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Chapter 1

ASSESSMENT OF INDOOR ENVIRONMENT QUALITY AND SCHOOLWORK PERFORMANCE IN UNIVERSITY BUILDINGS

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ABSTRACT

The education of future generations is an important subject and high-quality school buildings are required to facilitate quality education. These buildings should provide good thermal comfort and suitable quantities of fresh air. Indoor environment quality (IEQ) is characterized, for example, by thermal comfort parameters (i.e., air temperature, air humidity, and air velocity) and indoor air quality (IAQ) variables (e.g., carbon dioxide (CO_2) and volatile organic compounds (VOCs) concentration), which depend on several physical, physiological and psychological factors.

The importance of thermal comfort in the indoor environment cannot be underestimated, especially in educational buildings. Thermal discomfort in such buildings can create unsatisfactory conditions for both staff and students. This can be distracting for the occupants and is likely to reduce their productivity and performance. Even though the potential productivity benefits are quite substantial, they are not generally considered in conventional economic cost-benefit calculations pertaining

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to building design and operation. For these reasons, research on the thermal comfort of educational buildings is being carried out in various parts of the world.

The indoor environment in higher education schools has been studied much less than in other buildings such as offices. The primary aim of this study is to assess thermal comfort based on the PMV (predicted mean vote) and PPD (predicted percent dissatisfied) indices using subjective and experimental measurements in two air-conditioned classrooms at a university, where the air-exchange rate is assured by natural ventilation. The influence of the air-conditioning system and ventilation provided by manually operated windows during the cooling season on thermal comfort parameters (i.e., temperature, relative humidity, air velocity) and CO_2 concentration is also investigated by in situ measurements. The secondary aim of this chapter is to show how indoor environmental conditions during the cooling season affect students' performance. To estimate schoolwork performance, a prediction model is developed based on three Gaussian correlations between performance and air temperature, air relative humidity and CO_2 concentration, respectively. The model is developed using three sets of 12 experiments containing the concentrated (Kraepelin) and distributive (Prague) attention tests for students. Finally, a simulation model in the TRNSYS (Transient System Simulation) program of the PMV-PPD indices and heating/cooling energy demand for an amphitheatre with natural ventilation is proposed. The application of this model shows that without a monitoring and control system, local HVAC installation cannot assure an adequate level of thermal comfort during the entire year.

1. INTRODUCTION

The education of future generations is an important subject and high-quality school buildings are required to facilitate quality education. These buildings should provide good thermal comfort and suitable quantities of fresh air. Indoor environment quality (IEQ) is characterized, for example, by thermal comfort parameters (i.e., air temperature, air humidity, and air velocity) and indoor air quality (IAQ) variables (e.g., carbon dioxide (CO_2) and volatile organic compounds (VOCs) concentration), which depend on several physical, physiological and psychological factors [1].

The importance of thermal comfort in the indoor environment cannot be underestimated, especially in educational buildings. Thermal discomfort in such buildings can create unsatisfactory conditions for both staff and students. This can be distracting for the occupants and is likely to reduce their productivity and performance. For these reasons, research on the thermal comfort of educational buildings is being carried out in various parts of the world [2-5].

To define a common measurement method, standard EN 15251 [6] defines the criteria to evaluate and design building energy performances to satisfy IEQ, taking into consideration thermal, visual and acoustic comfort. ASHRAE Standard 55 [7] provides comprehensive general guidelines on thermal environmental conditions for human occupancy, specifying the combinations of thermal environmental factors and personal factors. According to this standard, if 80% of the subjects are satisfied with the current environmental conditions, then the environment is comfortable and acceptable. ASHRAE Handbook: Fundamentals [8] lists human comfort fundamentals in terms of useful parameters for operating systems and providing comfort to building occupants.

Another well-known international standard is EN ISO 7730 [9], which provide methods for predicting personnel's thermal sensation and thermal dissatisfaction. The calculation of the PMV (predicted mean vote) and PPD (predicted percent dissatisfied) indices associated with other environmental conditions enables the analytical investigation and interpretation of thermal comfort. The standard EN ISO 10551 [10] defines the questionnaire requirements to evaluate the PMV and PPD indices. This seeks to assess the thermal environment influence using subjective judgment scales. At the same time, P.O. Fanger [11] presented a statistical approach to clarify comfort sensations, with the aim of identifying an index that could establish a relationship among metabolic activity, clothing and the physical parameters of the environment. ASHRAE Standard 62.1 [12] and European Standard CEN CR 1752 [13] specify minimum acceptable ventilation rates and IAQ for human occupants in buildings.

The measurement of thermal comfort takes into account several objective parameters (i.e., the physical condition of the environment, including temperature, humidity and other factors) and subjective parameters, such as physiology, activity, age and psychology, including cognitive processes.

The main purpose of classroom ventilation is to create indoor environmental conditions that reduce the risk of health problems among occupants and minimise their discomfort in order to eliminate any negative effects on learning. A study on the ventilation rates in UK schools by Clements-Croome et al., [14] demonstrates the effect of a minimum acceptable ventilation rate on occupants' health and performance. Di Perna et al., [15] studied alternative ventilation strategies in a school in Italy to collect data on the optimisation of IEQ and energy consumption. Candido et al., [16] investigated acceptable air movement levels inside naturally ventilated classrooms. Recent experiments show that inadequate ventilation rates in classrooms can result in a high prevalence of acute health symptoms, better known as Sick Building Syndrome (SBS) [17-19]. Inadequate classroom ventilation can also reduce the speed at which language-based and mathematical tasks, which are typical of schoolwork, are performed by occupants. It can also increase absenteeism [20, 21], which is likely to have negative consequences for learning. Despite this growing body of evidence, most of the data published in the scientific literature indicate that classroom ventilation in many schools is still inadequate and that the fresh air rates in schools are considerably lower than in offices [18, 22]. Thus, classroom ventilation is provided in many schools, including Romanian universities, by expecting users to open the windows. Achieving classroom ventilation by manually opening windows depends to a high degree on outdoor conditions, including the location of the school (i.e., urban and/or rural) and climatic conditions (i.e., wind speed and direction, outdoor air temperatures), as well as on occupants' window opening behaviour.

Adverse ambient conditions such as extreme temperatures, inadequate lighting and poor air quality undoubtedly have negative impacts on student performance, retention and attendance [23, 24]. A recent study by Wargocki and Wyon [25] demonstrated that classroom temperatures and air quality are important factors in the learning process and improving them should be given as much priority as improving teaching materials and methods.

The primary aim of this study is to assess thermal comfort based on the PMV and PPD indices using subjective and experimental measurements in two air-conditioned classrooms at a university, where the air-exchange rate is assured by natural ventilation. The influence of the air-conditioning system and ventilation provided by manually operated windows during the cooling season on thermal comfort parameters (i.e., temperature, relative humidity, air velocity) and CO_2 concentration is also investigated by in situ measurements and analysis. The secondary aim of this paper is to show how indoor environmental conditions during the cooling season affect students' performance. To estimate schoolwork performance depending on air temperature, classroom air relative humidity and CO_2 concentration in three simple Gaussian correlations are developed using three sets of 12 experiments containing the concentrated (Kraepelin) and distributive (Prague) attention tests for students. Finally, a simulation model on the Transient System

Simulation (TRNSYS) program of the PMV-PPD indices and heating/cooling energy demand for an amphitheatre with natural ventilation is developed.

2. Classroom Attributes Influencing Student Perceptions of Learning Environments

Classrooms should be configured to provide the best learning environments possible to promote student learning [26]. Trickett and Moos [27], and Walberg and Anderson [28] conducted one of the first studies about learning environments in late 60's and early 70's. A large number of instruments have been developed to assess students' perceptions of various aspects of learning environments [29, 30]. In general, students' perceptions can be divided into three categories: perception of the psychosocial environment such as belongingness and connection with classmates [31-33]; perception of the psychological environment such as motivation, self-efficacy and achievement [34, 35]; and perception of the physical environment such as classroom size, lighting and technology [36, 37].

Well-organised classroom environments can facilitate student learning and increase students' evaluations of the instructor and the course [38]. Moreover, physical learning environments can be improved through classroom design, maintenance and management.

Physical learning environments should be evaluated by studying both the physical attributes and the students' perceptions of those attributes. Based on the literature, physical attributes could be classified into three categories. The first category is the ambient environment, including attributes such as temperature, acoustics, lighting, daylight and air quality [39]. The second category consists of attributes related to the spatial environment, such as classroom layout [40], classroom furniture, visibility and accessibility of sightline [41]. The third category encompasses technology-related attributes including appropriateness of functions of high-tech hardware, ease of software use [42], and speed of net transfers.

These three types of physical attributes are correlated and closely related to the learning outcomes and student behaviour, which in turn determine student satisfaction and performance. Hill and Epps [43] suggested that attributes with satisfactory conditions, such as lighting, temperature, and space management, increased student satisfaction with learning environments. There is no perfect classroom environment to satisfy all types of academic activities [37].

