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THE LOCAL THERMAL COMFORT IMPACT ON WORKING PRODUCTIVITY LOSS IN NON-RESIDENTIAL BUILDINGS

Doctoral Dissertation

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Тамара С. Бајц

УТИЦАЈ ЛОКАЛНОГ СТАЊА ТОПЛОТНОГ КОМФОРА НА СМАЊЕЊЕ РАДНЕ СПОСОБНОСТИ У НЕСТАМБЕНИМ ЗГРАДАМА

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Београд, 2017. Аутор

Тамара С. Бајц, дипл. инж. маш.

THE LOCAL THERMAL COMFORT IMPACT ON WORKING PRODUCTIVITY LOSS IN NON-RESIDENTIAL BUILDINGS

Abstract

The dissertation is dedicated to the local thermal discomfort impact on occupants' productivity loss. The research was performed in real classroom, during the winter semester, for moderate climate conditions, involving voluntaries, students of the Mechanical engineering Faculty of Belgrade. The measurement had been performed for four weeks, on the different circumstances of thermal comfort conditions which had been provoked using four different scenarios and various methods. The local thermal discomfort is valuated using three scientific methods: experimental, statistical and numerical research. The improved methodology for measuring the physical parameters of the environment in real conditions was introduced. The local thermal discomfort is investigated using the key parameters: floor temperature, radiant asymmetry, vertical air difference and draught intensity. The student' skin temperature measurements are also presented, together with the results of thermal imaging camera recording used as a control method.

The various statistical surveys were performed and valuable data regarding occupants' thermal sensations and impact of local thermal comfort on working performances have been discussed. The statistical survey was conducted on young adult population, age between 20 and 25, predominantly male and healthy. The novel questionnaires had been developed, with special reference to the questions regarding local thermal comfort and occupants' productivity loss. The productivity of the students was evaluated using the novel questionnaires and concentration test developed especially for this purpose. The productivity results were gathered based on 240 tests that had been performed.

In numerical part of the survey, the novel models were developed and physical parameters were simulated using the commercial software for Computational Fluid Dynamics. The results were gathered for every point within the classroom model. These simulations can be used in a lack of measuring possibilities in similar types of buildings.

The evaluation of the local thermal comfort parameters was performed through the amalgamation of measurements, statistical and numerical results. All results have been synthesized and novel relations were derived, as an additional tool for engineers, helping in integrated building design phase. The new correlation relations between local thermal comfort indicators and the level of occupants' productivity were developed, so as the new correlation between the productivity and novel index "TIP" for the subjective quantification of the impact of thermal comfort on occupants' productivity loss.

The research findings are that the impact of personal factor is of a tremendous importance concerning the productivity in classrooms. The impact of local thermal discomfort is significant, but lower than the personal factor. The third dominant factor is also carbon dioxide concentration, which significantly contributes to the productivity loss in classrooms, when it is higher than recommended. So far known relations correlate only PMV index with productivity loss. Through this research, novel TIP index is developed, representing the students' personal evaluation of thermal environment impact on working productivity and concentration loss. The adopted recommendation of 5% dissatisfied was reconsidered and using the statistical survey, it was proven through this research that it is possible to have 0% of dissatisfied (obtained for percent dissatisfied with floor temperature, for overall PMV in classroom 0.29), concerning the some of the local thermal comfort parameters. The local approach instead of overall, for whole classroom, helps in distinguishing the higher productivity loss locally, in certain part of the observed space.

Key words: thermal comfort, local thermal discomfort, PMV, PPD, productivity loss, CFD simulations, productivity tests, indoor environmental quality, thermal imaging, skin temperature measurements

Scientific field: Mechanical engineering

Scientific sub-filed: Thermomechanics, Thermal science engineering

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УТИЦАЈ ЛОКАЛНОГ СТАЊА ТОПЛОТНОГ КОМФОРА НА СМАЊЕЊЕ РАДНЕ СПОСОБНОСТИ У НЕСТАМБЕНИМ ЗГРАДАМА

Резиме

Дисертација обухвата разматрање утицаја стања локалног топлотног дискомфора на смањење продуктивности корисника простора. Истраживање је спроведено у реалним условима, у учионици, у току зимског семестра, за умерено-континенталне климатске услове, укључујући добровољно учешће студената Машинског факултета Универзитета у Београду. Мерења су вршена током четири недеље, у различитим условима топлотног комфора, који је вариран у четири различита сценарија, коришћењем више метода. Локални топлотни дискомфор је оцењен анализом резулатата који су добијени коришћењем три научне методе истраживања: експерименталне, статистичке и нумеричке методе истраживања. Унапређена је методологија мерења физичких параметара унутрашње средине у реалним условима. Локални топлотни дискомфор је разматран на основу анализе више кључних параметара, као што су: температура пода, радијантна асиметрија, вертикална температурска разлика и интензитет промаје. Резултати мерења температуре површине коже студената и снимци термовизијском камером, који су коришћени као контролно мерење, су такође презентовани у раду.

Различите статистичке анализе су спроведене и значајни подаци о утисцима корисника о утицају локалног топлотног комфора на смањење радне способности су разматрани. Статистичко истраживање је извршено на претежно мушкој, здравој популацији, која обухвата младе, одрасле људе, старости између 20 и 25 година. Нови упитници су развијени, са посебном пажњом усмереном на питања о локалном топлотном комфору и утицају на радну способност корисника. Продуктивност корисника је оцењена помоћу нових упитника и тестова концентрације који су развијени у оквиру истраживања. Резултати продуктивности корисника су обрађени на основу 240 тестова који су спроведени.

У оквиру нумеричког дела истраживања, развијени су нови модели и извршене су симулације помоћу комерцијалног софтвера за нумеричку механику флуида. Резултати су добијени за све тачке у оквиру посматране запремине. Овакве симулације се могу користити у недостатку могућности за спровођење мерења у зградама сличне типологије и намене.

Евалуација параметара локалног топлотног комфора је извршења синтезом измерених, статистичких и нумеричких резултата. Сви резултати су обједињени и нове релације су изведене, као помоћно средство инжењерима у фази интегралног пројектовања зграда. Нови корелациони изрази између индикатора локалног топлотног комфора и нивоа радне способности су развијени, као и нова зависност између продуктивности корисника и новоуведеног индекса „TIP“, који служи за процентуалну, субјективну квантификацију утицаја топлотног комфора на губитак продуктивности корисника.

Најважнији закључци истраживања су да је утицај личног фактора од изузетног значаја за продуктивност у учионицама. Утицај локалног стања топлотног дискомфора је значајан, али мањи од личног фактора. Трећи доминантни фактор је концентрација угљен-диоксида, која значајно доприноси смањењу радне способности у учионицама, ако је виша од препоручене вредности. До сада публиковане релације повезују само PMV индекс и смањење радне способности. У оквиру овог истраживања, уведен је нови ТИП индекс који описује личну оцену утицаја топлотне средине на радну способност и губитак концентрације. Усвојена препорука од 5% незадовољних је преиспитана кроз статистичку анализу и показано је да је могуће да постоји 0% незадовољних (добијено за проценат незадовољних температуром пода, при просечном PMV у учионици од 0.29), узимајући у обзир одређене параметре топлотног комфора. Локални приступ уместо генерализованог за читаву учионицу, помаже при дефинисању већих губитака радне способности локално, у одређеним деловима посматраног простора.

Кључне речи: топлотни комфор, локални топлотни дискомфор, PMV, PPD, губитак радне способности, CFD симулације, тестови продуктивности, квалитет унутрашње средине, снимање термовизијском камером, мерење температуре коже

Научна област: Машинство

Ужа научна област: Термомеханика, Термотехника

УДК број: 697.1:536.24:620.9(043.3)

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NOMENCLATURE

u	Air velocity component in x-direction, [m/s]
υ	Air velocity component in y-direction, [m/s]
w	Air velocity component in z-direction, [m/s]
t_a	Ambient air temperature, [°C]
M	Average metabolic rate for the work cycle, [W/m^2]
P	Averaged air pressure, [Pa]
t_g	Black globe temperature, [°C]
$E_b(T)$	Blackbody emissive power, [W/m^2]
G_k	Buoyancy production of turbulent kinetic energy
CO_2	Carbon dioxide concentration, [ppm]
ℓ	Characteristic turbulent length
I_{cl}	Clothing insulation, [m^{2}K/W]
f_{cl}	Clothing surface factor, [-]
t_{cl}	Clothing surface temperature, [°C]
F_{cl}	Clothing thermal efficiency, [-]
C	Convective heat loss, [W/m^2]
h_c	Convective heat transfer coefficient, [W/m^{2}K]
h_c	Convective heat transfer coefficient, [W/m^{2}K]
n	Design value of the number of persons in the room
t_i	Duration of i-activity, [min]
T	Duration of the work cycle, [min]
W	Effective mechanical power, [W/m^2]
$C_{\varepsilon 1}, C_{\varepsilon 2}, C_{\mu}$	Empirical constant for turbulent model
E_{sk}	Evaporative heat loss from skin, [W/m^2]
h_e	Evaporative heat transfer coefficient, [W/m^{2}K]
$R_{e,cl}$	Evaporative heat transfer resistance of clothing layer, [m^{2}kPa /W]
A	Floor area, [m^2]
t_f	Floor temperature, [°C]
L_{GAP}	Gap between nearby solid wall

q	Hit rate
R	Ideal (universal) gas constant for air, [J/kgK]
U_i	Vector of averaged air velocity (i=1,2,3), [m/s]
LR	Lewis ratio, [K/kPa]
h_r	Linear radiative heat transfer coefficient, [W/m^{2}K]
$t_{a,l}$	Local air temperature, [°C]
$\bar{v}_{a,l}$	Local mean air velocity, [m/s]
T_u	Local turbulence intensity
$\overline{t_r}$	Mean radiant temperature, [°C]
M_i	Metabolic rate for the *i*-activity, [W/m^2]
t_o	Operative temperature, [°C]
Pr	Prandtl number
Δt_{pr}	Radiant asymmetry temperature, [°C]
q	Radiation flux, [W/m2]
S_{rad}	Radiative heat flux
v_{ar}	Relative air velocity, [m/s]
RH	Relative humidity, [%]
s'	Scattering coefficient
P_k	Shear production of turbulent kinetic energy
t_{sk}	Skin surface temperature, [°C]
w	Skin wittedness, [-]
$\overline{u_i u_j}$	Symmetrical tensor of Reynolds turbulent stress.
T	Temperature, [K]
$\Delta t_{a,v}$	Temperature difference between the head and ankles, [°C]
R_{cl}	Thermal resistance of clothed body or clothing, [m^{2}K /W]
d	Thickness, [cm]
q_{tot}	Total ventilation rate, [l/s]
k	Turbulence kinetic energy
$\overline{\theta u_i}$	Turbulent heat flux vector
U	U-value, [W/m^{2}K]

g_i	Vector of gravity force, [m/s^2]
q_B	Ventilation rate for emission from building, [l/s/m^2]
q_p	Ventilation rate for occupancy per person, [l/s/pers]
p_a	Water vapor partial pressure, [Pa]
$p_{sk,s}$	Water vapor pressure at skin, [Pa]

Greek symbols

ρ	Air density, [kg/m^3]
β	Coefficient of air thermal expansion
ε	Dissipation rate
λ_{eff}	Effective thermal conductivity
ε'	Emissivity per unit length
$\sigma_k, \sigma_\varepsilon$	Empirical constant for turbulent model
δ_{ij}	Kronecker delta
ν	Molecular kinematic air viscosity, [m^2/s]
ρ_{ref}	Referent value of averaged air density, [kg/m^3]
σ	Stefan-Boltzmann constant, [W/m^{2}K^4]
λ	Thermal conductivity, [W/mK]
λ_{rad}	Thermal conductivity expressed in terms of radiant temperature, [W/mK]
ν_t	Turbulent kinematic air viscosity, [m^2/s]
σ_t	Turbulent Schmidt number

Abbreviations

ATC	Adaptive thermal comfort model
BRI	Building Related Illness
CFD	Computational Fluid Dynamics
CNTE	Can't be estimated
DR	Percent dissatisfied with draught, [%]
EPA	Environmental Protection Agency
EU	European Union
HVAC	Heating, ventilation and air-conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
PD	Percent dissatisfied, [%]
PLOS	Productivity loss, [%]
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
RTC	Rational thermal comfort model
SBS	Sick Building Syndrome
TIP	Quantitative subjective percentage of thermal comfort impact on students' concentration and productivity loss
TSV	Thermal sensation vote
WHO	World Health Organization

CHAPTER 1

"Everyone can reach his goals, if he is able to think,

if he is able to wait, if he is able to fast."

Hermann Hesse, Siddhartha

"Свако може да постигне свој циљ, ако уме да мисли,

ако уме да чека, ако уме да пости."

Херман Хесе, Сидарта

1. INTRODUCTION

1.1. Previous literature data analysis about the thesis subject

The literature information analysis, before the thesis subject determination, was based previously on the review of the different publications (papers, books, standards, etc), published by the current professional and scientific community, European and domestic organizations and institutions such as European commission, World health organization, national and international legislations and a great number of papers published in national and international journals.

Based on the analysis, the main conclusion is that the sustainable development and healthy, energy efficient building are not just in a main focus, but they represent the ultimate demand in future scientific progress, having in mind implementation of the results in practice, which would lead to the improvement of working conditions, decreasing the risk of health problems, decreasing green house gasses emission, and increasing energy savings. Further, in 2011, the Republic of Serbia adopted new legislation on the energy efficiency certification of buildings [1, 2]. This introduced new requirements which demand proof of adequate levels of thermal comfort in buildings by designing and conducting energy efficiency reports.

The most important conclusions from the literature survey about this subject can be summarized as follows:

1. Previous researches indicate that thermal discomfort can reduce the working performance for about 5 to 15 % [3, 4].
2. According to the results of 24 research studies on the air temperature impact on working productivity in offices [5], it is suggested that the working productivity is decreased 1% for every 1% temperature reduction regarding to the temperature for which is reached the equilibrium between the human body and the environment.
3. Looking at the thermal comfort in school classrooms, the study on the productivity of pupils, aged 10 and 12, implies that the decrease in temperature from 24-25 °C to 20°C can improve talkative and calculative performance for about 2 to 4 % [6].
4. It is important to emphasize that those results are based on the experiments that were performed in laboratories and do not include the results obtained from occupants' personal validation of performances.
5. There are attempts to correlate a thermal discomfort with working performance reduction trough the PMV and PPD indexes, but there are not studies that experimentally confirm this relation [7, 8].

Exactly those facts, that there are no experimental correlations between thermal comfort indicators and working productivity loss, indicate a possibility of novel approach and strong scientific contribution of this doctoral thesis.

1.2. The subject of the study

The subject of the study is directly connected to the sustainable development. The main principle of the sustainable development is energy efficiency of the building, but not just in the meaning of energy savings and energy consumption reduction, but in the meaning of minimizing the energy consumption while providing the desirable indoor environment for occupants. The second part of the definition of sustainable development takes into consideration not just a thermal comfort acquirement, but also indoor air quality impact on occupants' health and working performance. In accordance with this definition, it can be concluded that it is possible to discuss about the energy efficiency in buildings only when the targets regarding indoor environmental quality (IEQ) and minimized health risks are reached.

IEQ considers the reached level (category) of thermal, air, light, sound and aesthetical comfort. This thesis especially takes into consideration the thermal comfort.

Having in mind that the subjective thermal sensations are investigated, it is important to know the impact of the cognitive, physiological and physical processes that represents the background of the sensations. The fundamentals of heat transfer are used for describing the mechanism of sensible and latent heat transfer from the environment to the human, and the opposite way. According to this comprehensive approach in thermal comfort definition, the generally accepted indicators for thermal comfort validation are Predicted Percentage Dissatisfied (PPD) and Predicted Mean Vote (PMV), which are expressed trough the thermal sensation scale from -3 (very cold) to +3 (very hot) in accordance with ISO 7730:2005 [9]. Thermal comfort indexes PMV and PPD, together with the operative temperature, belong to the category of general, integral indicators defined as unique values for entire indoor space.

It is important to emphasize the main characteristic of PMV and PPD indexes, which represents the main motivation for this research: when the value PMV=0, and the total heat balance between the human body and the environment is reached, the Predicted Percentage Dissatisfied has a value PPD=5, in other words, 5% of the population is not satisfied with thermal comfort. The question is why 5% of the population is dissatisfied. Is this the consequence of the physiological characteristics of the individual, or the consequence of the physical state of the environment, expressed through non-uniform distribution of the crucial parameters (air temperature, radiant temperature, relative humidity, air velocity and turbulence intensity)? It is obvious that both factors have an impact on value PPD=5. The standard methodology considers the "standard person", but the problem of the impact of local environment's physical parameters values on the percentage of people dissatisfied is emphasized.

The goal of this research is to quantify the impact of local indoor environment parameters (air temperature, radiant temperature, relative humidity, air velocity and turbulence intensity) on the level of thermal comfort of non-residential buildings.

Looking at the local PPD values, it is necessary to obtain additional indicators that take into a consideration the local physical characteristics of the environment. The local thermal comfort indicators are also expressed through the percentage of dissatisfied taken on basis of the scales that presents the local characteristics of draft, radiant asymmetry, vertical temperature profile and floor temperature.

Also, according to the sustainable development definition and healthy building concept, the significant part of the research is dedicated to the derivation of correlation between the local thermal comfort indicators and the percentage of the working productivity loss.

Opposite to the single family houses, the public spaces, in which there are a significant number of occupants, are typical buildings in which non-uniform distribution of thermal comfort indicators is present.

Those typical examples are educational institutions (classrooms, amphitheaters, laboratories), health institutions (hospital rooms for several number of occupants), cultural and religious institutions (theatres, concert halls, churches), congress halls and restaurants, etc. Exactly these types of buildings are in the focus of this research.

1.3. The purpose of the research

The main goal of this dissertation is to quantify the impacts of local indoor environment parameters (air temperature, radiant temperature, relative humidity, air velocity and turbulence intensity) on the level of thermal comfort in the non-residential buildings.

A special purpose of this research is to derive the correlation between thermal comfort state of the environment and the working productivity loss. Furthermore, to do this in a way that provides the background for technical instructions and guidelines for the designers, in order to establish and maintain thermal comfort conditions into an integrated sustainable building design approach, already at the conceptual design phase of the building’s design.

1.4. The tasks of the research

The concrete tasks of this research were as follows:

1. To choose the appropriate building for the research.
2. To define the experimental investigation scope.
3. To define the experimental investigation program and measurement protocol.
4. To design questionnaires for the occupants' survey in situ, during the measurements.
5. To process the results of the experiments and the results of the surveys.
6. To define the mathematical model and numerical simulations.
7. To find the desired correlations using the comparative methods.
8. To define the technical instructions and guidelines for non-residential building design in a way of establishing the healthy building concept.

1.5. Basic assumptions

The basic assumption is that the local non-uniform distribution of physical environmental parameters (air temperature, radiant temperature, relative humidity, air velocity and turbulence intensity) has a great impact on the values of both general and local thermal comfort indicators and that it is directly correlated to the intensity of the occupants' working productivity loss.

1.6. The scientific research methods

In this dissertation the followed methods were used:

a) *Experimental methods*: In representative space, in defined periods of time, the measurements of air temperature, relative humidity, radiant temperature, air velocity and turbulence intensity in characteristic spots of the space were performed. These results were used in comparative analysis of non-uniform distribution of indoor environment physical parameters.

b) *Numerical methods*: The numerical simulations of the selected spaces, for defined scenarios were used for heat transfer model quantification and also to define the physical parameters of air in spots which were not covered by the measurements. According to the appropriate models for local thermal comfort determination, the possible working productivity loss intensity was obtained.

c) *Statistical methods*: During the measurements, the occupants' survey was performed in order to determine the subjective thermal sensations together with the results of working productivity loss. According to these results, the empirical correlations between thermal comfort indicators and intensity of the working productivity loss were obtained.

1.7. The structure of the dissertation

This dissertation is divided into eight chapters.

Chapter 1 is an introduction into the thesis subject, the details about the previous subject analysis, the purpose, goals and tasks of the research, the methods and basic assumptions that were used.

In Chapter 2, the literature analysis is presented, and the most important researches that have been published previously, which are connected to the scope of the dissertation, are discussed. As a base of the research, more than 570 documents were collected, sorted and the most influential ones were depicted. The impact of indoor environmental quality and thermal comfort on occupants' health and productivity is discussed.

Chapter 3 describes the literature analysis concerning the working productivity loss. This part of the survey is separated in an independent section having in mind the importance of the productivity loss on scope of the thesis.

In Chapter 4, the experimental investigation is presented, with detailed description of experiment methods, measuring equipment, the observed classroom and the results of physical parameters that were measured, calculated and discussed. Also, PMV, PPD indexes and productivity loss (PLOS in further) are presented for the observed classroom. The local thermal discomfort is discussed through the measurement of the key parameters: floor temperature, radiant asymmetry, vertical air difference and draught intensity. The students' skin surface temperature measurements are also presented, together with the results of the thermal imaging camera recording of the observed classroom's thermal envelope and the surface of users' clothing. The results obtained by the thermal imaging camera recording were used as a control measurement within each of the scenarios.

In Chapter 5, students' statistical survey is described and the most important results regarding the local thermal comfort and indoor environmental impacts on students' productivity are discussed. The students' subjective evaluation is presented and commented in correlation with measured thermal comfort parameters.

Chapter 6 provides the mathematical model and CFD simulation results for the observed classroom. The importance of CFD simulations for buildings in design phase of the project, as a valuable tool for thermal comfort prediction, is pointed out strongly through the results discussion and model validation. The model validation was performed using complex error validation methodology.

Chapter 7 represents the amalgamation of measuring, statistics and numerical results. The significant conclusions were pointed out and correlated through novel equations and relations that were developed in this research, as an additional tool for engineers and as a help in integrated building design phase.

Chapter 8 highlights the final conclusions and suggestions for future work.

CHAPTER 2

"It is a great strength in a man who is capable

to be silent even he has a right."

Leo Tolstoy

"Велика је снага у онога човека који уме

да прећути и када има право."

Лав Толстој

2. IEQ AND THERMAL COMFORT - LITERATURE REVIEW

According to US EPA Report to Congress, from the year 1989, people were spending approximately 93% of the time indoors [10]. This information directly brings up the question of an importance about the Indoor Environmental Quality (IEQ in further) and its impact on occupants' health. This field of research became one of the important ones in contemporary science branches about buildings, its design, sustainability and impact on global environmental issues. Having in mind the fact that the building sector is one of the biggest energy consumers, with a share of 26,8% in final energy consumption in EU-28 in 2013 [11], and that the costs of people in typical office buildings are 100 times higher than energy costs [12], it is essential to understand and implement the main principles of indoor environmental health at the very beginning of the building and HVAC systems design phase. The most generally accepted definition about health was constituted by 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." [13]. The IEQ observation has been increased dramatically in recent decades, as a result of increased complaining by occupants about the poor indoor air quality and two type of diseases have been identified since, such as Sick Building Syndrome (SBS) and Building-Related Illness (BRI) [13]. SBS defines a numerous health symptoms which are related to occupancy in sick buildings, such as: mucosal irritation, fatigue, headache, skin irritation, lower respiratory symptoms, nausea, etc, if the mentioned symptoms persist for more than two weeks. All these symptoms were classified by WHO into four groups [13]:

- Sensory irritation in the eyes, nose, or throat
- Skin irritation
- Neurotoxic symptoms
- Odor and taste complaints.

According to the various studies [14-18] that were performed, regarding risk of SBS in mechanically and naturally ventilated buildings, it is concluded that the occupants in buildings with mechanical HVAC systems have a bigger chance to get sick, compared to the occupants in naturally ventilated buildings or a mechanical ventilation systems without cooling [18]. Studies also showed the link between SBS and occupants' productivity [19, 20].

There are numerous studies and papers regarding IAQ and IEQ in naturally and mechanically ventilated buildings. Some of them are focused on occupants' health and productivity in connection with IEQ indicators, some on users' behavior and its impact on IAQ and energy consumption, the others describe the ranking of indoor comfort and gives a different methods and tools for the occupants' ratings and comfort predictions, some of them study ventilation rates and indoor airflow in a function of occupants and furniture, the others describes the impact of materials on users' health, and some give the relationship between the indoor air humidity, mold growth and risk of diseases. The impact of poor ventilation and thermal comfort conditions in winter season on occupants' health in non-residential buildings was investigated by Bajc et al. [21].

During the past ten years, the research concerning thermal comfort has been dramatically increased, with a peak in 2011, when almost 900 documents about thermal comfort were published [22].

According to Zomorodian et al. [23], there are two main approaches in thermal comfort modeling: rational (RTC) or static model [23] and adaptive (ATC) [24]. Rational model includes Fanger's PMV model [25] which gives decent results in comparison with actual mean vote of occupants in air-conditioned buildings, with passive occupants' behavior, such as the office buildings without openings, or schools in which the thermal preferences of teachers are dominant and in which pupils are not allowed to act in order to change the comfort level [23]. The other stream propagates the adaptive approach which observes the occupants as active participants in a creation of thermal environment. This approach was firstly proposed in the 1970s [26] and it takes into account the physiological, psychological and behavioral elements. The ATC model is based on external temperatures for comfort temperature prediction, and it could be rather inadequate for classrooms, where the occupants' actions are usually limited, according to Zomorodian et al. [23]. There are numerous studies about these two models and very nice review for the last five decades is given in [23].

The newest studies have observed the thermal comfort conditions in classrooms by measuring and also using the questionnaires for students. Almeida et al. [27] investigated the thermal comfort in classrooms in mild climate, in Portugal, on a sample of children aged 4 years up to the university students. The data from 10 educational spaces, with 32 measurements, using 490 questionnaires was collected. Stevanović [28, 29], measured the thermal comfort indices among children 8 and 9 years of age in primary school in Serbia and defined the turbulence models of air flow in school buildings. Alfano et al. [30] investigated the PMV and PPD indices in naturally ventilated classrooms, on a sample of more than 4000 students, between the ages of 11 and 18 years, in Southern Italy, both in summer and winter seasons. All schools were naturally ventilated, with operable windows. Martinez-Molina et al. [31] researched the post-occupancy sensations regarding thermal comfort in primary school in Spain, comparing the teachers' and pupils' thermal comfort subjective evaluation. The significant differences were noted in teachers' and pupils' thermal sensation votes. Wang et al. [32] also investigated the indoor environments in primary and secondary school classrooms. They conducted the research in China, in 36 classrooms, on sample of 1126 pupils, in winter conditions. The results showed that the pupils were less sensitive to temperature changes than it was expected. Trebilcook et al. [33] conducted a study on thermal comfort in 12 schools in Chile, in winter and spring. The pupils were 9 to 10 years old. The research pointed out the influential correlation between the thermal sensation votes and the socio-economic background of pupils, coming from socially vulnerable area of Santiago, who accepted the lower temperature as a comfortable in winter period. The published results showed that Fanger's approach for naturally ventilated buildings in warm climates gives a good agreement with the subjective votes if appropriate expectancy factor is implemented. Also, the percentage of dissatisfied was higher when the respondents were questioned directly about the acceptability, in comparison with the respondents who voted ±2 or ±3 [30].

According to Zomorodian et al. [23] the investigation of thermal comfort in University buildings in Europe was done only in Portugal in 2014 and in Italy in 2015, for mid-season and spring. The sample size consisted of 52 and 126 students respectively. In Portugal, a rational model was used, and in Italy, both the rational and adaptive ones. The important conclusion was that the Fanger's heat balance equation had to be revised having in mind the nature of its coefficient development and the limitation of the results obtained in limited experimental investigation [23]. The local thermal comfort conditions in classrooms have a big impact on productivity losses and are very much different in comparison to the average values. This kind of investigation hasn't been researched enough for the adults, university students' level, according to the available literature.

2.1. Standards regarding IEQ and thermal comfort

There are numerous standards regarding thermal comfort and indoor environmental parameters. The most important standards for this research are presented in this chapter.

2.1.1. ISO 7730:2005

International standard ISO 7730:2005 [9] determines the "methods for predicting thermal sensations and degree of discomfort of people exposed to moderate thermal environments". The scope considers healthy men and women exposed to a desirable thermal comfort, but with possible moderate deviations. The special attention should be taken into account regarding ethnic, national or geographical differences, having in mind different clothing, habits and climate characteristics. It describes the PMV and PPD as a function of the activity and clothing. The PPD and PMV indexes express warm and cold discomfort for the whole body. The limits for the light, mainly sedentary activity during the winter period are given in standard. The operative temperature would be between 20°C and 24°C. The vertical air temperature difference between head and ankle level would be less than 3°C. The relative humidity should be between 30 and 70% [9, 34].

2.1.2. ASHRAE Standard 55

This standard defines the thermal environmental conditions for human occupancy. It describes the metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, humidity and position of the measuring equipment. Operative temperature or PPD, PMV should be measured or calculated at a height of 0.6 m above the floor level for seated occupants and 1.1 m above the floor level for standing occupants [35].

2.1.3. SRPS EN 15251:2010

Basic criteria for indoor air quality and ventilation rates in non-residential buildings are given in SRPS EN 15251:2010, trough Method based on person and building component, Method based on ventilation rate per person or per square meter floor area and recommended values of carbon dioxide for energy calculation. This standard is identical to EN15251:2007 [36], and it is valid in Europe and also in Republic of Serbia, according to Institute for Standardization of Serbia. Recommended ventilation rates can be calculated, according to this standard, using the following equation:

$$q_{tot} = nq_p + Aq_B \tag{1}$$

where:
q_{tot} is total ventilation rate of the room [l/s],
n is design value for the number of the persons in the room,
q_p is ventilation rate for occupancy per person [l/s/pers]
A is room floor area [m^2]
q_B is ventilation rate for emission from building [l/s/m^2].

