EXPERIMENTAL AND STATISTICAL SURVEY ON LOCAL THERMAL COMFORT IMPACT ON WORKING PRODUCTIVITY LOSS IN UNIVERSITY CLASSROOMS

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The paper presents an experimental analysis of the relationship between local thermal comfort and productivity loss in classrooms. The experimental investigation was performed in a real university classroom during the winter semester in Belgrade. Measurements were taken for four scenarios, with different indoor comfort conditions. Variations were made by setting the central heating system on/off, adding an additional heat source to provoke higher indoor temperatures, and measuring the radiant asymmetry impact. Innovative questionnaires were developed especially for the research, in order to investigate students' subjective feelings about local thermal comfort and indoor environmental quality. Local PMV and PPD indices were calculated using data measured in situ. The results were compared to existing models recommended in literature and European and ASHRAE standards. Student productivity was evaluated using novel tests, designed to fit the purposes of the research. Surveys were conducted for 19 days under different thermal conditions, during lectures in a real classroom, using a sample of 240 productivity test results in total. Using the measured data, new correlations between the PMV, CO_2, personal factor and productivity loss were developed. The research findings imply that local thermal comfort is an important factor that can impact productivity, but the impact of the personal factor is of tremendous importance, together with CO_2 concentration in the classroom.

Key words*: PMV, PPD, local thermal comfort, working productivity loss, IEQ*

1. Introduction

The most generally accepted definition of health was developed by the World Health Organization (WHO): “Health is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity”[1]. Indoor Environmental Quality (IEQ) observation has increased dramatically in recent decades, as a result of increased complaints from occupants about poor indoor air quality and the identification of two types of related diseases, Sick Building Syndrome (SBS) and Building-Related Illness (BRI) [1]. Additionally, research concerning thermal comfort has dramatically increased over the past ten years, with a peak in 2011, when almost 900 documents were published on the subject [2]. According to Zomorodian et al.[3], there are two main approaches to thermal comfort modeling: rational (RTC) or static models, and adaptive models (ATC) [4]. Rational models include Fanger’s PMV model [5],which gives decent results in comparison to the actual mean vote of occupants in air-conditioned buildings, with passive occupants’ behavior, such as office buildings without openings, or schools in which the thermal preferences of teachers are dominant, and pupils are not allowed to act in order to change the comfort level [4]. The other stream of thought propagates an adaptive approach, which observes the occupants as active participants in the creation of thermal environments. This approach was first proposed in the 1970s [6] and it takes into account the physiological, psychological and behavioral elements. Latest studies have observed thermal comfort conditions in classrooms by measuring physical parameters and using questionnaires for students. Almeida et al. [7] investigated the thermal comfort in classrooms in a mild climate, in Portugal, on a sample of children aged four years up to university students. The data from 10 educational spaces, in 32 measurements, using 490 questionnaires was collected. Stevanović [8, 9] measured thermal comfort indices among children in primary school in Serbia, aged eight to nine, and defined the turbulence models of air flow in school buildings.

Alfano et al. [10] investigated the PMV and PPD indices in naturally ventilated classrooms, on a sample of more than 4000 students, between the ages of11 and 18 years, in Southern Italy, in both summer and winter seasons. All schools were naturally ventilated, with operable windows. Results showed that Fanger’s approach provides good agreement with the subjective votes for naturally ventilated buildings in warm climates, if an appropriate expectancy factor is implemented. Additionally, the percentage of people dissatisfied was shown as a higher value when the respondents were questioned directly about the acceptability in comparison to the respondents who voted ±2 or ±3.

The definition of productivity is given in literature [11] as “an index ratio of output relative to input.” The same research gives the conclusion that poor IEQ may reduce working performance in extreme conditions by 100%, causing employee absence [11]. Bajc et al. [12]investigated the IEQ in non-residential buildings in Mediterranean climate conditions and its impact on occupants’ health. This highlighted the importance of proper ventilation during the winter period, in order to achieve desirable thermal comfort levels, and a healthy and productive working environment. Hermann M. [13] investigated the productivity of teachers and their absence from work prior to and during the examination period, and found that there is a direct negative connection with students’ exam performance. Other studies [14, 15] have shown that the work performance increases with increased air quality. Kosonen and Tan [14] published research demonstrating that productivity loss of 0,5 to 2% had an economic impact of about the same as the annual cost of the total air-conditioning system. In another theoretical study, Kosonen and Tan [16] investigated productivity loss in an air-conditioned office building using the PMV index. They compared two office tasks - thinking and typing - and compared productivity loss as a function of PMV using polynomial expression. They concluded that the greatest productivity of 100% is expected when the air temperature is 20°C, and PMV=-0.21. The key finding was that when PMV has a value of +0.5, the productivity loss for thinking is about 12% and for typing around 26%.

Li Lan [17] investigated the effects of thermal comfort changes on the emotions and working performance of occupants through neurobehavioral tests, and with “the Profile of mood states”. Tests showed that performance was decreased when the thermal environment deviated from neutral conditions. Participants felt uncomfortably hot at a high temperature, experienced more negative moods and needed to usemore effort to maintain working performance [17].

The impact of local thermal comfort on productivity loss was investigated by Bajc et al. [18]using CFD simulations for naturally ventilated classrooms in continental climate conditions. The results indicated air temperature changes locally up to 2°C, in comparison with an average value for the classroom, which can influence the thermal comfort conditions and thus increase productivity loss.

Through the literature survey it was noticed that the data regarding local thermal comfort and its correlation with productivity loss in university level classrooms, obtained both experimentaly and statisticaly in situ, are limited. The main objective of this paper is to correlate local thermal comfort with productivity loss using new equation obtained through the experimental and statistical results gathered in real conditions, during on going winter semester. The novel productivity tests were developed, and according to 240 results of students’ productivity and large portion of experimental data for thermal comfort paramethers and CO_2 concentrations, new conclusions were brought out.

