1_C49

IEQ Assessment in Free-Running University Classrooms

Giannis Papadopoulos **Giorgos Panaras, PhD** *Member ASHRAE* **Evangelos I. Tolis, PhD**

ABSTRACT

Investigation of Indoor Environmental Quality (IEQ) in various types of buildings is a rather intense research activity by recent years. IEQ refers to the acceptable levels of thermal, visual and acoustic comfort in addition to Indoor Air Quality (IAQ). In the proposed work, a systematic measurement campaign in university classrooms in the Educational School of the University of Western Macedonia, Florina, Greece, is presented; the campaign was performed by the end of the spring semester, in free-running classrooms. Measurements include thermal comfort parameters, as well as IAQ ones, namely volatile organic compounds (VOCs), CO_2 and NO_2 concentration. As far as thermal comfort is concerned, the validity of the adaptive model approach is examined, while Fanger's thermal comfort indices are also calculated per person; both approaches are implemented on the basis of the measured data. Moreover, a comparison is made through the support of questionnaires investigating the actual thermal comfort level of the students while being in the classrooms, aiming at providing insight on the validity of the examined comfort models. Also, survey includes questions about parameters of IEQ. In terms of air quality, measurements are made both indoors and outdoors, allowing the determination of indoor/outdoor correlations. Lighting and acoustic measurements are also performed, contributing to an integrated IEQ assessment.

1 INTRODUCTION

Indoor environmental quality (IEQ) issues have gained significant interest in the scientific and technical community involved in buildings analysis, as demonstrated also by the recent amendment of the Directive 2010/31/EU on the energy performance of buildings (EU 2010) (well known as EPBD), that is Directive 2018/844/EU (EU 2018), and Directive 2012/27/EU on energy efficiency (EU 2012). The multi-annual European roadmap for energy efficient buildings describes IEQ as an important area of investigation by 2020 (EC 2013). IEQ refers to the acceptable levels of thermal, acoustic, visual comfort and indoor air quality (IAQ) (Al horr et al. 2016).

The case of University Classrooms presents high interest, as the maintaining of comfort and healthy indoor climate can positively affect the occupants' learning performance and participation in the educational procedure (Corgnati et al. 2007). Related studies concentrate on thermal comfort using the Fanger Model (Aghniaey et al. 2019; Jindal 2018), adaptive models (Mustapa et. Al., 2016) or the combination of these two models (Teli et. al., 2012). It should be noted that most investigations which combine thermal comfort and IAQ parameters concentrate on CO_2 values (Agüera et al. 2019; Liu et al. 2019; Merabtine et al. 2018), while in principle, visual and acoustic aspects are also of importance (Riciardi and Buratti 2018; Zuhaid et al. 2018). Works investigating all IEQ aspects are also referred to (Bughio et al. 2020; Zhong et al. 2020).

The proposed work is part of a greater investigation regarding IEQ in university classrooms in the Educational School of the University of Western Macedonia, Florina, Greece. The results of this invistigation by the winter time, when indoor thermal conditions were regulated by the heating system, have been presented and discussed in the work of Papadopoulos et. al. (2020). The campaign presented in this work was performed through spring time, when the classrooms were naturally conditioned. Measurements aim to assess thermal, acoustic and visual comfort, as well as Indoor Air Quality (IAQ), through the determination of the concentration of substances as CO_2, volatile organic compounds (VOCs) and NO_2. For all aforementioned factors affecting comfort, additional data through the support of questionnaires were collected, aiming at providing information on an adaptive sensation level for the students.

Giannis Papadopoulos is a PhD student in the Department of Mechanical Engineering, University of Western Macedonia, Kozani, Greece. **Giorgos Panaras** is an Assistant Professor in the Department of Mechanical Engineering, University of Western Macedonia, Kozani, Greece. **Evangelos I. Tolis** is a Teaching and Research Associate at the Department of Mechanical Engineering, University of Western Macedonia, Kozani, Greece.