A comprehensive statistical analysis was conducted by Yang et al., [44] to investigate student perceptions of different classroom attributes, determinants of each attribute perception, and the impact of non-classroom factors on perception. The study found that student perceptions of their learning environments highly relied on spatial attributes (such as room layout and furniture) and ambient attributes (such as temperature and air quality), and the reported perceptions were roughly determined by the presence of corresponding descriptive conditions. Additionally, non-classroom factors provided important contextual fingerprints for student perceptions of classroom attributes especially for visibility, acoustics and furniture. These findings illustrate the potential value of effort to improve design, management and maintenance for higher education classrooms, while also providing guidance about beneficial changes to implement.

3. DESCRIPTION OF BUILDING AND CLASSROOMS

The building selected is a typical higher educational facility with six floors located in the Polytechnic University Timisoara. It was built of porous brick in the yearly 1980s and rehabilitated in 2007. The City of Timisoara is located in the West of Romania, and its latitude and longitude are 45°47’ N and 21°17’ E, respectively. This city has a continental temperate climate with four different seasons and an annual mean outdoor temperature of 11.1°C. The heating season runs from 1 October to 30 April, and the cooling season runs from 1 May to 30 September. For the purpose of the present measurements, one amphitheatre and one seminary classroom located in the ground floor of the Civil Engineering Faculty building were selected. These university classrooms are occupied by both female and male students.

The amphitheatre (Figure 1) has an area of 231 m^2 and a height of 4.90 m. The seminary classroom (Figure 2) has an area of 67.5 m^2 and a height of 3.70 m. The ventilation in these classrooms is through manually operated windows. The two university classrooms are heated by water-filled radiators placed under the windows. The radiators are equipped with thermostatic valves. The amphitheatre is cooled by split air conditioners placed above the windows. The seminary classroom is cooled by a self VRV air-conditioning system type Daikin that consists of an exterior unit RSX5K (cooling power 14 kW; remote control 18-100%), in which three interior units are connected: one unit of model FXYSP63K (total cooling power Q_t = 7.1 kW; sensible cooling power Q_s = 5.11 kW) and two units of model FXYCP25K (Q_t = 2 × 2.8 kW; Q_s = 2 × 2.03 kW). Each interior unit model is endowed with a wire telecontrol, type BRC1D52.

4. EVALUATION OF THERMAL COMFORT IN THE AMPHITHEATRE BY SUBJECTIVE AND EXPERIMENTAL MEASUREMENTS

The amphitheatre was occupied by 40 students for the exams session during a 3-day experimental program in both the winter and summer seasons. The duration of an exam was 2.5 h. The microclimate conditions (i.e., air temperature, mean radiant temperature, air velocity, relative humidity and CO_2 emissions) were monitored during each exam period. The outdoor CO_2 was not monitored, but was assumed 350 ppm according to CEN CR 1752 [13].

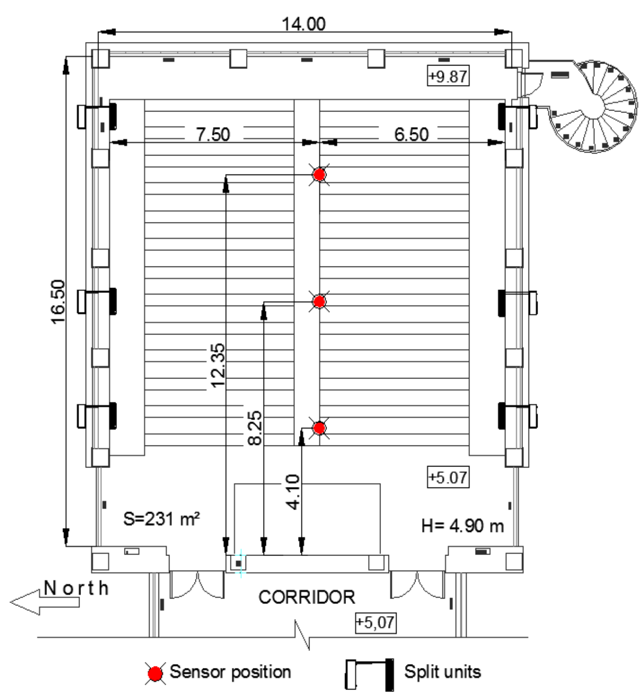

Figure 1. Schematic of the amphitheatre and sensor locations.

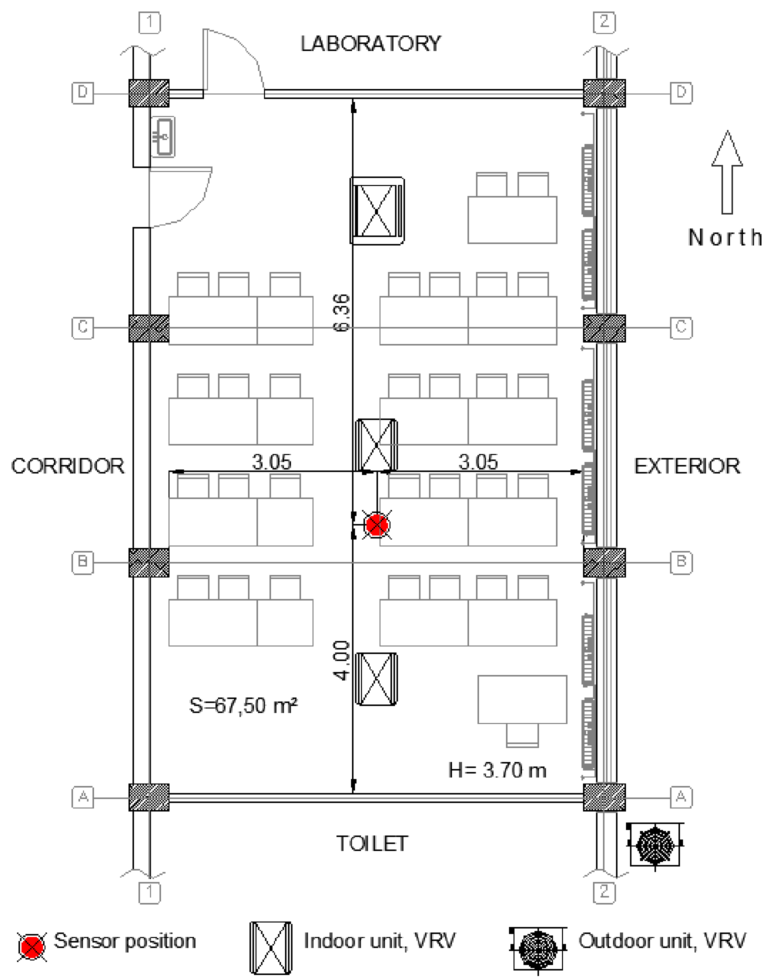

Figure 2. Schematic of seminary classroom and sensor locations.

4.1. Methodology

The method adopted to evaluate thermal comfort requires two different approaches:

(a) The objective (i.e., quantitative) approach, which is based on measurements of the microclimate conditions according to EN ISO 7730 and related standards. The experiments were conducted for three-day periods in January 2012 for the heating season, when the mean outdoor air temperature was approximately 4°C, and in June 2012 for the cooling season, when the mean outdoor air temperature was 23.3°C. The following measurements were carried out within the amphitheatre: CO_2 concentration measured using a sensor (accuracy: ±50 ppm) located centrally in the amphitheatre and connected to a TESTO 350 apparatus that also recorded the indoor air temperature (t_i, in °C) (accuracy: ±0.4°C), relative humidity (RH_i, in%) (accuracy: ±2%), air velocity (v, in m/s) using a hot wire (accuracy: ±0.03%) and black globe temperature (t_g, in °C) (accuracy: ±0.5). The apparatus specifications for the field measurements are summarised in Table 1. The tests of temperature, humidity and air velocity were performed at the height of 1.1 m for standing occupants and the test of CO_2 was performed at the height of 0.1 m (Figure 1). All measurement instruments were calibrated regularly according to the manufacturer's instructions. The mean radiant temperature t_{mr}, in °C, is calculated according to the following equation, adopted from ISO 7726 [45]:

$$t_{mr} = \left[(t_g + 273)^4 + \frac{1.1 \cdot 10^8 v_i^{0.6}}{\varepsilon D_g^{0.4}} (t_g - t_i) \right]^{0.25} - 273 \quad (1)$$

where v_i, is the air velocity in m/s, D_g is the diameter of the globe (150 mm) in m, ε is the emissivity of the globe, and t_g and t_i are the black globe temperature and the air temperature, respectively. To calculate the PMV and PPD indices [46], occupants' metabolic rate is estimated to be 1.2 met (sedentary activity) and the thermal resistance of clothing is determined according to EN ISO 7730, resulting in the mean values of 0.5 clo for the cooling season and 1.0 clo for the heating season.

(b) The subjective (i.e., qualitative) approach, which is based on a questionnaire following the EN ISO 10551 (i.e., subjective judgment scale) standard. In this specific case study, the subjects are students who were asked to complete the questionnaires regarding their perception of the indoor environment before exiting the amphitheatre at the end of the exam. The questionnaires were structured in three parts:

(1) The first part contains subjects' general data (i.e., age, sex, clothing, activity type);

(2) The second part contains students' perception of comfort (i.e., temperature, air velocity, humidity, illumination, noises) and air quality (CO_2);

(3) The third part contains data on outdoor climatic parameters.