2. Research methodology

2.1. Experimental set-up

The observed classroom is located at the Automatic Control Department, Faculty of Mechanical Engineering, University of Belgrade, Serbia. The experiments were done for winter conditions, during the period from 16th of November to 11th of December 2015. It is very important to emphasize that all measurements and research surveys were conducted “live”, in real conditions, during the winter semester and during the classes, colloquiums and regular teaching activities. The kindness of the whole Automatic Control Department staff and willingness of the students helped to realize this research.

The classroom is 8.12m long, 6.34m wide and 3.3m high. The total heated area is 51.48 m^2 and the net volume is 169.9 m^3. Each window has an area of 3.63 m^2 and the door area is 3.91 m^2. The area of the blackboard on the Southwest inner wall is 7.6 m^2. The total number of seating places is 30. The classroom photo is shown in fig.1.

Fig.1 Observed classroom with measuring equipment

The measurements were done according to the established measurement protocols for four scenarios in order to determinate the following physical values: temperatures of the inner surfaces at several measurement points, which are defined in the measurement protocol - all walls, glass, windows frame, floor, ceiling and heat sources (radiators and additional heaters); the temperatures and relative humidity in 39 measurement points across the classroom; radiant temperatures in five measurement points; the air velocities in three measurement points; CO_2 concentrations in three measurement points; and the temperatures, relative humidity and CO_2 concentration of the outside air. The created scenarios were established to investigate student satisfaction and productivity in different thermal environments. In the first scenario, the heating system was turned off using the radiator thermostatic valves, and the doors and windows were closed during the lectures. In the second scenario, the thermostatic valves on the radiators were set to value three, which corresponds to a set temperature of 20°C in the classroom. The third scenario included three additional convective heaters; model "Vivax Home CH-2004 F", 750W power each. The heating system was also turned on. In the fourth scenario, heating was provided by only the additional convective heaters, set behind the students' backs, the same as in the third scenario. These kinds of experimental protocols were established to determine local thermal comfort parameters in the observed classroom.

The classroom was divided into five sections, marked M01 to M05, as shown in figure 2. These positions were marked for easel positions carrying the black globe probe, together with the equipment for velocity, air temperature, relative humidity measurements and IAQ probe. The characteristics of the equipment used for indoor and outdoor measurements are shown in tab. 1.

Tab. 1. Characteristics of the measuring instruments

Instrument	Measured parameter	Measuring range	Accuracy
Testo 435	Hot wire probe: Air velocity, air temperature	0-20 m/s, -20 to +70°C,	±(0.03 m/s +5% of mv), ±0.3 °C (-20 to +70 °C)
Testo 435	IAQ (CO_2, humidity, temperature and absolute pressure)	0 to+10000 ppm CO_2, 0 to +100 %RH, 0 to +50 °C, +600 to +1150 hPa	±(75 ppm CO_2 ±3% of mv) (0 to +5000 ppm CO_2) ±(150 ppm CO_2 ±5% of mv), %RH (+2 to +98 %RH), ±0.3 °C ±2, (+5001 to +10000 ppm CO_2) ±10 hPa
Testo 445	Degree of	0 to +5 m/s, 0 to +50 °C	±(0.03 m/s +4% of m.v.) (0 to +5

Instrument	Measured parameter	Measuring range	Accuracy
	turbulence: air velocity, air temperature		m/s), ±0.3 °C (0 to +50 °C)
Testo 445	Ambient CO_2	0...+1Vol.%CO_2, 0...+10000ppmCO_2	±(75 ppm CO_2 +3% of m.v.) (0 to +5000 ppm CO_2) ±(150 ppm CO_2 +5% of m.v.) (+5001 to +10000 ppm CO_2)
Testo 445 - globe probe (D=150mm)	Radiant temperature	0 to + 120 °C	Class 1
Testo 174H	Temperature and humidity	-20 to +70 °C, 0 to 100 %rH	±0.5 °C (-20 to +70 °C), ±3 %RH (2 to 98 %RH)
Testo 175H1	Temperature and humidity	-20 to +55 °C, 0 to 100 %rH	±0.4 °C (-20 to +55 °C), ±2 %RH (2 to 98 %RH) at +25 °C
Testo 830-T2	Temperature	-50 to +500 °C	±0.5 °C of reading at rated temperature 22°C
FLIR E40bx	Temperature	-20°C to 120°C	±2°C or ±2% of reading

Each seating position was labeled on the table, as shown in fig. 2., so the students could fill in the label marks in the questionnaire, due to the anonymous character of the survey. The measured physical values were used for PMV and PPD indices calculations, based on refined code given in Annex D of standard ISO 7730:2005 [19].