2 METHODOLOGY

2.1 Description of the classrooms

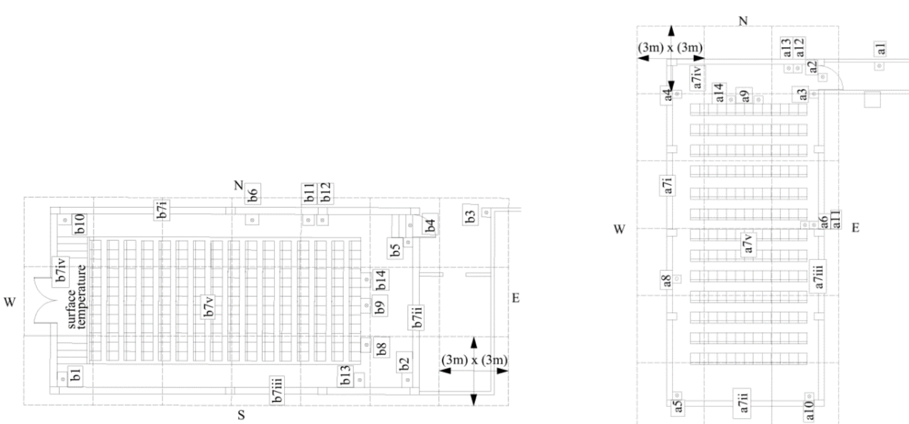
The building under investigation is that of the School of Primary Education of the University of Western Macedonia, located three kilometers outside of the town of Florina, on the Florina-Niki National Road. The climate of Florina is characterized as the coldest one, regarding Greece (Florina is ranked on D climate zone according to the Greek version of the EPBD (TEE 2010a)), because of its location and altitude (687m); rainfall is generally moderate, summers are mild and snowfall is frequent in the winter months. Average annual temperature of 12 °C is reported (TEE 2010b), while in the winter months, temperature may reach -20°C or even lower. Especially for the month of May, when the investigation took place, the average temperature is 21° C, with maximum average temperature at 22 °C and minimum average temperature at 9.2 °C (TEE 2010b). The relative humidity in May is 63.4%, while 69.2% annually.

The Premises of the School of Primary Education can be divided in three main departments. Section I is the oldest one (built in the late '70s), while by the early '90s Section II was built, and later on Section D (hosting mainly administrative services). Section D is two-floored, while Sections I and II are one-floored. The building shell consists of cement-brick walls with double glazed windows, presenting inadequate thermal insulation (mean heat loss coefficient U values of 1.12-1.48 W/m²K are reported for the different floors and Departments (Valcanos et al. 2018)), especially taking into account the strict requirements of climatic zone D (TEE 2010a). The total area of the building is 10,297.63 m², of which 9,360.99 m² refer to conditioned (heated) spaces.

Indoor environmental parameters were investigated in two classrooms, located in the ground floor. One classroom (small amphitheater, indicated thereafter as Amph) lies in Section II with total surface 125 m2 and the other one (indicated thereafter as Cls) lies in Section I, with total surface 89 m2. Both classrooms are heated through conventional heating appliances, carrying hot water (Amph uses radiation type ones and Cls fan-coil), while ventilation is performed naturally through the opening of the windows and doors; cooling devices are not installed. Amph has very limited windows area, ventilated through the door, while for Cls the N and NW sides are dominated by windows presence. During the measurements the heating system was not operating, while both classrooms were naturally ventilated.

2.2 Experimental measurements set-up

The measuring quantities, in terms of thermal comfort, include the temperature (T) and the relative humidity (RH) of indoor air, radiant temperature, indoor air-speed, while outdoor air meteorological conditions, i.e. temperature and relative humidity were also recorded. In Figure 1, the sensors positions for the two classes are indicated.