Table 1. Apparatus for field measurement

Apparatus model	Probe	Operative range	Accuracy
TESTO 350	Temperature sensor	–20…+70°C	±0.3°C
	Humidity sensor	0–100% RH	±2%RH
	Hot-wire sensor	0–10 m/s	±0.03 m/s
	Glob thermometer	0–120°C	±0.4°C
	CO_2 sensor	0–10,000 ppm	±50 ppm
TESTO 435	Temperature sensor	–20…+70°C	±0.3°C
	Hot-wire sensor	0–20 m/s	±0.03 m/s
KIMO AMI 300	Temperature sensor	–20…+80°C	±0.25°C
	Humidity sensor	3–98% RH	±2%RH
	Hot-wire sensor	0.1–30 m/s	±0.03 m/s

Thermal comfort votes were cast on a 5-point numerical scale: –2 (cool), –1 (slightly cool), 0 (neutral), +1 (slightly warm) and +2 (warm). The scale used to collect air quality perceptions is: very strong, strong, normal, low, and very low. The PMV and PPD indices calculations followed the EN 10551 standard using the student questionnaire results. The PMV index is the arithmetic mean of questionnaire results (Table 2), and each questionnaire vote has one pointing (from –2 cool to +2 warm); the PMV is a mean between the numbers and vote point divided by the number of votes, as described in the formula:

$$\mathrm{PMV} = \frac{\sum_{k,j} Q_k n_j}{\sum_j n_j} \tag{2}$$

where Q_k is the value representing the questionnaire vote k (–2 cool, +2 warm etc.), and Σn_j is the number of students who answered the questionnaire. The predicted percent dissatisfied PPD is a function of the PMV index as follows:

$$\mathrm{PPD} = 100 - 95\exp(-0.0335\mathrm{PMV}^4 - 0.2179\mathrm{PMV}^2) \tag{3}$$

Table 2. Thermal comfort perceived questionnaire subjective judgment results

Measurement	Specification	Subjective judgment scale					Total	PMV [–]	PPD [%]
		Cool	Slightly cool	Neutral	Slightly warm	Warm			
		–2	–1	0	+1	+2			
Cooling season									
1	Subjects	0	1	14	21	4	40	0.67	14.4
2	Subjects	0	2	18	18	3	40	0.55	11.3
3	Subjects	0	1	19	16	4	40	0.59	12.3
Mean [%]		0	3	42	46	9	100	–	–
Heating season									
1	Subjects	6	18	16	0	0	40	–0.73	16.2
2	Subjects	5	17	18	1	0	40	–0.64	13.6
3	Subjects	5	18	16	0	0	40	–0.70	15.3
Mean [%]		13	44	42	1	0	100	–	–

4.2. Measurement Results

In this paragraph, the results of the microclimate measurement and questionnaires are reported. As seen from Figure 3, there is a pronounced growth in the indoor air's average temperature t_i within 30 min, after which it becomes constant at approximately 26.8°C during the cooling season and 19.5°C during the heating season, for an average outdoor air temperature of 31.3°C and 4°C, respectively. The indoor relative humidity RH_i (Figure 4) is within the comfort range according to EN ISO 7730, varying slightly around the value of 50.9±0.74% in summer and around the value of 44.1±0.50% in winter. The air velocity v_i is quite small (Figure 5), with an average value of 0.05 m/s in both seasons and a maximum value of 0.23 m/s in the cooling season and of 0.17 m/s during the heating season, which corresponds to category C in EN ISO 7730 [9] and CEN CR 1752 [13].

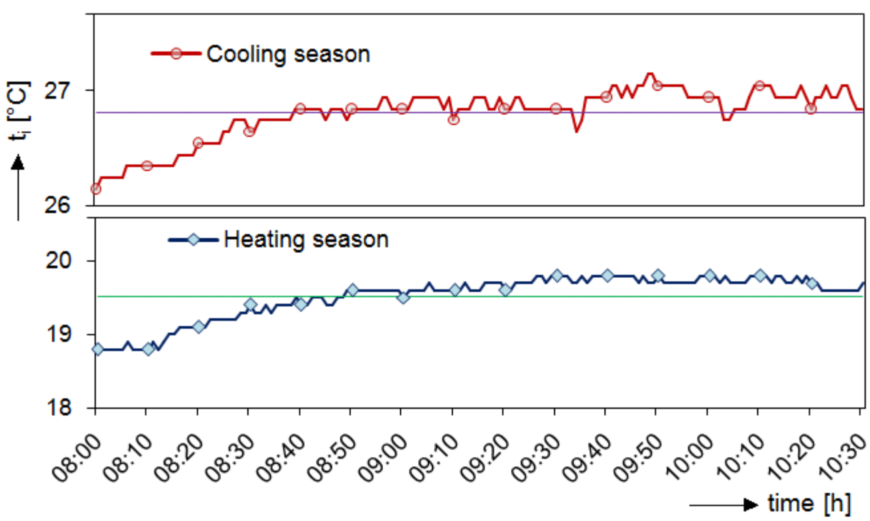

Figure 3. Variation of mean indoor air temperature in amphitheatre.

Figure 6 shows how the total CO_2 concentration increased during the heating season to the maximum value of 1450 ppm, toward the total CO_2 concentration for the cooling season, which varied within a narrow range, with an average of 670 ppm. The maximum CO_2 concentration in winter is close to the maximum admissible limit of 1500 ppm for category C in EN ISO 7730 and CEN CR 1752, as the amphitheatre does not have a mechanical ventilation system. The lower value of the CO_2 concentration in summer is because the windows were opened manually. These provide fresh air but do not maintain the indoor temperature within the thermal comfort limit without an air conditioner.

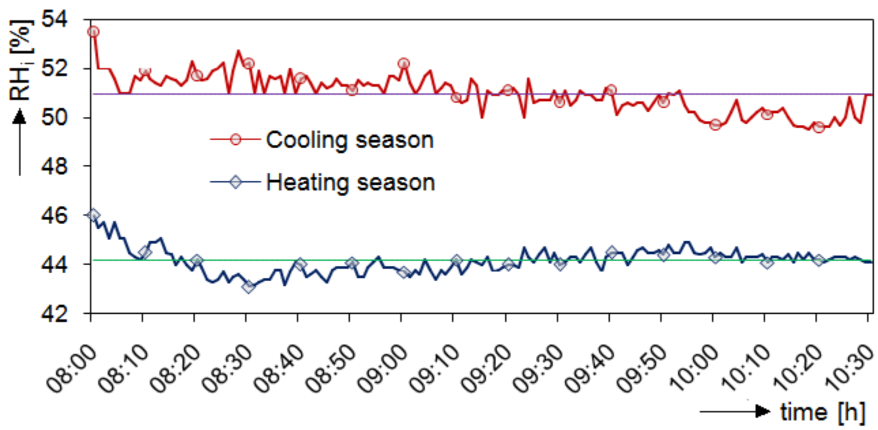

Figure 4. Variation of mean relative humidity in amphitheatre.

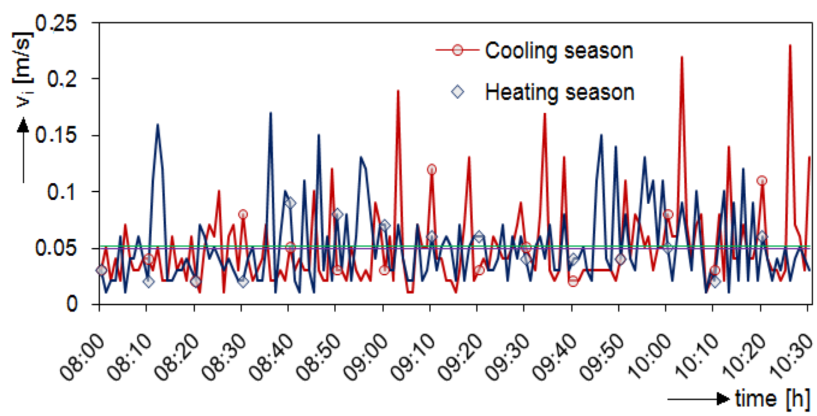

Figure 5. Variation of mean air velocity in amphitheatre.

The students' responses to the questionnaire that express the thermal comfort and air quality sensations are summarized in Figure 7 and Figure 8, respectively. Figure 7 displays the detailed distribution of the thermal sensation vote using the 5-point scale during the cooling and heating seasons. In the heating season, the students with a "slightly cool" perception were a higher percentage of 44%, followed by a "neutral" perception percentage of

42%. In the cooling season, the students with a “slightly warm” perception were a higher percentage of 46%, followed also by a “neutral” perception percentage of 42%. The majority of respondents consider IAQ to be “normal” (64% in the cooling season and 52% in the heating season) and none of the respondents considers IAQ to be “very strong.” The occupants were most sensitive to temperature variations for the thermal comfort evaluation than to CO_2 concentration variations for the IAQ evaluation.