The ventilation rates for given occupants and building's emissions are given in the standard as a function of the building category. For category II, temperature range for heating is between 20 and 25°C, and recommended airflow per person is 7 l/s/pers and 0,7 l/s/m^2 for low polluting building. Expected percentage of dissatisfied is 20. Corresponding CO_2 above outdoors for energy calculation is 500 ppm for category II as it is given in standard [36].

2.1.4. ASHRAE Standard 62.1

Standard 62.1:2016 [37] gives ventilation criteria for acceptable IAQ when the mechanical ventilation system is designed. According to this standard, minimum ventilation outdoor air rate in breathing zone for office space per person is 2.5 l/s/pers, while the outdoor air rate per area is 0.3 l/s/m^2. Maximal allowed CO_2 concentration for offices, according to ASHRAE 62.1:2016 [37] is 700ppm higher than outdoor air level. Typical CO_2 concentration level in outdoor air is between 300 and 500 ppm, so maximal recommended CO_2 concentration for offices is from 1000 to 1200 ppm, but it should be emphasized that the CO_2 concentration level is not the only and the most representative criteria for IAQ. Besides this, Volatile Organic Compounds also has an influence on IAQ. It is important to emphasize that the allowed concentration should always be determined as the difference between indoor and outdoor concentration [37].

2.1.5. ISO 8996

ISO Standard 8996:2004 [38] specifies methods for determination of metabolic rate as a function of ergonomics of the thermal environment in different working climates. The standard determines the metabolic rate estimation in context of the task requirements from the following: the body segment involved into work, the workload from that part of the body, the body posture and the working speed. The overall metabolic rate for a work cycle can be calculated using equation [38]:

$$M = \frac{1}{T}\sum_{i=1}^{n} M_i t_i \quad , \tag{2}$$

where:

M is the average metabolic rate for the work cycle [W/m^2],

M_i is the metabolic rate for activity i [W/m^2],

t_i is the duration of i-activity [min],

T is the duration of the work cycle and represents the sum of the partial durations t_i [min].

According to this standard, metabolic rate can be estimated from the tables given in the standard, or using heart rate or oxygen consumption.

2.2. Thermal comfort indicators - literature review

Comfort has been defined as “that condition of mind that expresses satisfaction with the…environment” [39]. Thermal environment can be described with the following main physical parameters:

- Air temperature
- Mean radiant temperature
- Relative air speed
- Humidity.

Thermal comfort is also affected by the personal factors such as:

- Clothing and
- Metabolic heat production.

Besides these factors, it is also necessary that there is no local discomfort, at any part of the occupant’s body, that is caused by asymmetric thermal radiation, draughts, warm or cold floors, nor vertical air temperature differences [39]. Temperature is usually the most important parameter that affects thermal comfort. Change in temperature by three degrees affects the response on the thermal sensation scale (Table 1.) by about one scale unit for sedentary persons. The persons who are more active are less sensitive to the temperature change in the room.

Table 1. ASHRAE thermal sensation scale [39, 40]

Index value	Thermal sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The prediction of thermal comfort is usually expressed by using PMV and PPD as the indexes for thermal sensations. The human thermal sensation is usually related to the thermal balance of a whole body. This balance is affected by the personal parameters, such as the activity level and clothing, together with the parameters of the environment, such as mean radiant temperature, air temperature, air velocity and humidity. These parameters can be calculated or estimated by calculating PMV index. The thermal discomfort can be estimated by the PPD index, which can be obtained from PMV. Thermal discomfort can be caused by the local factors that affect comfort such as: draught, radiant temperature asymmetry, vertical air temperature difference and cold or warm floor.

By the definition given in standard ISO 7730:2005 [9], the PMV is “an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale”. This scale is given in Table 1. The PMV can be calculated using the following equations [9]:

$$PMV = [0.303 \cdot \exp(-0.036 \cdot M) + 0{,}028]\{(M-W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-W) - p_a] - 0.42 \cdot [(M-W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t_r} + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\}, \quad (3)$$

$$t_{cl} = 35.7 - 0.028 \cdot (M-W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t_r} + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\}, \quad (4)$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & \text{for values} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & \text{for } \; 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases} \quad (5)$$

$$f_{cl} = \begin{cases} 1.00 + 1.29 \cdot I_{cl} & \text{for } I_{cl} \le 0.078\ \mathrm{m^2K/W} \\ 1.05 + 0.645 \cdot I_{cl} & \text{for } I_{cl} > 0.078\ \mathrm{m^2K/W} \end{cases} \quad (6)$$

where

M is metabolic rate [W/m^2],

W is the effective mechanical power [W/m^2],

I_{cl} is the clothing insulation [m^{2}K/W],

f_{cl} is the clothing surface factor,

t_a is the air temperature [°C],

$\bar{t_r}$ is the mean radiant temperature [°C],

v_{ar} is the relative air velocity [m/s],

p_a is the water vapour partial pressure [Pa],

h_c is convective heat transfer coefficient [W/m^{2}K],

t_{cl} is the clothing surface temperature [°C].

In order to combine the effect of room air temperature and mean radiant temperature, the term "operative temperature" is enrolled. The equation describing operative temperature is as follows [39]:

$$t_o = \frac{h_c}{h_c + h_r} \cdot t_a + \left(1 - \frac{h_c}{h_c + h_r}\right) \cdot \overline{t_r}. \tag{7}$$

The mean radiant temperature for Testo Globe probe with diameter 15cm and emissivity 0.95, can be calculated using the equation for natural convection [41]:

$$\overline{t_r} = \left[\left(t_g + 273\right)^4 + 0.4 \cdot 10^8 \cdot \left|t_g - t_a\right|^{0.25} \cdot \left(t_g - t_a\right)\right]^{0.25} - 273. \tag{8}$$

The predicted percentage dissatisfied (PPD), by the ISO 7730:2005 standard definition, is "an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm". The PPD index is possible to calculate when the PMV index is already determined, by using the following equation [9]:

$$PPD = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2). \tag{9}$$

The distribution of individual thermal sensation votes, according to ISO 7730:2005 is given in Table 2.

Table 2. The distribution of individual thermal sensation votes and correlation between PMV and PPD indexes [9]

PMV	PPD	Persons predicted to vote [%]		
		0	-1 or +1	-2,-1,+1 or +2
+2	75	5	25	70
+1	25	30	75	95
+0.5	10	55	90	98
0	5	60	95	100
-0.5	10	55	90	98
-1	25	30	75	95
-2	75	5	25	70

According to ISO 7730:2005 standard, the PMV and PPD indexes and local discomfort describe the thermal environment categories and distribute it in three categories: A, B and C, as it is shown in Table 3.

Table 3. The thermal environment categories [9]

Category	Thermal comfort		Local discomfort			
	PPD [%]	PMV	DR[1] [%]	PD[2] with vertical air temp. diff. [%]	PD with warm or cool floor [%]	PD with radiant asymmetry [%]
A	< 6	-0.2<PMV<+0.2	< 10	< 3	< 10	< 5
B	< 10	-0.5<PMV<+0.5	< 20	< 5	< 10	< 5
C	< 15	-0.7<PMV<+0.7	< 30	< 10	< 15	< 10

The air movement has a cooling effect, and due to that air speed should be lower than 0.15 m/s. If the air speed is higher, operative temperature should be increased. A draught rating should stay lower than 15%. The draught is a function of mean air speed, local air temperature and fluctuation of air speed [39]. Combination of mean air speed, air temperature and turbulence intensity for draught rating of 15% is adopted from CIBSE[3] Guide [39] and shown on Figure 1.

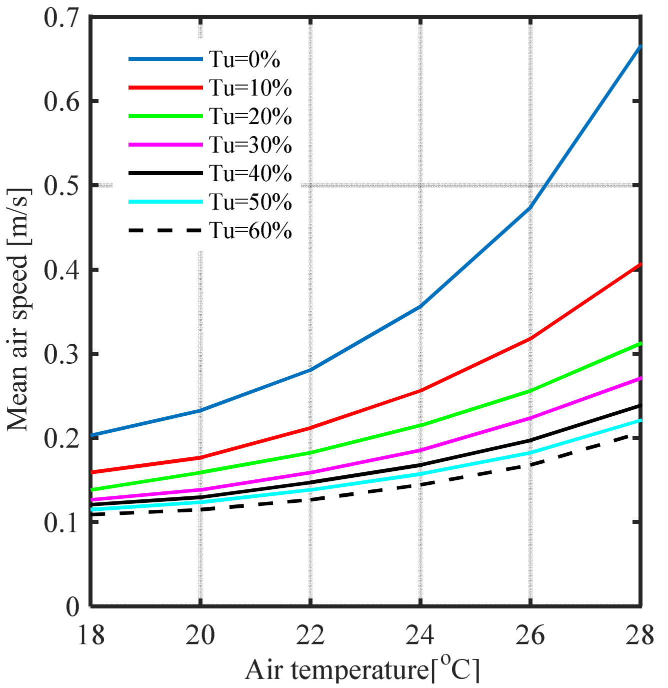

Figure 1. Combination of mean air speed, air temperature and turbulence intensity for draught rating of 15% [39]

The local thermal discomfort is commonly caused by draught. According to Fanger's

[1] DR – the percentage of people dissatisfied with draught; draught rate
[2] PD – the percentage dissatisfied
[3] CIBSE – The Chartered Institution of Building Service Engineers

model [42], the draught rate (DR) can be calculated as follows [9]:

$$DR = (34 - t_{a,l})(\bar{v}_{a,l} - 0.05)^{0.62}(0.37 \cdot \bar{v}_{a,l} \cdot T_u + 3.14), \tag{10}$$

where

$t_{a,l}$ is the local air temperature [°C],

$\bar{v}_{a,l}$ is the local mean air velocity [m/s] and

T_u is the local turbulence intensity [%].

The other cause of local discomfort can also be the vertical air temperature difference between head and ankles. The percentage of dissatisfied can be calculated using the equation [9]:

$$PD = \frac{100}{1 + \exp(5.76 - 0.856 \cdot \Delta t_{a,v})}, \tag{11}$$

where $\Delta t_{a,v}$ [°C] is the temperature difference between the head and ankles.

The local discomfort caused by warm or cold floors can be described as follows:

$$PD = 100 - 94 \cdot \exp(-1.387 + 0.118 \cdot t_f - 0.0025 \cdot {t_f}^2), \tag{12}$$

where t_f [°C] is the floor temperature.

The cause of dissatisfaction can also be the radiant asymmetry, because people are very sensitive to a temperature difference between warm ceiling or cold walls or windows, or cold ceilings and warm walls. The percentage dissatisfied caused by the radiant asymmetry can be calculated using the equations in Table 4.

Table 4. Percentage dissatisfied caused by radiant asymmetry [9]

Warm ceiling $\Delta t_{pr} < 23$°C	$PD = \frac{100}{1 + \exp(2.84 - 0.174 \cdot \Delta t_{pr})} - 5{,}5$ (13)
Cool ceiling $\Delta t_{pr} < 15$°C	$PD = \frac{100}{1 + \exp(9.93 - 0.50 \cdot \Delta t_{pr})}$ (14)
Warm wall $\Delta t_{pr} < 35$°C	$PD = \frac{100}{1 + \exp(3.72 - 0.052 \cdot \Delta t_{pr})} - 3{,}5$ (15)
Cool wall $\Delta t_{pr} < 15$°C	$PD = \frac{100}{1 + \exp(6.61 - 0.345 \cdot \Delta t_{pr})}$ (16)

Relative humidity has a low influence on warmth until the operative temperature is lower than 26-28°C. Relative humidity in the range between 40 and 70% is generally acceptable [39]. The International standard ISO 7730:2005 [9] allows a bit wider range, from 30 to 70%.

Thermal comfort is also influenced by clothing. Clothing provides insulation which consists of effective resistance of the material and thermal resistance of the air layer that is located in the gap between the clothing and the skin. Clothing insulation value can be expressed in clo units 1clo=0.155 m^2K/W. The clothing thermal efficiency is possible to calculate using following equation [40]:

$$F_{cl} = \frac{t_{cl} - t_o}{t_{sk} - t_o}, \tag{17}$$

where t_{cl}, t_o and t_{sk} are temperature of clothed body or clothing, operative temperature and skin temperature respectively. The typical insulation and permeability values for clothing ensembles are given in Table 5 [39].

Table 5. The typical insulation and permeability values for clothing ensembles [40]

Ensemble description	I_{cl}**[clo]**	f_{cl}	i_{cl}
Trousers, short-sleeved shirt, briefs/panties, socks and shoes	0.57	1.15	0.36
Trousers, long-sleeved shirt, briefs/panties, socks and shoes	0.61	1.20	0.41
Trousers, long-sleeved shirt, suit jacket, briefs/panties, socks and shoes	0.96	1.23	
Trousers, long-sleeved shirt, long-sleeved sweater, T-shirt briefs/panties, socks and shoes	1.01	1.28	
Knee-length skirt, long-sleeved shirt, half slip, panty hose, long-sleeved sweater, shoes	1.10	1.46	

For sedentary persons, a chair has also insulating effect that should be taken into a consideration. The clothing insulation effect is increased for a person sitting on a chair up to 0.15 clo [40], or even 0.3 clo [39] depending of the chair material and the contact area between the chair and the body.

Second personal factor that influence thermal comfort is metabolic heat production. It is directly dependent on the activity. A resting adult produces about 100W of heat, and the most of that heat is transferred to the environment through the skin. The average male skin surface area is about 1.8 m^2, and female is about 1.6 m^2. The metabolic activity is usually characterized by per unit area of skin, and for resting person it is 58 W/m^2, which is represented as 1 met [40]. Typical metabolic heat generation in a function of activities is given in Table 6.

Table 6. Typical metabolic heat generation in a function of activities [40]

Activity	Metabolic activity [met]	Heat generation [W/m2]
Resting seated, quiet	1	60
Resting standing, relaxed	1.2	70
Office reading, seated	1	55
Office writing, seated	1	60
Office typing, seated	1.1	65

The total sensible heat loss form skin can be calculated combining conduction, convection and radiation heat transfer, described by [40]:

$$C + R = \frac{t_{sk} - t_{cl}}{R_{cl}}, \qquad (18)$$

$$C = f_{cl} h_c (t_{cl} - t_a), \qquad (19)$$

$$R = f_{cl} h_r (t_{cl} - \bar{t}_r), \qquad (20)$$

where

C is convective heat loss [W/m^2],

h_c is convective heat transfer coefficient [W/m^{2}K],

h_r is linear radiative heat transfer coefficient [W/m^{2}K],

f_{cl} is clothing area factor [-] which is a ratio of area of the clothed body and DuBois surface area (nude body surface area) A_{cl}/A_D,

R_{cl} is thermal resistance of clothed body or clothing [m^{2}K /W],

t_a is the temperature of ambient air [°C] and,

$\bar{t}_r$ is the mean temperature[°C].

Sensible heat transfer mechanism includes heat transfer from the skin surface, through the clothing insulation, to the outer clothing surface and from the outer clothing surface to the ambient.

Evaporative heat loss from skin depends on the amount of moisture on the skin and the difference between the water vapor pressure at the skin and in the ambient, and it can be calculated using following formula [40]:

$$E_{sk} = \frac{w(p_{sk,s} - p_a)}{R_{e,cl} + 1/(f_{cl} h_e)}, \qquad (21)$$

where:

E_{sk} is evaporative heat loss from skin [W/m^2],

h_e is evaporative heat transfer coefficient [W/m^{2}K],

$R_{e,cl}$ is evaporative heat transfer resistance of clothing layer [m^{2}kPa /W],

w is skin wittedness [-],

$p_{sk,s}$ is water vapor pressure at skin [kPa] and,

p_a is water vapor pressure in ambient air [kPa].

The total skin heat loss is a measure of thermal environment and can be calculated as a sum of sensible and evaporative heat loss, as it follows [40]:

$$q_{sk} = \frac{t_{sk}-t_o}{R_{cl}+R_{a,cl}} + \frac{w(p_{sk,s}-p_a)}{R_{e,cl}+1/(LRh_c f_{cl})}, \tag{22}$$

where $R_{a,cl}$ is thermal resistance at outer body (skin or clothing) [m^{2}kPa /W] and,

LR is Lewis ratio which is relation between convective and evaporative heat transfer coefficients [K/kPa].

According to Fanger [43], a numerous studies showed a correlation between skin temperature and the thermal sensations. According to this, it was generally accepted that the skin temperature of 33-34°C, without sweating or shivering, provides physiological conditions for comfort, which was experimentally confirmed for sedentary activity by Fanger [25].

Fanger [25] introduced the skin temperature t_{sk} [°C] and sweat secretion E_{sw} [W/m^2] equations for steady state conditions [43]:

$$t_{sk} = 35.7 - 0.0276 \cdot M, \tag{23}$$

$$E_{sw} = 0.42 \cdot (M - 58), \tag{24}$$

where M stands for metabolic rate, and he concluded that preferable skin temperature for sedentary activity was 34°C.

Luo et al. [44] derived the conclusion that the metabolic rate increase from 0.9 met to 1.5 met indices more than 2°C variation in predicted neutral temperature and around 1.5 unit difference in PMV scale. The metabolic rate is strongly influenced by the air temperature, mean radiation temperature, air velocity, relative humidity, activity level and clothing. According to Yang et al. [45] the key temperature which causes the metabolic rate changes is 24°C. Under this point, from 18-24°C, the metabolic rate fluctuation is relatively slow, but from 24-33°C this rate is significant.

Havenith et al. [46] investigated the impact of clothing and activity on PMV calculation. They pointed out the relevance of the clothing vapour resistance on skin wetness, and thus the comfort. Further, they showed that metabolic rate measurements are necessary for more precise comfort determination, and concluded that more accurate method for metabolic rate estimation is required than it is suggested in ISO 8996.

The studies [22, 47] also showed the differences between male and female impressions regarding thermal comfort. Some of the researchers noted that females express higher dissatisfaction with environmental conditions than males [47]. On the contrary, Ciuha [48] pointed out in the study that the differences between genders “had no significant effect on the range of temperatures perceived as thermally comfortable for different skin regions and overall body”.

The differences in thermal sensations votes between young, adult and elderly people were discussed in [49].

CHAPTER 3

"One can't choose the time of the birth, parents neither the country of the origin,

but one can choose how he will act: whether as a good or a bad man."

Serbian Patriarch Pavle

"Човек не може да бира време у коме ће се родити и живети,

од њега не зависи ни од којих родитеља, нити од ког народа ће се родити,

али од њега зависи како ће поступати у датом времену:

да ли као човек или као нечовек."

Патријарх српски Павле

3. WORKING PRODUCTIVITY LOSS - LITERATURE REVIEW

The definition of productivity is given in [50] as "an index ratio of output relative to input". In the same literature is also said that poor IEQ may reduce working performance, in extreme conditions even 100% when employee is absent from work [50]. The costs of absence and productivity loss due to health problems among workers in the U.S. between the ages of 16 and 64 years, was estimated at $260 billion per year [51]. From total sum of economic lost mentioned, the $27 billion goes on the losses caused by the reduced productivity [51]. The American Productivity Audit, taken by telephone on a random sample of 28902 U.S. workers stated that 71% of the costs was explained by reduced performance at work [52]. Hermann M. [53] investigated the teachers' productivity and absence from work prior to and during the examination period and found that it is directly connected to the student exam performance in very negative way. The other studies [54, 55] showed that the performance on work increases with the increased air quality. Wargocki et al. [55] stated that the increase in moderate air quality, which corresponds to the 10% of dissatisfied people, can improve the performance of typical office work by approximately 1.5%. He also emphasized the economic benefit from air quality increase, obtained when ventilation rate was higher than the minimal value which is recommended according to ventilation standards. They suggested that an increase of ventilation rate in office buildings by the double leads to an increase of typing performances by 1.8%, to an increase of addition by 1.5% and to an increase of proof-reading performances by 2.8% [55].

Kosonen and Tan [54] published that the productivity loss from 0.5 to 2% had an economic impact as about the same as the annual cost of the total air-conditioning system. They also noted "that 1% to 2% reduction of the productivity loss is equivalent to 5% to 10% of the proportion dissatisfied reduction" [54]. In another theoretical study, Kosonen and Tan [8] investigated the productivity loss in air-conditioned office building using PMV index. They compared two tasks in office, thinking and typing, and compared the productivity loss as a function of PMV using the polynomial expression. They concluded that the productivity of 100% is expected when the air temperature is 20°C and PMV= - 0.21. The key finding was that when the PMV had a value of +0.5, the productivity loss for thinking was about 12%, and for typing was around 26% [8]. Kosonen and Tan suggested two equations, correlating productivity loss and PMV. The first one was suggested for the typing activity, for office work, in a form as follows [8]:

$$y = -60.543 \cdot x^6 + 198.41 \cdot x^5 - 183.75 \cdot x^4 - 8.1178 \cdot x^3 + 50.24 \cdot x^2 + 32.123 \cdot x + 4.8988, \tag{25}$$

and the second one was suggested for productivity loss for thinking activity:

$$y = 1.5928 \cdot x^5 - 1.5526 \cdot x^4 - 10.401 \cdot x^3 + 19.226 \cdot x^2 + 13.389 \cdot x + 1.8763, \tag{26}$$

where *y* stands for productivity loss [%], and *x* for PMV.

Seppanen et al. [56] investigated the correlation between the room temperature and office work and concluded that the highest productivity is expected at temperature around 22°C. In the same paper, they also suggested the equation, correlating the productivity with room temperature [56].

The recent researches imply that thermal discomfort can reduce the working performance by 5% to 15% [3, 4]. Li Lan [57] investigated the effect of thermal comfort changes on occupants' emotions and working performances through neurobehavioral tests and with "the Profile of mood states". The tests showed that the performance was decreased when the thermal environment deviated from neutral conditions. The participants felt uncomfortably hot at a high temperature, experienced more negative moods and gave more effort to maintain the working performance [57]. The other study from the same author showed that the optimal performance is achieved when people felt slightly colder, so the author suggested that the PMV range in workplaces should be between -0.5 and 0 [58]. He established the relation between relative performance and thermal sensation index for office work, changing the set-up temperature to 22 and 30°C. The observed office had a mechanical ventilation system, with a constant ventilation rate of 10 l/s. The survey was conducted in the presence of twelve volunteers.

According to Shaughnessy et al. [59] “there is limited data linking poor IAQ in the classrooms to student performance”. They investigated the classroom along with a ventilation system, varying the ventilation rates from less than 2.25 l/s-person to more than 4.5 l/s-person. The obtained results were confusing, with not enough sample in number of people participating, but they were leading to the conclusion that there is non-linear connection between IAQ and productivity loss. They suggested more comprehensive studies with complex protocols involving the impact of various indicators regarding IAQ, such as volatile compounds, dust and moisture impact, etc.

Wu et al. [60] also concluded that the optimal working performance correlates with a “slightly cool” thermal environment when the human body exergy consumption is minimal. They also concluded that the optimal thermal comfort in office environment not necessarily means that the occupants’ working performances will also be optimal.

The lack of the data regarding productivity loss, gathered through the experimental research in educational buildings that was conducted on larger sample of students working in actual thermal environment, was the main impeller for this research.

CHAPTER 4

"The human is born to work, to stand and to struggle.

Who doesn't act like this is dedicated on failure."

Nikola Tesla

"Човек је рођен да ради, трпи и да се бори.

Ко тако не чини, мора пропасти."

Никола Тесла

4. EXPERIMENTAL INVESTIGATION

4.1. Belgrade weather data

The investigation is performed in Belgrade, Serbia. Serbia has a temperate continental climate, with more or less dominant local characteristics. It is important to point out that one of the contributions of this research is that the measurements were done for a temperate continental climate. According to the literature survey, there is a very limited data on this kind of investigation for Western Balkan countries, or on the moderate climate, for naturally ventilated educational buildings.

Average annual air temperature (Figure 2.) in areas with an elevation less than 300m is 10.9°C [61]. Belgrade has an elevation of 117m and the highest average winter season temperature in January is 0.4°C due to dominant heat island effect of urban area. The hottest month is July, with an average monthly temperature between 20 and 22°C. The lowest temperatures measured in the period from 1961 to 1990 were between -35.6°C (registered in Sjenica, Serbia) to -21°C (in Belgrade). The highest temperatures in this period were between 37.1 and 42.3°C (Figure 3.) [61]. These data are adopted from Republic Hydrometeorological Service of Serbia.

Through the research in this PhD thesis, the measurements of local outside air temperature and humidity were taken during the experiments, using Testo 175H1 sensor with data logger. The sensor was placed on external wall, in a place hidden from a direct sunlight, rain and severe weather.

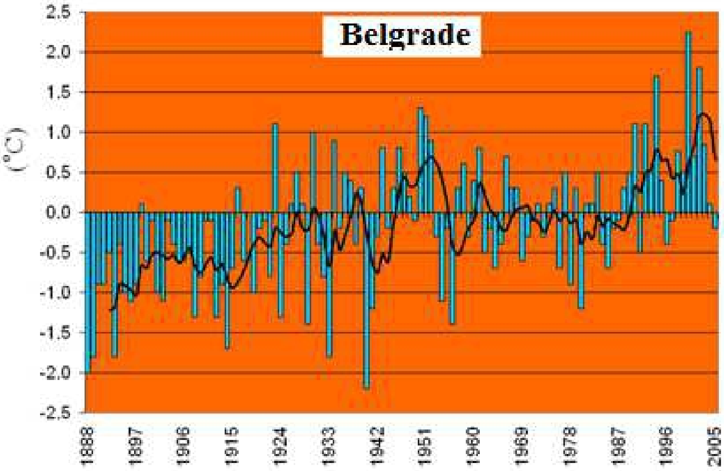

Figure 2. Average annual temperature deviation for Belgrade in the period from 1888 to 2005. Reference period is from 1961 to 1990 [62]

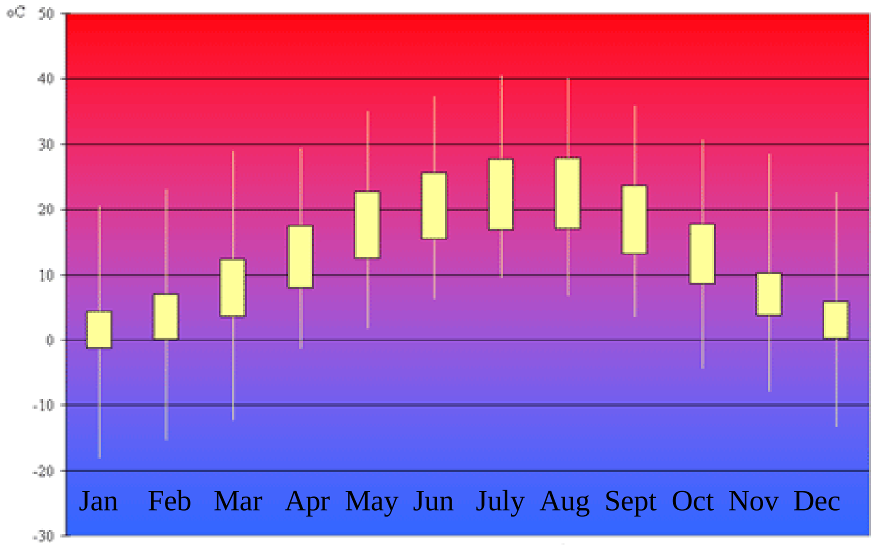

Figure 3. Average and absolute maximal monthly temperature for Belgrade. Reference period is from 1971 to 2000 [62]

The outside temperature and relative humidity have been measured during the whole year and a half, starting from April 2015 until now, but the relevant period for this investigation was from 16th of November until 11th of December 2015. In Scenario 1, from 16th of November until 20th of November the average outside temperature measured was 15.84°C and average relative humidity was 49.7%. During the period in Scenario 2, from 23rd until 27th of November, the average outside temperature measured was 6.21°C, and average relative humidity was 74.04%. In Scenario 3, from 30th of

November until 4th of December, the average outside temperature measured was 11.1°C, and average relative humidity was 61.79%. In Scenario 4, from 7th until 11th of December 2015, the average outside temperature measured was 6.36°C, and average relative humidity was 77.89%. The outside temperature and humidity were measured and recorded every 5 minutes and the results are shown on Figure 4. for the whole period of measurement.