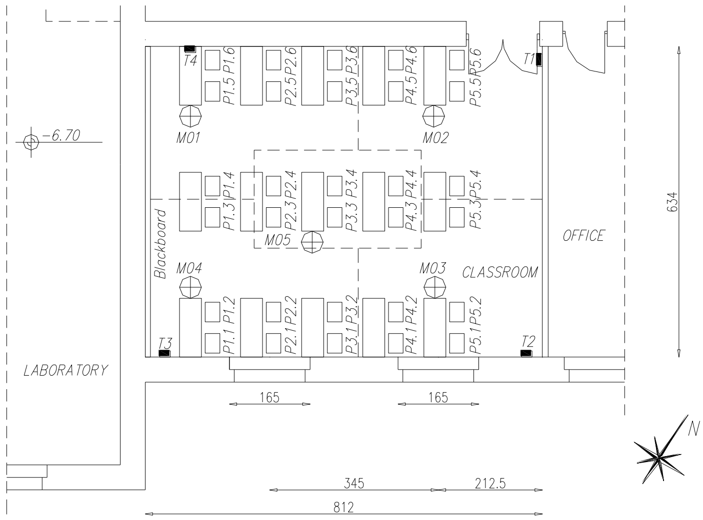


Fig.2 Observed classroom with labeled seats and five-section division

2.2. Statistical survey characteristics and protocol

The subjective evaluation regarding thermal comfort, IAQ and student productivity in the classroom was performed using two types of questionnaire. The first type was developed based on ISO EN 10551[20] recommendations, but designed especially for this research. This type of questionnaire was named as general, concerning the questions divided into three sections. The first part relates to general information about the student, his overall health conditions and clothes; the second part refers to the overall and local thermal comfort conditions in the classroom, correlated with the impact on productivity loss; and the third part includes questions about IAQ in correlation to the impact on student health and productivity. The second type of questionnaire was designed in the form of different texts with similar information regarding world wonders, biology or history, which are very different subjects to the usual fields of study in mechanical engineering, and are considered not widely known. These texts were read to students each day directly after the relevant number of classes, during an observed investigation period over four weeks. After the reading, the students were given the tests with five questions from the text that had been read. In this manner, student productivity and concentration were tested each day in four scenarios. The interesting nature of the texts, compared to the much more difficult learning material, was one of the difficulties for evaluation of student productivity during the learning process in university classrooms. The respondents were university level students, predominantly male, age 20-25, healthy and in good physical shape. The average attire was typical winter clothing, such as: a sweater or jacket, t-shirt or shirt, trousers or jeans, socks, classic underwear, and sneakers or shoes. According to the ASHRAE Handbook – Fundamentals and ASHRAE Standard 55-2013 [21] and having in mind the winter conditions and students' descriptions through the questionnaires, the average value of clothing ensembles used through the entire dataset was 1.01 clo. For sedentary school activity, the typical recommended value for metabolic rate is 1.2 Met [21, 22].

3. Results and analysis

3.1. Measurement results

Measurements were performed for the temperature of black globe, the air velocity, air temperature, relative humidity and other relevant paramethers in every 5 minutes during whole day, than the period of time relevant for statistical survey was considered (never less than 90 minutes), and all results were averaged for each day, during the surveyed period, and then for each scenario, and also for each seating position. This approach was used due to a large portion of collected data and with avareness of investaigation performed "live", during on going semester, in realistic environmental conditions.

Outside temperature and humidity were measured through the entire research period, together with the indoor parameters. The results are shown in fig. 3. As can be seen, the highest outdoor temperatures were recorded during Scenario 1, when sunny periods were also recorded. The consequence of this was higher indoor temperatures in the classroom, even though the heating system was turned off.

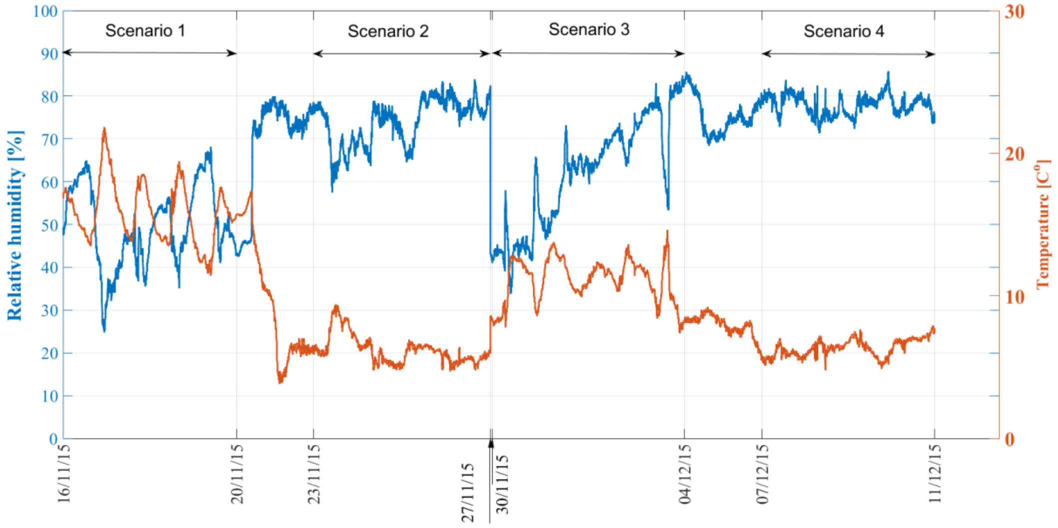


Fig. 3 Outside temperature and relative humidity during four scenarios [℃]

The radiant temperature in the classroom for the four scenarios was calculated using the physical parameter measurements in five easel positions, as shown in Figure 1. These positions were depicted as characteristic, due to the local impact of windows, external walls and additional electric heaters. A black globe probe, "Testo 445", with diameter D=150 mm was used. The measurements were performed every day over a four-week period. The radiant temperatures, as one of the most important parameters for thermal comfort, are presented in fig. 4. for the four scenarios.

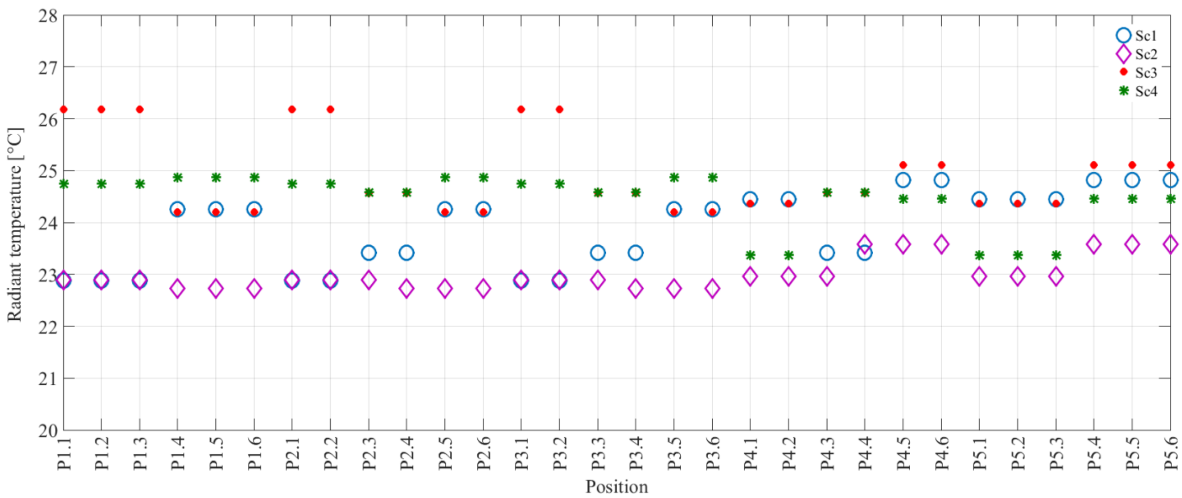


Fig. 4 Radiant temperature in classroom for four scenarios [℃]

The highest radiant temperature was noted in the third scenario, locally even higher than 26°C, while the second scenario came up with a radiant temperature of around 23°C. This three degrees Celsius causes almost one unit of change on the PMV scale, as was measured and shown in fig. 5. Furthermore, the difference between PPD indices in the third and second scenario (fig. 6) leads to an environment category change from "A" to "C", according to the ISO 7730 [19].

