15] (or 70 W/m^2) to 1.5 met (or 85 W/m^2), according to the activity but considering students age, around 11–12 years, whose metabolic rate was higher
W (Mechanical work rate)	0 met	'*W* is considered to be null, because this was a very low value in the context of the balance equation'[3]
I_{cl} (clothing insulation)	0.9 clo	Although variable among individuals answering the questionnaire (0.8 to 1.0 clo), 0.9 clo was used as a representative medium value
T_a (Air temperature)	19°C	Although not measured on 25 February, T_a was estimated from the difference between indoor and outdoor temperatures, based on the difference values on days 11 February, 26 and 27 May at 9:15, questionnaire time, ≈5°C to 6°C. Exterior temperature on 25 February was 13.9°C
HR (Relative humidity)	50%	HR admitted value considered 'reasonable' for a non rainy day. Not determinant once PPD and PMV indices were not very 'sensible' to RH
T_r (Mean radiant temperature)	16°C to 17°C	Since it was not continuously monitored, the assumed value was an estimated approximation from T_a decreasing, 2°C to 3°C, based upon measurements carried out *a posteriori*
V_{ar} (relative air velocity)	0.1 m/s	Although doors and windows were closed, room A.11 was not absolutely tight, for which ~~was admitted~~ a minimum air velocity value ≠0 m/s, ~~admitting~~ infiltration from the openings

PPD: predicted percentage of dissatisfied; PMV: predicted mean vote.

25 February, the considered values for each of the parameters are presented next.

From the variation of two of the inserted parameters, M and T_r, using the simulation computational tool referred, four results were obtained (see the Appendix 1).

Comparison between PPD and PMV indices and results from the questionnaire. The simulated results show that the percentage of dissatisfied people becomes lower when the mean radiant temperature is higher.

Table 5. Summarizing table of the obtained results in the four simulations.

	Simulation			
Parameters	I	II	III	IV
M	1.2 met	1.2 met	1.5 met	1.5 met
W	0 met	0 met	0 met	0 met
I_{cl}	0.9 clo	0.9 clo	0.9 clo	0.9 clo
T_a	19°C	19°C	19°C	19°C
HR	50%	50%	50%	50%
T_r	16°C	17°C	16°C	17°C
V_{ar}	0.1 m/s	0.1 m/s	0.1 m/s	0.1 m/s
PMV	−1.03	−0.93	−0.37	−0.29
PPD	27.4	23.2	7.8	6.7

PPD: predicted percentage of dissatisfied; PMV: predicted mean vote; M: metabolic heat production rate; W: mechanical work rate; I_{cl}: clothing insulation; T_a: air temperature; HR: relative humidity; T_r: mean radiant temperature; V_{ar}: relative air velocity.

The same reasoning can be applied to metabolic rate. As expressed by Gameiro da Silva,[13,14] PMV value 'is calculated from the heat balance of the human body (...), obtained by the difference between the heat produced (...) and the sum of the exchanges with the surrounding environment'. Since in all four situations the balance result was negative (see the Appendix 1), 'the body is in a net loss of heat, which means that the simulated person would feel cold, even though slightly'.[13,14]

Comparing the simulation results with those obtained in the questionnaire, where a significant majority of students answered being in a state between cold or slightly cold, the most approximate estimate was simulation I.

Estimation of IAQ based on the school data collection

Indoor comfort analysis based on CO_2 concentration values. Another analysis of indoor comfort was conducted based on CO_2 concentration values inside room A.11. On 25 February 2010, the class ~~answering~~ the questionnaire at 9:15 was the same class present on 11 February, the first day ~~on~~ IAQ measurements. ~~Admitting the same value of~~ CO_2 concentration, 1680 ppm obtained on 25 February; and from Figure 10 that around 32% of the individuals ~~may~~ be dissatisfied with the conditions. 3

Conclusion

In the present work, the envelope characteristics of this school have been investigated and a relation between