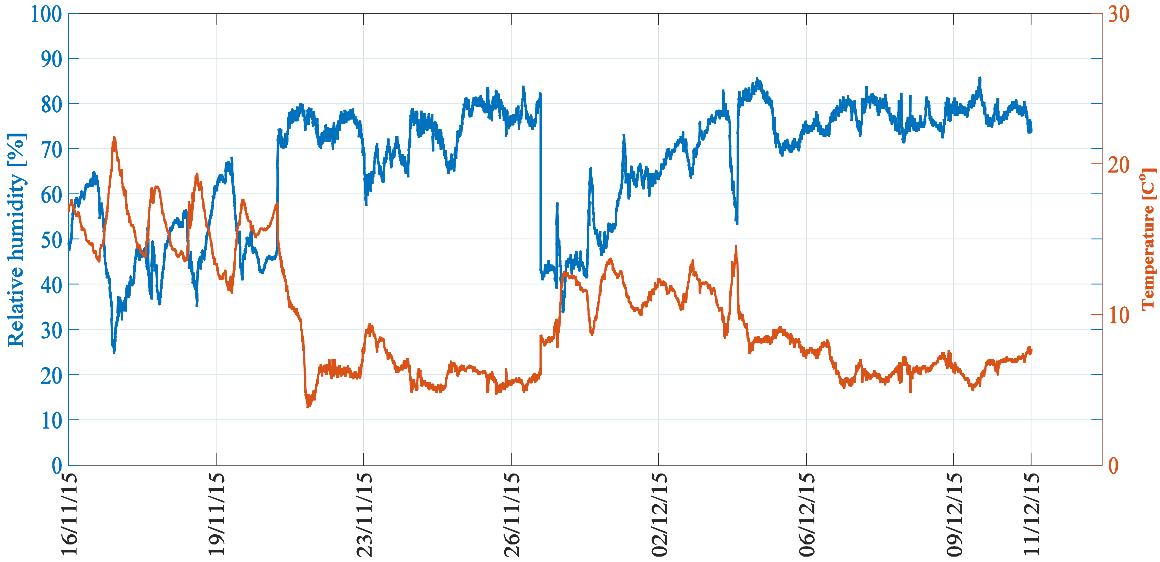

Figure 4. Outside air temperatures and relative humidity for model building measured every 5 minutes for the period from 16th of November to 27th of November and from 30th of November to 11th of December.

4.2. Building description

The experiments were done in classroom at Automatic control laboratory at Faculty of Mechanical engineering, University of Belgrade, in period from 16th of November until 11th of December 2015. It is very important to emphasize that all the 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 staff and voluntarism of the students helped to realize this research.

The building is located in Belgrade, Serbia. The observed classroom (Figure 5) is south-east oriented with one external wall, partly beneath ground level, with two windows and three internal walls. Beneath the floor is sandstone. The south-west internal wall is a barrier between the classroom and the unheated space. The north-west internal wall is the wall between the classroom and the corridor, with lower design temperature (18°C according to the Main mechanical project and Serbian regulation). The entrance door to the classroom is located in this wall. The third, south-east oriented internal wall, is a barrier between the heated office and the classroom.

Figure 5. The monitored classroom with measuring equipment

The thermal characteristics of the construction envelope are given in Table 7.

Table 7. The thermal characteristics of the construction envelope[4]

Number	Material	d [cm]	λ [W/mK]	R [m^2K/W]
External Wall 1				
	Indoor			0.125
1	Lime mortar	3	0.81	0.037
2	Full brick	45	0.85	0,529
3	Grout	3	1.4	0.021
	Outdoor			0.043
				U=1.325 W/m^2K

[4] Data were adopted from Main mechanical project for old Faculty of Mechanical engineering building

Number	Material	d [cm]	λ [W/mK]	R [m^2K/W]
External Wall beneath ground level 2				
	Indoor			0.125
1	Lime mortar	3	0.81	0.037
2	Full brick	45	0.85	0.529
3	Grout	3	1.4	0.021
U=1.306 W/m^2K				
Internal Wall 1				
	Indoor			0.125
1	Lime mortar	3	0.81	0.037
2	Full brick	45	0.85	0.589
3	Lime mortar	3	0.81	0.037
	Indoor			0.125
U=1.095 W/m2K				
Internal Wall 2				
	Indoor			0.125
1	Lime mortar	3	0.81	0.037
2	Full brick	29	0.85	0.341
3	Lime mortar	3	0.81	0.037
	Indoor			0.125
U=1.504 W/m^2K				
Internal Wall 3				
	Indoor			0.125
1	Lime mortar	3	0.81	0.037
2	Full brick	10	0.85	0.118
3	Lime mortar	3	0.81	0.037
	Indoor			0.125
U=2.262 W/m^2K				
Ceiling				
	Indoor			0.167
1	Parquet	2	0.21	0.095
2	Grout	2	1.4	0.014
3	Concrete	25	0.93	0.267
4	Grout	2	1.4	0.014
	Indoor			0.167
U=1.382 W/m^2K				
Floor on ground				
	Indoor			0.167
1	Linoleum	2	0.19	0.105

Number	Material	d [cm]	λ [W/mK]	R [m^{2}K/W]
2	Grout	2	1.4	0.014
3	Concrete	38	0.93	0.409
4	Sandstone	10	1.7	0.059
				U=1.326 W/m^{2}K
Window – double glazed wooden				U=2.30 W/m^{2}K
Internal wooden door				U=2.30 W/m^{2}K

The classroom is 8.12 m long, 6.34 m wide and 3.3 m 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 south-west inner wall is 7.6 m^2. The total number of seating places is 30. The classroom plan is shown on Figure 6 and in Appendix 6.

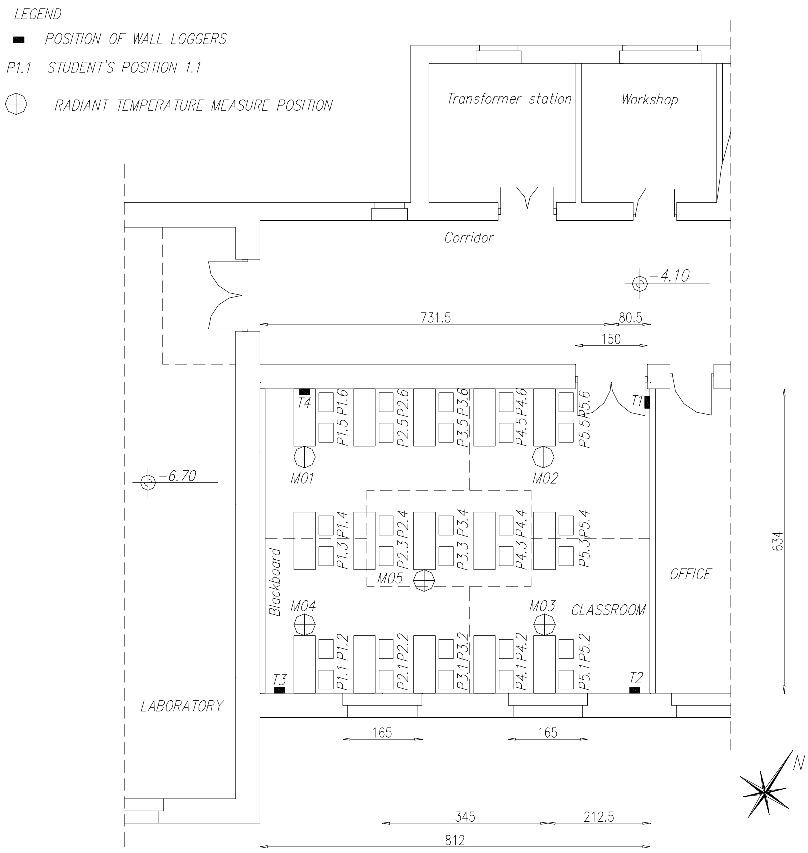

Figure 6. The classroom plan

4.3. Heating system description

The heating system in whole building, and observed classroom as well, is designed according to standard DIN 4701:1959 [63]. The building is in II climate zone, with prescribed design temperature for Belgrade -18°C in winter season, according to mentioned standard. According to these recommendations, the heat losses were calculated, and two pipe central heating system was designed. The monitored classroom has two aluminum radiators “Global Vox 700” with 13 elements each. This is the only installed mechanical system.

4.4. Experimental set-up

The experiments were performed in order to obtain the data about the following physical values:

1) The temperatures of the inner surfaces in several measurement points, which are defined in measurement protocol: all walls, glassing, window frame, floor, ceiling and heat sources (radiators and additional heaters).
2) The temperatures and relative humidity in several measurement points across the classroom.
3) The temperature of students’ cheeks.
4) The radiant temperatures in several measurement points.
5) The air velocities in several measurement points.
6) CO_2 concentrations in several measurement points.
7) The temperatures, relative humidity and CO_2 concentrations of outside air.

The measurements were done according to created measurement protocols for four scenarios.

The scenarios were created in order to gather data in different environmental conditions and to create a possible model for prediction and evaluation of users’ subjective evaluations and working performance. The scenarios are created as follows:

1) Scenario 1: The door and windows were closed during the classes and were opened during the 15 minutes break between classes. The thermostatic valves on radiators were closed during the entire Scenario 1.
2) Scenario 2: The door and windows were closed during the classes and were opened during the 15 minutes break between classes. The thermostatic valves on radiators were set on value 3 which corresponded to set temperature of 20°C in the classroom.
3) Scenario 3: The door and windows were closed during the classes and were

opened during the 15 minutes break between classes. The thermostatic valves on radiators were set on value 3 which corresponded to set temperature of 20°C in the classroom. Additional heat sources were brought to the classroom (three convective heaters model “Vivax Home CH-2004 F”, set to 750 W power each (from a maximum power of 1500 W)) and were turned on during the classes.

4) Scenario 4: The door and windows were closed during the classes and were opened during the 15 minutes break between classes. The thermostatic valves on radiators were closed. Additional heat sources were brought to the classroom (three convective heaters model “Vivax Home CH-2004 F”, set to 750 W power each (from a maximum power of 1500 W)) and were turned on during the classes.

The performed measurement can be classified in three groups, according to the duration and ASHRAE Guideline 14-2002 [64]:

- spot measurement
- short-term measurements
- long-term measurements

Spot measurements are classified as measurements taken briefly, in a period shorter than one hour. The instruments are portable or hand-held and are not left in situ, but data was collected in current conditions. This method was usually used to determine actual conditions and was also used as input data for computational simulations. This type of measurement was used for measuring the temperature of classroom envelope with infrared hand-held piston and thermal camera, and also for students' cheeks temperature measurements with infrared thermometer. The students' cheeks temperature measurements were performed each day, immediately after the subjective statistical survey, only for students’ that voluntarily wanted to participate in this kind of experiment. The thermal camera photo shooting was performed during the survey of the students. The measuring of the classroom envelope temperature with infrared hand-held piston was performed each day, at the end of the measurements, respectively at the end of the classes.

Short-term measurements were performed with instruments which were temporarily installed for the short-term periods of time such as one whole day, or few days up to six months. This kind of measurement was used for air temperature, relative humidity, radiant temperature, CO_2 concentration and air velocity in classroom. Those physical values were measured during the classes every day for each scenario and were gathered at the end of the each day.

Long-term measurements are usually performed during the period of six months and longer, with permanently installed instruments. This type of measurement was used to gather data on outdoor air temperature and humidity in situ. The outer data logger was placed on north-west outer wall of the building, hidden from the direct sunlight and rain. The values were gathered for the whole year, starting from 17^{th} of April 2015 until 17^{th} of April 2016. The values recorded in research period are previously shown on Figure 4.

4.5. Measuring equipment description

The used equipment was calibrated in certified laboratory of Vinca Institute of Nuclear Sciences, Serbia. The measuring instruments' characteristics are shown in Table 8.

Table 8. Characteristics of 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 turbulence: air velocity, air temperature	0 to +5 m/s, 0 to +50 °C	±(0.03 m/s +4% of m.v.) (0 to +5 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

4.6. Physical parameters measurement

Outside air temperature and humidity were measured every day, as given on Figure 4, as it was explained previously. The average values for each scenario are presented in Table 9.

Table 9. Average outside air temperature and humidity

Scenario	t_{out} [°C]	RH $_{out}$ [%]
1	15.84	49.70
2	6.21	74.04
3	11.10	61.79
4	6.36	77.89

During the Scenario 1, the outside temperature was significantly higher than in other scenarios (Table 9), and it was sunny also, which caused higher surfaces temperatures, especially the window glasses temperatures.

The inner surfaces temperatures of the classroom envelope were measured using hand-held infrared piston Testo 830-T2 calibrated in Vinca laboratory. Each surface temperature (Figure 7) was measured on five spots, in every corner and in the middle, and was averaged.

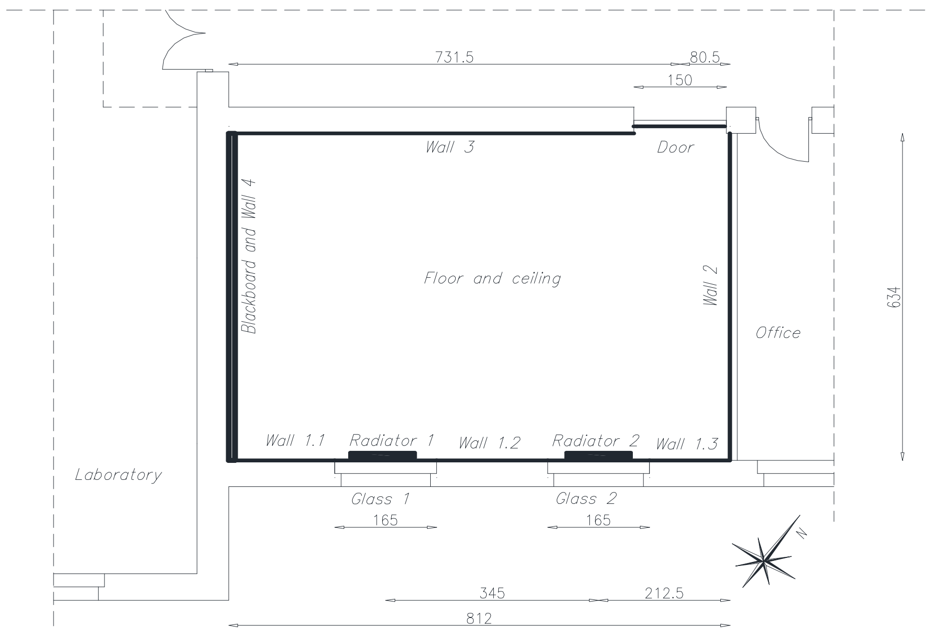

Figure 7. Surface positions and labeling

The measurements were conducted every day, after the survey of the students. The values were averaged for each scenario and given in Table 10. The results from each day, and each scenario are given in Appendix 1. These values were used for calculations of percentage dissatisfied with floor temperature and radiant asymmetry and were used as the initial conditions for CFD simulations.

Table 10. The temperatures of the classroom envelope surfaces

Surface	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Glass 1	23.84	18.95	22.28	19.4
Glass 2	23.94	19.00	22.68	19.42
Wall 1.1	22.74	21.95	23.00	22.32
Wall 1.2	22.84	21.78	22.98	22.30
Wall 1.3	22.62	21.83	22.98	22.34
Wall 2	23.48	23.10	24.32	23.72
Wall 3	23.54	23.15	24.08	23.94
Wall 4	23.00	22.98	23.78	23.26
Floor	22.36	21.55	21.98	21.64
Ceiling	23.86	24.43	25.14	25.44
Radiator 1	22.60	27.85	24.78	22.92
Radiator 2	22.82	30.05	26.30	23.00
Blackboard	23.50	23.35	24.36	23.78
Door	23.34	22.85	23.98	23.56

The indoor air temperature and humidity were measured and logged in 34 spots all over the classroom and they were classified in 3 groups according to the height on which the loggers were placed. The positions of these loggers are marked on Figure 8. Fifteen loggers were placed on one foot of the each table, 10 cm above the floor level, the other fifteen loggers were placed in the middle, on the bottom side of the tables, cca.60 cm above the floor level. Four loggers were placed in four corners of the classroom 1.6 m above the floor level (they are marked as T1, T2, T3 and T4 on Figure 8). The measured data were collected on Fridays, at the end of each scenario. These values were etaloned for each logger and averaged for every position from Monday to Friday, for every scenario and they are shown in Tables 11-14.

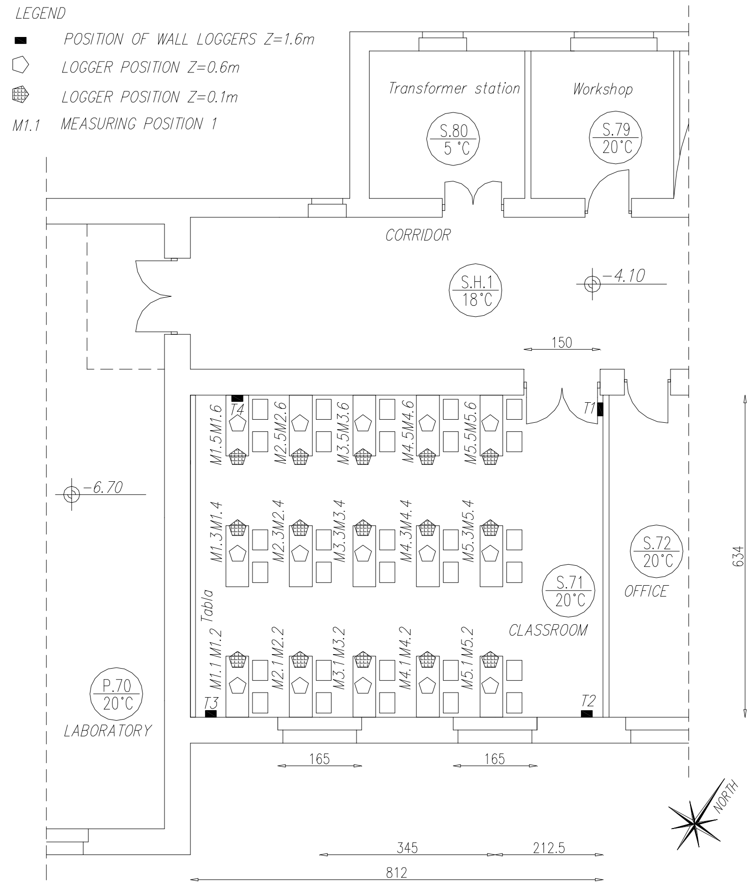

Figure 8. Displacement of data loggers

Besides the indoor and outdoor air temperatures and humidity, the indoor CO_2 concentrations were also measured in different spots every day and were averaged for every scenario and student's position. They are presented in tables mentioned before. The outside CO_2 concentration was about 450 ppm in all scenarios. The precise values are given in Appendix 2.

The indoor CO_2 concentration was measured from Monday to Friday on two measuring spots in classroom, using two probes, one on the easel beside the black globe and the other one behind the seats P5.3 and P5.4. Probe beside the black globe (the black globe varied from place M01 to M05, as it is shown on Figure 9) was adopted as the referent one, and the other CO_2 probe was used as a control one.

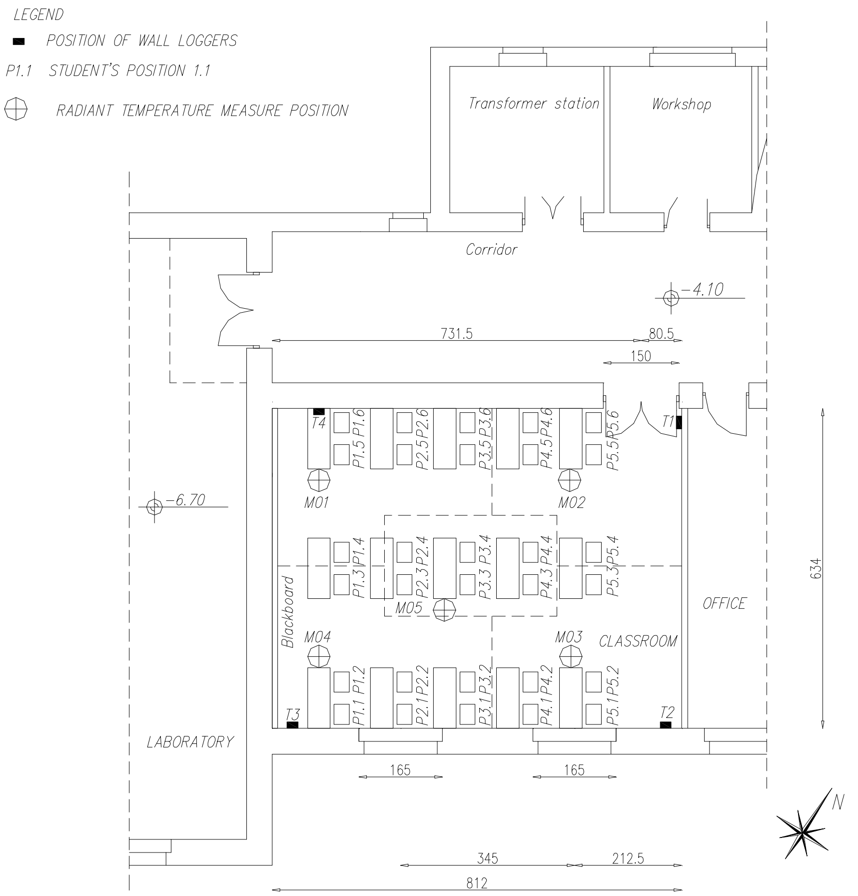

Figure 9. The black globe probe displacement

The values were distributed in the five fields mentioned before, and were averaged for every student's position in each field. Every Monday, black globe was placed on the position M01, on Tuesdays on the position M02, etc. Also, the same easel for black globe probe carried also the equipment for velocity, air temperature, relative humidity measurements and IAQ probe. The black globe probe was used for measuring the globe temperature and the radiant temperature calculation, which is one of the main physical parameters concerning thermal environment. One of the varied easel positions is shown on Figure 10.

Figure 10. The easel position M05 with black globe, IAQ and HOT wire probe.

In the third and fourth scenario, additional electrical heaters were installed in classroom. The heaters were placed on three school tables (73 cm above the floor level) behind the students’ back in order to provoke a local thermal discomfort, precisely the radiant asymmetry and vertical temperature difference and to investigate the students’ satisfaction or dissatisfaction caused by a temperature difference and its impact on productivity loss (Figure 11).

Figure 11. Additional electrical heaters with hot wire and turbulent probe instruments

According to the experiment protocol, the hot wire and turbulent probe were placed near the windows in scenario 1 and 2 (Figure 12A), and 0.5 m in front of the electrical heaters in scenarios 3 and 4 (Figure 12B).

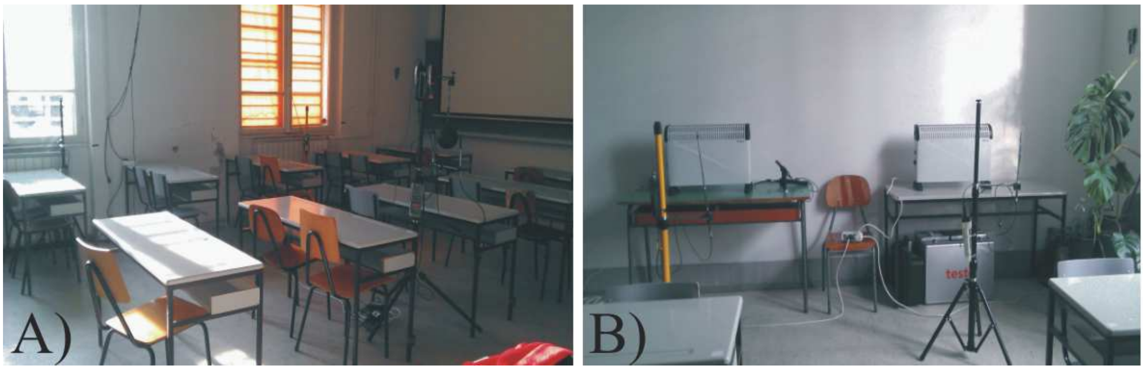

Figure 12. Hot wire and turbulent probe position for A) Scenarios 1 and 2 B) Scenarios 3 and 4

The averaged and filtered measured values of physical parameters: the air temperature on various heights (0.1, 0.6, 1.1, and 1.6 m), radiant temperature, relative humidity and CO_2 concentrations were measured according to the measurement protocols and are given in Tables 11 to 14. Radiant temperature was calculated indirectly, using measured temperature of a globe probe.

Table 11. Averaged values of physical parameters measured for Scenario 1

Position index	t_{a1} (0.1m) °C	t_{a2} (0.6m) °C	t_{a3} (1.1m) °C	t_{a5} (1.6m) °C	t_{rad} (1.1m) °C	RH1 (0.1m) %	RH2 (0.6m) %	RH3 (1.6m) %	CO_2 ppm
P1.1	22.48	22.72	24.03	22.97	22.88	47.10	42.43	37.17	1027
P1.2	22.48	22.72	24.03	22.97	22.88	47.10	42.43	37.17	1027
P1.3	23.01	23.11	24.03	23.20	22.88	41.94	41.75	37.17	1027
P1.4	23.01	23.11	24.46	23.20	24.26	41.94	41.75	35.62	1818
P1.5	22.75	22.99	24.46	23.23	24.26	43.76	42.13	35.62	1818
P1.6	22.75	22.99	24.46	23.23	24.26	43.76	42.13	35.62	1818
P2.1	22.29	22.93	24.03	23.57	22.88	46.95	41.73	37.17	1027
P2.2	22.29	22.93	24.03	23.57	22.88	46.95	41.73	37.17	1027
P2.3	23.10	23.66	22.94	24.21	23.42	42.51	42.22	37.17	809
P2.4	23.10	23.66	22.94	24.21	23.42	42.51	42.22	35.62	809
P2.5	22.91	23.71	24.46	24.51	24.26	41.87	42.10	35.62	1818
P2.6	22.91	23.71	24.46	24.51	24.26	41.87	42.10	35.62	1818
P3.1	22.49	23.43	24.03	24.37	22.88	44.96	41.27	37.17	1027
P3.2	22.49	23.43	24.03	24.37	22.88	44.96	41.27	37.17	1027
P3.3	23.18	23.87	22.94	24.57	23.42	41.77	40.20	37.17	809
P3.4	23.18	23.87	22.94	24.57	23.42	41.77	40.20	35.62	809
P3.5	23.01	23.26	24.46	23.50	24.26	41.43	41.86	35.62	1818
P3.6	23.01	23.26	24.46	23.50	24.26	41.43	41.86	35.62	1818
P4.1	22.48	23.26	24.69	24.03	24.45	44.90	41.86	37.06	1676
P4.2	22.48	23.26	24.69	24.03	24.45	44.90	41.86	37.06	1676
P4.3	23.12	23.84	22.94	24.56	23.42	40.64	39.45	37.06	809
P4.4	23.12	23.84	22.94	24.56	23.42	40.64	39.45	35.38	809
P4.5	22.88	24.13	24.85	25.37	24.82	41.45	39.56	35.38	1711
P4.6	22.88	24.13	24.85	25.37	24.82	41.45	39.56	35.38	1711
P5.1	22.37	23.26	24.69	24.15	24.45	44.40	39.87	37.06	1676
P5.2	22.37	23.26	24.69	24.15	24.45	44.40	39.87	37.06	1676
P5.3	23.08	23.68	24.69	24.28	24.45	40.30	39.01	37.06	1676
P5.4	23.08	23.68	24.85	24.28	24.82	40.30	39.01	35.38	1711
P5.5	23.20	23.60	24.85	24.00	24.82	41.28	40.98	35.38	1711
P5.6	23.20	23.60	24.85	24.00	24.82	41.28	40.98	35.38	1711
Average	22.82	23.43	24.16	24.04	23.90	43.02	41.10	36.33	1390

Table 12. Averaged values of physical parameters measured for Scenario 2

Position index	t_{a1} (0.1m) °C	t_{a2} (0.6m) °C	t_{a3} (1.1m) °C	t_{a5} (1.6m) °C	t_{rad} (1.1m) °C	RH1 (0.1m) %	RH2 (0.6m) %	RH3 (1.6m) %	CO_2 ppm
P1.1	21.06	21.52	22.81	22.01	22.90	38.47	35.39	44.00	1058
P1.2	21.06	21.52	22.81	22.01	22.90	38.47	35.39	44.00	1058
P1.3	21.68	21.67	22.81	22.01	22.90	34.16	34.57	39.68	1058
P1.4	21.68	21.67	22.77	22.69	22.73	34.16	34.57	39.68	1086
P1.5	21.57	21.73	22.77	22.69	22.73	35.07	34.50	40.82	1086
P1.6	21.57	21.73	22.77	22.69	22.73	35.07	34.50	40.82	1086
P2.1	21.72	21.89	22.81	22.01	22.90	36.61	34.07	44.22	1058
P2.2	21.72	21.89	22.81	22.01	22.90	36.61	34.07	44.22	1058
P2.3	21.60	21.92	22.81	22.01	22.90	35.10	35.63	40.51	1058
P2.4	21.60	21.92	22.77	22.69	22.73	35.10	35.63	40.51	1086
P2.5	21.64	21.93	22.77	22.69	22.73	34.54	35.62	39.54	1086
P2.6	21.64	21.93	22.77	22.69	22.73	34.54	35.62	39.54	1086
P3.1	21.44	21.74	22.81	22.01	22.90	35.32	35.18	41.93	1058
P3.2	21.44	21.74	22.81	22.01	22.90	35.32	35.18	41.93	1058
P3.3	21.68	21.92	22.81	22.01	22.90	35.00	34.11	39.99	1058