The calculation of PMV and PPD indexes were done for every 5 minutes, according to the measured values of temperature of the black globe, the air velocity, air temperature, relative humidity and other relevant paramethers, then results were averaged for the surveyd period each day, and then averaged for the scenario and shown for the each seating position (fig. 5 and 6). The easel position was changed each day in all scenarios, through the five sections in classroom, as it is shown on fig. 2 and the results were used for the students' positions in that section. The hudge portion of data was collected, and the idea was to correlate the measured data and the occupants' personal sensations. The statistical survey was performed once per day, due to the complexity of the experiment and the possibilities given by the faculty and with the respect to non-disturbing the lectures.

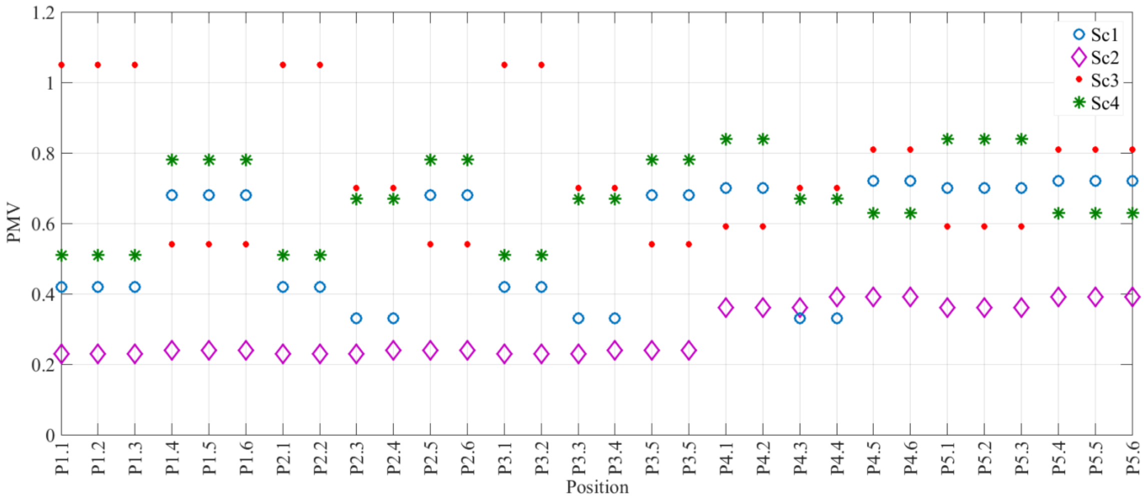


Fig. 5 PMV index measured for different seating positions in classroom

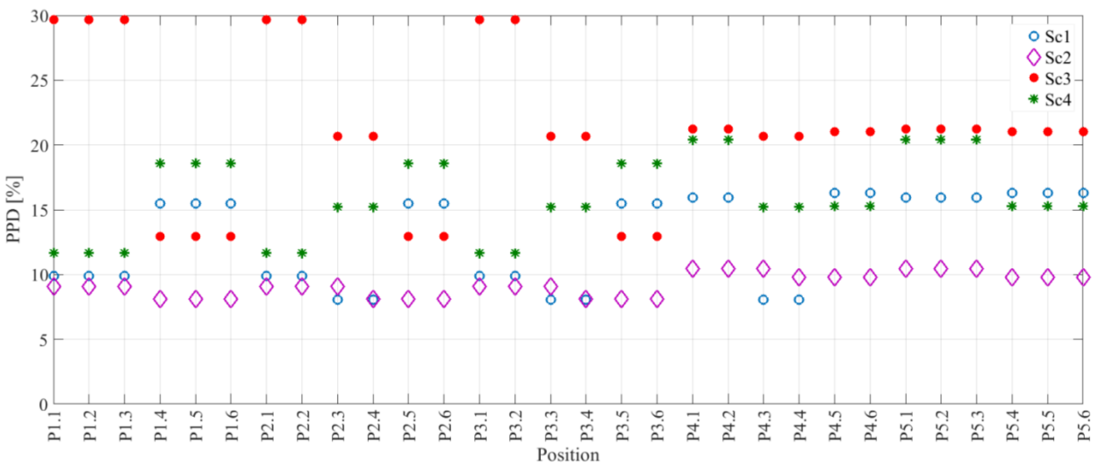


Fig. 6 PPD index measured for different seating positions in classroom

CO_2 concentration was measured in three spots, one outside of the building and two in the classroom. One position in the classroom was on the easel, carrying a black globe probe as well, as shown in fig. 2, and the second position was the control one, placed behind the students, behind positions P5.3 and P5.4. The local concentrations for each student position are given in fig. 7. Significantly higher concentrations were noted in the fourth scenario, compared to the others, in which the average value for the classroom exceeded 2000 ppm.