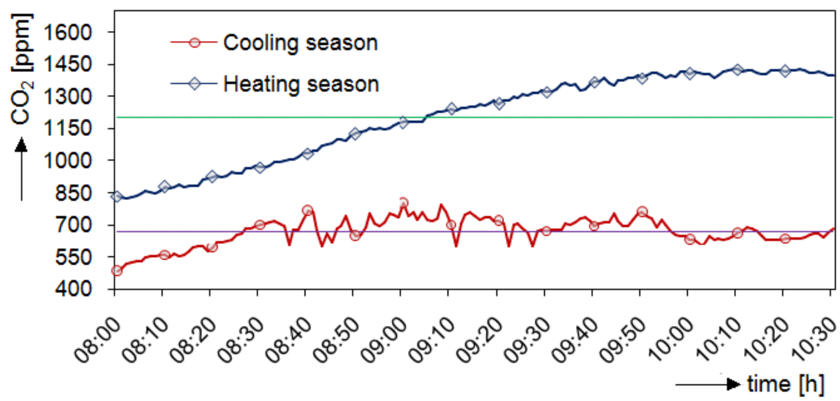

Figure 6. Variation of mean CO_2 concentration in amphitheatre.

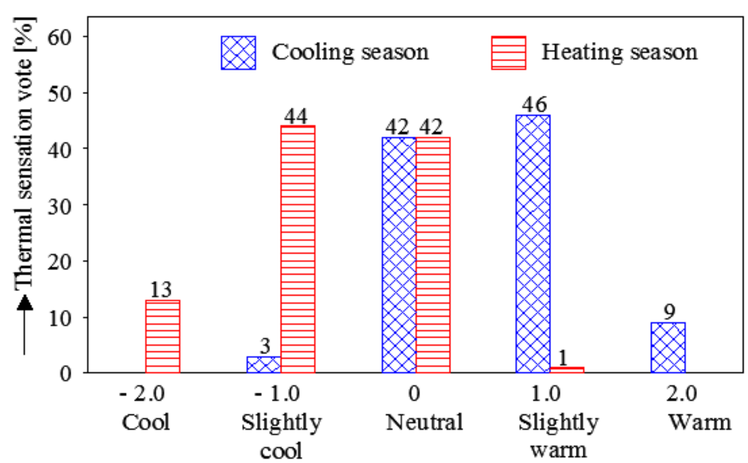

Figure 7. Average of thermal comfort perceived from the questionnaire’s subjective judgment results.

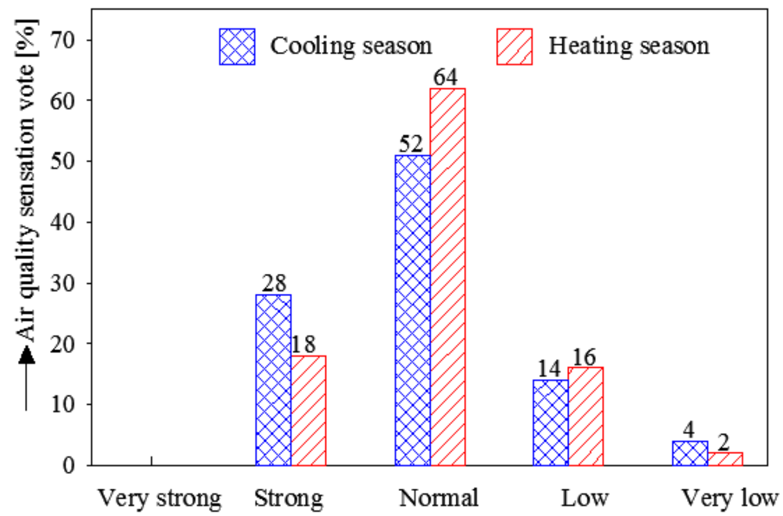

Figure 8. Air quality perceived from the questionnaire’s subjective judgment results.

Table 3 shows the PMV and PPD values obtained with experimental (EXP) and subjective (SBJ) measurements. Only during the heating season was the limit of 85% thermally satisfied occupants (PPD < 15%) exceeded on the first and third measurement days. The difference between the subjective PMV and the experimental PMV varies in the range of –0.03…+0.10 in the cooling season and in the range of +0.01…–0.13 in the heating season. In the cooling season, the PMV index has mean values of 0.60 and 0.55 for the subjective and experimental measurements, respectively. In the heating season, the PMV index has mean values of –0.69 and –0.61 for the subjective and experimental measurements, respectively. The mean value of the subjective and experimental PPD index ranged from 11.66% to 15.04%. This range results in the conditions for thermal comfort being respected as adequate for category C in the EN ISO 7730 standard.

4.3. Uncertainty Analysis

Uncertainty analysis (the analysis of uncertainties in experimental measurement and results) is necessary to evaluate the experimental data [47, 48].

Table 3. The PMV measured experimentally and by subjective judgment scale (questionnaire)

Measurement	Cooling season					Heating season				
	PMV [–]			PPD [%]		PMV [–]			PPD [%]	
	SBJ	EXP	Difference [%]	SBJ	EXP	SBJ	EXP	Difference [%]	SBJ	EXP
1	0.67	0.70	–0.03	14.43	15.31	–0.73	–0.61	–0.12	16.22	12.80
2	0.55	0.45	+0.10	11.33	9.23	–0.64	–0.65	+0.01	13.60	13.87
3	0.59	0.51	+0.08	12.30	10.44	–0.70	–0.57	–0.13	15.31	11.81
Mean value	0.60	0.55	0.05	12.69	11.66	–0.69	–0.61	–0.08	15.04	12.83

An uncertainty analysis was performed using the method described by Holman [48]. A result Z is a given function of the independent variables x_1, x_2, $x_3 \ldots x_n$. If the uncertainties in the independent variables w_1, w_2, $w_3 \ldots w_n$ are all given with same odds, then uncertainty in the result w_Z having these odds is calculated by the following equation [48]:

$$w_Z = \sqrt{\left(\frac{\partial Z}{\partial x_1} w_1\right)^2 + \left(\frac{\partial Z}{\partial x_2} w_2\right)^2 + \ldots + \left(\frac{\partial Z}{\partial x_n} w_n\right)^2} \qquad (4)$$

In the present study, the temperatures, the relative humidity, the air velocity and CO_2 concentration were measured with appropriate instruments explained previously. Error analysis for estimating the maximum uncertainty in the experimental results was performed using Eq. (4). It was found that the maximum uncertainty in the results is in the PMV, with an acceptable uncertainty range of 9% in heating operation mode and of 10% in cooling operation mode.

5. Prediction of Student Schoolwork Performance Depending on the IEQ Parameters

5.1. Methodology

The experiments were performed in the seminar classroom (Figure 2) in the cooling season, from May 12 to June 30, 2012. The mean values of the outdoor environmental parameters during the measurements are summarized in Table 4. The classroom was occupied by 18 students who were healthy, normotensive, non-obese and non-smokers and had the characteristics presented in Table 5. During the experiments, the students performed a learning activity. The microclimate conditions (i.e., air temperature, mean radiant temperature, air velocity, relative humidity and CO_2 emissions) were monitored and recorded during the experiments. The indoor environmental parameters (i.e., indoor air temperature t_i, relative humidity RH_i, air velocity v, black globe temperature t_g and CO_2 concentration) were measured with the sensors (Figure 2) connected to the TESTO 350 apparatus (Table 1). The tests of temperature, humidity and air velocity were performed at the height of 1.1 m for standing occupants and the test of CO_2 was performed at the height of 0.1 m.

Table 4. Mean values of outdoor environmental parameters

Hour	t_e [°C]	RH_e [%]	v_e [m/s]	CO_2 [ppm]
07:50	20.2	71,5	0.37	373
10:30	26.4	53,6	0.31	381
Mean value	23.3	62.8	0.34	377

Table 5. Subjects characteristics

The characteristic	Value
Age [years]	21.17±0.79
Height [m]	1.70±0.07
Mass [kg]	65.06±14.33
Body surface area [m^2]	1.74±0.19

Three scenarios of classroom air conditioning were assumed:

(1) without a cooling system,
(2) without a cooling system but with natural ventilation during a pause and
(3) with a cooling system (indoor air temperature set-point of 23.3°C).

The average results obtained in a set of 12 experiments performed during 12 different days for 2.15 h/day, between 8:00 and 10:15, for each of the three classroom air-conditioning scenarios is considered to achieve satisfactory precision. Performance refers to the quality and quantity of each finished task. The schoolwork performance of each person is recorded for each set of experiments. Each experiment consists of measuring the climate parameters to evaluate the PMV and PPD indices and all students responding to a concentrated attention tests (Kraepelin test) and a distributive attention tests (Prague test) [49, 50], to establish the relationship between student schoolwork performance and indoor environmental parameters (e.g., temperature, relative humidity and CO_2 concentration). The experimental programme is illustrated in Figure 9. After 15 min, when the subjects were completely adapted to the environment under different conditions, they responded to the two tests. The solution times are 10 min for the Kraepelin test (K) and 7 min for the Prague test (P). Each test was completed by the students at the beginning and end of the measurements.

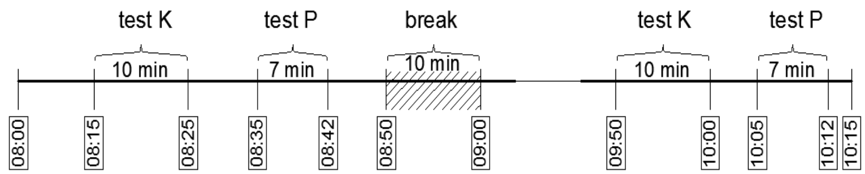

Figure 9. Experimental program.