Position index	t_{a1} (0.1m) °C	t_{a2} (0.6m) °C	t_{a3} (1.1m) °C	t_{a5} (1.6m) °C	t_{rad} (1.1m) °C	RH1 (0.1m) %	RH2 (0.6m) %	RH3 (1.6m) %	CO_2 ppm
P3.4	21.68	21.92	22.77	22.69	22.73	35.00	34.11	39.99	1086
P3.5	21.69	21.63	22.77	22.69	22.73	34.28	35.08	38.98	1086
P3.6	21.69	21.63	22.77	22.69	22.73	34.28	35.08	38.98	1086
P4.1	20.90	21.45	23.59	22.20	22.96	38.22	35.60	42.98	968
P4.2	20.90	21.45	23.59	22.20	22.96	38.22	35.60	42.98	968
P4.3	21.35	21.53	23.59	22.20	22.96	34.84	34.27	39.36	968
P4.4	21.35	21.53	23.52	22.67	23.58	34.84	34.27	39.36	1076
P4.5	21.48	21.77	23.52	22.67	23.58	34.87	34.59	39.24	1076
P4.6	21.48	21.77	23.52	22.67	23.58	34.87	34.59	39.24	1076
P5.1	21.73	21.52	23.59	22.20	22.96	35.16	33.99	42.17	968
P5.2	21.73	21.52	23.59	22.20	22.96	35.16	33.99	42.17	968
P5.3	21.37	21.74	23.59	22.20	22.96	34.96	33.74	39.11	968
P5.4	21.37	21.74	23.52	22.67	23.58	34.96	33.74	39.11	1076
P5.5	21.16	21.53	23.52	22.67	23.58	35.43	35.79	39.41	1076
P5.6	21.16	21.53	23.52	22.67	23.58	35.43	35.79	39.41	1076
Average	21.47	21.70	23.10	22.39	23.00	35.47	34.81	40.80	1052

Table 13. Averaged values of physical parameters measured for Scenario 3

Position index	t_{a1} (0.1m) °C	t_{a2} (0.6m) °C	t_{a3} (1.1m) °C	t_{a5} (1.6m) °C	t_{rad} (1.1m) °C	RH1 (0.1m) %	RH2 (0.6m) %	RH3 (1.6m) %	CO_2 IAQ ppm
P1.1	21.98	22.84	26.67	24.36	26.18	44.93	39.54	38.24	1107
P1.2	21.98	22.84	26.67	24.36	26.18	44.93	39.54	38.24	1107
P1.3	22.93	23.35	26.67	24.36	26.18	38.80	38.24	38.24	1107
P1.4	22.93	23.35	24.20	24.92	24.20	38.80	38.24	36.56	1438
P1.5	22.39	22.82	24.20	24.92	24.20	41.47	38.69	36.56	1438
P1.6	22.39	22.82	24.20	24.92	24.20	41.47	38.69	36.56	1438
P2.1	22.45	23.30	26.67	24.36	26.18	42.70	38.02	38.24	1107
P2.2	22.45	23.30	26.67	24.36	26.18	42.70	38.02	38.24	1107
P2.3	22.95	23.71	24.99	24.36	24.57	39.23	39.16	38.24	1050
P2.4	22.95	23.71	24.99	24.92	24.57	39.23	39.16	36.56	1050
P2.5	22.55	23.48	24.20	24.92	24.20	39.82	39.20	36.56	1438
P2.6	22.55	23.48	24.20	24.92	24.20	39.82	39.20	36.56	1438
P3.1	22.37	23.78	26.67	24.36	26.18	41.31	38.21	38.24	1107
P3.2	22.37	23.78	26.67	24.36	26.18	41.31	38.21	38.24	1107
P3.3	22.99	23.94	24.99	24.36	24.57	38.61	37.16	38.24	1050
P3.4	22.99	23.94	24.99	24.92	24.57	38.61	37.16	36.56	1050
P3.5	22.71	23.38	24.20	24.92	24.20	39.38	38.40	36.56	1438
P3.6	22.71	23.38	24.20	24.92	24.20	39.38	38.40	36.56	1438
P4.1	21.72	23.08	24.39	24.41	24.36	44.18	39.31	38.42	1239
P4.2	21.72	23.08	24.39	24.41	24.36	44.18	39.31	38.42	1239
P4.3	22.77	23.65	24.99	24.41	24.57	37.95	37.04	38.42	1050
P4.4	22.77	23.65	24.99	24.83	24.57	37.95	37.04	37.02	1050
P4.5	22.47	23.70	25.31	24.83	25.11	39.80	37.29	37.02	1872
P4.6	22.47	23.70	25.31	24.83	25.11	39.80	37.29	37.02	1872
P5.1	23.10	23.06	24.39	24.41	24.36	38.61	38.09	38.42	1239
P5.2	23.10	23.06	24.39	24.41	24.36	38.61	38.09	38.42	1239
P5.3	22.85	23.66	24.39	24.41	24.36	37.67	36.81	38.42	1239
P5.4	22.85	23.66	25.31	24.83	25.11	37.67	36.81	37.02	1872
P5.5	22.24	23.09	25.31	24.83	25.11	40.66	38.86	37.02	1872
P5.6	22.24	23.09	25.31	24.83	25.11	40.66	38.86	37.02	1872
Average	22.57	23.39	25.15	24.63	24.91	40.34	38.27	37.53	1322

Table 14. Averaged values of physical parameters measured for Scenario 4

Position index	t_{a1} (0.1m) °C	t_{a2} (0.6m) °C	t_{a3} (1.1m) oC	t_{a3} (1.6m) °C	t_{rad} (1.1m) °C	RH1 (0.1m) %	RH2 (0.6m) %	RH3 (1.6m) %	CO2 IAQ ppm
P1.1	21.61	22.54	24.16	23.98	24.75	49.28	43.31	42.02	1600
P1.2	21.61	22.54	24.16	23.98	24.75	49.28	43.31	42.02	1600
P1.3	22.52	22.95	24.16	23.98	24.75	43.25	41.60	42.02	1600
P1.4	22.52	22.95	24.99	24.77	24.87	43.25	41.60	39.74	2472
P1.5	22.09	22.60	24.99	24.77	24.87	46.05	42.49	39.74	2472
P1.6	22.09	22.60	24.99	24.77	24.87	46.05	42.49	39.74	2472
P2.1	22.06	22.77	24.16	23.98	24.75	47.82	42.64	42.02	1600
P2.2	22.06	22.77	24.16	23.98	24.75	47.82	42.64	42.02	1600
P2.3	22.61	23.44	24.65	23.98	24.58	43.28	42.52	42.02	1178
P2.4	22.61	23.44	24.65	24.77	24.58	43.28	42.52	39.74	1178
P2.5	22.24	23.28	24.99	24.77	24.87	43.72	42.73	39.74	2472
P2.6	22.24	23.28	24.99	24.77	24.87	43.72	42.73	39.74	2472
P3.1	21.91	23.03	24.16	23.98	24.75	46.46	42.91	42.02	1600
P3.2	21.91	23.03	24.16	23.98	24.75	46.46	42.91	42.02	1600
P3.3	22.56	23.58	24.65	23.98	24.58	42.18	40.58	42.02	1178
P3.4	22.56	23.58	24.65	24.77	24.58	42.18	40.58	39.74	1178
P3.5	22.40	23.35	24.99	24.77	24.87	42.97	41.59	39.74	2472
P3.6	22.40	23.35	24.99	24.77	24.87	42.97	41.59	39.74	2472
P4.1	21.35	22.69	25.62	23.92	23.37	48.85	43.25	42.76	2542
P4.2	21.35	22.69	25.62	23.92	23.37	48.85	43.25	42.76	2542
P4.3	22.39	23.47	24.65	23.92	24.58	40.72	39.91	42.76	1178
P4.4	22.39	23.47	24.65	24.53	24.58	40.72	39.91	40.50	1178
P4.5	22.24	23.20	24.21	24.53	24.46	43.83	40.88	40.50	2641
P4.6	22.24	23.20	24.21	24.53	24.46	43.83	40.88	40.50	2641
P5.1	22.15	22.72	25.62	23.92	23.37	46.63	41.77	42.76	2542
P5.2	22.15	22.72	25.62	23.92	23.37	46.63	41.77	42.76	2542
P5.3	22.38	23.56	25.62	23.92	23.37	40.59	39.10	42.76	2542
P5.4	22.38	23.56	24.21	24.53	24.46	40.59	39.10	40.50	2641
P5.5	21.95	22.88	24.21	24.53	24.46	44.12	42.20	40.50	2641
P5.6	21.95	22.88	24.21	24.53	24.46	44.12	42.20	40.50	2641
Average	22.16	23.07	24.70	24.31	24.47	44.65	41.83	41.18	2050

4.6.1. The mean radiant and operative temperatures

The mean radiant temperature, firstly introduced by Fanger [65], is one of the most important parameters defining thermal comfort.

The mean radiant and operative temperatures were calculated using the formulas (7) and (8), according to [39], using measured data for all scenarios. The calculation was done using the refined code given in Annex D of standard ISO 7730:2005 [9] and the results are shown in Table 15.

Table 15. Calculated operative and radiant temperature based on measured values of physical parameters measured in four scenarios

	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
Position index	**t_o °C**	**t_g °C**	**t_{rad} °C**	**t_o °C**	**t_g °C**	**t_{rad} °C**	**t_o °C**	**t_g °C**	**t_{rad} °C**	**t_o °C**	**t_g °C**	**t_{rad} °C**
P1.1	23.48	23.18	22.88	22.97	22.88	22.90	26.46	26.33	26.18	25.21	23.59	24.75
P1.2	23.48	23.18	22.88	22.97	22.88	22.90	26.46	26.33	26.18	25.21	23.59	24.75
P1.3	23.48	23.18	22.88	22.97	22.88	22.90	26.46	26.33	26.18	25.21	23.59	24.75
P1.4	24.39	24.31	24.26	22.78	22.72	22.73	24.23	24.20	24.20	24.97	24.88	24.87
P1.5	24.39	24.31	24.26	22.78	22.72	22.73	24.23	24.20	24.20	24.97	24.88	24.87
P1.6	24.39	24.31	24.26	22.78	22.72	22.73	24.23	24.20	24.20	24.97	24.88	24.87
P2.1	23.48	23.18	22.88	22.97	22.88	22.90	26.46	26.33	26.18	25.21	23.59	24.75
P2.2	23.48	23.18	22.88	22.97	22.88	22.90	26.46	26.33	26.18	25.21	23.59	24.75
P2.3	23.20	23.21	23.42	22.97	22.88	22.90	24.84	24.72	24.57	24.66	24.62	24.58
P2.4	23.20	23.21	23.42	22.78	22.72	22.73	24.84	24.72	24.57	24.66	24.62	24.58
P2.5	24.39	24.31	24.26	22.78	22.72	22.73	24.23	24.20	24.20	24.97	24.88	24.87
P2.6	24.39	24.31	24.26	22.78	22.72	22.73	24.23	24.20	24.20	24.97	24.88	24.87
P3.1	23.48	23.18	22.88	22.97	22.88	22.90	26.46	26.33	26.18	25.21	23.59	24.75
P3.2	23.48	23.18	22.88	22.97	22.88	22.90	26.46	26.33	26.18	25.21	23.59	24.75
P3.3	23.20	23.21	23.42	22.97	22.88	22.90	24.84	24.72	24.57	24.66	24.62	24.58
P3.4	23.20	23.21	23.42	22.78	22.72	22.73	24.84	24.72	24.57	24.66	24.62	24.58
P3.5	24.39	24.31	24.26	22.78	22.72	22.73	24.23	24.20	24.20	24.97	24.88	24.87
P3.6	24.39	24.31	24.26	22.78	22.72	22.73	24.23	24.20	24.20	24.97	24.88	24.87
P4.1	24.61	24.37	24.45	23.31	23.18	22.96	24.37	24.28	24.36	23.78	24.99	23.37
P4.2	24.61	24.37	24.45	23.31	23.18	22.96	24.37	24.28	24.36	23.78	24.99	23.37
P4.3	23.20	23.21	23.42	23.31	23.18	22.96	24.84	24.72	24.57	24.66	24.62	24.58
P4.4	23.20	23.21	23.42	23.58	23.55	23.58	24.84	24.72	24.57	24.66	24.62	24.58
P4.5	24.88	24.82	24.82	23.58	23.55	23.58	25.25	25.16	25.11	24.36	24.37	24.46
P4.6	24.88	24.82	24.82	23.58	23.55	23.58	25.25	25.16	25.11	24.36	24.37	24.46
P5.1	24.61	24.37	24.45	23.31	23.18	22.96	24.37	24.28	24.36	23.78	24.99	23.37
P5.2	24.61	24.37	24.45	23.31	23.18	22.96	24.37	24.28	24.36	23.78	24.99	23.37
P5.3	24.61	24.37	24.45	23.31	23.18	22.96	24.37	24.28	24.36	23.78	24.99	23.37
P5.4	24.88	24.82	24.82	23.58	23.55	23.58	25.25	25.16	25.11	24.36	24.37	24.46
P5.5	24.88	24.82	24.82	23.58	23.55	23.58	25.25	25.16	25.11	24.36	24.37	24.46
P5.6	24.88	24.82	24.82	23.58	23.55	23.58	25.25	25.16	25.11	24.36	24.37	24.46
Average	24.06	23.92	23.90	23.10	23.03	23.00	25.07	24.97	24.91	24.66	24.46	24.47

The highest mean radiant temperature which had been averaged for the whole classroom was measured in Scenario 3, when the local highest mean radiant temperature reached was 26.18°C, and the lowest one, 22.73°C, was measured in Scenario 2, as it is presented in Table 15.

4.7. PMV, PPD and PLOS results

The calculation of PMV and PPD indices was done using the refined code given in Annex D of standard ISO 7730:2005 [9]. The indices are dependent on the input variables for clothing, metabolic rate, air temperature, mean radiant temperature, relative air velocity, relative humidity and water vapour pressure, and all were calculated for natural convection regime. The measured input values were presented in previous text. The productivity loss was calculated based on the regression correlations available in literature [7], for the warm side of comfort zone, which is also incorporated in Phoenics FLAIR, together with regression correlations for productivity loss in office buildings given in [8]. These results are shown in Table 16.

Table 16. The local PMV, PPD and PLOS results for four scenarios

Position index	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	PMV	PPD [%]	PMV	PPD [%]	PMV	PPD [%]	PMV	PPD [%]
P1.1	0.42	9.87	0.23	9.08	1.05	29.69	0.51	11.67
P1.2	0.42	9.87	0.23	9.08	1.05	29.69	0.51	11.67
P1.3	0.42	9.87	0.23	9.08	1.05	29.69	0.51	11.67
P1.4	0.68	15.47	0.24	8.09	0.54	12.94	0.78	18.57
P1.5	0.68	15.47	0.24	8.09	0.54	12.94	0.78	18.57
P1.6	0.68	15.47	0.24	8.09	0.54	12.94	0.78	18.57
P2.1	0.42	9.87	0.23	9.08	1.05	29.69	0.51	11.67
P2.2	0.42	9.87	0.23	9.08	1.05	29.69	0.51	11.67
P2.3	0.33	8.06	0.23	9.08	0.70	20.67	0.67	15.22
P2.4	0.33	8.06	0.24	8.09	0.70	20.67	0.67	15.22
P2.5	0.68	15.47	0.24	8.09	0.54	12.94	0.78	18.57
P2.6	0.68	15.47	0.24	8.09	0.54	12.94	0.78	18.57
P3.1	0.42	9.87	0.23	9.08	1.05	29.69	0.51	11.67
P3.2	0.42	9.87	0.23	9.08	1.05	29.69	0.51	11.67
P3.3	0.33	8.06	0.23	9.08	0.70	20.67	0.67	15.22
P3.4	0.33	8.06	0.24	8.09	0.70	20.67	0.67	15.22
P3.5	0.68	15.47	0.24	8.09	0.54	12.94	0.78	18.57
P3.6	0.68	15.47	0.24	8.09	0.54	12.94	0.78	18.57
P4.1	0.70	15.96	0.36	10.47	0.59	21.25	0.84	20.40
P4.2	0.70	15.96	0.36	10.47	0.59	21.25	0.84	20.40
P4.3	0.33	8.06	0.36	10.47	0.70	20.67	0.67	15.22
P4.4	0.33	8.06	0.39	9.77	0.70	20.67	0.67	15.22
P4.5	0.72	16.32	0.39	9.77	0.81	21.05	0.63	15.28
P4.6	0.72	16.32	0.39	9.77	0.81	21.05	0.63	15.28
P5.1	0.70	15.96	0.36	10.47	0.59	21.25	0.84	20.40

Position index	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	PMV	PPD [%]	PMV	PPD [%]	PMV	PPD [%]	PMV	PPD [%]
P5.2	0.70	15.96	0.36	10.47	0.59	21.25	0.84	20.40
P5.3	0.70	15.96	0.36	10.47	0.59	21.25	0.84	20.40
P5.4	0.72	16.32	0.39	9.77	0.81	21.05	0.63	15.28
P5.5	0.72	16.32	0.39	9.77	0.81	21.05	0.63	15.28
P5.6	0.72	16.32	0.39	9.77	0.81	21.05	0.63	15.28
MAX	**0.72**	**16.32**	**0.39**	**10.47**	**1.05**	**29.69**	**0.84**	**20.4**
MIN	**0.33**	**8.06**	**0.23**	**8.09**	**0.54**	**12.94**	**0.51**	**11.67**
Average	**0.56**	**12.90**	**0.29**	**9.20**	**0.74**	**21.13**	**0.68**	**16.05**

The lowest PMV was recorded in Scenario 2, with averaged value for whole scenario of 0.29, but locally varying from 0.23 to 0.39. According to the ISO 7730:2005, this indicates that the thermal environment belongs to the category "B". The highest PMV index was recorded in Scenario 3, reaching maximally 1.05, as it is shown in Table 16. Non-uniformity of physical parameters locally, such as air and radiant temperatures and air velocities, cause a deviation of local PMV and so the PPD values, also, along the observed classroom. The significance of the local thermal comfort indexes analysis is evident through the very wide differences of PMV locally, which is even more expressed in scenarios with hotter conditions. This conclusion is an important base for the productivity loss analysis.

The values for productivity loss were obtained using existing model for typing and thinking tasks suggested by Kosonen and Tan [8], based on PMV indexes measured in all four scenarios and presented in Table 17.

Table 17. Productivity loss for typing and thinking task using equations (25) and (26)

	Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**	
Position index	**PLOSS typing** %	**PLOSS Thinking** %	**PLOSS typing** %	**PLOSS Thinking** %	**PLOSS typing** %	**PLOSS Thinking** %	**PLOSS typing** %	**PLOSS Thinking** %
P1.1	4	10	2	6	13	25	6	12
P1.2	4	10	2	6	13	25	6	12
P1.3	4	10	2	6	13	25	6	12
P1.4	8	17	2	6	6	13	10	19
P1.5	8	17	2	6	6	13	10	19
P1.6	8	17	2	6	6	13	10	19
P2.1	4	10	2	6	13	25	6	12
P2.2	4	10	2	6	13	25	6	12
P2.3	3	8	2	6	8	17	8	16

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Position index	**PLOSS typing** %	**PLOSS Thinking** %	**PLOSS typing** %	**PLOSS Thinking** %	**PLOSS typing** %	**PLOSS Thinking** %	**PLOSS typing** %	**PLOSS Thinking** %
P2.4	3	8	2	6	8	17	8	16
P2.5	8	17	2	6	6	13	10	19
P2.6	8	17	2	6	6	13	10	19
P3.1	4	10	2	6	13	25	6	12
P3.2	4	10	2	6	13	25	6	12
P3.3	3	8	2	6	8	17	8	16
P3.4	3	8	2	6	8	17	8	16
P3.5	8	17	2	6	6	13	10	19
P3.6	8	17	2	6	6	13	10	19
P4.1	8	17	3	9	7	14	10	20
P4.2	8	17	3	9	7	14	10	20
P4.3	3	8	3	9	8	17	8	16
P4.4	3	8	4	9	8	17	8	16
P4.5	9	17	4	9	10	20	7	15
P4.6	9	17	4	9	10	20	7	15
P5.1	8	17	3	9	7	14	10	20
P5.2	8	17	3	9	7	14	10	20
P5.3	8	17	3	9	7	14	10	20
P5.4	9	17	4	9	10	20	7	15
P5.5	9	17	4	9	10	20	7	15
P5.6	9	17	4	9	10	20	7	15
MAX	**9**	**17**	**4**	**9**	**13**	**25**	**10**	**20**
MIN	**3**	**8**	**2**	**6**	**6**	**13**	**6**	**12**
Average	**6**	**14**	**3**	**7**	**9**	**18**	**8**	**16**

The maximal PLOS obtained using this model is 25% in third Scenario. This result is pretty much different from the results obtained in productivity test performed through this research, which is going to be discussed in further chapters.

4.8. The local thermal discomfort

The local thermal discomfort was evaluated using standard ISO 7730:2005 [9] and the calculated values for number of people dissatisfied with draught intensity, vertical air difference, warm and cold floor and radiant asymmetry.

4.8.1. Vertical air temperature difference

The percentage of dissatisfied with vertical air temperature difference, measured on a height level between 0.1m and 1.1m, was also calculated for all scenarios in accordance with ISO 7730:2005, using formula (11). The results are presented in Table 18. The averaged values for scenarios 1 and 2 are lower than 2%, which implies that the classroom belongs to thermal environment category "A", according to Table 3. Scenarios 3 and 4 had a difference higher than 6%, but still lower than 10%, which corresponds to category "C" of thermal environment. Since the percentage of people dissatisfied with vertical air temperature difference is lower than 2% in Scenario 1 and 2, the influence of this factor on productivity loss can be neglected in this scenarios, but in scenarios 3 and 4 its impact is notable.

Table 18. Percentage of people dissatisfied with vertical air difference, heights between 0.1 and 1.1 m

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Position Index	**PD dTair %**	**PD dTair %**	**PD dTair %**	**PD dTair %**
P1.1	2.05	1.39	26.63	5.50
P1.2	2.05	1.39	26.63	5.50
P1.3	1.22	0.82	14.43	2.97
P1.4	1.76	0.80	1.99	5.87
P1.5	1.94	0.87	2.37	6.20
P1.6	1.94	0.87	2.37	6.20
P2.1	2.19	0.79	13.86	5.10
P2.2	2.19	0.79	13.86	5.10
P2.3	0.49	0.88	4.06	4.45
P2.4	0.49	0.85	4.06	4.45
P2.5	1.74	0.82	2.18	5.54
P2.6	1.74	0.82	2.18	5.54
P3.1	2.20	1.01	18.50	6.01
P3.2	2.20	1.01	18.50	6.01
P3.3	0.45	0.82	3.95	4.27
P3.4	0.45	0.79	3.95	4.27
P3.5	1.58	0.79	2.02	5.19
P3.6	1.58	0.79	2.02	5.19
P4.1	3.37	3.05	5.05	19.95
P4.2	3.37	3.05	5.05	19.95
P4.3	0.50	2.09	4.82	4.97

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Position Index	**PD dTair %**	**PD dTair %**	**PD dTair %**	**PD dTair %**
P4.4	0.50	1.97	4.82	4.97
P4.5	2.37	1.78	5.83	3.12
P4.6	2.37	1.78	5.83	3.12
P5.1	3.52	1.53	2.01	17.53
P5.2	3.52	1.53	2.01	17.53
P5.3	2.04	2.06	2.79	10.19
P5.4	2.34	1.94	5.93	3.28
P5.5	2.39	2.31	7.43	4.43
P5.6	2.39	2.31	7.43	4.43
Average	**1.90**	**1.39**	**7.42**	**6.89**

This calculation was done for the temperature difference on a height level between 0.1 and 1.1m since the highest temperature was in breathing zone. In this analysis height level between ankle and head was compared.

4.8.2. The percent dissatisfied with floor temperature

The percentage of people dissatisfied with floor temperature was calculated in accordance with ISO 7730:2005 (formula (12)) and it is presented in Table 19. According to the obtained values, the classroom belongs to the category "A" of thermal environment, based on this parameter (Table 3).

Table 19. Calculated values of PD caused by warm or cold floors

Scenario	t_{floor} [°C]	PD_{floor} [%]
1	22.36	5.85
2	21.55	6.48
3	21.98	6.11
4	21.64	6.39

It is a question why are these 6% of dissatisfied taken as a minimum in ISO 7730:2005 standard. The answer to this question is explained through the results obtained in this research and is presented in Result synthesis chapter.

4.8.3. Draught

Studying the available literature [66, 67] , it is concluded that the Fanger's model of draught (equation (10)) was obtained using the equipment that had an accuracy for air velocity measurement of 0.05 m/s, hence the formula for percentage of people dissatisfied with draught had a form (10). The novel velocity probes are more accurate, and in this research Testo 0635 1025 telescopic temperature and velocity probe with accuracy 0.03 m/s ±5% were used, so the equation (10) was upgraded into a following equation:

$$DR = (34 - t_{a,l})(\bar{v}_{a,l} - 0.03)^{0,62}(0.37 \cdot \bar{v}_{a,l} \cdot T_u + 3.14), \tag{27}$$

and used in this research as given above. This is also one of the contributions of this thesis. The turbulent intensity T_u was calculated according to a measured air velocities for four scenarios and presented in Appendix 3. The results of percentage of the people dissatisfied with draught intensity for four scenarios are presented in Table 20.

Table 20. Percentage of the people dissatisfied with draught intensity calculated according to ISO 7730:2005

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Position Index	**PD draught %**	**PD draught %**	**PD draught %**	**PD draught %**
P1.1	1.40	15.20	0.00	0.00
P1.2	1.40	15.20	0.00	0.00
P1.3	1.40	15.20	0.00	0.00
P1.4	2.00	0.00	0.00	0.00
P1.5	2.00	0.00	0.00	0.00
P1.6	2.00	0.00	0.00	0.00
P2.1	1.40	15.20	0.00	0.00
P2.2	1.40	15.20	0.00	0.00
P2.3	0.00	15.20	0.00	0.00
P2.4	0.00	0.00	0.00	0.00
P2.5	2.00	0.00	0.00	0.00
P2.6	2.00	0.00	0.00	0.00
P3.1	1.50	15.20	0.00	0.00
P3.2	1.50	15.20	0.00	0.00
P3.3	0.00	15.20	0.00	0.00
P3.4	0.00	0.00	0.00	0.00
P3.5	1.80	0.00	0.00	0.00
P3.6	1.80	0.00	0.00	0.00
P4.1	2.70	15.47	1.59	3.50

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Position Index	**PD draught %**	**PD draught %**	**PD draught %**	**PD draught %**
P4.2	2.70	15.47	1.59	3.50
P4.3	0.00	15.47	0.00	0.00
P4.4	0.00	0.00	0.00	0.00
P4.5	0.00	0.00	0.40	0.00
P4.6	0.00	0.00	0.40	0.00
P5.1	2.70	15.47	1.59	3.50
P5.2	2.70	15.47	1.59	3.50
P5.3	2.70	15.47	1.59	3.50
P5.4	0.00	0.00	0.40	0.00
P5.5	0.00	0.00	0.40	0.00
P5.6	0.00	0.00	0.40	0.00
Average	**1.22**	**7.65**	**0.33**	**0.58**

From the results presented in Table 20. it can be concluded that the draught intensity is almost negligible in all scenarios, except in Scenario 2 for the positions near windows. It is obvious that during the Scenario 2, was windy and the impact of air movement was noticeable, but still lower than 10% averaged for whole classroom which indicates that the thermal environment category is "A" globally, but locally it changes into "B" category. This also implies that local approach is more detailed and reliable when drawing the conclusions on productivity loss. This factor can be neglected in Scenarios 1, 3 and 4 as irrelevant for students' productivity loss.

4.8.4. Radiant asymmetry

According to the investigations worldwide, the radiant asymmetry is considered to be a significant cause of local thermal discomfort. Sakoi et al. [68] had investigated the thermal comfort concerning the whole body and local parts of the body as well, in different asymmetric radiant fields, and they concluded that the manikin skin temperature changes locally depending on the non-uniformity of the thermal environment even though the mean skin temperature is almost the same. They also concluded "that the distribution of the sensible heat loss varies depending on the magnitude and direction of the environmental non-uniformity".

The radiant asymmetry and percentage of dissatisfied caused by radiant asymmetry was calculated according to the literature [9, 69-75].

For Scenario 1 and Scenario 2, the direction from external wall and its windows to the wall 3 (Figure 7) was adopted as an dominant direction for side-to-side asymmetry, causing higher asymmetry discomfort as suggested in standard ISO 7730:2005. In Scenario 3 and Scenario 4, the dominant asymmetry direction was the direction from blackboard to electrical heaters (front to back). The results are presented in Tables 21 to 24 for all scenarios. The surface temperatures used for these calculations are presented in Table 10 and Table A1.1 in Appendix 1. View factors were calculated with respect to the students' position regarding the radiant surface, according to the methodology suggested in [70].

For Scenario 1 and Scenario 2: The view factor F_1 was calculated with respect to the left side of students' body, facing the external wall and its windows, and factor F_2 was calculated with respect to the right body side orientation, parallel with Wall 3. Temperature t_1 is appropriate surface temperature on left side with respect to the positions, and t_2 is the temperature of the Wall 3. The radiant temperature asymmetry is Δt_{pr} and it was calculated as a temperature difference between the left and the right sides of classroom thermal envelope, and were multiplied with appropriate view factors.