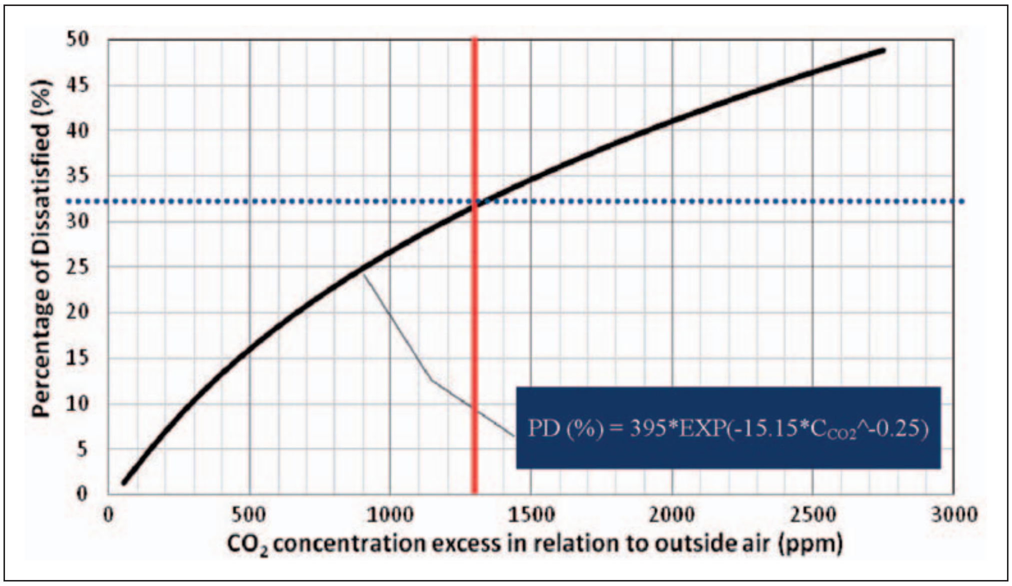

Figure 10. IAQ in function of CO_2 (CR 1752–1998).[16,17]
IAQ: Indoor air quality.

these and the school's TC behaviour was determined. Therefore, in order to improve indoor climate, a refurbishment intervention in the exterior walls and openings should be considered.

Human health could be affected by multi-dimensional facet of factors and, therefore, we should consider not only the physical factors but also the psychological and social environment that could be contributed to the holistic well-being of people in any environment. Humans have 'survival needs', related to environmental health factors such as air, water and acoustic levels, and 'well-being needs' that include both social and psychological health factors. With regard to ITQ the main conclusions of this study are:

- Measuring CO_2 concentration in classrooms during occupation period would allow the interpretation that non-warmed rooms, with the absence of adequate ventilation systems would not assure comfortable temperatures and the desirable CO_2 concentration value (even if adopting a relaxation criteria admitting as reference 1500 ppm) was clearly exceeded;
- The PMV and PPD comfort indices, even if normally used for evaluating TC in HVAC buildings, were confirmed by the results obtained in the survey, illustrating the degree of dissatisfied individuals in room A.11, where TC measurements were conducted.

With regard to natural ventilation (NV), research has shown that when enhanced by users, it can help improve IAQ ~~and should for this reason be explored~~. To evaluate NV potential, further studies considering real needs of fresh air flow rate should be conducted, based on *in-field* monitoring or computer simulations. In case of a 'genuine' intervention in the buildings, it would be interesting to compare the new indoor conditions with the present ones and contrast them with other refurbished schools in which HVAC systems were implemented: both in terms of IEQ parameters and occupants' satisfaction.

Acknowledgements

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Appendix 1: PPD and PMV indices calculation