The K test consists of a numerical calculation that requires much mental activity for the large number of items that must be done correctly in a short time. The P test aims to capture the expressions of distributive attention and involves the spirit of observation and visual memory.

Attention tests require concentration and targeting selective attention, the visual memory and the perception of fixed discrimination. The advantages of these tests are their short application time, the limited amount of information to be tracked and that performance is evaluated quantitatively and qualitatively simultaneously. Extending the solution time of the test would cause fatigue, training problems, autocorrelation and finally, decreasing dynamics.

5.2. Influence of Air-Conditioning Scenarios on Microclimate Parameters and Assessment of Thermal Comfort

Figure 10 shows that air temperature t_i has a greater increase from 22.9°C to 28.5°C in the first scenario and maintains an approximately constant value of 23.8°C in the third scenario. In the second scenario, one period of purge ventilation was performed. This caused a temperature drop of approximately 1°C in the pause of 10 min when the windows were opened manually at 8:50 and the air temperature in the room reaches 27.4°C at the end of measurement.

The variation in indoor air relative humidity RH_i (Figure 11) is between the comfort limits according to the requirements of the EN ISO 7730 standard. In Scenario 1, without a cooling system, RH_i decreases suddenly to 54% in the first 35 min and then maintains a mostly constant value. During the pause of 10 min, when the windows were opened manually at 8:50 to achieve the purge ventilation, the RH_i increases slightly due to the higher level of outdoor air humidity. In Scenario 3, with a cooling system, the RH_i decreases constantly from 57.2% to 42.9% during the 2.5 h. Indoor humidity is a fairly high value at the beginning of the measurements because it has been raining during the night on the previous days.

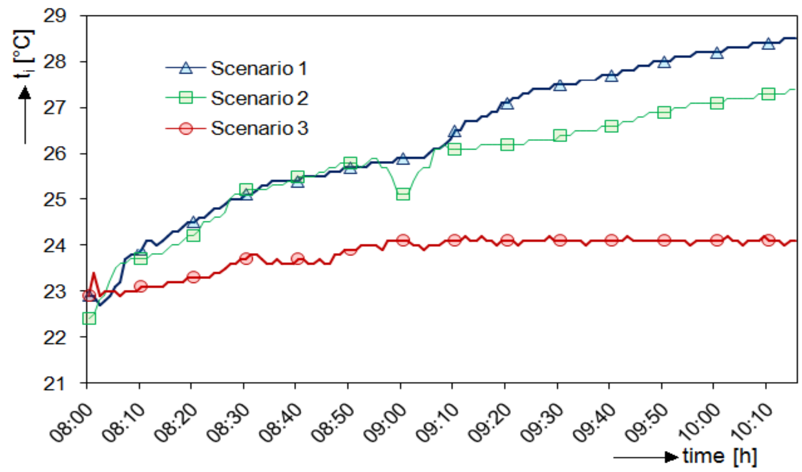

Figure 10. Variation of mean indoor air temperature in seminary classroom.

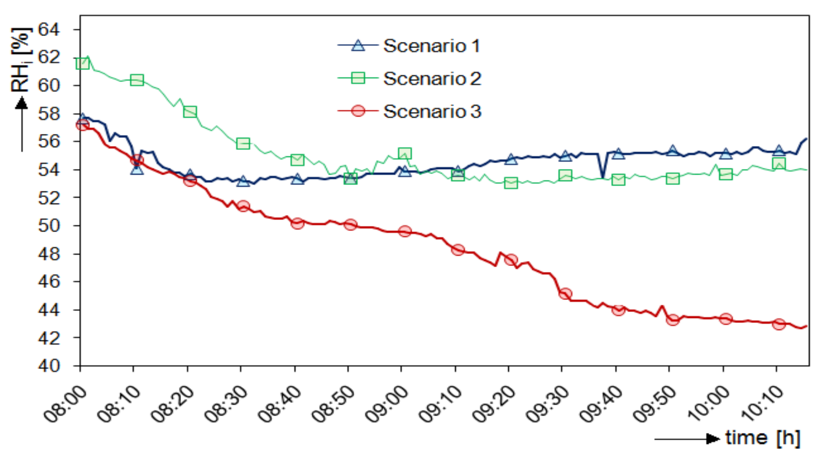

Figure 11. Variation of mean relative humidity in seminary classroom.

Figure 12 shows that during the measurement for the first scenario, the CO_2 concentration increases to the value of 2400 ppm, which is greater than the admissible limit of 1500 ppm. For the third scenario, when the windows were opened manually to achieve classroom ventilation during the pause, the CO_2 concentration decreases significantly to a final value of approximately 1500 ppm, which corresponds to category C in EN ISO 7730.

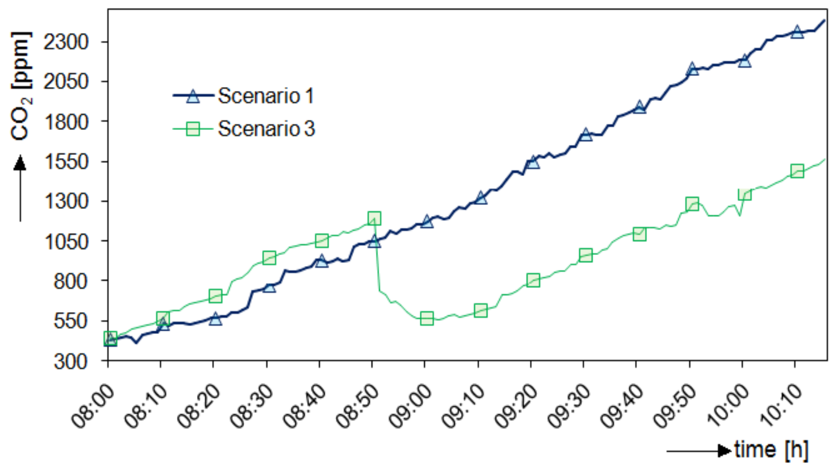

Figure 12. Variation of mean CO_2 concentration in seminary classroom.

To calculate the PMV and PPD indices, the occupants' metabolic rate was estimated to be 1.2 met (sedentary activity) and the thermal resistance of clothes was determined to be 0.5 clo using EN ISO 7730. The mean values of the PMV and PP indices for each scenario are summarized in Table 6. It is noted that in the first scenario, the PMV and PPD indices increase during the 2 h of measurement, from –0.34 to +0.87 and from 7.4% to 21%, respectively; therefore, an unsatisfactory thermal comfort is realised. In the second scenario, by opening the windows, the final values of the PMV and PPD indices decrease to 0.52 and 10.7%, respectively, showing improved thermal comfort. In the third scenario, the PMV and PPD indices reach the final values of –0.34 and 7.4%, respectively, which indicate notably improved comfort through the use of an air-conditioning system.

5.3. Prediction Model of Student Schoolwork Performance

5.3.1. Correlation of Measured Data

A first analysis of the collected test data is to check the correlation among them. Two variables are correlated if they not are independent statistics. For two measured values x_i and y_i of a set of n measured data, the Pearson correlation coefficient r_{xy} is given by [51]:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{5}$$

where $\bar{x}$ and $\bar{y}$ are the mean values of all measured data points.

Table 6. Mean values of PMV and PPD indices

Scenario	Hour			
	8:00		10:00	
	PMV	PPD	PMV	PPD
1	–0.34	7.4	0.87	21.0
2	–0.37	7.8	0.52	10.7
3	–0.74	16.5	–0.34	6.7

It is considered the average of the three data sets, each having 12 measured values. The matrix **M** of the correlation coefficients r_{xy} follows:

$$\mathbf{M} = \begin{bmatrix}
1.000 & 0.982 & -0.019 & 0.891 & 0.954 & 0.975 & 0.956 & 0.718 & 0.339 & 0.010 & 0.983 & 0.788 \\
0.982 & 1.000 & -0.131 & 0.848 & 0.946 & 0.958 & 0.927 & 0.626 & 0.164 & -0.116 & 0.972 & 0.884 \\
-0.019 & -0.131 & 1.000 & 0.112 & 0.056 & 0.135 & 0.109 & -0.095 & 0.655 & 0.072 & 0.083 & -0.407 \\
0.891 & 0.848 & 0.112 & 1.000 & 0.951 & 0.829 & 0.959 & 0.832 & 0.396 & 0.342 & 0.880 & 0.683 \\
0.954 & 0.946 & 0.056 & 0.951 & 1.000 & 0.927 & 0.993 & 0.705 & 0.300 & 0.085 & 0.947 & 0.821 \\
0.975 & 0.958 & 0.135 & 0.829 & 0.927 & 1.00 & 0.928 & 0.577 & 0.370 & -0.140 & 0.987 & 0.741 \\
0.956 & 0.927 & 0.109 & 0.959 & 0.993 & 0.928 & 1.000 & 0.754 & 0.405 & 0.156 & 0.941 & 0.757 \\
0.718 & 0.626 & -0.095 & 0.832 & 0.705 & 0.577 & 0.754 & 1.000 & 0.535 & 0.687 & 0.624 & 0.402 \\
0.339 & 0.164 & 0.655 & 0.396 & 0.300 & 0.370 & 0.405 & 0.535 & 1.000 & 0.508 & 0.308 & -0.271 \\
0.010 & -0.116 & 0.072 & 0.342 & 0.085 & -0.140 & 0.156 & 0.687 & 0.508 & 1.000 & -0.085 & -0.258 \\
0.983 & 0.972 & 0.083 & 0.880 & 0.947 & 0.987 & 0.941 & 0.624 & 0.308 & -0.085 & 1.000 & 0.779 \\
0.788 & 0.884 & -0.407 & 0.683 & 0.821 & 0.741 & 0.757 & 0.402 & -0.271 & -0.258 & 0.779 & 1.000
\end{bmatrix} \tag{6}$$

This matrix shows that all experimental data are correlated with each other.