Table 21. The view factors regarding the students' position, radiant temperature asymmetry and percent dissatisfied for Scenario 1

Position index	F_1	$F_1 \cdot t_1$ [°C]	F_2	$F_2 \cdot t_2$ [°C]	Δt_{pr} [°C]	PD [%]
P1.1	0.11	2.52	0.01	0.24	2.28	0.30
P1.2	0.10	2.19	0.01	0.24	1.95	0.26
P1.3	0.03	0.76	0.02	0.38	0.38	0.15
P1.4	0.02	0.36	0.03	0.79	-0.43	0.12
P1.5	0.01	0.23	0.11	2.49	-2.26	0.06
P1.6	0.01	0.23	0.11	2.64	-2.41	0.06
P2.1	0.10	2.41	0.01	0.24	2.18	0.28
P2.2	0.08	2.00	0.01	0.24	1.77	0.25
P2.3	0.02	0.50	0.01	0.19	0.32	0.15
P2.4	0.01	0.14	0.02	0.55	-0.42	0.12
P2.5	0.01	0.24	0.10	2.25	-2.01	0.07
P2.6	0.01	0.24	0.10	2.42	-2.18	0.06
P3.1	0.10	2.41	0.01	0.24	2.18	0.28
P3.2	0.08	2.00	0.01	0.24	1.77	0.25
P3.3	0.02	0.50	0.01	0.19	0.32	0.15
P3.4	0.01	0.14	0.02	0.55	-0.42	0.12
P3.5	0.01	0.24	0.10	2.25	-2.01	0.07
P3.6	0.01	0.24	0.10	2.42	-2.18	0.06

Position index	F_1	$F_1 \cdot t_1$ [°C]	F_2	$F_2 \cdot t_2$ [°C]	Δt_{pr} [°C]	PD [%]
P4.1	0.11	2.54	0.01	0.24	2.30	0.30
P4.2	0.10	2.22	0.01	0.24	1.99	0.27
P4.3	0.04	0.82	0.02	0.38	0.44	0.16
P4.4	0.02	0.42	0.03	0.79	-0.38	0.12
P4.5	0.01	0.23	0.11	2.49	-2.26	0.06
P4.6	0.01	0.23	0.11	2.64	-2.41	0.06
P5.1	0.11	2.65	0.01	0.24	2.41	0.31
P5.2	0.10	2.28	0.01	0.24	2.04	0.27
P5.3	0.03	0.74	0.02	0.38	0.37	0.15
P5.4	0.01	0.32	0.03	0.79	-0.47	0.11
P5.5	0.01	0.24	0.11	2.49	-2.25	0.06
P5.6	0.01	0.24	0.11	2.64	-2.40	0.06
min						**0.06**
max						**0.31**
average						**0.16**

The results for Scenario 2 are presented in Table 22.

Table 22. View factors regarding the students' position, radiant temperature asymmetry and percent dissatisfied for Scenario 2

Position index	F_1	$F_1 \cdot t_1$ [°C]	F_2	$F_2 \cdot t_2$ [°C]	Δt_{pr} [°C]	PD [%]
P1.1	0.11	2.43	0.01	0.23	2.20	0.29
P1.2	0.10	2.11	0.01	0.23	1.88	0.26
P1.3	0.03	0.73	0.02	0.37	0.36	0.15
P1.4	0.02	0.35	0.03	0.78	-0.43	0.12
P1.5	0.01	0.22	0.11	2.45	-2.23	0.06
P1.6	0.01	0.22	0.11	2.60	-2.38	0.06
P2.1	0.10	1.92	0.01	0.23	1.68	0.24
P2.2	0.08	1.59	0.01	0.23	1.36	0.21
P2.3	0.02	0.40	0.01	0.18	0.22	0.14
P2.4	0.01	0.11	0.02	0.54	-0.44	0.12
P2.5	0.01	0.19	0.10	2.22	-2.03	0.07
P2.6	0.01	0.19	0.10	2.38	-2.19	0.06
P3.1	0.10	1.92	0.01	0.23	1.68	0.24
P3.2	0.08	1.59	0.01	0.23	1.36	0.21
P3.3	0.02	0.40	0.01	0.18	0.22	0.14
P3.4	0.01	0.11	0.02	0.54	-0.44	0.12
P3.5	0.01	0.19	0.10	2.22	-2.03	0.07
P3.6	0.01	0.19	0.10	2.38	-2.19	0.06
P4.1	0.11	2.42	0.01	0.23	2.19	0.29
P4.2	0.10	2.12	0.01	0.23	1.89	0.26
P4.3	0.04	0.78	0.02	0.37	0.41	0.15
P4.4	0.02	0.40	0.03	0.78	-0.38	0.12

Position index	F_1	$F_1 \cdot t_1$ [°C]	F_2	$F_2 \cdot t_2$ [°C]	Δt_{pr} [°C]	PD [%]
P4.5	0.01	0.22	0.11	2.45	-2.23	0.06
P4.6	0.01	0.22	0.11	2.60	-2.38	0.06
P5.1	0.11	2.10	0.01	0.23	1.87	0.26
P5.2	0.10	1.81	0.01	0.23	1.58	0.23
P5.3	0.03	0.59	0.02	0.37	0.22	0.15
P5.4	0.01	0.26	0.03	0.78	-0.52	0.11
P5.5	0.01	0.19	0.11	2.45	-2.26	0.06
P5.6	0.01	0.19	0.11	2.60	-2.41	0.06
min						**0.06**
max						**0.29**
average						**0.15**

In case of Scenario 3 and Scenario 4, the dominant radiant asymmetry was caused by electrical heaters from the students' back, so the face-back direction was adopted as a dominant direction. The view factors and radiant temperature asymmetry were calculated regarding electrical heaters, and were marked as F_1 and t_1 respectively. In Scenario 3 and Scenario 4, the surface temperature of electrical heaters was adopted in accordance with thermal imaging results, where average front surface temperature value was 45°C. View factor F2 was calculated with respect to the students' positions and position of the Wall 4 and blackboard. The temperatures of the surfaces were given in Table 10 and Appendix 1.

According to the ISO 7730:2005, the highest asymmetry discomfort is caused by side-to-side (left to right) asymmetry. This fact was also confirmed with calculated view factors, which were lower for front-back than for left to right asymmetry.

Table 23. View factors regarding the students' position, radiant temperature asymmetry and percent dissatisfied for Scenario 3

Position index	F_1	$F_1 \cdot t_1$ [°C]	F_2	$F_2 \cdot t_2$ [°C]	Δt_{pr} [°C]	PD [%]
P1.1	0.001	0.05	0.10	2.38	-2.33	0.06
P1.2	0.001	0.05	0.10	2.38	-2.33	0.06
P1.3	0.001	0.05	0.10	2.38	-2.33	0.06
P1.4	0.001	0.05	0.10	2.38	-2.33	0.06
P1.5	0.001	0.05	0.10	2.38	-2.33	0.06
P1.6	0.001	0.05	0.10	2.38	-2.33	0.06
P2.1	0.0016	0.07	0.07	1.66	-1.59	0.08
P2.2	0.0016	0.07	0.07	1.66	-1.59	0.08
P2.3	0.0016	0.07	0.07	1.66	-1.59	0.08
P2.4	0.0016	0.07	0.07	1.66	-1.59	0.08

Position index	F_1	$F_1 \cdot t_1$ [°C]	F_2	$F_2 \cdot t_2$ [°C]	Δt_{pr} [°C]	PD [%]
P2.5	0.0016	0.07	0.07	1.66	-1.59	0.08
P2.6	0.0016	0.07	0.07	1.66	-1.59	0.08
P3.1	0.003	0.14	0.05	1.19	-1.05	0.09
P3.2	0.003	0.14	0.05	1.19	-1.05	0.09
P3.3	0.003	0.14	0.05	1.19	-1.05	0.09
P3.4	0.003	0.14	0.05	1.19	-1.05	0.09
P3.5	0.003	0.14	0.05	1.19	-1.05	0.09
P3.6	0.003	0.14	0.05	1.19	-1.05	0.09
P4.1	0.01	0.23	0.04	0.95	-0.73	0.10
P4.2	0.01	0.23	0.04	0.95	-0.73	0.10
P4.3	0.01	0.23	0.04	0.95	-0.73	0.10
P4.4	0.01	0.23	0.04	0.95	-0.73	0.10
P4.5	0.01	0.23	0.04	0.95	-0.73	0.10
P4.6	0.01	0.23	0.04	0.95	-0.73	0.10
P5.1	0.02	0.72	0.03	0.71	0.01	0.13
P5.2	0.02	0.72	0.03	0.71	0.01	0.13
P5.3	0.02	0.72	0.03	0.71	0.01	0.13
P5.4	0.02	0.72	0.03	0.71	0.01	0.13
P5.5	0.02	0.72	0.03	0.71	0.01	0.13
P5.6	0.02	0.72	0.03	0.71	0.01	0.13
min						**0.06**
max						**0.13**
average						**0.09**

Table 24. View factors regarding the students' position, radiant temperature asymmetry and percent dissatisfied for Scenario 4

Position index	F_1	$F_1 \cdot t_1$ [°C]	F_2	$F_2 \cdot t_2$ [°C]	Δt_{pr} [°C]	PD [%]
P1.1	0.001	0.05	0.10	2.33	-2.28	0.06
P1.2	0.001	0.05	0.10	2.33	-2.28	0.06
P1.3	0.001	0.05	0.10	2.33	-2.28	0.06
P1.4	0.001	0.05	0.10	2.33	-2.28	0.06
P1.5	0.001	0.05	0.10	2.33	-2.28	0.06
P1.6	0.001	0.05	0.10	2.33	-2.28	0.06
P2.1	0.0016	0.07	0.07	1.63	-1.56	0.08
P2.2	0.0016	0.07	0.07	1.63	-1.56	0.08
P2.3	0.0016	0.07	0.07	1.63	-1.56	0.08
P2.4	0.0016	0.07	0.07	1.63	-1.56	0.08
P2.5	0.0016	0.07	0.07	1.63	-1.56	0.08
P2.6	0.0016	0.07	0.07	1.63	-1.56	0.08
P3.1	0.003	0.14	0.05	1.16	-1.03	0.09
P3.2	0.003	0.14	0.05	1.16	-1.03	0.09
P3.3	0.003	0.14	0.05	1.16	-1.03	0.09

Position index	F_1	$F_1 \cdot t_1$ [°C]	F_2	$F_2 \cdot t_2$ [°C]	Δt_{pr} [°C]	PD [%]
P3.4	0.003	0.14	0.05	1.16	-1.03	0.09
P3.5	0.003	0.14	0.05	1.16	-1.03	0.09
P3.6	0.003	0.14	0.05	1.16	-1.03	0.09
P4.1	0.01	0.23	0.04	0.93	-0.71	0.11
P4.2	0.01	0.23	0.04	0.93	-0.71	0.11
P4.3	0.01	0.23	0.04	0.93	-0.71	0.11
P4.4	0.01	0.23	0.04	0.93	-0.71	0.11
P4.5	0.01	0.23	0.04	0.93	-0.71	0.11
P4.6	0.01	0.23	0.04	0.93	-0.71	0.11
P5.1	0.02	0.72	0.03	0.70	0.02	0.14
P5.2	0.02	0.72	0.03	0.70	0.02	0.14
P5.3	0.02	0.72	0.03	0.70	0.02	0.14
P5.4	0.02	0.72	0.03	0.70	0.02	0.14
P5.5	0.02	0.72	0.03	0.70	0.02	0.14
P5.6	0.02	0.72	0.03	0.70	0.02	0.14
min						**0.06**
max						**0.14**
average						**0.10**

According to the results of the measurements, the very low percent dissatisfied was predicted during all scenarios regarding radiant asymmetry, which is explained by relatively similar temperatures of the classroom thermal envelope and small radiant surfaces of the electrical heaters. There was no record of any significantly cold surface in the classroom. The asymmetry would be more conspicuous if there were cold walls surfaces surrounding the students. The percent dissatisfied never even reached 0.5%, which indicates that the thermal environment was in category "A". This result turned out to be more different than it was predicted in initial hypothesis. Initially, the expected higher impact of radiant asymmetry was correlated with additional electrical heaters behind the students' back. This impact turned out to be significant only for the students seating right in front of the heaters. For the others, this influence was of no importance in radiant point of view, because of the small heaters' surfaces. Only the impact of higher air temperature in whole classroom was dominant, and thus the overall radiant temperature, also.

4.9. Skin surface temperature measurements

The various studies regarding correlation between the skin temperature and thermal comfort were conducted in the past, mostly in climate chambers, on manikins, [47, 48, 68, 76-81]. One of the pioneering investigations was conducted in 1985 by Fanger et al. [65]. They correlated the impact of the radiant asymmetry and percent dissatisfied with thermal environment, with the skin temperature. The most important conclusions were that the local cold surfaces more likely cause discomfort than the warm ones, that the skin temperature of the part of the body exposed to the radiant asymmetry is changeable and causes the heat losses from the human body and that it is preferable for a human to have higher temperature in a feet zone and lower in the zone of the head (for more details see [65]).

Foda and Siren [82] applied Pierce two-node model for local skin temperature prediction using modifications. They performed the investigation in controlled environment and validated the model accuracy. Their results showed that the revised model predicts local skin temperature with average deviation of ±0.3°C [82]. According to Doherty and Arens [83], Pierce two-node model for local skin temperature prediction gives decent predictions for people seated at rest, but for the activity level, such is exercising, it is not accurate enough.

The complex nature of the human body and its physiological and psychological state are in a direct relationship with people thermal sensation votes. The skin temperature is one of the indicators of possible local discomfort, together with the psychological state, which is very difficult to evaluate.

In order to determine the impact of the indoor environment on occupants' physiological state, the measurements of skin surface temperature were performed on a group of voluntaries every day, right after the statistical survey. The results of measurements are presented in Figure 13.

The measurements were done, for the both right and the left cheeks, using IC thermometer in order to investigate hypothesis about non-uniform local thermal conditions and asymmetric radiation. In general, the temperatures of the left and right cheek turned out to be the same. The slight deviations of 0.1°C were within accuracy range of the thermometer. Due to the similar results and comprehensive number of data, the diagrams were formed only for the left side values. The voluntaries which were chosen as relevant ones for the research stated that they were in a good physical shape, with no illness symptoms whatsoever suggested in questionnaire.

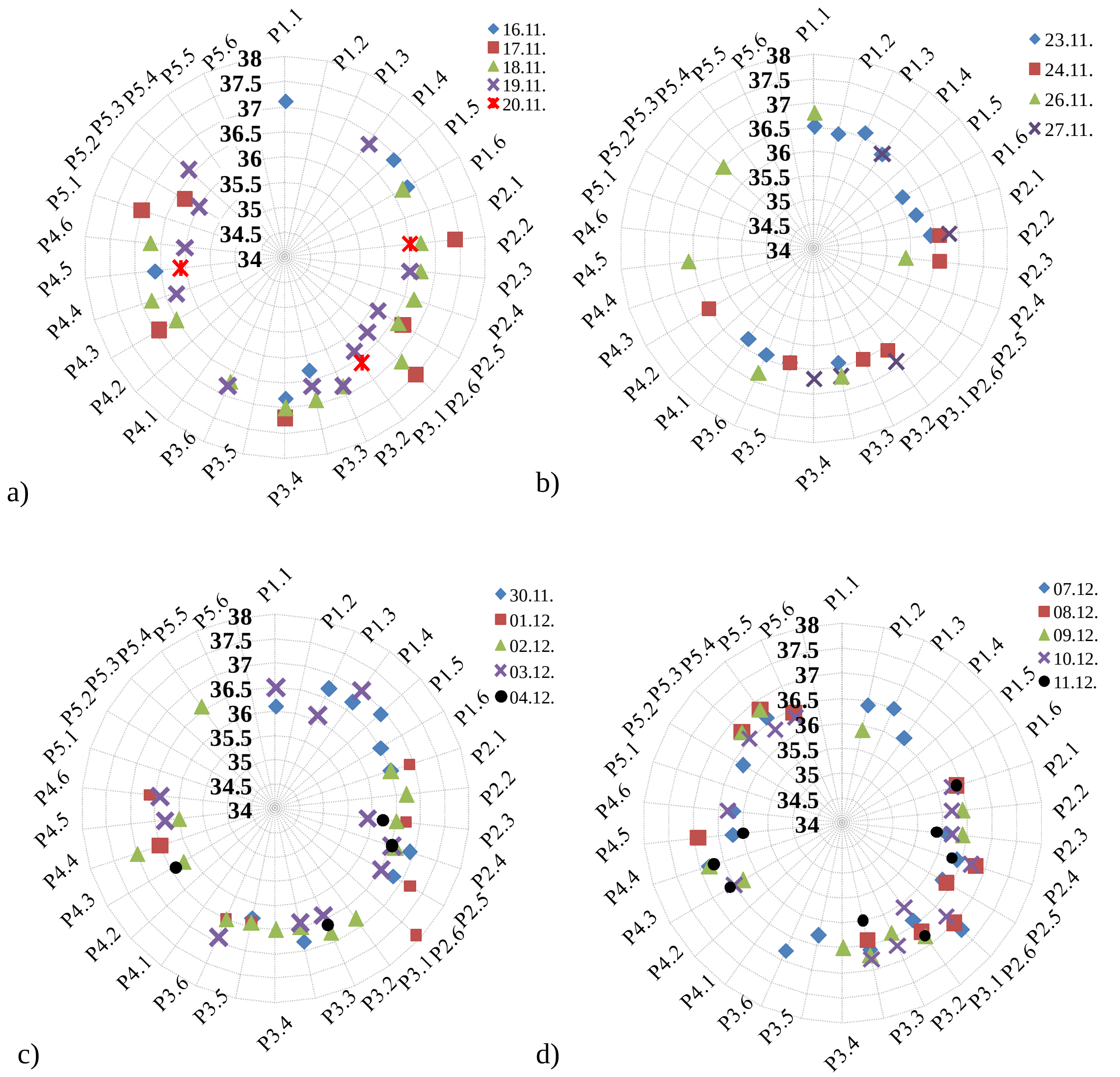

Figure 13. Students' skin temperature for four scenarios: a) Scenario 1, b) Scenario 2, c) Scenario 3 and d) Scenario 4

The total number of valid data, measured on voluntaries in Scenario 1 was 42, in Scenario 2 was 29, in Scenario 3 was 47 and in Scenario 4 was 58, which is 176 data for four scenarios in total. The average skin temperature was between 36.5 and 36.7°C. More obvious deviations regarding the temperature of the left and right side of the cheeks appeared in Scenario 4, among the students seated right in front of the electrical heaters, where the deviations reached 0.4°C, which can indicate the non-uniformity of the thermal environment caused by local radiant asymmetry.

The correlation between the students' cheek temperature and thermal sensation votes (TSV) is presented on Figure 14.

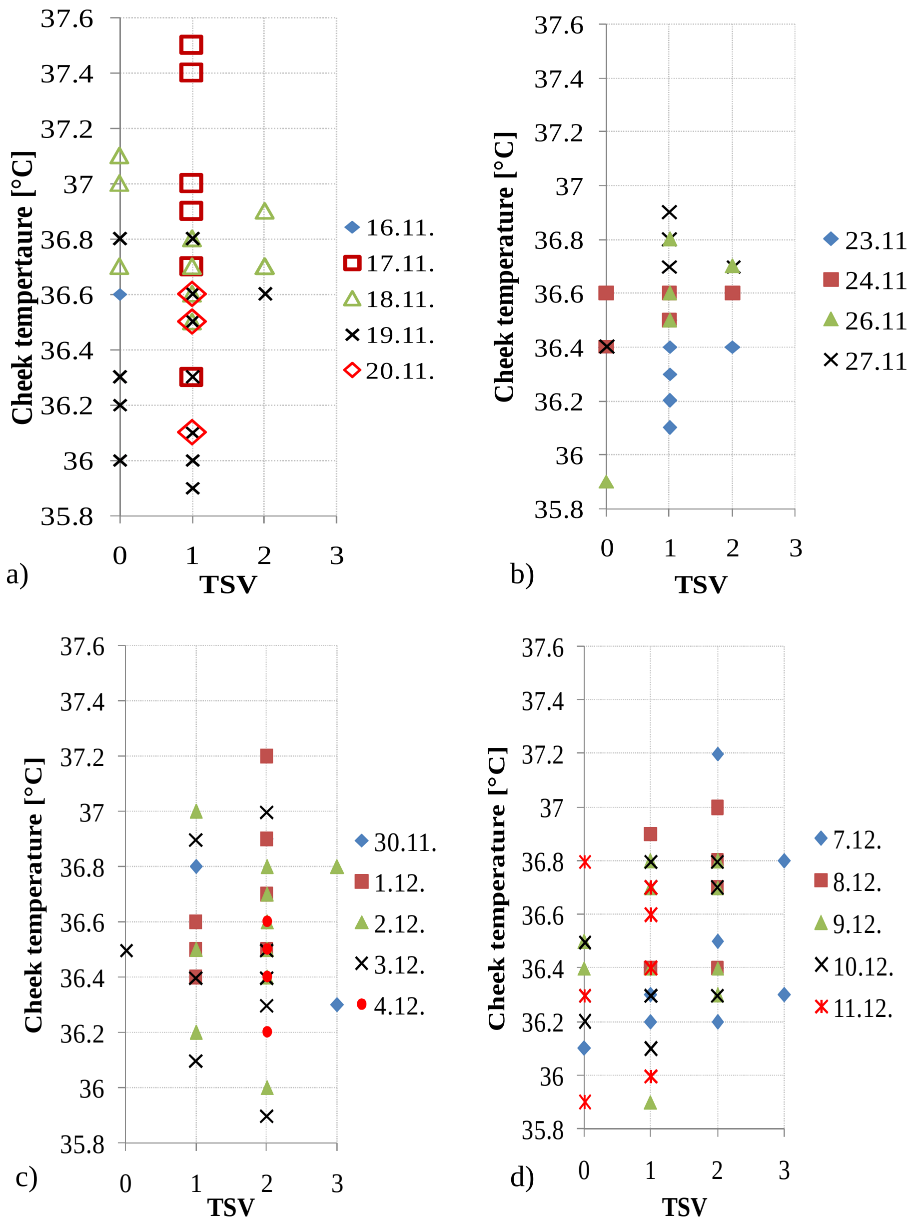

Figure 14. Students' thermal sensation votes for a) Scenario 1, b) Scenario 2, c) Scenario 3 and d) Scenario 4

According to the measurements, the most uniformed students' cheek temperature and TSV was noticed in Scenario 2, which was recognized as the most comfortable one. The biggest variations in TSV were noticed in Scenario 4, where the votes were allotted almost equally from neutral to warm, with some students having thermal sensation of hot environment also.

4.10. The results of the thermal imaging camera recording

The spot measurements of temperature taken by thermal imaging camera were performed right after the statistical survey, productivity tests and cheek temperature measurements, in order to measure the clothes and body temperature, and to check and compare the temperature of the local surfaces, also. The thermal imaging camera FLIR E40bx was used. The emissivity factor for human skin was set to value of 0.98 [84]. These measurements were not used for the calculations. The temperature of the front side of the electrical heaters was used, as an input result for the radiant asymmetry calculation. The obtained camera shots are presented on Figure 15 to 19.

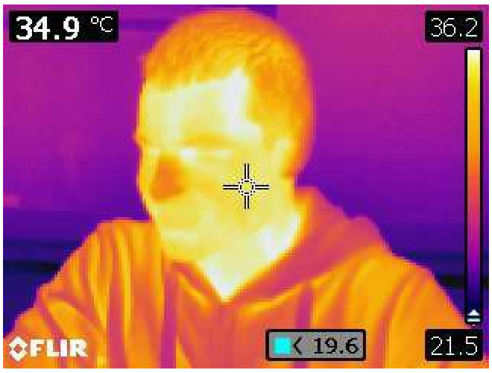

Figure 15. Camera shot taken in Scenario 1, on Friday, 20.11.2015.

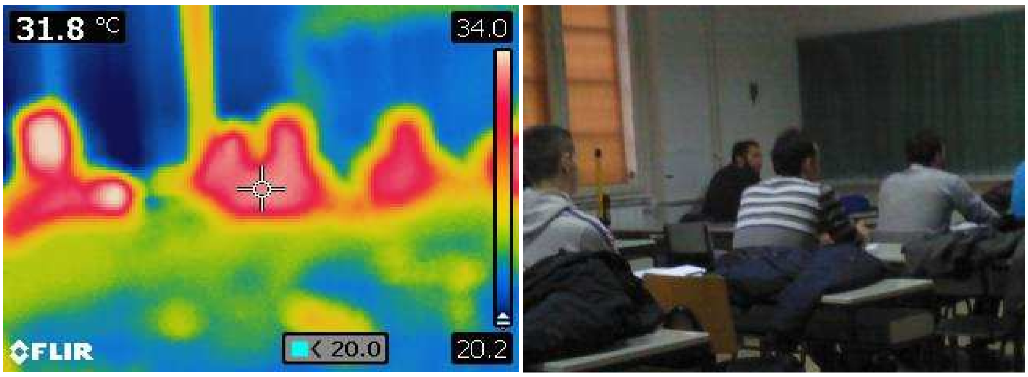

Figure 16. Camera shot taken in Scenario 2, on Thursday, 26.11.2015.

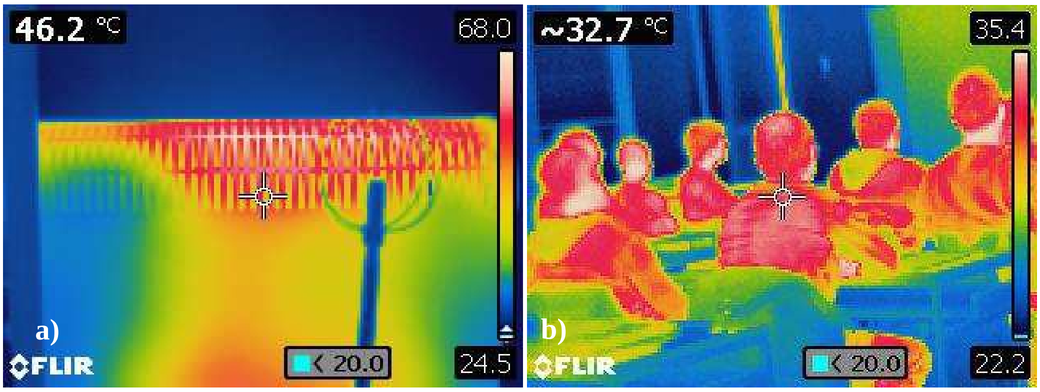

Figure 17. Camera shot taken in Scenario 3: a) on Tuesday, 1.12.2015.

b) on Wednesday, 2.12.2015.

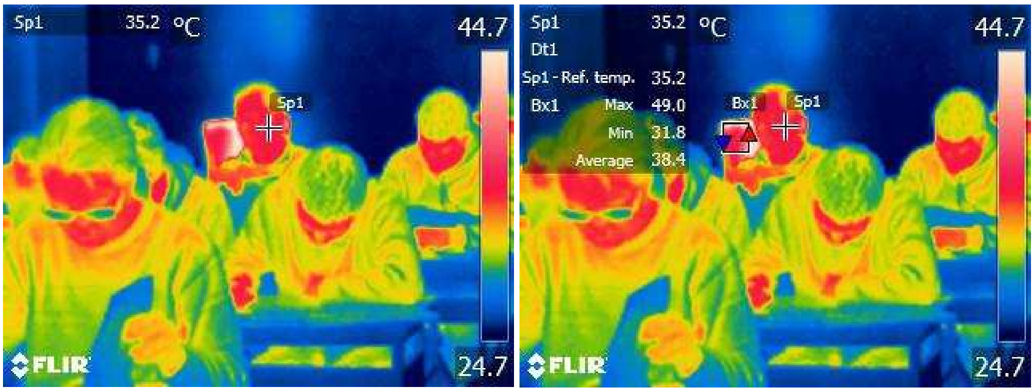

Figure 18. Camera shots taken in Scenario 4, on Tuesday, 8.12.2015.

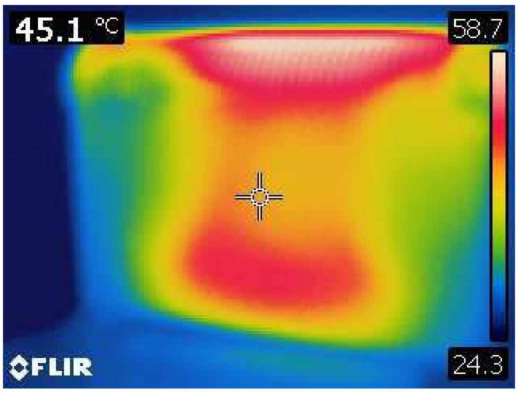

Figure 19. Camera shot taken in Scenario 4, on Wednesday, 9.11.2015.

As the control measurements within each of the scenarios, the results of the thermal imaging camera recording of the observed classroom's thermal envelope, together with the surface of users' clothing and the surface skin temperature, were used and are shown in this chapter.

CHAPTER 5

"If you don't go after what you want, you'll never have it.
If you don't ask, the answer is always no.
If you don't step forward, you're always in the same place."
Nora Roberts
"Ако не трагате за оним што желите, нећете га имати.
Ако не питате, одговор је увек не.
Ако не искорачите, увек ћете стајати у месту."
Нора Робертс

5. STATISTICAL SURVEY

5.1. Methodology of subjective evaluation

In order to establish the relations between the objective measured physical parameters of thermal comfort in observed classroom and the students' subjective feelings, the standard procedure with questionnaires was performed.

Some examples of questionnaires for occupants' subjective evaluation are given in EN 15251:2007 [36]. The questionnaires should had been filled out after the continuous stay in evaluated space, and not just after arrival or lunch break [36]. The types of questionnaires that were used in this research were created for this purpose with a special attention to the impact of productivity loss. The general one is presented in Appendix 4.