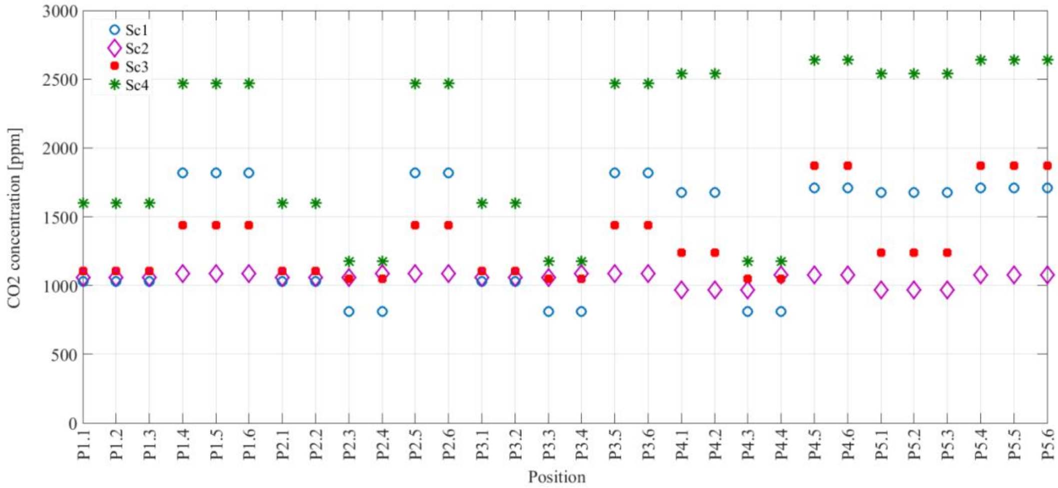


Fig. 7 CO_2 concentration locally for four scenarios

3.2. Statistical survey

3.2.1 Overall thermal comfort – subjective perception

The special contribution of this research is a new index, introduced for the first time, describing the quantitative subjective percentage of thermal comfort impact on students' concentration and productivity loss (referred to as TIP from now on). The index was introduced through the questionnaires and its' main purpouse is to express the percentage of the dissatisfaction of each occupant with the local conditions in the classroom. According to this it is possible to locate the positions of the highest local dissatisfaction. In this manner, it is possible to analyze the possible causes of the dissatisfaction and productivity loss localy. TIP is subjective evaluation rating and has values from 0% to 100%, where 0% indicates no impact of thermal comfort on productivity, and 100% represents total dissatisfaction with thermal comfort conditions and has a huge impact on productivity. It is used to evaluate personal perception of thermal comfort in indoor space. The impact of student dissatisfaction regarding thermal comfort on productivity is shown in fig. 8 to 11, for each day within the four scenarios.