(a) (b)

Figure 1. Classroom lay-out and relevant instrumentation position: **a**. Amph, **b.** Cls

The relevant instrumentation included dataloggers with temperature and relative humidity sensors, indicated in the following analysis as a_1, a_2, a_6, a_{11}, a_{13}, b_3, b_4, b_6, b_{11}, b_{13}, while their combination with CO_2 sensor allowed the measuring of CO_2 concentration as well (a_4, a_5, a_{10}, b_1, b_2, b_{10}, a_{12}, b_{12}). Surface temperature was measured through thermocouple sensors (a_7, b_7), and air-speed with 3-D

anemometer (a_3, b_5). The acquisition rate for each of the measured thermal comfort parameter was 60 s, expect from the radiant temperature parameter that was 10 mins. As regards IAQ, apart from the concentration of CO_2, that of NO_2 was measured (a_8, b_8), with Portable Air Quality Monitor , and that of various VOCs through air sampling pumps and chromatography, indicated (a_9, b_9). The visual parameter of illumination (lux) was measured through the aforementioned dataloggers which some of them are equipped with light sensor, while noise level, in terms of A-weighted sound pressure (dBA), was measured through soundmeter (a_{14}, b_{14}).
For the needs of the present analysis, it has been attempted to surround the indoor air space of the classes, while the installed height of equipment was mostly in the range of 0.5-2.5 m, aiming to investigate spatial behavior of measured quantities. In the calculations of the thermal comfort indices, the values of the sensors placed at the height of 1m were used.
Especially regarding VOCs, air-samples were taken using low-volume personal pumps and pre-conditioned glass tubes filled with Tenax TA at flow ratios of about 80 ml/min for 30 min. Moreover, duplicate samples were taken, and blank tubes were analyzed for quality assurance/quality control purposes. Samples were analyzed using a thermal desorption unit coupled to a gas chromatograph, equipped with a mass spectroscopy detector.

3 RESULTS

3.1 Thermal comfort

In the following table 1, the average, minimum and maximum values for thermal comfort parameters, together with CO_2 concentration, for each class, are presented. The values presented refer to the average indication of all sensors for the periods the classes were crowded; these periods are presented in table 2.

Table 1. Indoor air climatic parameters during measurement period for classrooms

	Amph			Cls		
Parameter	Mean	Min	Max	Mean	Min	Max
T(°C)	20.1	19.2	20.8	23.2	20.7	25.5
RH (%)	58.8	55.4	61.4	48.6	44.9	51.5
CO_2 (ppm)	1602.3	672.3	2456.3	1355.7	649.2	2141.9
Wind Speed (m/s)	0.061	0.029	0.094	0.07	0.033	0.137

Table 2. Periods of crowded classrooms

	Amph	Cls
Period 1	21/5/2019 09:30-11:30	22/5/2019 09:15-11:15
Period 2	21/5/2019 12:15-13:45	22/5/2019 15:15-17:45
Period 3	21/5/2019 18:15-19:45	22/5/2019 19:45-20:45

The Predicted Mean Vote index (PMV) and the Percentage of People Dissatisfied index (PPD) (Fanger's thermal comfort indices) were calculated according to the relations proposed by EN ISO 7730, Annex D (CEN 2005). Calculation was implemented for each specific period the classes were crowded. The PMV was estimated from measured thermal comfort parameters (air temperature, radiant temperature, air velocity and relative humidity) along with physical parameters of metabolic rate and clothing. Metabolic rate was calculated according to the EN ISO 7730, Annex A (CEN 2005) for sedentary activity, while clothing was recorded during the point-in-time survey. Regarding the measured parameters entering calculations, it is noted that the radiant temperature was estimated on the basis of the measured parameters of surface temperatures, taking also into account verification during specific periods through the support of a thermal imaging camera (FLIR TG167).

Table 3. Calculated thermal comfort values

	Amph		Cls	
Parameter	PMV	PPD	PMV	PPD
Period 1	-0.85±0.19	21.08±6.51	-0.39±0.20	9.09±4.43
Period 2	-0.80±0.22	19.52±7.80	0.42±0.15	9.29±2.70
Period 3	-0.62±0.20	13.99±5.47	0.35±0.14	7.85±2.08

As can be seen in table 3, PMV values for the Amph were out of the comfort range of (-0.5,0.5) according to the ASHRAE Standard

55-2017 (ASHRAE 2017), in contrast to the values of the Cls. As regards the European Standard EN15251 (CEN 2012) only the value of the period 3 from the Amph lies within the indicated limits of category III (-0.7, 0.7), while all values of the Cls belong to category II (-0.5, 0.5).