The measurement and the survey were performed during four weeks, every day. On Mondays, Tuesdays and Wednesdays the experiments were done in the afternoon, from 2 pm until 7 pm, and on Thursdays and Fridays in the morning, from 8 or 9 am until 1 pm. The investigated group of students was the same during these four weeks. The total number of students which were officially involved in the subjects is 115 during the week, but not all of them were always present, although not all of the lectures were obligatory. Usually, around 30-60 students were involved in investigation in each scenario during the week.

For the purpose of the survey, each seat at every school desk was labeled with a label, on which the first mark defined the row and the second one defined a student's position (where *P1.1* stands for position 1 in first row), as it is presented in Figure 20.

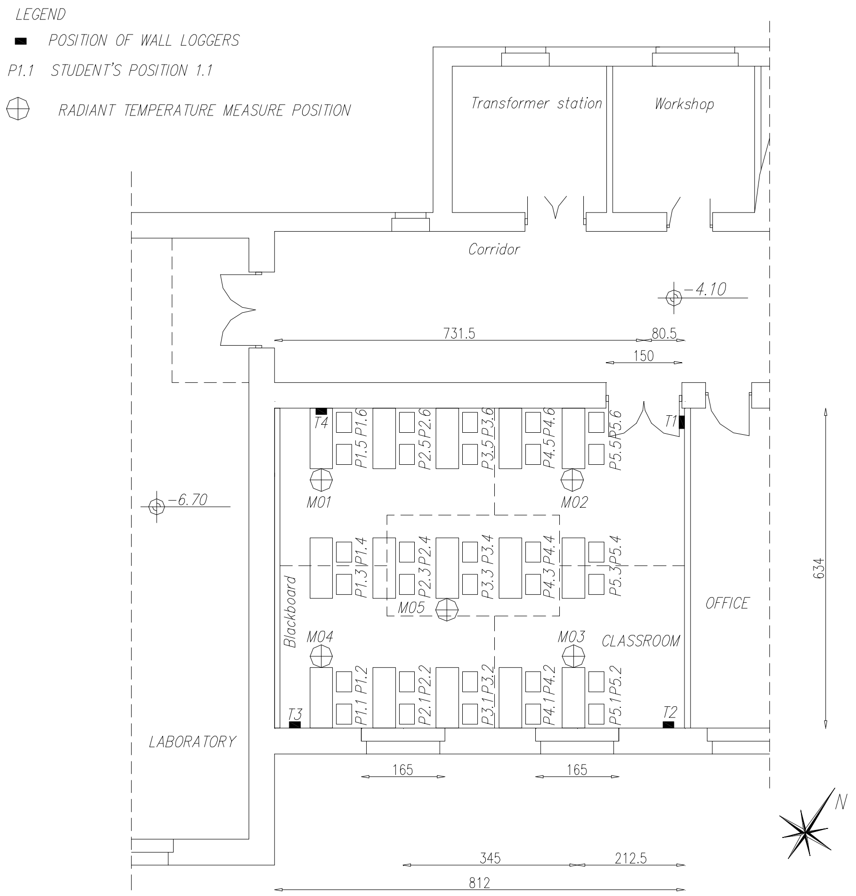

Figure 20. Students' positions and five characteristic classroom segments

The surveys were performed every day, after the relevant number of classes, but never before at least than two classes (90 minutes) in continuity in order to secure the students' adaptation to the environment. The observed population was between the ages of 20 and 25 years, predominantly male, healthy and in good shape. As the experiments were done in the winter period, the men clothing was pretty much the same: a sweater or a jacket, t-shirt or a shirt, trousers or jeans, socks, classic underwear, and sneakers or shoes. According to ASHRAE Handbook – Fundamentals [40] and ASHRAE Standard 55-2013 [35], as it is given in Table 3, clothing ensembles mentioned has a value of 1.01 clo. For sedentary school activity, typical recommended value for metabolic rate is 1.2 Met [35, 36].

The questionnaires were divided in two types. First type of questionnaire was general one, asking the questions about the physical state of the student, type of the clothing, questions about the general thermal comfort, local discomfort, subjective evaluation of productivity loss and the general air quality. In this questionnaire, the important part was the question about students' physical health, which was an elimination factor, in order to exclude the subjective response given by students with fever, headache, toothache, sniffle or sore throat. The answers of the students feeling sick were excluded from the research analysis. In this manner, the objectivity of answers was higher. The example of the questionnaire is given in Appendix 4.

The second part of the survey was dedicated to the concentration test in order to evaluate the productivity loss which is in correlation with local thermal comfort. The test was different each day. After the significant number of classes, without the break, the prepared text with approximately 200 words was read to the students. After the reading, the students were given the tests with 5 questions from the text that they had to fulfill. The texts were different each day, with subjects that were interesting, but not very well known. Usually, they were given texts about some of the geographical wonders all over the world, or some interesting historical facts, which were not the subjects that they were studying. The students were asked about the names, years or some facts from the text. Having in mind that these subjects were not their field of research at university, and also were not widely known, it is assumed that the facts were totally unknown to them. This assumption was of a big interest for concentration estimation. It is important to emphasize that students had in mind that they were tested and wanted to fulfill the tests as best as they could, regardless the anonymous character of the tests, so they had higher attention during the reading, which was not the same level as during the classes. Also, the interesting nature of the texts was an aggravating factor for the estimation. ***This kind of research hasn't been conducted before in this manner and it is one of the contributions of this research. It is very difficult to conduct the mental concentration tests in real conditions, during the real classes. This was a huge challenge.***

5.2. The results of the survey regarding students' subjective evaluations

5.2.1. The overall IAQ - survey estimation

The part of the general survey was the overall students' estimation of indoor air quality in classroom. The students were asked about air quality, the symptoms they felt and about the percent of IAQ impact on their thinking concentration and intensity of memory loss. The questionnaire is given in Appendix 4, together with the students' answers. The overall analysis for Scenario 1 is given in Figure 21. Around 51% of students (from 55 answers in total) estimated the air quality as poor. The average percent of poor IAQ impact on students' productivity and concentration was 19%. About 56% of 55 votes in total stated that they had some or all of the symptoms given in questionnaire such as: stuffiness, sleepiness, reduced concentration and hard breathing. Only 4% felt all of the symptoms.

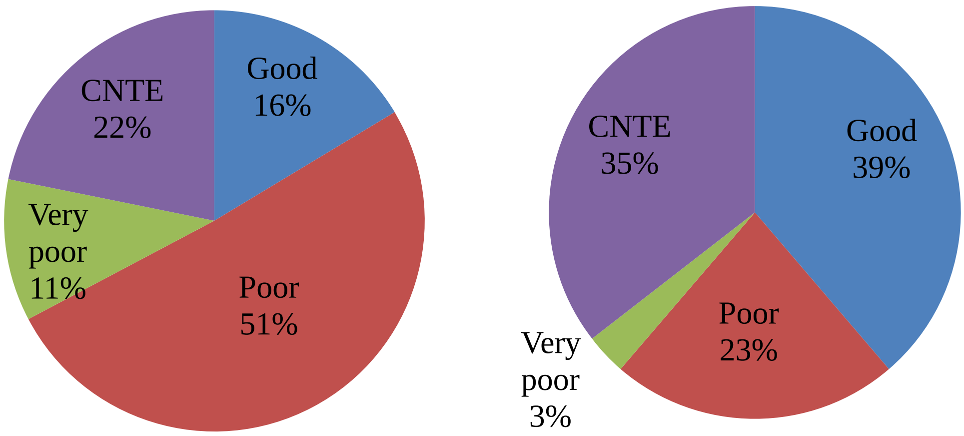

Figure 21. Students' votes for IAQ for Scenario 1 (left) and Scenario 2 (right)[5]

Scenario 2 showed better results, as it was expected. The overall share of votes is shown on Figure 21. About 39% of students evaluated the IAQ as good. In this scenario, no one stated to have all four symptoms given in questionnaire. Further, 26% of students (from 31 votes in total) felt some of the symptoms, and no one stated to feel all of them.

The Scenario 3 proved to be the most uncomfortable for the occupants. Of 55 votes in total, 51% stated that the IAQ in classroom was poor during the third scenario. The distribution of votes is given in Figure 22. According to the analysis, 71% of students had some or all of the symptoms described in questionnaire (Appendix 4), and 15% had all of the symptoms.

[5] Abbreviation CNTE - can't be estimated.

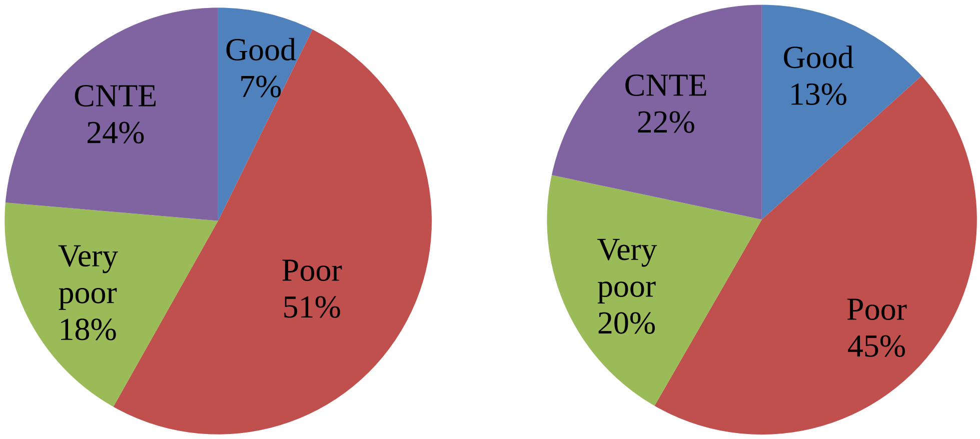

Figure 22. The IAQ during the Scenario 3 (left) and Scenario 4 (right) - students' survey

Also, the Scenario 4 turned out to be one with a poor IAQ in classroom, with 20% of votes for very poor and 45% of 60 votes in total for poor IAQ. The distribution is given in Figure 23.

During the Scenario 4, around 63% of students stated that they felt one, two, three or four of the symptoms offered in questionnaires, such as: stuffiness, sleepiness, reduced concentration and hard breathing. Also, 15% of students felt all four symptoms.

The reduced concentration and thinking ability caused by poor IAQ in classroom, according to the subjective students' evaluation is obtained for each scenario, as a percent of votes in overall number of votes, separately for each scenario and are presented together on Figure 23.

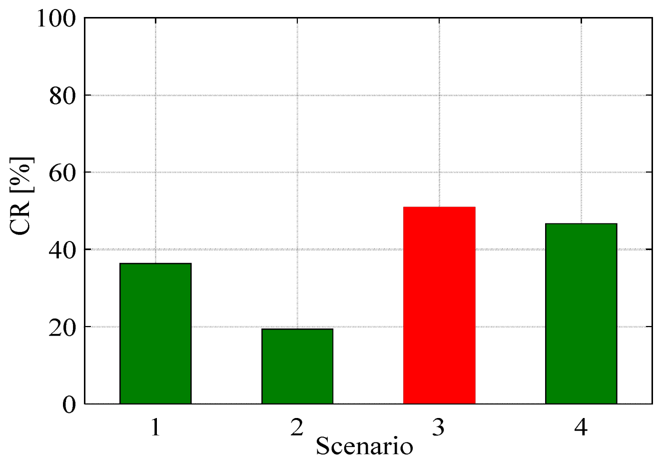

Figure 23. Students' evaluation regarding reduced concentration ability caused by poor IAQ in classroom

The concentration loss was the lowest in Scenario 2 (around 20%), and the highest in Scenario 3 (more than 50%). It is interesting to notice that the students' perception about concentration ability loss caused by poor IAQ in classroom was around 20% in neutral thermal conditions, when also the measured CO_2 concentration was within the desirable level (Table 12) in accordance with standards.

Looking at the overall results for IAQ for all scenarios, the conclusions can be drawn as follows:

the students' subjective feelings about IAQ in classroom generally match with overall results on IAQ obtained by measurements; the occupants were most sensitive to high temperatures and lack of ventilation (in scenarios with measured high CO_2 concentrations); negative impact on students’ health was noticeable, having in mind that students' were also additionally complaining on having a headache in Scenario 3 and Scenario 4; the thinking productivity and memory ability was also decreased, according to students' votes.

5.2.2. PMV evaluations and impact on PLOS

Through questionnaires the students were asked to vote the thermal comfort parameters in the classroom every day, for each scenario. The results are shown in Figures 24 to 31. The students who didn’t feel well during the evaluations are excluded, and their subjective rating is not considered in a result analysis.

The special contribution of this research is the novel index, introduced for the first time describing the quantitative subjective percentage of thermal comfort impact on students' concentration and productivity loss, TIP in further text. TIP has values from 0% to 100%, meaning that 0% is for no impact of thermal comfort on productivity and 100% is for total dissatisfaction with thermal comfort and a huge impact on productivity. It is used to evaluate the personal perception of thermal comfort in indoor space.

Students' votes distribution regarding PMV index in Scenario 1 is shown on Figure 24.

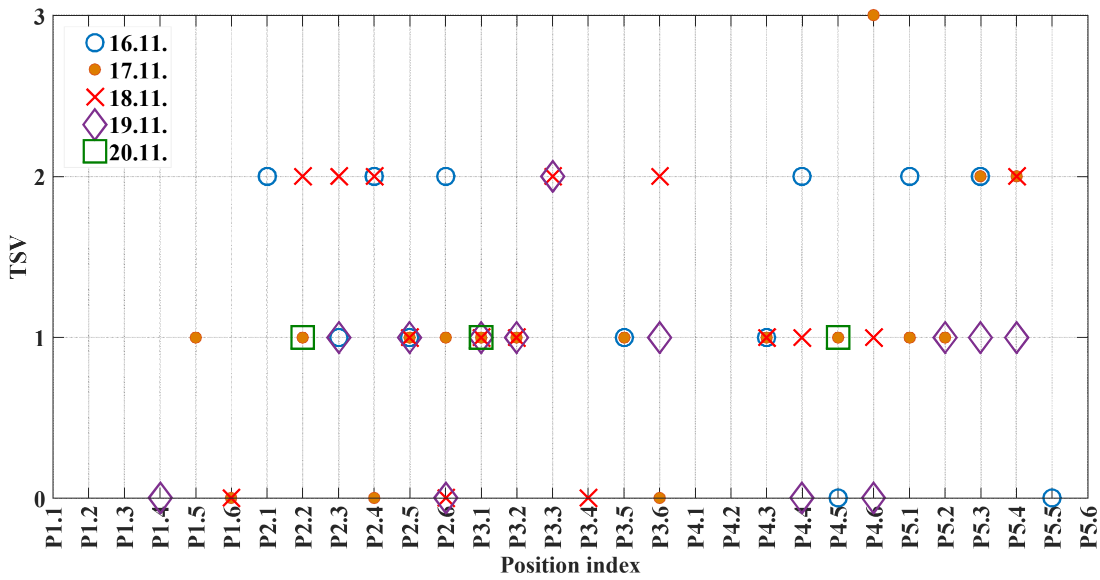

Figure 24. Students' votes distribution regarding TSV index in Scenario 1

The results showed that 53% of 60 votes in total had a TSV index 1. Another 20% felt neutral, with TSV=0. Further, 25% had the worm thermal sensation, and only 1 vote stated that in the classroom was hot.

As it is shown on Figure 25. high percentage of students' votes showed that the TIP index in classroom during Scenario 1 was around and lower than 20%.

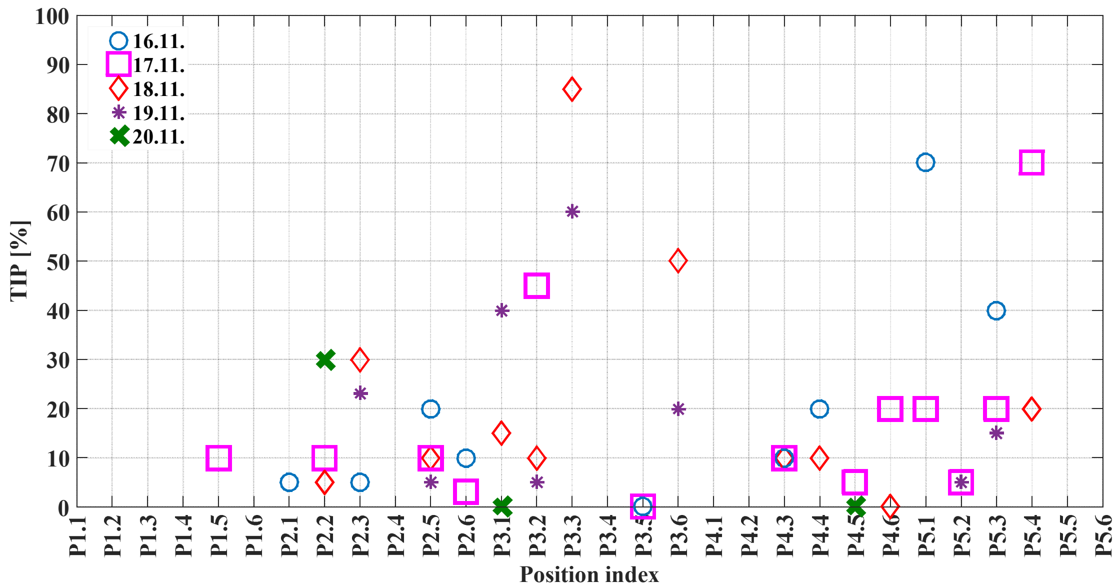

Figure 25. Students' votes distribution regarding dissatisfaction in Scenario 1

The averaged TSV for Scenario 1 was 1.1, while TIP was around 20.6%.

The students' votes regarding TSV and TIP indexes in Scenario 2 are shown on Figure 26 and 27 respectively.

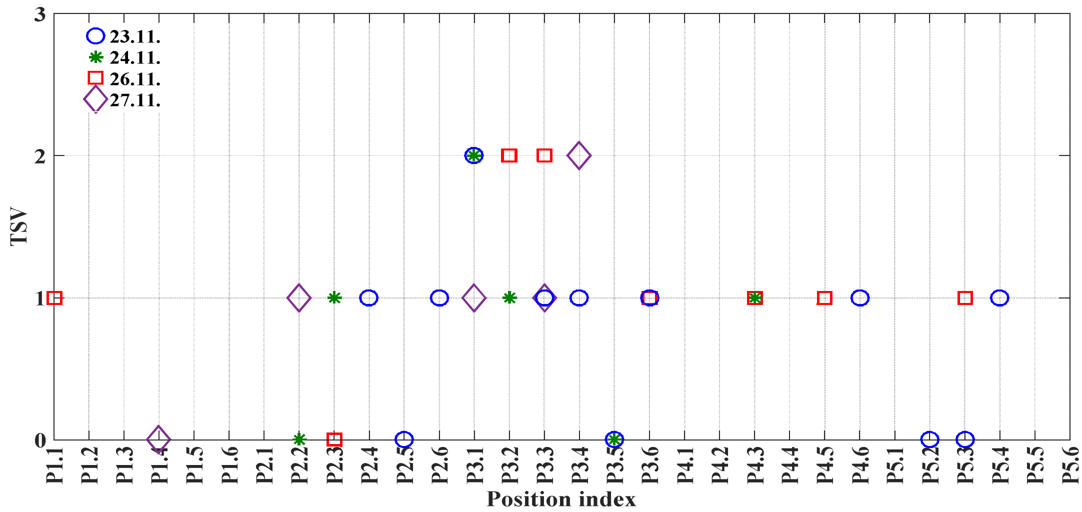

Figure 26. TSV index voted by students for Scenario 2

According to analysis of students' subjective evaluation, the 58% of students had a feeling of slightly warm environmental conditions in classroom, while 26% felt neutral. The rest of 16% felt warm, while no one evaluated the environment as hot. The averaged TSV for Scenario 2 was 0.9.

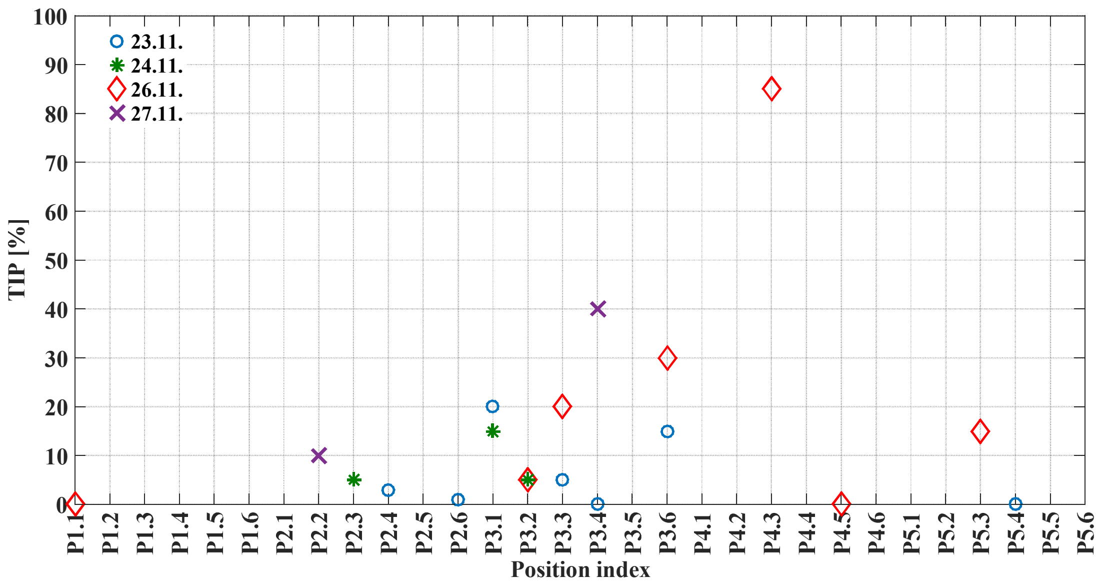

Figure 27. The students' subjective dissatisfaction with thermal comfort in Scenario 2

The averaged subjective percent of thermal environment impact on productivity loss for this scenario was 14%.

Third scenario was the list pleasant, according to the TSV index voted by students.

The subjective evaluation showed that the average TSV was 1.6, while the averaged percent of dissatisfaction, according to votes was 27.3%. The subjective evaluation for thermal sensation for Scenario 3 is given on Figure 28. The 56% of students stated that it was warm in the classroom, 37% felt slightly warm, while 6% stated that it was hot.

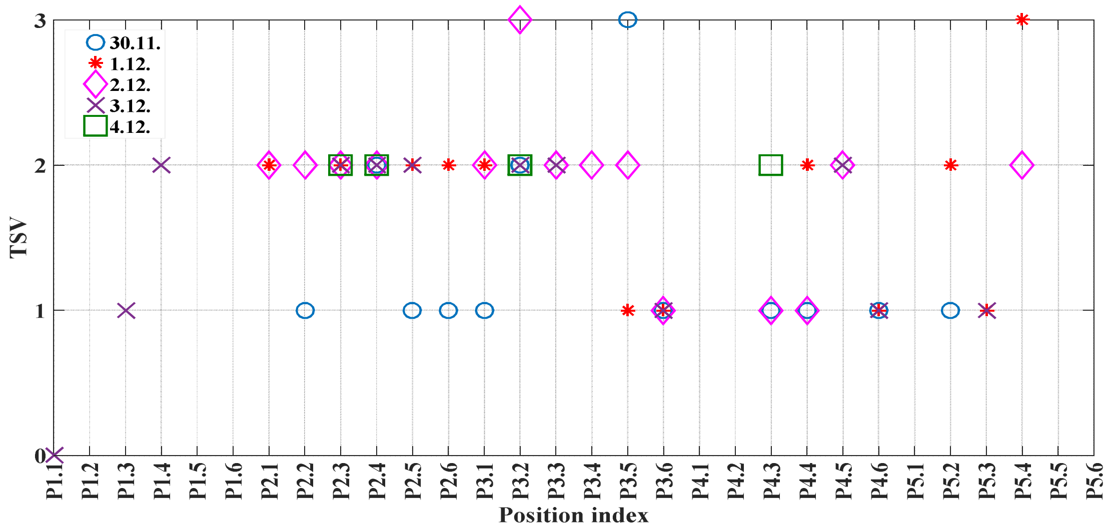

Figure 28. Students' votes for thermal environment sensation in Scenario 3

The students' evaluation of thermal comfort impact on productivity loss in Scenario 3 is shown on Figure 29. Averaged feeling was that thermal comfort impacted around 25.4% students' capability of thinking and productivity loss.

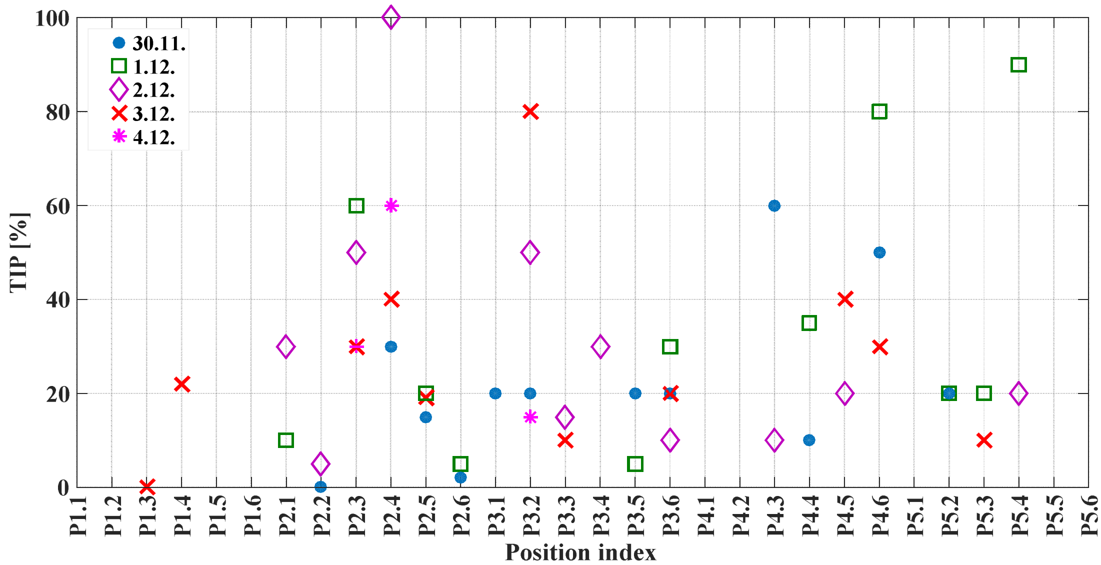

Figure 29. The students' subjective dissatisfaction with thermal comfort in Scenario 3

In Scenario 4, average feeling of thermal environment was evaluated as TSV=1.3 (Figure 30). The average impact on PLOS was evaluated as27.3%, which indicated that the overall feeling of dissatisfaction with thermal comfort was highest precisely in the fourth scenario (Figure 31). Having in mind the votes for thermal environment satisfaction, where 19% stated to feel neutral, 37% slightly warm, 39% warm and 5% hot, it can be concluded that the overall dissatisfaction was not just caused by the temperature, but also by the global conditions in the classroom, which was expected according to the measurements of CO_2 concentration in Scenario 4, which is shown to be the highest precisely in this scenario.

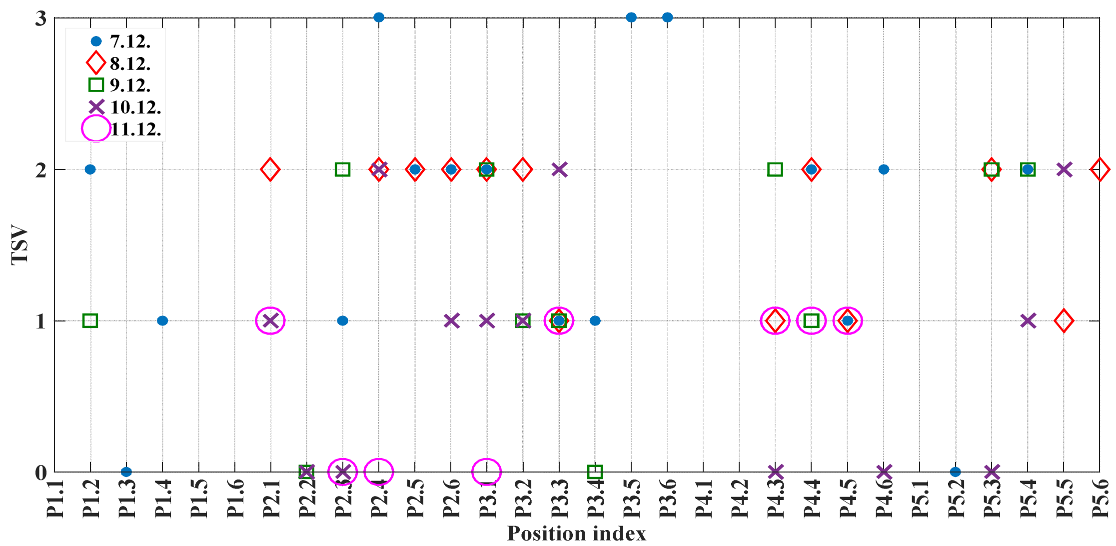

Figure 30. Students' votes for thermal comfort in Scenario 4

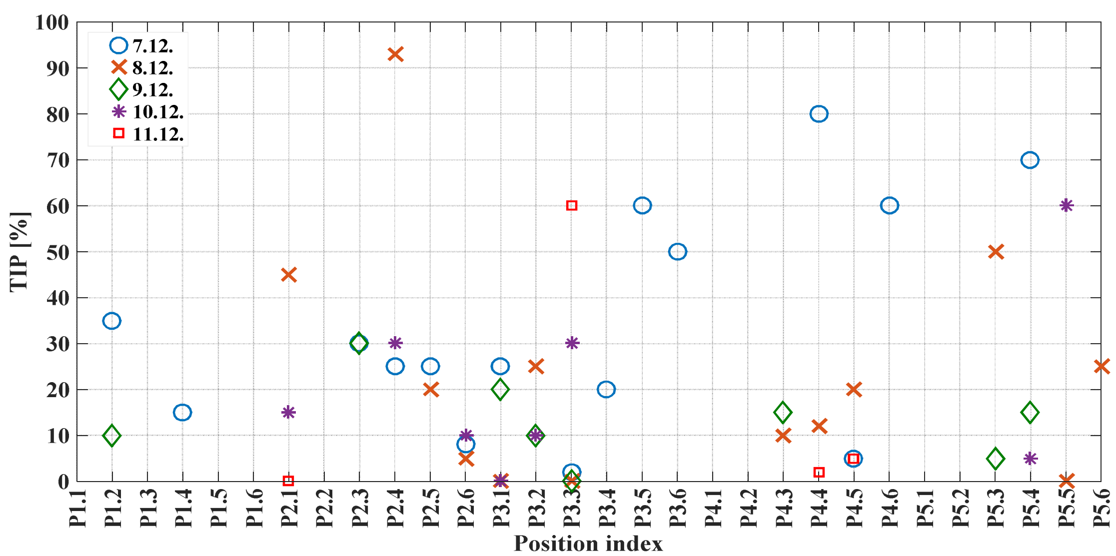

Figure 31. Students' dissatisfaction with thermal comfort for Scenario 4

The summarized votes for all scenarios, for each position are shown in Table 25. The averaged values show that the Scenario 4 was the most unpleasant, with around 27% percent impact on PLOS, right next to the Scenario 3 with 25.4% percent impact on PLOS. It is interesting that the TSV evaluation showed that students in Scenario 3 felt more unpleasant, voted 1.6, than for Scenario 4, when TSV was voted 1.3.