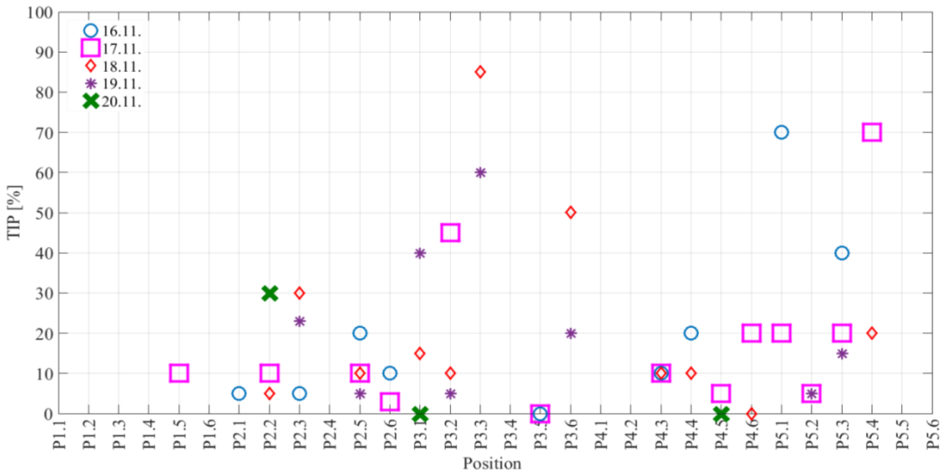


Fig. 8 Distribution of student votes regarding dissatisfaction in Scenario 1

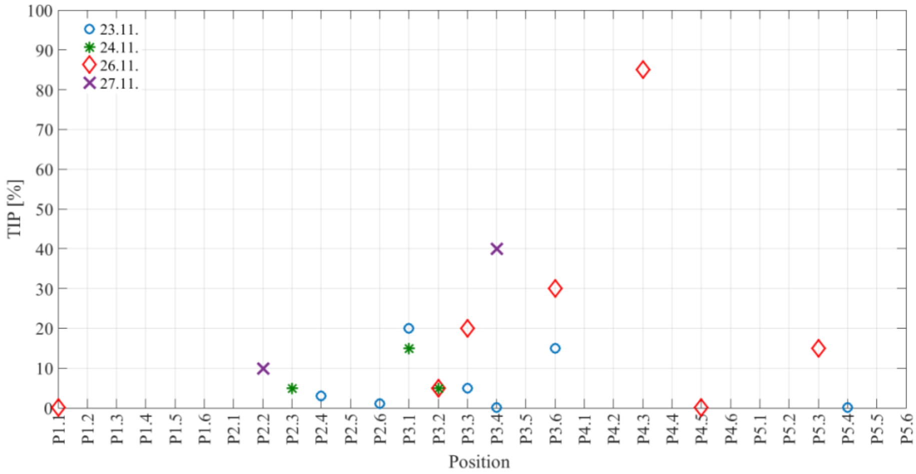


Fig. 9 Students' subjective dissatisfaction with thermal comfort in Scenario 2

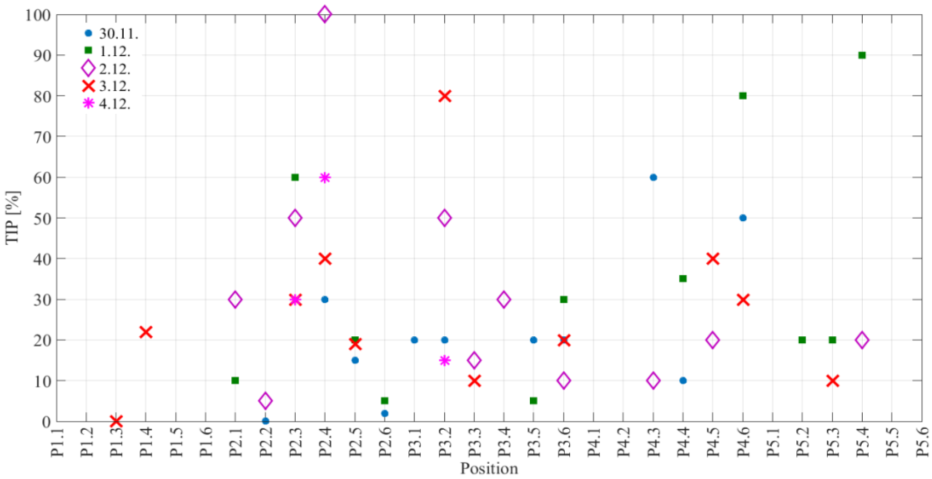


Fig. 10 Students' subjective dissatisfaction with thermal comfort in Scenario 3

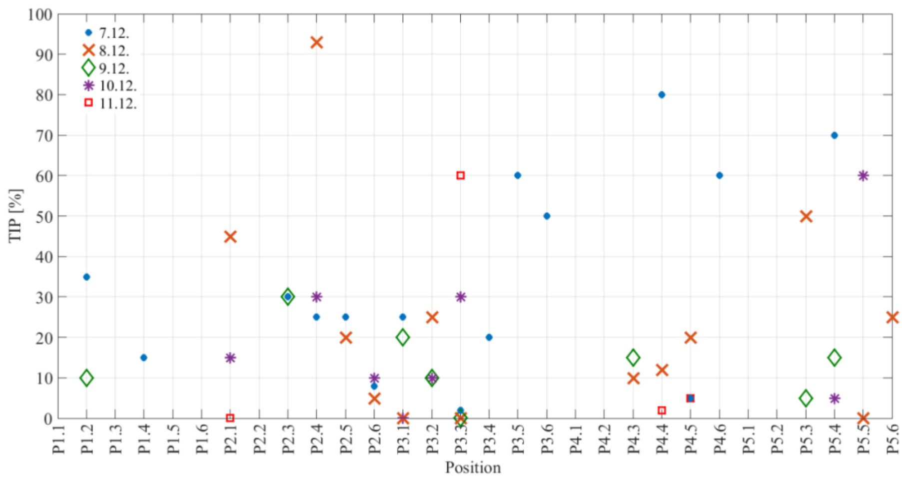


Fig. 11 Students' dissatisfaction with thermal comfort in Scenario 4

The highest dissatisfaction was noticed in the fourth scenario, when average TIP was around 27%, while in the second scenario, average TIP was evaluated as 14%. The results indicate that higher air temperatures and higher CO_2 concentrations cause higher dissatisfaction among occupants.

3.2.2 Local thermal comfort parameters – subjective evaluation

The second part of the research was conducted using the questionnaires. Students were asked to vote on the local thermal comfort parameters in the classroom each day, after the relevant hours spent in classroom (a minimum of two school classes). The questionnaires were created in accordance with EN ISO 10551[20], with additional questions designed to evaluate the impact of local thermal comfort on students' concentration, productivity and health.

3.2.2.1 Local discomfort caused by radiant asymmetry

In this part of questionnaires students' were asked to vote whether they were satisfied with radiant asymmetry in classroom and how many percent it could influence on their productivity. The results are presented in tab. 1. The biggest dissatisfaction was noted in third scenario, when more than 35% of students felt uncomfortable regarding radiant asymmetry, which affected around 17% on their productivity loss.

Table 1. PD caused by radiant asymmetry obtained from students' survey

Scenario	Number of votes	Unsatisfied	PD [%]	Impact on PLOS [%]
1	56	5	8.9	7
2	31	4	12.9	2.26
3	54	19	35.2	17.33
4	62	11	17.7	9.81

3.2.2.2 Local discomfort caused by vertical air temperature difference

The vertical air temperature difference was surveyed by asking if students felt the air temperature difference around their ankles, legs, belly, hands or head. They were then asked whether they were satisfied, and at what percentage the air temperature difference affected their productivity. As shown in tab. 2, the greatest influence was noticed in the third scenario, when almost 40% of students felt dissatisfaction. In this scenario, when both the radiators and additional electrical heaters were turned on, the average measured vertical air temperature difference between ankles and head level was around 2.5°C. According to the ISO 7730 standard, this result indicates that the environment belongs to the "B" category [19].

Table 2. Percentage dissatisfied with vertical air temperature difference and subjective evaluation of personal productivity loss

Scenario	Number of votes	Unsatisfied	PD [%]	Impact on PLOS [%]
1	56	9	16.1	5.7
2	31	4	12.9	4.4
3	54	21	38.9	15.2
4	62	19	30.6	14.3

3.2.2.3 Local discomfort caused by cold floor

Satisfaction with floor temperatures was evaluated through part of the questionnaire regarding the students' sensitivity towards floor temperatures (cold or hot) and its impact on productivity loss. The floor temperature was measured each day using a hand held infrared piston ”Testo 830-T2”. The measurements were performed in five characteristic spots on the floor: near the corners and in the middle of the classroom, and were averaged for each scenario, as shown in tab. 3. The percentage dissatisfied with floor temperature PD_{floor} was calculated according to the measured values and suggestions given in standard ISO 7730. The results are compared with answers from the student survey and the conclusions were remarkable: it is possible to have 0% of dissatisfied people with some of the local comfort parameters if all other thermal comfort parameters are in anacceptable range. This conclusion was drawn for the second scenario, where the average operative temperature was 23.10°C, average relative humidity 35%, average measured CO_2 concentration in classroom around 1000 ppm and average PMV index 0.29, while calculated PPD was around 9%. This is a very important observation, bearing in mind the suggestion from standard ISO 7730 that the minimal percent of dissatisfied is 5%. This implies that the equation suggested in standard ISO 7730 could be reconsidered in order to have more realistic data. The results of the study showed that occupants were satisfied with the floor temperature when all other relevant comfort paramethers were satisfied.

The measured floor temperatures were around the same in all scenarios, but occupants correlated the feeling of dissatisfaction regarding other parameters with the floor temperature, which is clearly visible when compared to the results from tab. 3. Due to the similar temperatures during the four weeks, this local comfort parameter can be considered as not influential on student productivity in the observed classroom.