During the spring season, heating system is not operating, and the building is only naturally ventilated (cooling devices are not installed). As PMV has been found to underestimate the range of comfort in naturally conditioned spaces (Jindal 2018), the adaptive comfort model is used to assess the thermal neutrality of the occupants. The adaptive comfort models are based on relationships between the outdoor and indoor temperatures and give the opportunity to occupants to operate the windows and adjust their clothing. The ranges of acceptability (operative temperatures) for the building are plotted against the prevailing mean outdoor air temperatures, lying between 10 and 32.5 °C, while the limits for clothing (0,5 clo- 1 clo) and metabolic (1 met-1.3 met) are satisfied. The equation (1) was used to calculated the prevailing mean outdoor air temperatures, where α is a constant between 0 and 1 that controls the speed at which the running mean responds to changes in weather and $t_{e(d-n)}$ represents the mean daily outdoor temperature for the previous days. The meteorological data were taken from the Hellenic National Meteorological Services upon request, while the constant a has been set to 0.8, as it is suggested that this value has better performance in midlatitude climates (Nicol and Humphreys 1998).

$$\overline{t_{pma(out)}} = (1-\alpha)\left[t_{e(d-1)} + a t_{e(d-2)} + a^2 t_{e(d-3)} + a^3 t_{e(d-4)} + \cdots\right] \quad (1)$$

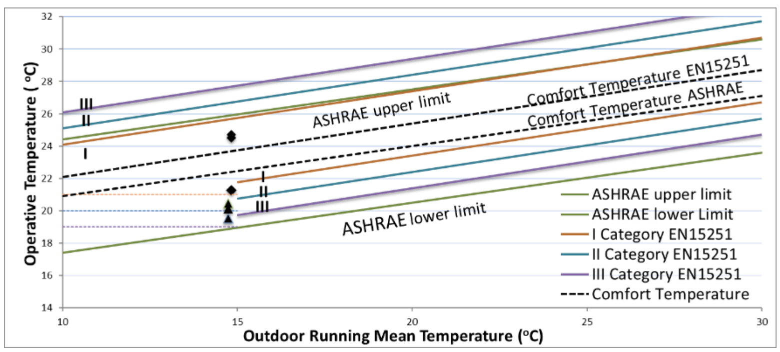


Figure 2. Adaptive comfort chart for free running classrooms

As can be seen in figure 2, operative temperature for both classrooms lie within the acceptable limits of ASHRAE Sandard 55-2017 (ASHRAE 2017). Concerning the EN15251 standard (CEN 2012), the values for all periods of Cls measurements lie in category I (90% acceptability), while the Amph periods 2 and 3 lie within the limits of category II (80% acceptability) and period 1 of category III (60% acceptability). It seems generally that, in both classrooms, thermal comfort sensation is more favourable by afternoon hours, instead of the morning hours, especially for the Cls.

3.2 IAQ parameters

In figure 3, the CO_2 concentration in various positions of the classes is presented. Values for both classes, are in agreement with the ones presented in table 1, clearly exceeding the acceptable level of 1000-1100 ppm (CEN 2007; ANSI/ASHRAE 2019) for all periods of measurements, expect from the period 6, where the windows were opened and CO_2 concentration was decreased; the peak values are quite high, especially for Amph. Despite some differences in the profiles for the two classes, mainly attributed to the difference ventilation rates, the respective charts clearly indicate the crowding pattern of the classes through CO2 concentration values.

Regarding NO_2, the outdoor values, as presented in table 4, are higher than the indoor values in both classrooms; this can be atributed to the lack of NO_2 sources inside the two classrooms. The NO_2 concentration in both cases is the result of the infiltration process; one should indicate the case of period 3, where the increased values in Cls (0.120 mg/m3) lie very close to the outdoor ones (0.126 mg/m3), by a time the windows of the classroom were totally open.