Simulations based on EMF estimated data

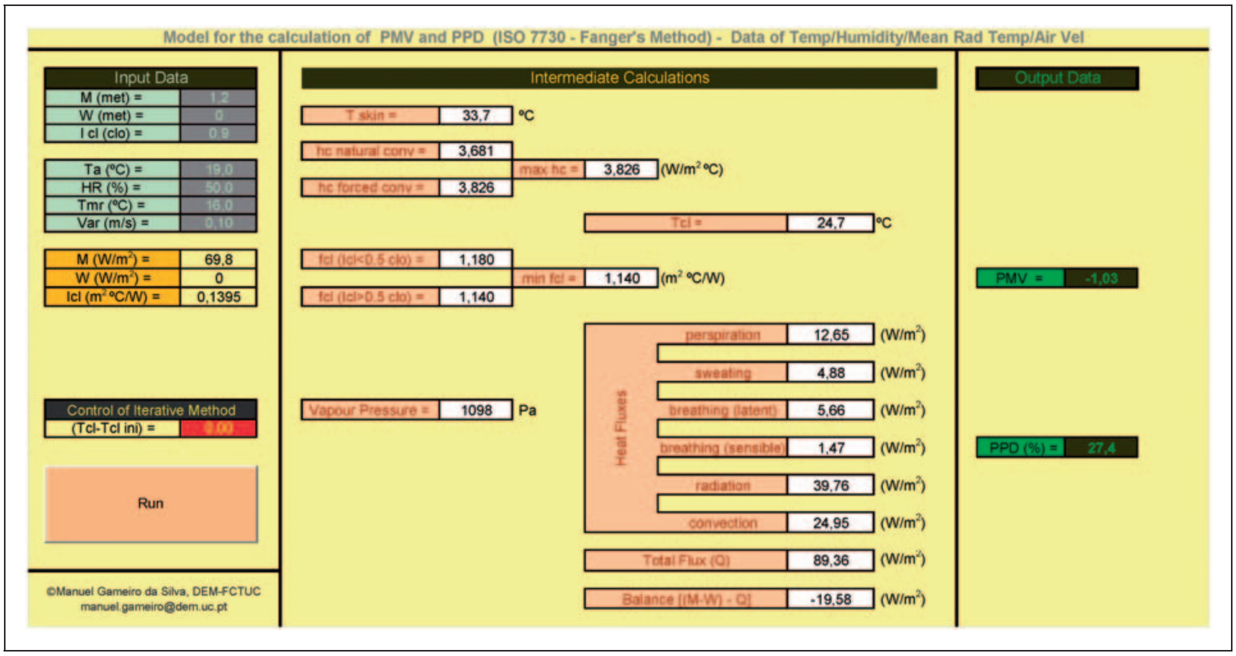

Figure 11. Graphical interface of the computational tool after simulation I.

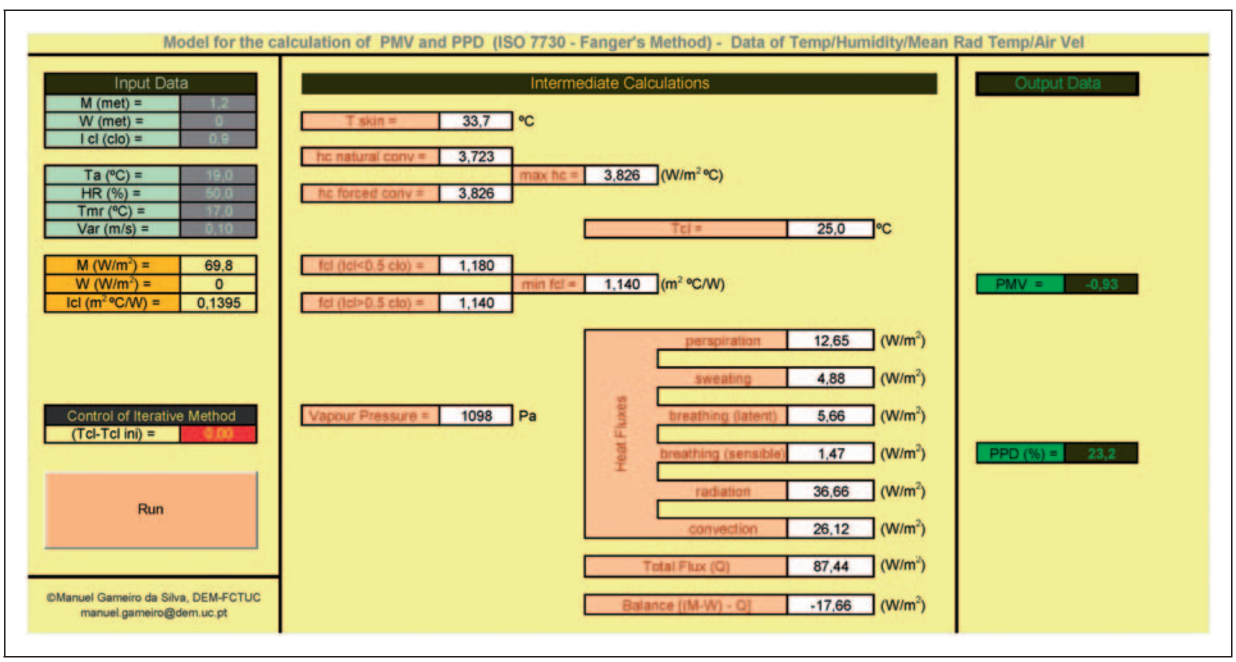

Figure 12. Graphical interface of the computational tool after simulation II.