Table 3. Percentage dissatisfied calculated by ISO 7730 and evaluated by students

Scenario	t_{floor} [°C]	PD_{floor} [%]	PD_{fl} (Q) [%]
1	22.36	5.85	1.8
2	21.55	6.48	0
3	21.98	6.11	9.3
4	21.64	6.39	9.7

3.2.2.4 Local discomfort caused by draught

The local mean air velocity was measured in three spots in the classroom. In the first and second scenarios, the hot wire probe and turbulent probe were placed on two window opening gaps. The third probe was placed on an easel next to the black globe probe and was moved during the week, using the pattern M01 to M05 from fig. 2. In the third and fourth scenarios, the hot wire and turbulent probe were placed 0.5m in front of the electrical heaters, right between the heaters and the students' back. According to the measurements, the average air velocities were lower than 0.05 m/s, except in the second scenario, when average air velocity was around 0.10 m/s. These values of air velocities indicated a negligible air movement in classroom, keeping in mind that this was a naturally ventilated type of building with double-glazed windows, with air space between the first and second window frames (fig. 1.).

Looking at tab. 4., it is very interesting to note that the students evaluated the draught intensity as 0% in the second scenario, when the actual measured air velocity was double that of other scenarios.

Table 4. Draught intensity evaluated by students

Scenario	Sensitive [%]	Total votes	Draught intensity [%]
1	37	51	0.7
2	39	31	0
3	40	53	3.2
4	32	62	0.6

The highest evaluated draught intensity was noticed in the third scenario, but actual measured mean air velocity for third scenario averaged the lowest at 0.03 m/s. These results strongly identify the subjectivity of occupants' personal feelings regarding thermal comfort in buildings.

3.2.3 Students' productivity evaluation

Student productivity was tested every day, as previously described in section 2.2. The test results were observed individually and grouped in five sections, as the measuring results and findings turned out to be different than expected. So far, published theoretical studies, such as the investigation of Kosonen and Tan [16],about productivity loss in air-conditioned office buildings correlates only PMV index and productivity loss. Looking at the productivity test results (fig. 12.) in correlation with measured PMV indices for every scenario, divided into classroom sections, it is strongly visible that there is no strictly clear connection between these two parameters alone. The results are shown in fig. 13.

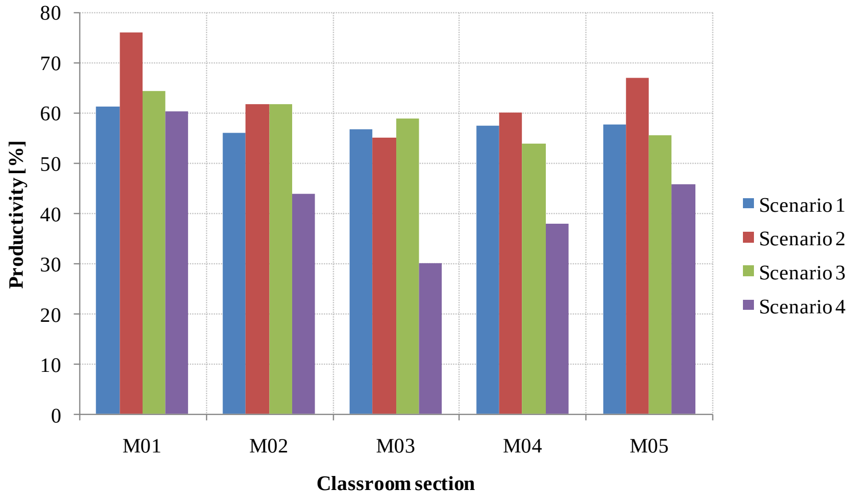
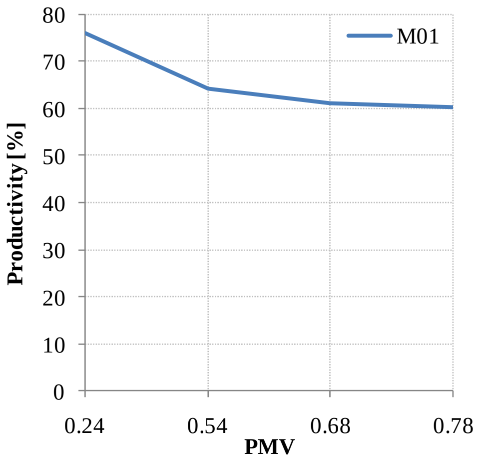


Fig. 12 Students' productivity in five sections of the classroom for all scenarios

a)



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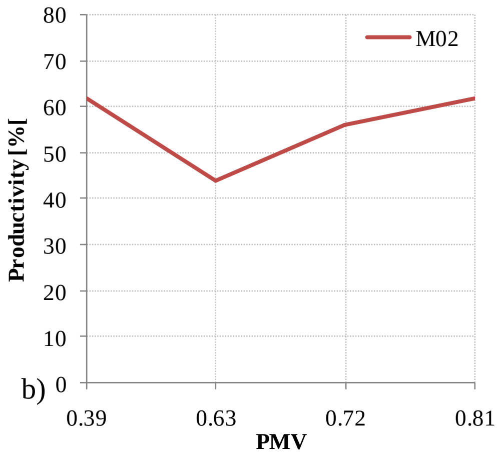