5.3.2. Relationship between Schoolwork Performance and Indoor Air Temperature

Results obtained by each student for the 12 K tests are expressed by values between 0 and 600, which correspond to the number of correct answers. The partial performance $\eta_{t,K}$ of each student depending on the indoor air temperature t_i obtained through the K tests is illustrated in Figure 13.

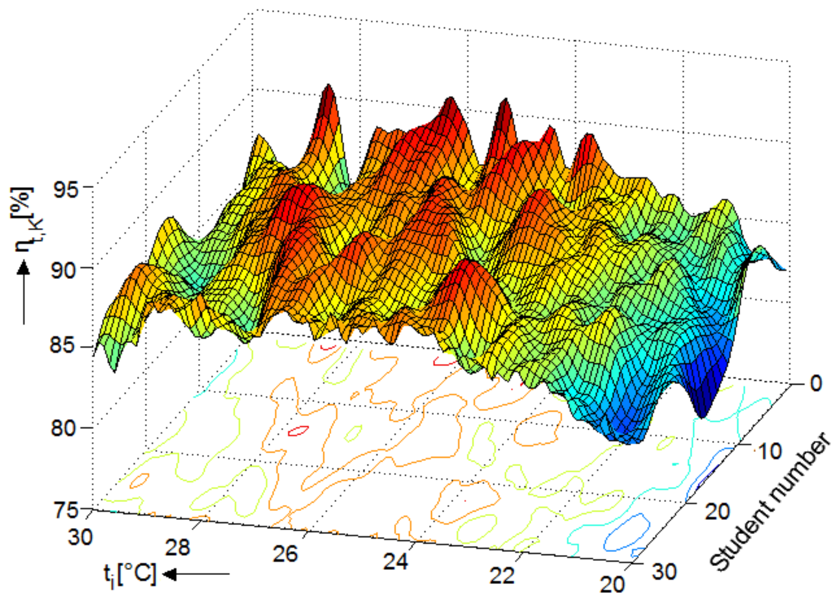

Figure 13. Results obtained by all students for K tests.

Because it is difficult to work with such a chart, a relationship to estimate the performance based on t_i can be obtained using the average of all results obtained by students for each test. For this purpose, a quadratic interpolation function is explored and, after obtaining its coefficients, the coefficients of a Gaussian function are calculated to approximate the input data. Finding a quadratic function of the type:

$$p(x) = p_1 x^2 + p_2 x + p_3 \tag{7}$$

requires determining the coefficients p_1, p_2 and p_3 so that input data minimize the sum of [52]:

$$S = \sum_{i=1}^{n} [y_i - p(x_i)]^2 \tag{8}$$

in which y_i represents the expected result for input x_i.

Once the coefficients of the quadratic function $p(x)$ are obtained, its transformation into a Gaussian functions of the form:

$$g(x) = a \cdot \exp\left(-\frac{(x-b)^2}{2c^2}\right) \tag{9}$$

is performed using the formulas:

$$c = \sqrt{-\frac{1}{2p_1}}; \quad b = p_2 c^2; \quad a = \exp\left(p_3 + \frac{b^2}{2c^2}\right) \tag{10}$$

Some statistical methods, such as the root-mean squared (*RMS*); the coefficient of variation (c_v) and the coefficient of multiple determinations (R^2) may be used to compare the predicted and actual values for model validation.

The error can be estimated by the *RMS* defined as [53]:

$$RMS = \sqrt{\frac{\sum_{m=1}^{n}(y_{pre,m} - y_{mea,m})^2}{n}} \tag{11}$$

In addition, the coefficient of variation c_v in percent and the coefficient of multiple determinations R^2 are defined as follows:

$$c_v = \frac{RMS}{|\bar{y}_{mea,m}|} 100 \tag{12}$$

$$R^2 = 1 - \frac{\sum_{m=1}^{n}(y_{pre,m} - y_{mea,m})^2}{\sum_{m=1}^{n} y_{mea,m}^2} \tag{13}$$

where n is the number of measured data points in the independent data set, $y_{mea,m}$ indicates the predicted value, $y_{mea,m}$ is the measured value of one data point m, and $\bar{y}_{mea,m}$ is the mean value of all measured data points.

Statistical values such as *RMS*, c_v and R^2 are given in Table 7 for some correlations types between performance and different indoor environmental parameters.

- Using the average of the results achieved by all students for each of the 12 K tests and using the mathematical process previously described the following correlation between the performance $\eta_{t,K}$ and indoor air temperature t_i was obtained:

$$\eta_{t,K} = 88.1 \cdot \exp\left[-\frac{(t_i - 25.685)^2}{516.554} \right] \tag{14}$$

The graph of function (14) and all 12 average values are shown in Figure 14. It is noted that retains the form from Figure 13 and the R^2-value approaches 1. The maximum values of performance $\eta_{t,K}$ are in the interval from 24 to 26°C. Moderate changes in room temperature beyond the comfort zone affect students' abilities to perform mental tasks requiring concentration.

- The P test results include some values ranging in the interval [0-40]. The performance $\eta_{t,P}$ of each student depending on the indoor temperature t_i obtained in the P tests is illustrated in Figure 15. These results reveal that the temperature in the classroom affects the ability of students to grasp instruction. Higher values of student's performance are observed, toward those obtained on the K test for the same indoor temperatures and also a change of the maximum performance zone to temperatures that are 2°C higher.

Table 7. Statistical values for some correlations between performance and different indoor environmental parameters

Parameter	Test	Correlation	*RMS*	c_v	R^2
Air temperature	K	(14)	0.0870	0.000997	0.99999901
	P	(15)	0.0925	0.001002	0.99999900
	K+P	(16)	3.4900	0.038854	0.99924500
Relative humidity	K+P	(17)	3.5050	0.039025	0.99923900
CO_2 concentration	K+P	(18)	3.9860	0.044718	0.99909900

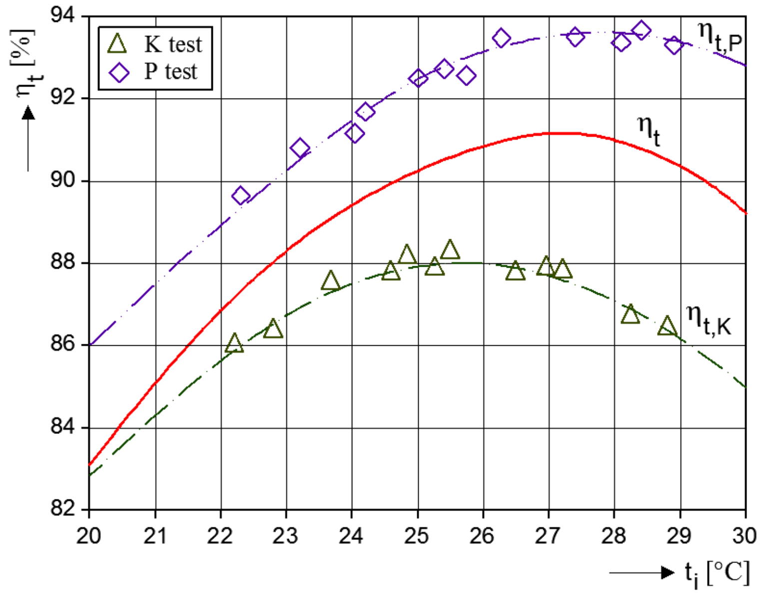

Figure 14. Gaussian correlations between mean performance and air temperature for K and P tests.

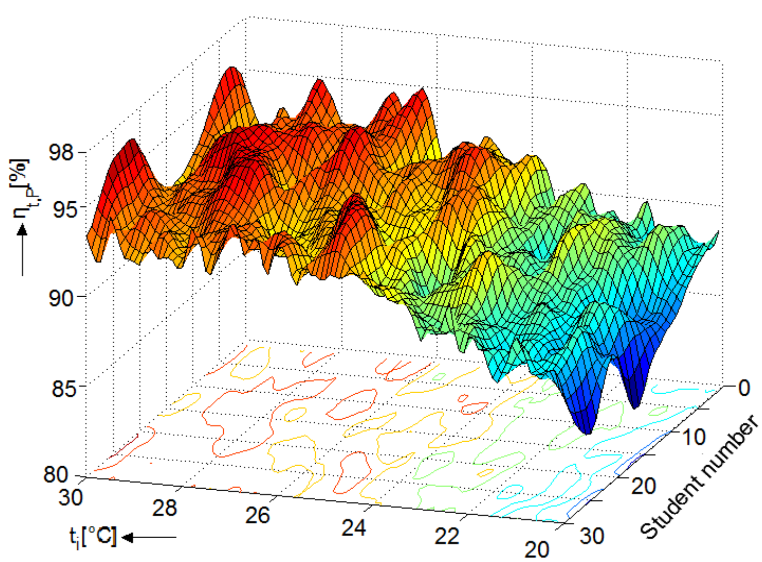

Figure 15. Results obtained by all students for P tests.