In figure 4, one may see the VOCs' concentration values for both classrooms, in contrast to the outside ones. As it can be seen, the outside values are in general higher than the ones for the two classrooms. There are two exceptions in this trend, concerning a-pinene, trimethylbenzenes and d-limonene for the Amph, and 1,2,4 trimethylbenzene and d-limonene for the Cls; the limonene presents the highest difference. The later is probably due to the presence of students wearing personal care product which emit such terpenes (Bartzis et al. 2015). b-pinene is the compound which is not detected in any sample taken in the whole campaign.

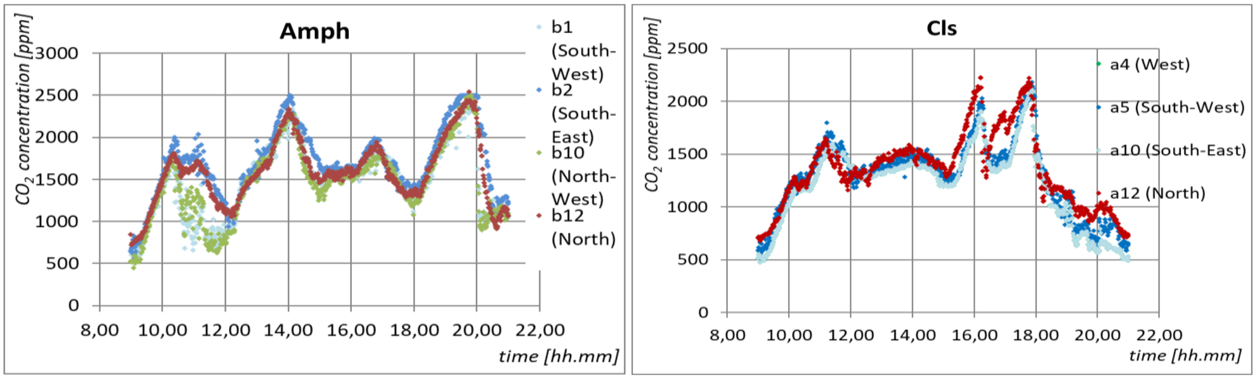


Figure 3. CO_2 concentrations in various positions of the Classrooms throughout daily measurement

Table 4. NO_2 concentration indoors and outdoors during periods of classes

	NO_2 concentration (mg/m^3)			
	Amph		Cls	
	IN	OUT	IN	OUT
Period 1	0.025±0.005	0.133±0.019	0.056±0.020	0.123±0.028
Period 2	0.037±0.012	0.156±0.044	0.086±0.015	0.127±0.049
Period 3	0.038±0.005	0.158±0.035	0.120±0.088	0.126±0.030

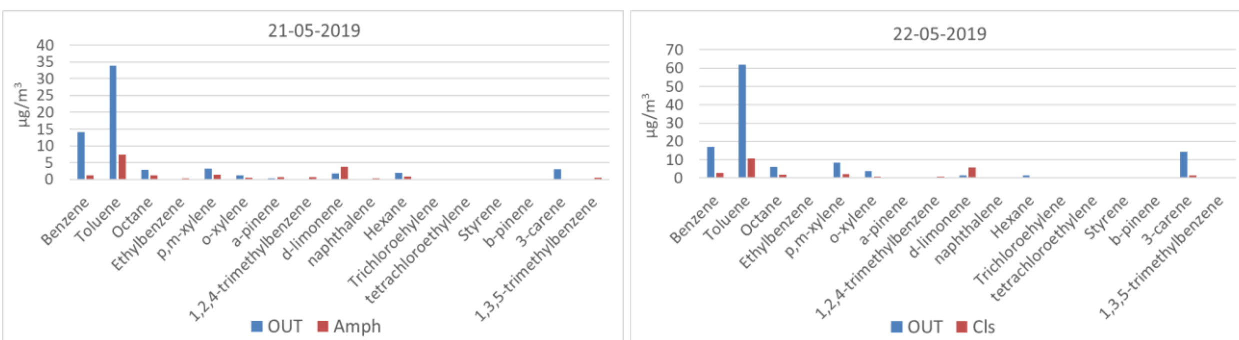


Figure 4. Average VOCs concentration (μg/m3) for the two classrooms of the Florina campus