Table 25. The students' answers regarding PMV and TIP summarized for all scenarios

	Scenario 1 averaged			Scenario 2 averaged			Scenario 3 averaged			Scenario 4 averaged		
Position index	**TSV**	**TIP %**	**Posit. occupancy %**	**TSV**	**TIP %**	**Posit. occupancy %**	**TSV**	**TIP %**	**Posit. occupancy %**	**TSV**	**TIP %**	**Posit. occupancy %**
P1.1			0	1.0	0.0	25	0.0		20			0
P1.2			0			0			0			40
P1.3			0			0	1.0	0	20	0.0		20
P1.4	0.0		20	0.0		25	2.0	22	20	1.0	15.0	20
P1.5	1.0	10.0	20			0			0			0
P1.6			20			0			0			0
P2.1	2.0	5.0	40			0	2.0	20	40	1.3	20.0	60
P2.2	1.3	15.0	60	0.5	10.0	50	1.5	3	40	0.0		60
P2.3	1.3	19.3	80	0.5	5.0	50	2.0	43	80	0.8	30.0	100
P2.4	1.3		80	1.0	3.0	75	2.0	58	80	1.8	49.3	100
P2.5	1.0	11.3	80	0.0		75	1.7	18	60	2.0	22.5	40
P2.6	0.8	6.5	80	1.0	1.0	25	1.5	4	40	1.7	7.7	60
P3.1	1.0	18.3	100	1.7	17.5	75	1.7	20	60	1.4	11.3	100
P3.2	1.0	20.0	80	1.5	5.0	75	2.3	41	100	1.3	15.0	60
P3.3	2.0	72.5	80	1.3	12.5	75	2.0	13	80	1.2	18.4	100
P3.4	0.0		80	1.5	20.0	50	2.0	30	60	0.5	20.0	60
P3.5			60			50	2.0	13	60	3.0	60.0	20
P3.6	1.0	35.0	80	1.0	22.5	50	1.0	20	80	3.0	50.0	20
P4.1			0			0			0			0
P4.2			0			0			0			0
P4.3	1.0	10.0	100	1.0	85.0	50	1.3	35	60	1.0	12.5	100
P4.4	1.0	15.0	60			25	1.3	23	80	1.5	31.3	80
P4.5	0.7	2.5	80	1.0	0.0	25	2.0	30	40	1.0	10.0	60
P4.6	1.3	10.0	80	1.0		25	1.0	53	60	1.0	60.0	60
P5.1	1.5	45.0	60			25			0			0
P5.2	1.0	5.0	60	0.0		25	1.5	20	40	0.0		20
P5.3	1.7	25.0	60	0.5	15.0	50	1.0	15	80	1.3	27.5	60
P5.4	1.7	45.0	80	1.0	0.0	50	2.5	55	40	1.7	30.0	80
P5.5	0.0		40			0			0	1.5	30.0	40
P5.6			40			0			0	2.0	25.0	0
Average	1.1	20.6		0.9	14.0		1.6	25.4		1.3	27.3	

This could be the consequence of subjective feeling of the highest operative and radiant temperatures in Scenario 3, having in mind that in Scenario 4, the radiators were turned off. The other possibility is the CO_2 concentration which was almost 35% higher in Scenario 4 (Table 14), and almost twice as high than the ones recommended in standard ISO 7730:2005, so the students had more unpleasant sensations of the overall comfort in the classroom.

The overall results of students' evaluation are in accordance with the measured values for four scenarios. The values are higher than calculated, having in mind the ASHRAE thermal scale, and the questionnaire structure in which the values on scale are from -3 to +3, with a step 1. The measured values are presented for minor notches of the scale. Regardless the size of the notches, the distribution of the average voted value of TSV for each scenario is in accordance with a measured PMV.

5.2.3. The local thermal discomfort survey

5.2.3.1. Discomfort caused by draught

The students' subjective evaluation was performed every day in each scenario and presented for each position in all scenarios. The number of students participating in the evaluation is expressed through the percent of position occupancy. So, if a student seated at the position and voted only one day a week, the total occupancy value for that position is 20%. If there was no one on a position, the row was left blank, as if the student didn't answer that question. The total number of valid answers in Scenario 1 was 53. The answers which were obviously not objective and could not be included into the final conclusion were excluded and highlighted red. About 35.8% of the students stated that they were sensitive to draught, but averaged draught intensity voted by students was only 0.46%.

Gray fields represent the students who stated that didn't feel well, having the symptoms previously described. The students were asked if they were sensitive to draught (given in tables as "Sens. Y/N" for "Yes" and "No") and the percent of draught intensity that they felt in the classroom (DR [%]).

Looking at the students' evaluations from Table 26 for Scenario 1, the draught was not noticeable in the classroom. Only the students seated near the windows (position P2.2 and P3.1 and 3.3) felt some air movement, subjectively expressed as a 10% of the intensity.

Table 26. Draught intensity voted by students in Scenario 1

Position index	16.11		17.11		18.11		19.11		20.11		Percentage of position occupancy	Number of answers
	Sens.	DR	Sens.	DR	Sens.	DR	Sens.	DR	Sens.	DR		
	Y/N	%	Y/N	%	Y/N	%	Y/N	%	Y/N	%	%	
P1.1											0	0
P1.2											0	0
P1.3											0	0
P1.4							Y	0			20	1
P1.5			Y	0							20	1
P1.6			Y	0	N	0					20	2
P2.1	N	0									40	1
P2.2			N	10	Y	0				0	60	3
P2.3	N	0			N	0	N	0			80	3
P2.4			N	0	N	0					80	2
P2.5	N	0	N	0	N	0	N	0			80	4
P2.6	N	0	N	0	N	0					80	3
P3.1					N	10	Y	0	N	0	100	3
P3.2			N	0	Y	0					80	2
P3.3							N	10			80	1
P3.4					N	0					80	1
P3.5	N	0	Y	0							60	2
P3.6			N	0			Y	0			80	2
P4.1											0	0
P4.2											0	0
P4.3			N	0	Y	0					100	2
P4.4	N				Y	0	Y	0			60	3
P4.5	Y	0	N	0						0	80	3
P4.6			N	0	N	0	Y	0			80	3
P5.1	N	0	Y	0							60	2
P5.2			Y	0			N	0			60	2
P5.3	Y	0	Y	0			N	0			60	3
P5.4			N	0	N	0	Y	0			80	3
P5.5	Y	0									40	1
P5.6											40	0

Note: (Gray fields represent the students who stated that they didn't feel well, having the symptoms described above.)

In Scenario 2, no one (from 31 answers) felt the air movement neither the draught, and 39% of students stated that they were sensitive to draught, as it was shown in Table 27. which was not in correlation with the measured values. The measured velocities near windows showed that there was some draught impact at these positions (Table A3.1. given in Appendix 3). The Scenario 2 had four days of measurements due to lack of classes on 25.11.2015.

Table 27. Draught intensity voted by students in Scenario 2

Position index	23.11		24.11		26.11		27.11		Percentage of position occupancy	Number of answers
	Sens.	DR	Sens.	DR	Sens.	DR	Sens.	DR		
	Y/N	%	Y/N	%	Y/N	%	Y/N	%	%	
P1.1					N	0			25	1
P1.2									0	0
P1.3									0	0
P1.4							Y	0	25	1
P1.5									0	0
P1.6									0	0
P2.1									0	0
P2.2			N	0			N	0	50	2
P2.3			Y	0	N	0			50	2
P2.4	N	0							75	1
P2.5	N	0							75	1
P2.6	N	0							25	1
P3.1	N	0	N	0			N	0	75	3
P3.2			Y	0	Y	0			75	2
P3.3	Y	0			N	0	N	0	75	3
P3.4	N	0					N	0	50	2
P3.5	N	0	N	0					50	2
P3.6	Y	0			Y	0			50	2
P4.1									0	0
P4.2									0	0
P4.3			N	0	Y	0			50	2
P4.4									25	0
P4.5					Y	0			25	1
P4.6	Y	0							25	1
P5.1									25	0
P5.2	N	0							25	1
P5.3	Y	0			N	0			50	2
P5.4	Y	0							50	1
P5.5									0	0
P5.6									0	0

Note: (Gray fields represent the students who stated that they didn't feel well, having the symptoms described above.)

In scenario 3 (Table 28) some of the students, from total 53 answers, felt the draught, the ones near the windows and also at the positions closer to electrical heaters, which also caused air movement, driven by the buoyancy effect. Averaged subjective feeling was 3.3% of draught intensity for the whole scenario, and 39.6% of students stated that they are sensitive to draught. On Monday and Tuesday, students felt around 8% of draught intensity averaged for all positions. On Thursday and Friday they felt no draught.

Table 28. Draught intensity voted by students in Scenario 3

Position index	30.11		1.12		2.12		3.12		4.12		Percent. of position occupancy	Numb. of answers
	Sens.	DR	Sens.	DR	Sens.	DR	Sens.	DR	Sens.	DR		
	Y/N	%	Y/N	%	Y/N	%	Y/N	%	Y/N	%	%	
P1.1							N	0			20	1
P1.2											0	0
P1.3							Y	0			20	1
P1.4							Y	0			20	1
P1.5											0	0
P1.6											0	0
P2.1			N	0	N	0					40	2
P2.2	N	0			Y	0					40	2
P2.3			Y	38	N	0	N	0	N	0	80	4
P2.4	Y	0			N	0	Y	0	N	0	80	4
P2.5	N	0	N	0			N	0			60	3
P2.6	N	0	N	0							40	2
P3.1	N	10	Y	11							60	2
P3.2	Y	0			Y	0	N	0	Y	0	100	4
P3.3					N	10	N	0			80	2
P3.4					Y	0					60	1
P3.5	Y	0	N	0	N	0					80	3
P3.6	N	0	Y	0	N	0	N	0			80	4
P4.1											0	0
P4.2											0	0
P4.3	N	0			Y	0			N	0	60	3
P4.4	Y	0	Y	0	N	0					80	3
P4.5					Y	0	N	0			40	2
P4.6	Y	70	N	50			N	0			60	3
P5.1											0	0
P5.2	N	10	N	0							40	2
P5.3			Y	0			Y	0			80	2
P5.4			N	0	Y	0					40	2
P5.5											0	0
P5.6											0	0

Note: (Gray fields represent the students who stated that they didn't feel well, having the symptoms described above.)

In scenario 4 (Table 29), only two students, from the total of 62 answers, stated that they felt the draught, the one in the middle of the classroom P2.3, and the other one at the positions P4.4 closer to electrical heaters, which also caused air movement, driven by the buoyancy effect.

Table 29. Draught intensity voted by students in Scenario 4

Position index	7.12		8.12		9.12		10.12		11.12		Percentage of position occupancy	Number of answers
	Sens.	DR	Sens.	DR	Sens.	DR	Sens.	DR	Sens.	DR		
	Y/N	%	Y/N	%	Y/N	%	Y/N	%	Y/N	%	%	
P1.1											0	0
P1.2	N	0			Y	0					40	2
P1.3	N	0									20	1
P1.4	N	0									20	1
P1.5											0	0
P1.6											0	0
P2.1			N	0			Y	0	Y	0	60	3
P2.2					Y	0	N	0			60	2
P2.3	Y	15			N	0	N	0	N	0	100	4
P2.4	N	0	Y	0			Y	0	N	0	100	4
P2.5	N	0	N	0							40	2
P2.6	N	0	N	0			N	0			60	2
P3.1	N	0	N	0	N	0	N	0	N	0	100	5
P3.2			Y	0	N	0	N	0			60	3
P3.3	Y	0	N	0	N	0	N	0	Y	0	100	5
P3.4	Y	0			N	0					60	2
P3.5	N	0									20	1
P3.6	Y	0									20	1
P4.1											0	0
P4.2											0	0
P4.3			N	0	N	0	Y	0	N	0	100	4
P4.4	Y	42	Y	0	N	0			Y	0	80	4
P4.5	N	0	N	0					N	0	60	3
P4.6	N	0					N	0			60	2
P5.1											0	0
P5.2	Y	0									20	1
P5.3			N	0	Y	0	N	0			60	3
P5.4	N	0			N	0	Y	0			80	3
P5.5			Y	0			N	0			40	2
P5.6			N	0							0	1

Note: (Gray fields represent the students who stated that they didn't feel well, having the symptoms described above.)

It is interesting to notice that same students, on the same positions felt some draught during the whole investigation, except in Scenario 2, when the draught actually existed, according to the measured air velocities (Appendix 3). The averaged draught intensity feeling was rated as 0.67%, and 32.3% percent of the students stated that they are sensitive to draught.

Comparing the survey results with measured air velocities from Appendix 3 (Table A3.1) and draught intensity calculations according to ISO 7730:2005 from Table 20. with students' survey, it is very interesting to notice that students evaluated the draught intensity as 0% in the second scenario, when the actual measured air velocity was doubled in relation to other scenarios. The highest evaluated draught intensity was noticed in third scenario, but actual measured mean air velocity averaged for third scenario was the lowest, as it was only 0.03 m/s. This result strongly implies subjectivity of occupants' feelings regarding thermal comfort in buildings.

Looking at the overall results of students' evaluation, it can be concluded that the draught intensity impact on students' productivity was very small and can be neglected, except for the positions near the windows. According to the survey, even the majority of students seated near the windows usually did not feel the draught.

5.2.3.2. The local discomfort caused by cold floor

The students were also asked to evaluate the impact of floor temperature on their work. Their answers are presented in Tables 30 to 33. In scenario 1, from total 56 answers, the averaged impact on work was evaluated as 3%. The total percent of the students dissatisfied with a floor temperature was 1.8%, which is significantly lower than predicted by ISO 7730:2005.

Table 30. The percentage of students dissatisfied with floor temperature for Scenario 1

Position index	Number of students felt the influence	Number of Unsatisfied	Impact on work [%]	Percentage of position occupancy [%]	Number of answers
P1.1				0	0
P1.2				0	0
P1.3				0	0
P1.4	1	0	0.0	20	1
P1.5	1	0	0.0	20	1
P1.6	1	0	0.0	20	2

Position index	Number of students felt the influence	Number of Unsatisfied	Impact on work [%]	Percentage of position occupancy [%]	Number of answers
P2.1	0	0	0.0	40	1
P2.2	0	0	3.3	60	3
P2.3	1	0	5.0	80	3
P2.4	1	0	0.0	80	3
P2.5	1	0	2.5	80	4
P2.6	2	0	0.0	80	4
P3.1	1	0	0.0	100	4
P3.2	1	0	1.0	80	2
P3.3	1	0	0.0	80	2
P3.4	1	0	0.0	80	1
P3.5	1	0	0.0	60	2
P3.6	0	0	25.5	80	3
P4.1				0	0
P4.2				0	0
P4.3	1	0	0.0	100	2
P4.4	1	0	0.0	60	2
P4.5	1	0	5.0	80	2
P4.6	1	0	0.0	80	3
P5.1	1	0	10.0	60	2
P5.2	0	0	0.0	60	2
P5.3	0	0	2.3	60	3
P5.4	2	1	17.5	80	3
P5.5	1	0	0.0	40	1
P5.6				40	0

In Scenario 2, from 31 answers, the averaged impact on work was 0.6%. There was not a single person dissatisfied with the floor temperature, which is a significant contribution of this research, showing that it is possible to have 0% of occupants dissatisfied, and not necessary 6% as it given in ISO 7730:2005.

Table 31. The percentage of students dissatisfied with floor temperature for Scenario 2

Position index	Number of students felt the influence	Number of Unsatisfied	Impact on work [%]	Percentage of position occupancy [%]	Number of answers
P1.1	0	0	0.0	25	1
P1.2				0	0
P1.3				0	0
P1.4	0	0	0.0	25	1
P1.5				0	0
P1.6				0	0
P2.1				0	0

Position index	Number of students felt the influence	Number of Unsatisfied	Impact on work [%]	Percentage of position occupancy [%]	Number of answers
P2.2	0	0	0.0	50	2
P2.3	1	0	0.0	50	2
P2.4	0	0	0.0	75	1
P2.5	0	0	0.0	75	1
P2.6	0	0	0.0	25	1
P3.1	0	0	0.0	75	3
P3.2	0	0	2.5	75	2
P3.3	0	0	6.5	75	3
P3.4	0	0	2.0	50	2
P3.5	0	0	0.0	50	2
P3.6	0	0	0.0	50	2
P4.1				0	0
P4.2				0	0
P4.3	2	0	0.0	50	2
P4.4				25	0
P4.5	0	0	0.0	25	1
P4.6	0	0	0.0	25	1
P5.1				25	0
P5.2	0	0	0.0	25	1
P5.3	2	0	0.0	50	2
P5.4	0	0	0.0	50	1
P5.5				0	0
P5.6				0	0

In Scenario 3, the number of answers was 54, and the overall impact on work was evaluated as 8.6%. Furthermore 9.3% of students were dissatisfied with the floor temperature.

Table 32. The percentage of students dissatisfied with floor temperature for Scenario 3

Position index	Number of students felt the influence	Number of Unsatisfied	Impact on work [%]	Percentage of position occupancy [%]	Number of answers
P1.1	1	0	0	20	1
P1.2				0	0
P1.3	1	0	0	20	1
P1.4	0	0	0	20	1
P1.5				0	0
P1.6				0	0
P2.1	0	0	0	40	2
P2.2	0	0	0	40	2
P2.3	1	1	20	80	4
P2.4	1	0	5	80	4

Position index	Number of students felt the influence	Number of Unsatisfied	Impact on work [%]	Percentage of position occupancy [%]	Number of answers
P2.5	1	1	0	60	3
P2.6	2	0	0	40	2
P3.1	0	1	5	60	3
P3.2	1	0	0	100	4
P3.3	1	0	0	80	2
P3.4	0	0	10	60	1
P3.5	1	0	3	60	3
P3.6	1	1	63	80	4
P4.1				0	0
P4.2				0	0
P4.3	1	1	2	60	3
P4.4	2	0	3	80	3
P4.5	1	0	0	40	2
P4.6	1	0	35	60	3
P5.1				0	0
P5.2	0	0	10	40	2
P5.3	0	0	0	80	2
P5.4	1	0	35	40	2
P5.5				0	0
P5.6				0	0

In Scenario 4, the number of answers was 62, and the overall impact on work was evaluated as 6.1%. In this scenario, 9.7% of students voted as dissatisfied with floor temperature.

Table 33. The percentage of students dissatisfied with floor temperature for Scenario 4

Position index	Number of students felt the influence	Number of Unsatisfied	Impact on work [%]	Percentage of position occupancy [%]	Number of answers
P1.1				0	0
P1.2	1	0	2.5	40	2
P1.3	0	0	0.0	20	1
P1.4	1	0	0.0	20	1
P1.5				0	0
P1.6				0	0
P2.1	1	1	5.0	60	3
P2.2	1	0	0.0	60	2
P2.3	1	1	45.0	100	4
P2.4	1	1	6.7	100	4
P2.5	0	0	0.0	40	2
P2.6	2	0	0.0	60	3
P3.1	2	1	9.3	100	5

Position index	Number of students felt the influence	Number of Unsatisfied	Impact on work [%]	Percentage of position occupancy [%]	Number of answers
P3.2	0	0	2.0	60	3
P3.3	3	0	5.0	100	5
P3.4	0	0	0.0	60	2
P3.5	0	0	30.0	20	1
P3.6	0	0	20.0	20	1
P4.1				0	0
P4.2				0	0
P4.3	2	1	0.0	100	4
P4.4	0	0	0.0	80	4
P4.5	1	0	1.5	60	3
P4.6	0	0	0.0	60	2
P5.1				0	0
P5.2	1	1	15.0	20	1
P5.3	0	0	5.0	60	3
P5.4	2	0	0.0	80	3
P5.5	0	0	0.0	40	2
P5.6	1	0	0.0	0	1

Looking at the overall results of students' evaluation, it can be concluded that the floor temperature impact on students’ productivity was very small in Scenarios 1 and 2 and can be neglected as non dominant for PLOS analysis. According to the survey, the floor temperature impact on students was as a bit higher (around 8.6%) in Scenario 3 and around 6% in Scenario 4. Looking at the Scenario 3, it is notable that the students in the positions closer to electrical heater voted that they felt the impact, and the students seated away from the heaters did not felt the impact of the floor temperature. Having in mind that the measured temperatures of the floor (Table 10) were almost the same in all scenarios, about 21.8°C, it can be concluded that the psychological aspect of the unpleasant indoor environment is also very important. The students reflected the disaffection with indoor environment on various aspects of thermal comfort indicators in their evaluation.

5.2.3.3. Radiant asymmetry survey results

The students' subjective evaluation in regards to radiant asymmetry impact on their performances is processed and presented in further. The total number of votes in Scenario 1 was 56 and 8.9% of people were dissatisfied with the radiant asymmetry.

The number of students who could feel the radiant asymmetry for each position is given in Tables 34 to 37, together with the number of students dissatisfied and the evaluation of radiant asymmetry impact on productivity loss for each scenario.

Table 34. The radiant asymmetry influence on productivity loss – statistical survey for Scenario 1

Position index	Radiant asymmetry			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P1.1				0	0
P1.2				0	0
P1.3				0	0
P1.4	1	0	0	20	1
P1.5	0	0	0	20	1
P1.6	1	0	0	40	2
P2.1	1	1	15	40	1
P2.2	2	2	1.67	60	3
P2.3	1	0	15	80	3
P2.4	0	0	0	80	2
P2.5	1	0	0	80	4
P2.6	3	0	0	80	4
P3.1	1	0	30	100	3
P3.2	1	1	14	80	2
P3.3	0	0	70	80	1
P3.4	1	1	0	80	1
P3.5	0	0	0	60	2
P3.6	2	0	0	80	3
P4.1	0			0	0
P4.2	0			0	0
P4.3	2	0	0	100	3
P4.4	2	0	0	60	3
P4.5	2	0	0	80	3
P4.6	1	0	0	80	3
P5.1	2	0	0	60	2
P5.2	1	0	0	60	2
P5.3	0	0	11	60	3
P5.4	0	0	12	80	3
P5.5	1	0	0	40	1
P5.6	0			40	0
average			7		

The total number of votes in Scenario 2 was 31 and 12.9% of people were dissatisfied with the radiant asymmetry.

Table 35. The radiant asymmetry influence on productivity loss – statistical survey for Scenario 2

Position index	Radiant asymmetry			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P1.1	0	0	0	25	1
P1.2				0	0
P1.3				0	0
P1.4	0	0	0	25	1
P1.5				0	0
P1.6				0	0
P2.1				0	0
P2.2	1	0	0	50	2
P2.3	0	0	2.5	50	2
P2.4	0	0	0	75	1
P2.5	1	0	0	75	1
P2.6	1	0	0	25	1
P3.1	2	2	5	75	3
P3.2	1	1	4	75	2
P3.3	0	0	6.5	75	3
P3.4	1	1	15	50	2
P3.5	0	0	0	50	2
P3.6	1	0	0	50	2
P4.1				0	0
P4.2				0	0
P4.3	1	0	5	50	2
P4.4				25	0
P4.5	1	0	0	25	1
P4.6	1	0	0	25	1
P5.1				25	0
P5.2	0	0	0	25	1
P5.3	0	0	5	50	2
P5.4	0	0	0	50	1
P5.5				0	0
P5.6				0	0
average			2.26		

The total number of votes in Scenario 3 was 54 and 35.2% of people were dissatisfied with the radiant asymmetry.

Table 36. The radiant asymmetry influence on productivity loss – statistical survey for Scenario 3

Position index	Radiant asymmetry			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P1.1	0	0	0	20	1
P1.2				0	0
P1.3	0	0	0	20	1
P1.4	1	1	18	20	1
P1.5				0	0
P1.6				0	0
P2.1	2	2	15	40	2
P2.2	1	0	0	60	2
P2.3	3	3	36.3	80	4
P2.4	1	1	10	80	4
P2.5	1	0	0	60	3
P2.6	2	0	0	40	2
P3.1	1	1	5	80	3
P3.2	3	3	27.5	100	4
P3.3	1	1	10	80	2
P3.4	1	1	30	60	1
P3.5	2	0	0	60	3
P3.6	2	2	56	80	4
P4.1				0	0
P4.2				0	0
P4.3	0	0	27.5	60	3
P4.4	2	1	25	80	3
P4.5	1	0	15	60	2
P4.6	1	1	43.3	60	3
P5.1				0	0
P5.2	1	0	0	40	2
P5.3	2	1	30	80	2
P5.4	1	1	33	40	2
P5.5				0	0
P5.6				0	0
average			17.33		

The total number of votes in Scenario 4 was 62 and 17.7% of people were dissatisfied with the radiant asymmetry.

Table 37. The influence of radiant asymmetry on productivity loss – statistical survey for Scenario 4

Position index	Radiant asymmetry			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P1.1				0	0
P1.2	0	0	2.5	40	2
P1.3	0	0	0	20	1
P1.4	1	0	0	20	1
P1.5				0	0
P1.6				0	0
P2.1	2	1	7.5	60	3
P2.2	1	0	0	60	2
P2.3	1	1	69	100	4
P2.4	2	2	39.3	100	4
P2.5	0	0	0	40	2
P2.6	2	0	0	60	3
P3.1	3	1	3.3	100	5
P3.2	1	1	2.3	60	3
P3.3	0	0	4.25	100	5
P3.4	0	0	0	60	2
P3.5	0	0	20	20	1
P3.6	0	0	20	20	1
P4.1				0	0
P4.2				0	0
P4.3	2	1	2.67	100	4
P4.4	3	2	39.5	80	4
P4.5	1	0	0	60	3
P4.6	0	0	0	60	2
P5.1				0	0
P5.2	1	1	10	20	1
P5.3	0	0	5	60	3
P5.4	2	1	10	80	3
P5.5	0	0	0	40	2
P5.6	1	0	0	20	1
average			9.81		

Total percent of students dissatisfied with radiant asymmetry is shown in Table 38. Students also evaluated their productivity loss caused by radiant asymmetry. It is obvious that the votes were granted to the Scenario 3 as the most uncomfortable, which is also in agreement with the measurements. The radiant asymmetry was marked as one of the most influential local thermal comfort factors on productivity loss in the observed classroom, concerning the students' votes.

Table 38. PD caused by radiant asymmetry obtained from students' survey

Scenario	Number of votes	Unsatisfied	PD [%]	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

5.2.3.4. Vertical air temperature difference – statistical survey

The statistical survey was also conducted concerning the vertical air temperature difference and its impact on students' productivity loss. The total number of votes in Scenario 1 was 56, and total percent of students dissatisfied was 16.1%. The students' answers for Scenario 1 are presented in Table 39.

Table 39. Vertical air temperature difference impact on productivity loss – statistical survey for Scenario 1

Position index	Vertical Tair difference			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P1.1				0	0
P1.2				0	0
P1.3				0	0
P1.4	1	1	10	20	1
P1.5	1	0	0	20	1
P1.6	1	0	0	40	2
P2.1	1	1	15	40	1
P2.2	0	1	5	60	3
P2.3	3	1	30	80	3
P2.4	0	0	0	80	2
P2.5	1	1	0	80	4
P2.6	3	0	10	80	4
P3.1	1	0	7.5	100	3
P3.2	2	1	35	80	2
P3.3	1	0	0	80	1
P3.4	1	0	0	80	1
P3.5	0	0	0	60	2
P3.6	1	0	2.5	80	3
P4.1				0	0
P4.2				0	0
P4.3	2	0	0	100	3
P4.4	2	0	0	60	3

Position index	Vertical Tair difference			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P4.5	1	0	2	80	3
P4.6	2	0	0	80	3
P5.1	1	0	10	60	2
P5.2	1	0	0	60	2
P5.3	2	2	0	60	3
P5.4	1	1	10	80	3
P5.5	1	0	0	40	1
P5.6				40	0
Average			5.7		

According to the students' subjective evaluation, the average PLOS caused by the vertical air temperature difference was around 5.7% in Scenario 1.