The P test results include some values ranging in the interval [0-40]. The performance $\eta_{t,P}$ of each student depending on the indoor temperature t_i obtained in the P tests is illustrated in Figure 15. These results reveal that the temperature in the classroom affects the ability of students to grasp instruction. Higher values of student's performance are observed, toward those obtained on the K test for the same indoor temperatures and also a change of the maximum performance zone to temperatures that are 2°C higher.

By using the average of the results obtained by all students in each of the 12 P tests, the following Gaussian correlation between the performance $\eta_{t,P}$ and the air temperature t_i was deduced:

$$\eta_{t,P} = 93.5 \cdot \exp\left[-\frac{(t_i - 27.902)^2}{743.591}\right] \tag{15}$$

In Figure 14 is illustrated the graph of the function (15) and the values that have been generated. In this case, the R^2-value approaches 1.

By integrating data from the K and P tests, the estimating correlation of partial performance η_t, depending on the indoor air temperature, was resulted with the form:

$$\eta_t = 90.95 \cdot \exp\left[-\frac{(t_i - 27.142)^2}{562.734}\right] \tag{16}$$

The graph of the interpolation function (16) is illustrated in Figure 14. The R^2-value is 0.99925, which can be considered very satisfactory. It is noted that the maximum performance is obtained at an air temperature of 27°C.

5.3.3. Relationship between Schoolwork Performance and Relative Humidity

The correlation for estimating the partial performance η_{RH} depending on relative humidity RH_i was obtained in manner similar to Eq. (13) and has the following expression:

$$\eta_{RH} = 90.33 \cdot \exp\left[-\frac{(RH_i - 60.79)^2}{7504.75}\right] \tag{17}$$

The graph of the interpolation function (17) is illustrated in Figure 16. The R^2-value is 0.99924, which can be considered very acceptable. It is observed that the maximum performance corresponds to a relative humidity RH_i of approximately 60%.

Comparative analysis of the variation curves of performance depending on temperature (Figure 14) and humidity (Figure 16) indicates that the relative humidity has less influence on the student performance than does temperature.

5.3.4. Relationship between Schoolwork Performance and CO_2 Concentration

On the basis of the data provided by the K and P tests and presented in Figure 17, the following linear regression was obtained to analyse the correlation between performance η_{CO_2} and CO_2 concentration:

$$\eta_{CO_2} = -0.0003 C_{CO_2} + 89.48 \tag{18}$$

where C_{CO_2} is the CO_2 concentration.

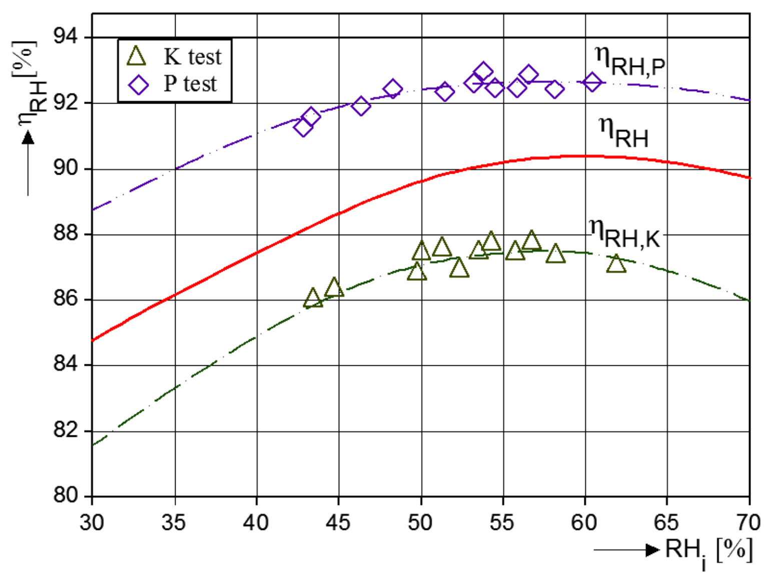

Figure 16. Gaussian correlations between mean performance and relative humidity for K and P tests.

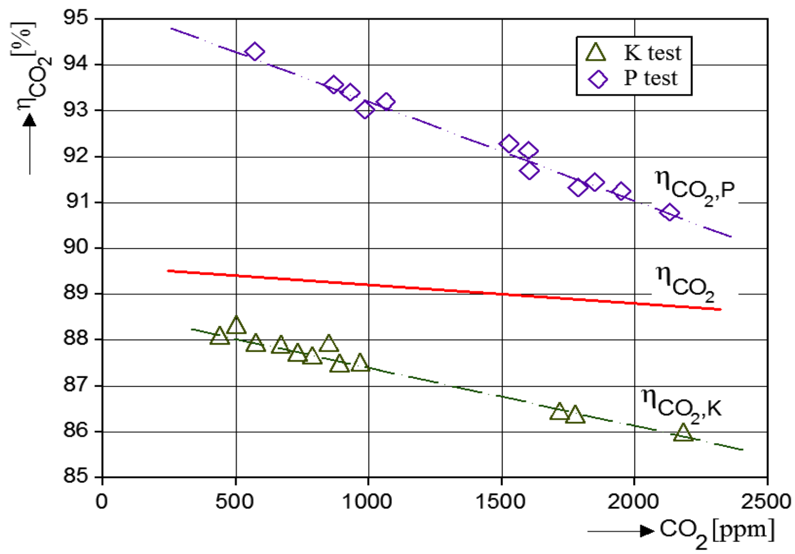

Figure 17. Linear regression between mean performance and CO_2 concentration for K and P tests.

The R^2-value is 0.99989 and the error is small. It can be seen from Figure 17 that student performance has an insignificant decrease of 0.6%, even if the increase of CO_2 concentration is a noticeable 87.5%.

6. Simulation of PMV-PPD Indices and Heating/Cooling Energy Demand Using Software TRNSYS

The TRNSYS software [54] is a flexible modelling and simulation tool and can solve very complex problems by decomposing the model into various interconnected model components (types). The basic principle of the TRNSYS program is the implementation of algebraic and first-order ordinary differential equations describing physical components into software subroutines (called types) with a standard interface. The STEC library is based on steady state energy conservation (i.e., 1st and 2nd laws) formulated in thermodynamic quantities (i.e., temperature, pressure, and enthalpy). One of the main advantages of TRNSYS for modelling and design is that it includes components for calculating building thermal loads; specific components for heating and cooling (HVAC), including circulating pumps, fans, fan coil units, heating and cooling coils and chillers; and climatic data files. This makes it a very suitable tool to model a complete air-conditioning installation to provide heating and cooling to a building.

6.1. Definition of the Operation Scheme

To simulate the thermal energy demand used to cover the heating/cooling load of the amphitheatre with natural ventilation and the PMV-PPD thermal comfort indices in this space, the operational connections were established between the building and all internal and external factors.

Figure 18 presents the operational scheme built in TRNSYS, where the building's thermal behaviour was modelled using a Type 56 subroutine. This subroutine was processed with the TRNBuild interface by introducing the main construction elements, their orientation and surface, shadow factors, and indoor activity type. Weather data for the Timisoara were obtained from the Meteonorm database [55] and the weather data readers Type 109 and Type 89d were used to convert the data into a form readable by TRNSYS.

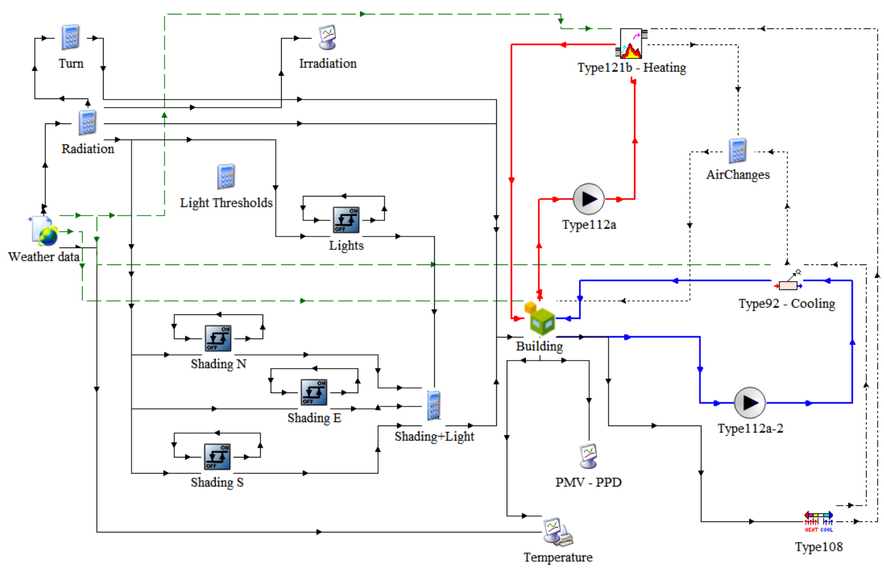

Figure 18. Operational scheme built in TRNSYS.