3.4 Visual and Acoustic Comfort

The levels of lighting environment during crowded hours are given in Table 5. The measured values for the Amph are under the acceptable limits of 500 lux, according to EN15251 (CEN 2012), justifying the poor artificial lighting and the lack of windows. Regarding Cls, all measurements were made under the daylight illuminance, without operation of artificial lighting. Average values for periods 1,3 are under the limit of 500 lux, instead of the average value of period 2, which is much higher than the 500 lux. According to the useful daylight illuminance (UDI) (Nabil and Mardaljevic 2006), the value of 1481 lux lies within the range of 100-2000 lux, which is considered either as desirable or at least tolerable.

To analyse the building's indoor acoustic environment, equivalent continuous linear weighted sound pressure level (Leq), by the periods the classrooms were crowded, was measured. Leq is a fundamental measurement parameter, designed to represent a varying sound source over a given time as a single number. Table 5 shows the average values of equivalent sound levels during the sampling period; average values, for the complete measurements period, lie within the acceptable limits of 30-40 dB, according to the Annex E of EN15251 Standard (CEN 2012).

Table 5. Average Values of Visual and Acoustic parameters

	Amph		Cls	
	Illuminance(lux)	Voice Meter(dB)	Illuminance(lux)	Voice Meter(dB)
Period 1	225	34.6	415	38.5
Period 2	242	35.7	1481	35.2
Period 3	208	35.1	322	-

3.5 Questionnaire analysis

A questionnaire was prepared and used for the scope of the presented research, namely the investigation of the actual comfort sensation of students and correlation with the predicted one. The questionnaire included anthropometric information for each person, namely gender, height and weight, if they felt healthy or sick at that moment, their length of exposure to the thermal environment in the room, information regarding their clothing and information regarding their perception towards specific parameters of thermal environment, air quality, including odors, lighting and noise. The following discussion focuses on thermal environment issues. A total number of 153 questionnaires was selected

Regarding the actual values of satisfaction with the thermal environment (TSV), these were calculated according to a seven-point scale response of their thermal sensation (ASHRAE 2017). Moreover, students were also asked if they would prefer a change to the current setting, with regard to a five-point scale response (ASHRAE 2017).

In this study, the Griffiths method is used in order to calculate, for each individual, the comfort temperature (T_c). Calculation is based on the respondents TSV votes and the mean temperature, through the appliction of the following equation (Griffiths 1990):

$$T_c = T - \frac{(0-TSV)}{\alpha} \qquad (2)$$

Where T is the operative temperature (°C) and α is the regression coefficient, which indicates the constant rate of thermal sensation change in relation to the room temperature. In this study, the value of a=0.5 was used (Humphreys et. al. 2013). When TSV equals zero, the comfort temperature is equal to the operative temperature.

In the following table (table 6), the average TSV, corresponding to the response of the students regarding their satisfaction with the thermal environment and the comfort temperatures using the Griffiths equation, is presented.

Table 6. Thermal sensantion vote and comfort temperatures

	Amph		**Cls**	
	TSV	T_c (°C)	TSV	T_c (°C)
Period 1	-0.64±0.78	20.64±1.57	-0.28±0.89	21.56±1.79
Period 2	-0.48±0.83	20.81±1.66	1.52±0.80	21.91±1.60
Period 3	-0.36±1.36	21.10±2.72	-0.52±0.90	25.85±1.81

The average values of TSV show that thermal comfort is satisfied for all classrooms, as the limits of comfort acceptability are -1.5≤TSV≤1.5 (ASHRAE 2017). The range of comfort temperature is about 20.5°C - 22°C, apart from the period 3 of the Cls; this is due to the fact that the windows were open during the lecture. Thus, despite the fact that the operative temperature was 24.5°C the feeling of occupants is -0.52.