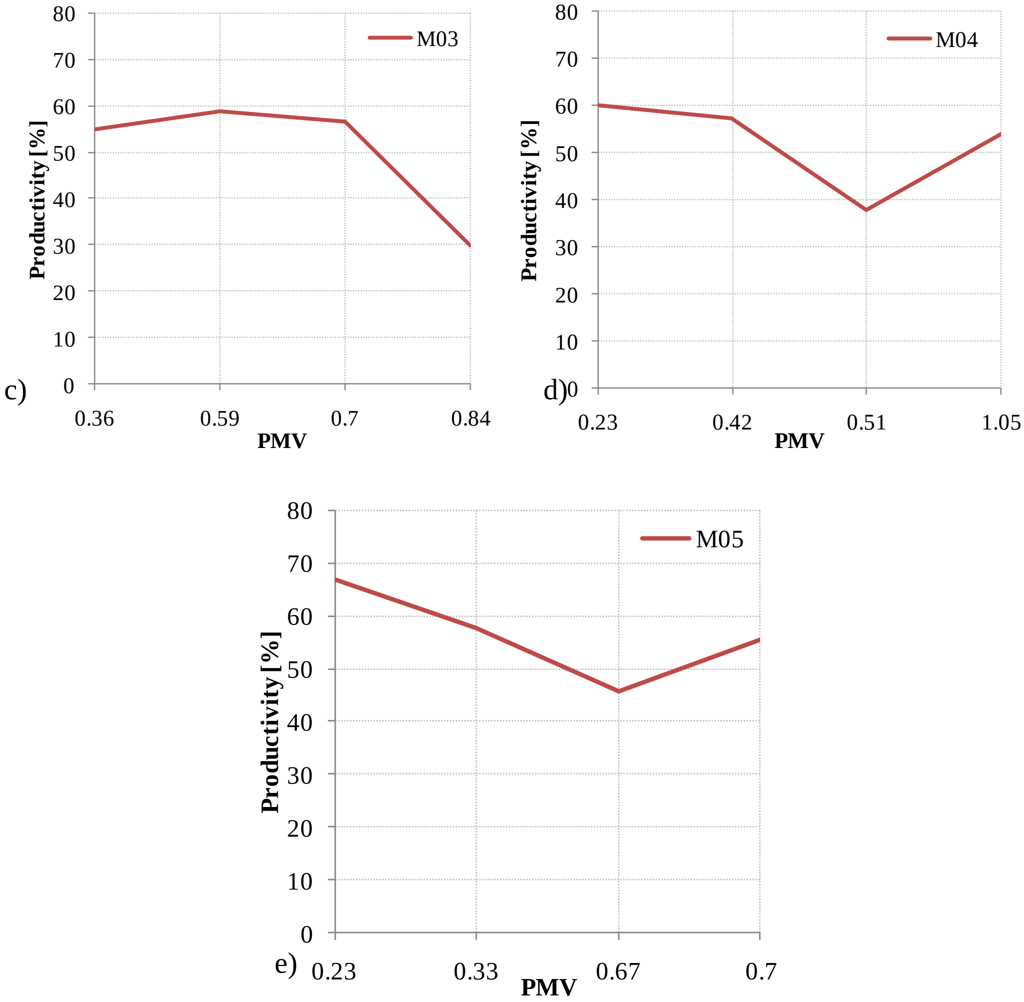

Fig. 13 Productivity as a function of measured PMV indices in different classroom sections for four scenarios a) Section M01 b) Section M02 c) Section M03 d) Section M04 and e) Section M05

The productivity loss equations published so far are a function of just the PMV index [16, 23], or thermal sensation votes [24]. Available data in the literature regarding the possible methods for productivity loss calculations are limited, and based on assumptions and research performed in experimental conditions on a relatively small number of volunteers. This investigation demonstrated that productivity and productivity loss are not just a function of PMV index. The correlations are shown in fig.12. There is no simple relation in real conditions that can link productivity with PMV index alone. The surveys were conducted for 19 days in different conditions of thermal environments, during lectures in a real classroom on a sample of 240 productivity test results in total. Only in M01 section of the classroom was the productivity as expected: lower when PMV increased. It interesting that this was the part of the classroom where the students with the best marks in university subjects were seated. In other parts of the classroom, the productivity was changed unexpectedly. The lowest productivity (fig. 11.) was noticed in the fourth scenario, when PMV indices were not the highest, but when CO_2 concentration was. Additionally, differences in productivity results were notable even though the PMV indices had almost the same value.

These conclusions led to a novel relation between productivity, CO_2 concentration and personal factors, combined together as follows:

$$\text{productivity} = f(PMV, CO_2, C_{pers}) \quad (1)$$

Novel parameter C_{pers} was introduced in order to highlight the personal impacts, such as the physical and psychological state of occupants, which unequivocally exist and change together with a person's daily biorhythm. This parameter is the most difficult for the evaluation, due to its individual and transient character.

A novel equation was developed using multiple regression analysis, according to the measured data for PMV in the classroom, CO_2 concentrations and productivity tests during 19 days, using 240 test results in this period. The suggested equation showed good agreement (the relative error is lower than, or equal 20% for 70% of the test results) with productivity test measurements. The obtained equation is as follows:

$$z = a + b \cdot x + c \cdot x^2 + d \cdot x^3 + e \cdot x^4 + f \cdot x^5 + g \cdot y + h \cdot y^2 + i \cdot y^3 + j \cdot y^4 + k \cdot y^5 \quad (2)$$

where z stands for productivity, x for PMV and y stands for CO_2 concentration; coefficients *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*, *i*, *j* and *k* are obtained using TableCurve 3D v4.0 software for curve fitting and have the values:

a = -358.808868, *b* = -10929.1291, *c* = 38910.35993, *d* = -64808.8852, *e* = 51070.70669,

f = -15370.0523, *g* = 5.747102797, *h* = -0.00788315, *i* = $5.04 \cdot 10^{-6}$, *j* = $-1.51 \cdot 10^{-9}$, *k* = $1.72 \cdot 10^{-13}$.

The novel equation, suggested in form (2), more realistically approaches the problem, as it also considers high CO_2 concentration in the classroom, which is marked as one of the key environmental parameters of productivity loss. A weakness of this model is the difficulty surrounding the personal factor C_{pers} prediction, and generalization of it in a global model equation for overall productivity.

4. Conclusions

A local instead of overall approach provides the opportunity to distinguish the reasons for higher productivity loss locally, in part of a classroom with more unfavorable thermal comfort conditions. Local thermal comfort parameters could be one of the most important causes of productivity loss, but not the only one or the most influential. IAQ is also a very important factor concerning productivity loss, but one of the biggest influences is certainly the personal factor, hiding the individual psychological and physiological state of occupants.

The personal influence of each student is strongly visible in the test results, but very difficult to precisely quantify and express mathematically, and due to this, was excluded from the equation. Asuggestion for future work would be to consider the personal factor through the variable $C_{pers,}$ which could be developed through the input tests used as an etalon for measuring the learning availabilities of each person, together with medical and neurobehavioral research.

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