The simulation model took into account the outdoor air infiltrations, interior gains, ventilation type, air exchange rate and type of air-conditioning system. Evaluation of the PMV-PPD indices according to EN ISO 7730 is integrated into the Type 56 subroutine.

The operational program of the amphitheatre was taken from the schedule menu. This allows the definition of the building's exact occupancy profile, which is used to determine both the interior gains and the operation mode of the ventilation and air-conditioning system. A working program for students and the electronic apparatus was defined from Monday to Friday between 9:00 and 18:00. The air-conditioning system operates during the cooling season so the indoor air temperature set-point is maintained only during the occupation of the amphitheatre. To extract the results, an online plotter (Type 65) is used.

6.2. Simulation Results

Using the TRNSYS program, the thermal comfort PMV and PPD indices were simulated during both the heating season and the cooling season (Figure 19) for the set-point indoor air temperature values of 20°C and 25°C, respectively.

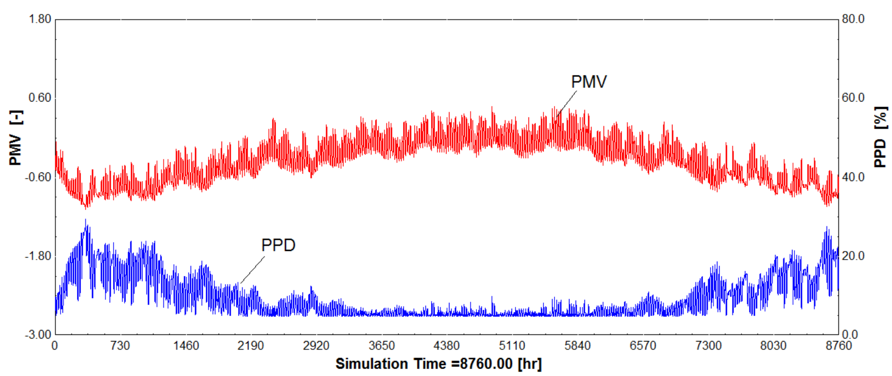

Figure 19. Simulation of PMV and PPD indices' variation during heating and cooling season.

Table 8. Heating-cooling energy demand for amphitheatre

Month	Heating energy demand [kWh]		Percentage difference [%]	Cooling energy demand [kWh]		Percentage difference [%]
	Simulated	Calculated		Simulated	Calculated	
January	12,608	12,578	+0.24	0.00	0.00	0.00
February	8803	8759	+0.50	0.00	0.00	0.00
March	5253	5270	–0.33	0.00	0.00	0.00
April	1810	1822	–0.65	0.00	0.00	0.00
May	0.00	0.00	0.00	1074	1066	+0.75
June	0.00	0.00	0.00	2271	2259	+0.53
July	0.00	0.00	0.00	3777	3798	–0.55
August	0.00	0.00	0.00	3303	3312	–0.27
September	0.00	0.00	0.00	973	981	–0.77
October	2034	2021	+0.67	0.00	0.00	0.00
November	5836	5792	+0.77	0.00	0.00	0.00
December	10,399	10,374	+0.24	0.00	0.00	0.00

Depending on the building's initial data, the mean radiant temperature is generated by the program. The metabolic activity of 1.2 met, the air velocity of 0.1 m/s, and the clothes thermal resistance of 1.0 clo during the heating season and 0.5 clo during the cooling season are defined in the TRNBuild subroutine. It is found that in the cooling season, the PMV index ranges from –0.40 to +0.42 and the PPD index has values up to 8.7%. As a result, the conditions for thermal comfort are respected, adequate for category B in EN ISO 7730. During the heating season, the PMV index ranges from –1.0 to +0.3, and the PPD index has values up to 26.1%. These lower comfort levels are due to the IEQ experienced by the occupants, which is additionally influenced by the absence of a monitoring and control system.

The simulation results of the heating-cooling energy demand for the amphitheatre is presented in Table 8 beside the calculated data in accordance with EN ISO 13790 [56]. Also, statistical values such as *RMS*, c_v and R^2 are given in Table 9. Both in the heating and cooling season, the maximum percentage difference is 0.77% and R^2-value is 0.9999%, which are very acceptable and the simulation model can be validated. The specific energy demand for the winter season is 204 kWh/m^2/yr, and for the summer season, it is 51 kWh/m^2/yr. The higher value of 26.1% for the PPD index demonstrates that this heating energy demand cannot be assured during some periods of the winter season by the actual heating system.

Table 9. Statistical values of thermal energy demand for amphitheatre

Operation mode	*RMS*	c_v	R^2
Heating	29.528	0.004434	0.999985
Cooling	12.552	0.005497	0.999975

CONCLUSION

In this study, thermal comfort and air quality were evaluated during the cooling and heating seasons for two air-conditioned classrooms of a higher educational building where the air-exchange rate is assured by natural ventilation, based on experimental and numerical investigation and a questionnaire for subjective judgment results. In addition, student learning performance in the cooling season was estimated based on concentrated and distributive attention tests of students. Some main conclusions have been drawn from evaluating the results presented in this study:

(1) The research conducted during both the cooling season and the heating season indicates the dependence of thermal comfort and air quality on microclimate parameters in university classrooms with and without air-conditioning systems and ventilated by manually opening the windows. The indoor environmental conditions were satisfactory and almost all situations fit within the comfort limits of category C required by EN ISO 7730.

(2) In the amphitheatre, the upward monitored temperature evolution is noticeable because of the absence of a control for the HVAC system. The indoor air temperature both in the cooling season and the heating season has a pronounced growth of 0.5-0.7°C during the first 30 min of measurements, after which it maintains an approximately constant value of 26.8°C and 19.5°C, respectively. The relative humidity varied slightly around the value of 50.9% during the summer and around the value of 44.1% during the winter. The air velocity in the room was very small, with a mean value of 0.05 m/s in both seasons. The CO_2 concentration rose sharply during the heating season, recording a maximum of 1450 ppm at the end of the experiments; in the cooling season, it had a constant variation around the value of 670 ppm due to ventilation by the manually operated windows. Comparing the PMV and PPD indices that were calculated based on the experimental and subjective (questionnaire) measurements indicates good agreement between them. The mean value of the PMV index ranges from 0.55 to –0.69 during both seasons; the mean value of the PPD index ranges from 11.66% to 15.04%.

(3) The influence of the air-conditioning system and natural ventilation in the summer on the indoor environmental parameters was investigated in the seminary classroom. In the absence of a cooling system and the ventilation rates, the air temperature increases to the value of 28.5°C, which exceeds the maximum comfort limit of 27°C; further, the PMV and PPD indices have the values of 0.87 and 21%, respectively. Additionally, the CO_2 concentration increases above the admissible limit, reaching a value of approximately 2400 ppm. By manually opening the windows, on break, the thermal comfort is improved as the indoor temperature decreases by approximately 1°C, reaching 27.4°C at the end of the measurements; the PMV and PPD values are 0.52 and 10.7%, respectively. The CO_2 concentration decreases significantly to 1500 ppm at the end of the 2 h of measurements. The thermal comfort is notably improved when in the room operating the cooling system. The air temperature remains almost constant around the value of 23.8°C, and the PMV and PPD indices have the values of –0.34 and 7.4%, respectively. Based on these results, mechanical ventilation in which an adequate air exchange rate is

assured can be recommended in classrooms. The classroom should have a CO_2 sensor for continuous monitoring and recording. A visual, “traffic light” type sensor could be used to alert the teacher to provide more ventilation when 1500 ppm is exceeded.

(4) Students' tests of concentrated and distributive attention have allowed developing three simple correlations to estimate the students’ performance in the cooling season depending on air temperature, relative humidity and CO_2 concentration. The R^2-values in all three correlations are approximately 0.999, which can be considered very satisfactory. This study has shown that indoor environmental conditions can strongly affect student performance. The maximum performance is obtained at an air temperature of 27°C in cooling season. The student performance has an insignificant decrease of 0.6%, even if the increase of CO_2 concentration is a noticeable 87.5%. These results must be validated by performing actual measurements in more occupied schools.

(5) By simulating the comfort indices in the amphitheatre for a year using the TRNSYS simulation model, the PMV index ranges from –0.40 to +0.42 in the winter and from –1.0 to +0.3 in the summer, which indicates that without a monitoring and control system, the local HVAC installation cannot assure an adequate level of thermal comfort during the entire year.

(6) Easily controllable, secure ventilation that can supply large quantities of fresh air without draughts, and the potential for utilising summer night cooling should be investigated on future designs.

(7) The developed TRNSYS simulation model can be used as a tool to assess the PMV and PPD indices in classrooms with air-conditioning systems in different operation modes to ensure users’ comfort throughout the year.

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