The thermal responses of subjects, expressed through acceptable temperature range, comfort temperature and thermal sensitivity can be deduced from a traditional linear regression model of ASHRAE scale votes against indoor operative temperature (Mustapa et. al. 2016). The regression equation for the classrooms, as demonstrated also in figure 5, is:

$$TSV = 0.26 \cdot T_{op} - 5.8 (R^2=0.21) \qquad (3)$$

Proceeding to a comparison between the recorded TSV values and the predicted PMV ones, it can be stated that, for all the periods of Amph and the period 1 of Cls, they are quite similar; this is not the case though for the periods 2 and 3 of Cls. This difference occurs when the solar radiation is high (period 2) and when the windows of Cls are opened (period 3). Thus, these two sets of measurements confirm the relevant literature regarding the weakness of the Fanger model in free-running buildings, when the occupants have some opportunities to modify the surrounding thermal environment. Figure 5, also demonstrates the linear regression relation between PMV and TSV, with the extracted equation being:

$$PMV = 0.45 \cdot TSV - 0.26 \; (R^2 = 0.42) \qquad (4)$$

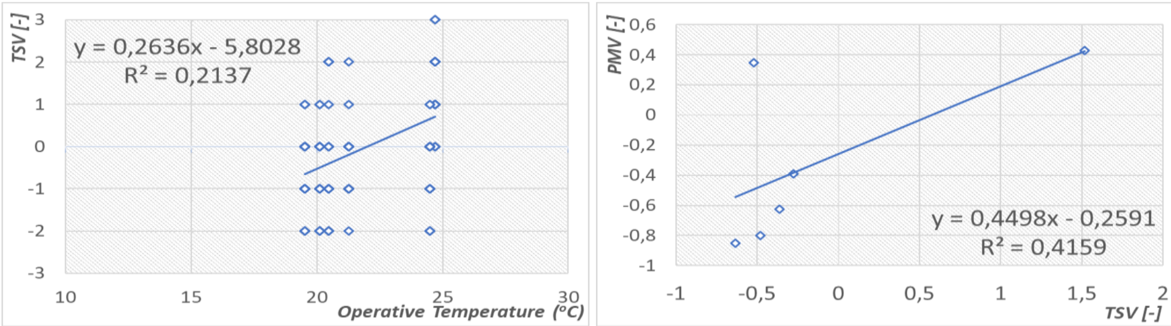


Figure 5. Linear regression model of comfort temperature and colleration between PMV-TSV

4 CONCLUSIONS

The analysis of the thermal comfort perception of the students in two university classrooms by spring time, demonstrated values of PMV indicating light cooling and neutral sensation. Analysis with the adaptive comfort model, as the studied building by spring time is free-running, demonstrated that the correlation of operative temperature with mean outdoor temperature, for both classrooms, was within the acceptable limits. Regarding IAQ, insufficient ventilation was observed, through the recording of quite high CO_2 concentration values, especially by the time the classrooms were crowded. VOCs concentration was within acceptable limits, while NO_2 was mostly affected by outdoor values.The illuminance levels of Amph, where artificial lighting was exclusive, were proven to be below acceptable ones, instead of Cls, where the windows assisted to the achievement of visual comfort sensation. Acoustic comfort was found to be within the recommended limits, where higher comfort may be a result of low outdoor noise and the building's location. The demonstrated findings, especially concerning thermal environment and IAQ, are in agreement with the ones referring to investigation through winter time, noting that by this period indoor thermal conditions were regulated by the heating system.

The subjective response of the students was in agreement with the values of PMV for the Amph, unlike to the ones of the Cls; this can be attributed to the fact that the Cls offers to the users the opportunity to modify the surrounding thermal environment. Moreover, limitations of prediction can be related to potential spatial effects of the measured parameters; even though this issue was not discussed in detail in this work, a range of temperature values in the order of 3°C was observed for Cls, due to the effect of solar radiation and natural ventilation. The comfort temperature, according to the questionnaire analysis using the Griffiths method, lies within the range of 20.5°C - 22°C, while the regression method for TSV - operative temperature led to a value of 22.3°C.

Future research could concentrate on providing a better insight for the findings regarding estimated and actual comfort sensation, mainly for thermal issues, but for all aspects of IEQ as well. The elaboration and suggestion of an IEQ indicator, aiming to effectively quantify and assess the comfort sensation in terms of the complete indoor environmental parameters is a challenging task.

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