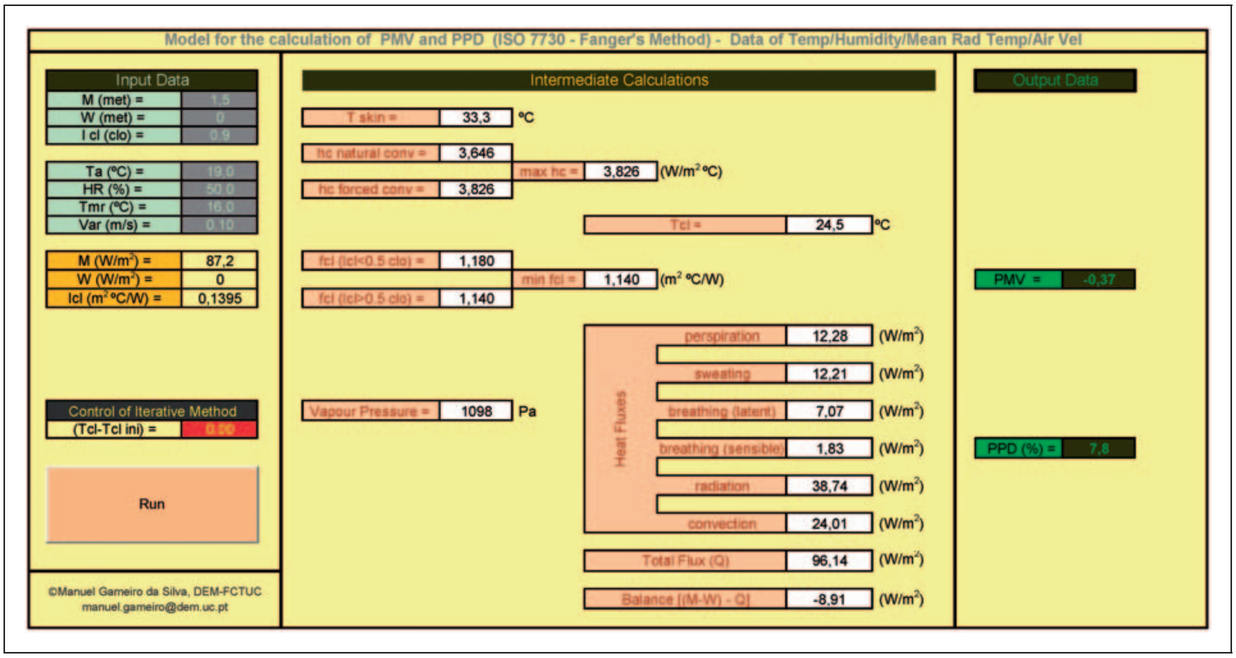

Figure 13. Graphical interface of the computational tool after simulation III.

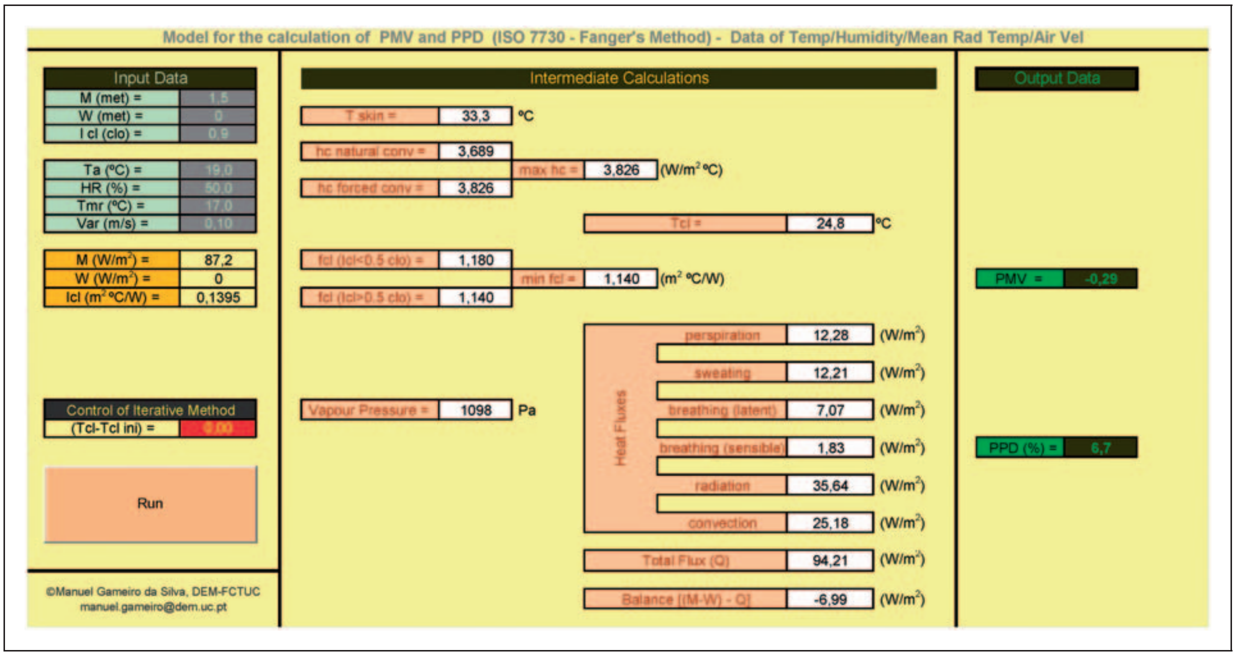

Figure 14. Graphical interface of the computational tool after simulation IV.