The total number of votes in Scenario 2 was 31, and total percent of occupants dissatisfied was 12.9%. The results are shown in Table 40.

Table 40. Vertical air temperature difference impact on productivity loss – statistical survey for Scenario 2

Position index	Vertical Tair difference			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P1.1	0	0	0	25	1
P1.2				0	0
P1.3				0	0
P1.4	0	0	0	25	1
P1.5				0	0
P1.6				0	0
P2.1				0	0
P2.2	1	0	0	50	2
P2.3	1	0	0	50	2
P2.4	0	0	0	75	1
P2.5	0	0	0	75	1
P2.6	1	0	0	25	1
P3.1	1	1	10	75	3
P3.2	0	0	3	75	2
P3.3	2	1	0	75	3
P3.4	1	1	40	50	2
P3.5	1	0	0	50	2
P3.6	1	0	0	50	2
P4.1				0	0
P4.2				0	0
P4.3	2	0	0	50	2

Position index	Vertical Tair difference			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P4.4				25	0
P4.5	1	1	15	25	1
P4.6	1	0	0	25	1
P5.1				25	0
P5.2	0	0	0	25	1
P5.3	1	0	15	50	2
P5.4	0	0	0	50	1
P5.5				0	0
P5.6				0	0
Average			4.4		

The impact on PLOS is evaluated as 4.4% in second scenario.

The results for third scenario are presented in Table 41. The total number of votes in Scenario 3 was 54, and total percent of students dissatisfied was 58.9%.

Table 41. Vertical air temperature difference impact on productivity loss – statistical survey for Scenario 3

Position index	Vertical Tair difference			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P1.1	0	0	0	20	1
P1.2				0	0
P1.3	1	0	0	20	1
P1.4	1	1	22	20	1
P1.5				0	0
P1.6				0	0
P2.1	0	1	20	40	2
P2.2	1	0	0	40	2
P2.3	2	2	24	80	4
P2.4	1	1	47.5	80	4
P2.5	1	0	10	60	3
P2.6	2	0	0	40	2
P3.1	1	1	5	60	3
P3.2	3	2	22.5	100	4
P3.3	2	0	0	80	2
P3.4	1	1	30	60	1
P3.5	2	2	5	60	3
P3.6	3	2	15.5	80	4
P4.1				0	0
P4.2				0	0
P4.3	1	1	32.5	60	3
P4.4	2	2	25	80	3

Position index	Vertical Tair difference			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P4.5	2	2	0	40	2
P4.6	3	1	65	60	3
P5.1				0	0
P5.2	1	1	0	40	2
P5.3	0	0	0	80	2
P5.4	2	1	10	40	2
P5.5				0	0
P5.6				0	0
Average			15.2		

The impact on PLOS in third scenario was rated as 15.2%, and evaluated as the worst case.

The total number of votes in Scenario 4 was 62, and total percent of students dissatisfied was 30.6% and results are shown in Table 42.

Table 42. Vertical air temperature difference impact on productivity loss – statistical survey for Scenario 4

Position index	Vertical Tair difference			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P1.1				0	0
P1.2	2	1	35	40	2
P1.3	0	0	0	20	1
P1.4	1	0	0	20	1
P1.5				0	0
P1.6				0	0
P2.1	1	1	11.67	60	3
P2.2	1	0	0	60	2
P2.3	2	2	37.5	100	4
P2.4	2	2	40.33	100	4
P2.5	0	0	0	40	2
P2.6	2	0	5	60	3
P3.1	3	2	14.25	100	5
P3.2	1	1	5	60	3
P3.3	4	2	3.33	100	5
P3.4	0	0	0	60	2
P3.5	0	0	20	20	1
P3.6	0	0	20	20	1
P4.1				0	0
P4.2				0	0
P4.3	2	0	0	100	4

Position index	Vertical Tair difference			Percentage of position occupancy [%]	Number of answers
	Influence	Unsatisfied	PLOS [%]		
P4.4	3	3	34.67	80	4
P4.5	2	0	0	60	3
P4.6	1	1	15	60	2
P5.1				0	0
P5.2	0	0	0	20	1
P5.3	1	1	10	60	3
P5.4	3	2	42.5	80	3
P5.5	2	1	50	40	2
P5.6	1	0	0	20	1
Average			14.3		

The evaluated impact on PLOS was lower in forth scenario than in third one, but still notable with its average value of 14.3%.

The overall evaluation for vertical air temperature difference impact on students' dissatisfaction with thermal environment for four scenarios is presented in Table 43.

Table 43. Percentage of students dissatisfied with vertical air temperature difference and subjective evaluation of personal productivity loss

Scenario	Number of votes	Unsatisfied	PD [%]	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

The worst case is again Scenario 3, with almost 40% of people dissatisfied. This factor is also marked as dominant potential cause of impact of local thermal comfort on productivity loss.

5.3. Students' productivity - experimental investigation

The productivity of students participated in this research was evaluated each day, using tests described previously in chapter “Methodology of subjective evaluation”. The purpose of these tests was to evaluate students' productivity in different thermal comfort conditions and to develop the correlations between the local thermal comfort and productivity loss. Each test was carefully prepared in order to have the listening tests of approximately equal weight. The students' task was to listen the test of approximately

200 words, and after that to answer five questions from the text which was read to them and given in a form of test. The questions were about years, names or some details from the text, but always similar type in order to achieve approximately equal weight. The results of the tests were scored in percentage and presented on Figures 32 to 35 for each scenario.

Total number of results in scenario 1 was 73. The averaged productivity for first scenario was 58.5%. 58% of the results were higher than average 58.5% productivity. In Scenario 2, the 37 results were processed with an averaged productivity of around 68%. Third scenario, with 62 results, had an averaged productivity of 58%. In scenario 4, 68 answers were observed and average productivity for whole scenario was 44.5%.

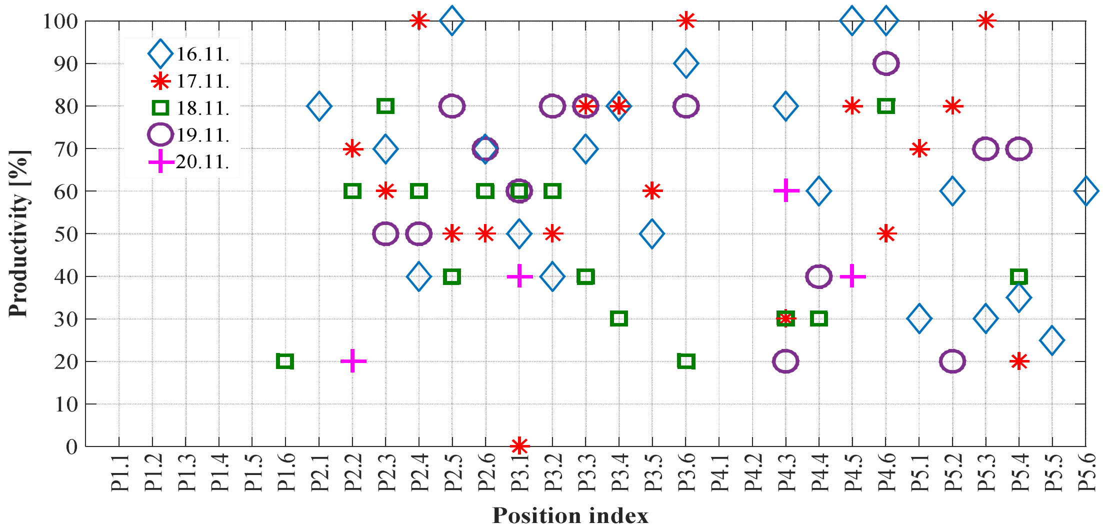

Figure 32. Productivity test results for each day in Scenario 1

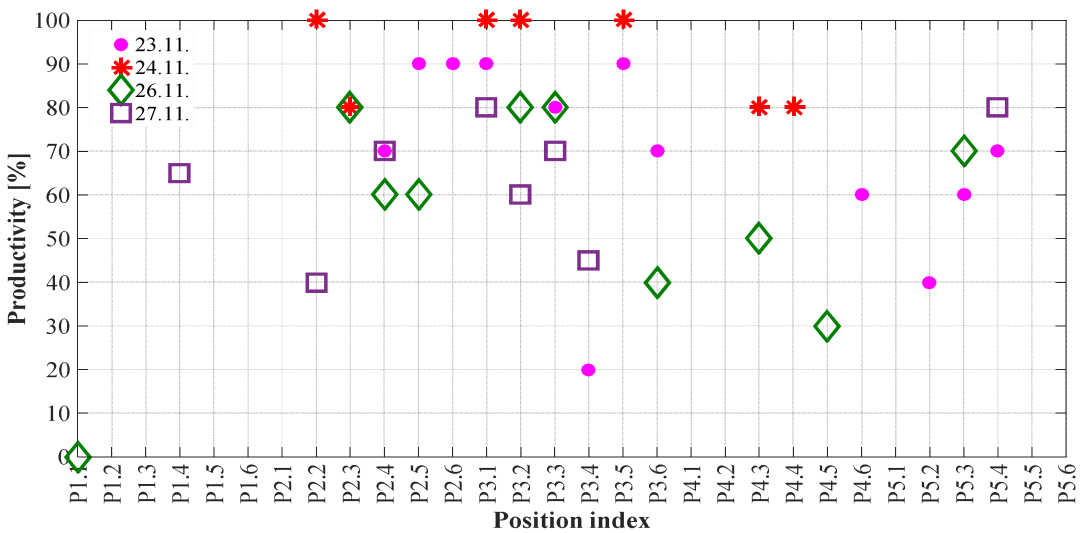

Figure 33. Productivity test results for each day in Scenario 2

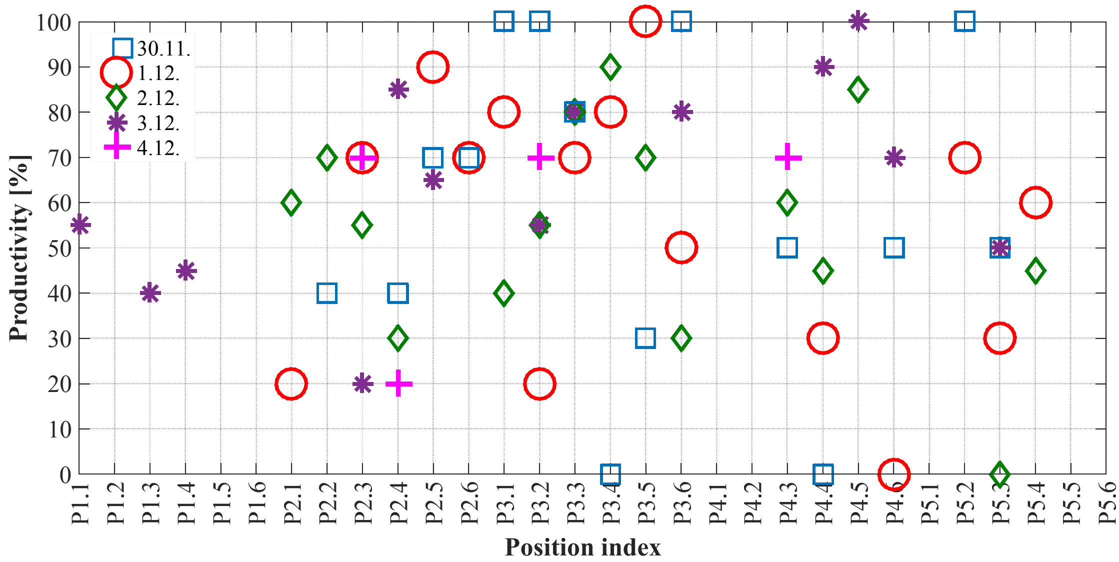

Figure 34 . Productivity test results for each day in Scenario 3

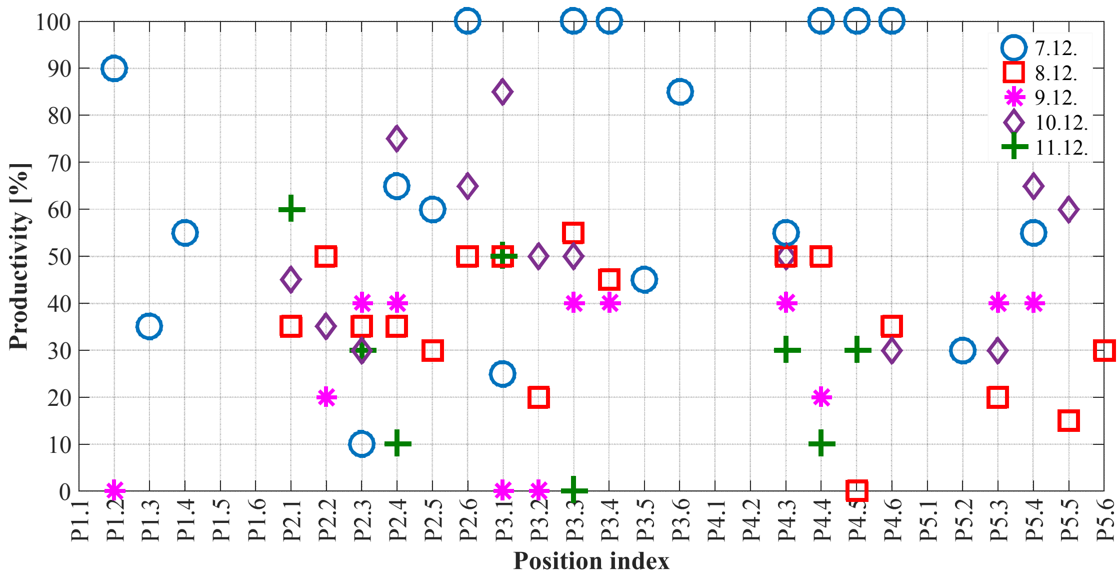

Figure 35. Productivity test results for each day in Scenario 4

The variety of the results obtained in this investigation, especially for the students sitting next to each other, and having the same local thermal comfort parameters, strongly implies that the personal factor, taking into a consideration student's personal skills, metabolism, and overall psychological and physiological state, is powerfully dominating over the environmental thermal comfort conditions. This conclusion is very important for this, and for future researches, as well.

CHAPTER 6

"Defeats are only resting places for future victories."

Mihajlo Pupin

„Порази су само кратка одморишта за будуће победе."

Михајло Пупин

6. NUMERICAL SIMULATIONS

This part of the research had been performed using the Computational Fluid Dynamics (CFD) model in order to obtain the temperatures, velocities, air turbulence and thermal comfort indexes. CFD is widely used model for air distribution prediction in buildings. The first CFD models of a ventilated room were developed in 1970s by Nielsen [85], and these days there are numerous studies on this topic.

A lot of authors had been investigating air flow, IAQ and indoor thermal environment using different model-rooms with furniture and occupants for CFD simulations. Zhuand et al. [86] had investigated the different ventilation schemes for twelve typical offices with different furniture. They had used RNG k-ε turbulence model in their simulations and compared the results with the experimental data on velocity, temperature and CO_2 concentration. They found a good agreement between the experimental results and the simulation. Horikiri et al. [87] also used RNG k-ε turbulence model for finding correlations between heat generation, ventilation velocity and thermal sensation indices. They made a model to investigate the effect of a furniture arrangement with and without heat generation and occupants in terms of indoor thermal comfort. Also, they concluded that the location of the occupants to the incoming flow stream is very important and that the PPD distribution is symmetrical in the span-wise position, but asymmetrical in stream-wise position [87]. Aryal and Leephakpreeda [88] investigated a relationship between the thermal comfort and position of partitions in air-conditioned building, using CFD and concluded that the partition installations in open spaces are not recommended when it comes to the thermal comfort, as well as energy consumption, which can increase by 24%. They compared the simulations results with the measurements of air temperature and relative humidity that also had been performed and verified that the maximal deviation was lower than 10%. Nielsen [89] gave an interesting 50-years review of CFD historical use and development in the indoor environment. He discussed about the right selection of the governing equations and turbulence models and gave the comparison of the usually chosen turbulence model, according to Zhang investigation [90]. Zhang had compared the characteristics of different turbulence models for room distribution and concluded that the best predictions for natural and mixed convection are obtained using V^2-f turbulence model, but computing time is twice as long when using RNG k-ε or SST k-ϖ model. For forced convection, RNG k-ε, LRN and V^2-f give decent predictions, while for the strong buoyancy the SST k-ϖ seems to be the most appropriate choice.

Bajc et al. [91] had been investigating a natural convection and radiative heat transfer inside a passive house and Trombe wall, using RNG k-ε turbulence model. The influence of radiation was implemented through DO radiation model and the use of solar calculator for Belgrade at a considered time of the year and day. In this research, the Boussinesq assumption was used in order to consider the buoyancy caused by temperature differences. The simulations were performed for steady-state and transient as well, for characteristic periods of the year: winter, summer and transient conditions. The model showed good results in both cases.

6.1. Mathematical background

The observed classroom is naturally ventilated space, without any additional ventilating system. The airflow mechanism in the classroom is natural convection, driven by the vertical temperature difference in room.

The problems of natural convection airflow and radiative heat transfer are governed by the conservation equations for mass, momentum in each flow direction and energy, together with the additional mathematical relation for closing the system of equations. Furthermore, the airflow is considered predominantly turbulent. The model of the turbulence was formed using a modification of standard k-ε model for natural convection with an additional buoyancy effects, using the model presented in [28]. The model also includes radiation heat transfer model through the non-transparent medium, also presented in [28].

6.1.1. The basic assumptions

In order to define the mathematical model it is necessary to define the appropriate assumptions for indoor natural convection. The basic assumptions are as follows [28]:

a) The flow is steady-state. The physical parameters' changes are very small during the time, and local changes of parameters are negligible. This implies that all derivates of physical parameters in time are equal to zero.

b) The flow is turbulent. Despite the fact that the natural convection is characterized by small velocities and Re numbers, the turbulent regime is dominant because of the volume forces fluctuations and high Re numbers. This phenomenon requires a modification of standard k-ε model, using the additional terms in differential turbulence equations.

c) The heat transfer models in room are convection, conduction and radiation. Looking at the conduction and convection, the heat transfer is observed through the air and also solid medium. Heat radiation model is considered for non-transparent medium (air), which implies the necessity of defining the relations for effective emissivity coefficients, air dissipation and CO_2 and water vapor concentration. The implemented heat radiative model is shaped using gradient technique, modeling the radiative heat flux in gradient formulation (analogously to conduction heat transfer).

d) The air is considered to be an ideal gas. This assumption closes the system of the equations (the number of relations is equal to the number of the independent variables). The ideal gas law is used to close the system of equations.

6.1.2. The governing equations

Mass conservation equation for 3D airflow [91]:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0, \tag{28}$$

where $\rho[\mathrm{kg/m^3}]$ stands for air density, and u, v, w for velocity components in x, y and z direction respectively. For the incompressible airflow, the air density is constant (the local variations in density are negligible to the local velocity variation), so equation (28) can be written in index notation as:

$$\frac{\partial U_i}{\partial x_i} = 0. \tag{29}$$

Navier-Stokes equation for the incompressible 3D airflow with constant viscosity (momentum conservation equations) [28, 92]:

$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial U_i}{\partial x_j} - \overline{u_i u_j}\right) - \left(\frac{1}{\rho}\right)\left(\rho - \rho_{ref}\right) g_i \tag{30}$$

where:

U_i is vector of averaged air velocity (i=1,2,3) [m/s],

P is averaged air pressure [Pa],

ρ is averaged air density [kg/m^3],

ρ_{ref} is referent value of averaged air density [kg/m^3],

ν is molecular kinematic air viscosity [m^2/s] ,

g_i is vector of gravity force (0, 0, -9,81) [m/s^2] and

$\overline{u_i u_j}$ is symmetrical tensor of Reynolds turbulent stress.

Energy conservation equation is applied for the air, and given in averaged, filtered form as follows [28, 92]:

$$U_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\frac{\nu}{\mathrm{Pr}}\frac{\partial T}{\partial x_i} - \overline{\theta u_i}\right) + S_{rad} \tag{31}$$

where:

T is temperature,

Pr is Prandtl number,

S_{rad} is a radiative heat flux,

$\overline{\theta u_i}$ is turbulent heat flux vector.

CO_2 concentration conservation equation can be written as scalar conservation equation in followed form [28]:

$$U_j \frac{\partial C_{CO_2}}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\frac{\nu}{\mathrm{Sc}}\frac{\partial C_{CO_2}}{\partial x_i}\right), \tag{32}$$

where C_{CO_2} [ppm$_v$] is averaged volumetric CO_2 concentration.

The ideal gas law is given with an equation:

$$\frac{P}{\rho} = RT, \tag{33}$$

where R is ideal (universal) gas constant for air [J/kgK].

The system of the equations (30), (31) and (32) is not closed because of the additional variables: $\overline{u_i u_j}$, S_{rad} and $\overline{\theta u_i}$. Due to that and also the turbulent nature of the airflow, it is necessary to introduce additional equations for turbulent flow model.

The turbulent flow model is based on the assumption of homogeneous and isotropic turbulence. Using the Bussinisq formulation, it is possible to write turbulent heat flux vector and tensor of Reynolds turbulent stress as follows [28]:

$$\overline{\theta u_i} = -\frac{\nu_t}{\sigma_t}\frac{\partial T}{\partial x_i}, \tag{34}$$

$$\overline{u_i u_j} = \frac{2}{3}k\,\delta_{ij} - \nu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right), \tag{35}$$

where:

ν_t is turbulent kinematic air viscosity [m^2/s],

σ_t is turbulent Schmidt number,

k is turbulence kinetic energy and

δ_{ij} is Kronecker delta which is a function $\delta_{ij} = \begin{cases} 1 \text{ for } j=i \\ 0 \text{ for } j\neq i \end{cases}$.

Introducing the turbulent kinematic air viscosity ν_t allows the system equations closure and defines the type of the model, but the expressions for ν_t do not represent the turbulent model. Kolmogorov and Prandtl [28] suggest that it is convenient to express the turbulent kinematic viscosity using the turbulence kinetic energy and characteristic turbulent length (ℓ), as it is written in the following equation [92]:

$$\nu_t = C_\mu \ell \sqrt{k} \,, \tag{36}$$

where C_μ is empirical constant for turbulent model.

In this manner, the turbulent kinematic air viscosity ν_t depends only from the turbulence characteristics of the flow, and not directly from the main flow. In literature it is possible to find a lot of expressions for ℓ [28], but it has shown that it was most convenient to use the turbulent kinetic energy dissipation rate *ε*, due to its energy character and the turbulent flow characteristics in the field of high Re numbers. The expression for turbulent viscosity ν_t :

$$\nu_t = c_\mu \rho \frac{k^2}{\varepsilon} \quad , \tag{37}$$

is well known as the standard *k*-*ε* model.

The *k*-*ε* model is a turbulence model in which transport equations are solved for the turbulent kinetic energy *k* and its dissipation rate *ε*. It combines ρ, *k* and *ε* with turbulent viscosity ν_t using constant c_μ, which can be experimentally obtained [85]. Those equations are not derived from basic principles of mass, momentum and energy conservation, and they cannot be named as basic equations, but more precisely the transport equations, because they define the transport phenomena of turbulent scalars *k* and *ε* [28]. This model requires two additional equations to be solved: transport equation for the turbulent kinetic energy *k* and its dissipation rate *ε*, but it obtains the good results in the domain of a developed turbulent flow, far from a stagnant region and stationary surfaces [93]. According to Nielsen et al. [85], the *k*-*ε* model has two main disadvantages: it over-predicts the shear stress in adverse pressure gradient flow and it requires near-wall modification. The standard *k*-*ε* model does not include buoyancy effect, which is dominant in natural convection.

In order to overcome those disadvantages, a lot of modifications of this model were developed, and the most common is RNG k-ε model [93] which takes into account the effect of a flow in the domain of low Re value. The second common turbulence model is k-ϖ, which is better than k-ε model in predicting adverse pressure gradient flows, so Menter [94] made a combination of these two models, known as SST (Shear Stress Transport) model [85]. Another usual model is V^2-f which is similar to standard k-ε model, but takes into account some near-wall turbulence anisotropy. It gives very good results for natural and mixed convection, but takes even double duration for computing [89].

In this research, the modified k-ε model is used. The first modification refers to the transport turbulent kinetic energy equation. On the right side of the equation one additional term is necessary, besides the shear production of turbulent kinetic energy P_k and its dissipation ε, and it is the buoyancy production of turbulent kinetic energy G_k. The modified transport equation for turbulent kinetic energy is [28, 92, 95]:

$$U_i \frac{\partial k}{\partial x_i} - \frac{\partial}{\partial x_i}\left\{\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right\} = P_k + G_k - \varepsilon \quad , \tag{38}$$

where:

$$P_k = \nu_t \left(\frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i}\right)\frac{\partial U_i}{\partial x_k}, \tag{39}$$

$$G_k = \nu_t \beta g_i \frac{\partial T}{\partial x_i} \tag{40}$$

and $\beta = 1/T_{ref}$ is the coefficient of air thermal expansion.

Also the transport equation for turbulent kinetic energy dissipation rate ε should be modified as follows [28, 92, 95]:

$$U_i \frac{\partial \varepsilon}{\partial x_i} - \frac{\partial}{\partial x_i}\left\{\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right\} = \frac{\varepsilon}{k}\left(C_{\varepsilon 1}P_k + C_{\varepsilon 3}G_k - C_{\varepsilon 2}\varepsilon\right) \quad , \tag{41}$$

where σ_k, σ_ε, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, C_μ are empirical constants for turbulent model. They had different values during the last decades, but these days standard values are taken from Low-Reynolds number *k*-*ε* model of Jones and Launder and they are given as follows [95]:

$$\sigma_k = 1;\ \sigma_\varepsilon = 1.314;\ C_{\varepsilon 1} = 1.44;\ C_{\varepsilon 2} = 1.92 \text{ and } C_\mu = 0.09. \tag{42}$$

The main characteristic of these constants is that they are independent from the relation between the basic flow directions and gravity vector direction. But the empirical coefficient $C_{\varepsilon 3}$ depends on gravity vector direction. During the last decades, this coefficient had different values, and the best results were obtained using values between 0 and 1. Stevanovic [28] suggested the assumption that this coefficient should be variable, depending on the local relation of dominant flow direction and the direction of gravity vector. For definition of this relation, the followed equation is used [28, 95]:

$$C_{\varepsilon 3} = \tanh\left(\frac{U_\downarrow}{U_\perp}\right), \tag{43}$$

where $U_\downarrow$ is the velocity component in direction of gravity vector, and $U_\perp = \sqrt{U_1^2 + U_2^2}$ is the component in lateral direction. This model is implemented in Phoenics FLAIR software code and used in CFD simulations in this research.

6.1.3. Thermal radiation model

Besides the heat convection and conduction mechanisms, a thermal radiation is also very important and it was implemented into a mathematical model and described in further section.

The implemented model is well known as a “radiosity or gradient model” and used in FLAIR software as the IMMERSOL model of radiation [96]. The radiation energy emitted by a blackbody per unit of time and surface area is known as Stefan-Boltzmann law and it is described with a following equation [75]:

$$E_b(T) = \sigma T^4 , \tag{44}$$

where:

$E_b(T)$ is a blackbody emissive power [W/m^2],

σ is a Stefan-Boltzmann constant, $\sigma = 5.67\times10^{-8}$ [W/m^{2}K^4],

T is an absolute temperature of the surface [K].

Using the equation (44), it is easy to introduce the radiant temperature T_{rad}, as an effect of the radiation. The expression can be transformed into the following:

$$E_b(T) = \sigma T_{rad}^4 . \tag{45}$$

In order to define this temperature, the equation (31) can be used and expressed as [28]:

$$U_j \frac{\partial T_a}{\partial x_j} = \frac{\partial}{\partial x_i}\left[\left(\frac{\nu}{\mathrm{Pr}} + \frac{\nu_t}{\mathrm{Pr_t}}\right)\frac{\partial T_a}{\partial x_i}\right] + S_{air-rad} , \tag{46}$$

where T_a stands for the air temperature in order to make a difference between the radiant temperature and this one. Having in mind the IMMERSOL model, the radiant temperature can be obtained from the differential equation, when member on left side of the equation is equal to zero. In that case, the convective part of radiant temperature does not exist [97]:

$$0 = \frac{\partial}{\partial x_i}\left(\lambda_{rad} \frac{\partial T_{rad}}{\partial x_i}\right) + S_{rad-air} , \tag{47}$$

where λ_{rad} is thermal conductivity expressed in terms of radiant temperature [96] and given with in form [28]:

$$\lambda_{rad} = \frac{4\sigma T_{rad}^3}{0.75(\varepsilon' + s') + \frac{1}{L_{GAP}}} , \tag{48}$$

where:

ε' is the emissivity per unit length,

s' is scattering coefficient per length of two phases in the transparent to radiation space,

L_{GAP} is the gap between nearby solid wall.

The energy transfer per unit volume $S_{rad-air}$ can be obtained using the relation:

$$S_{rad} = S_{air-rad} = -S_{rad-air} = \varepsilon' \sigma \left(T_{rad}^4 - T_a^4 \right). \tag{49}$$

Inside the solid body and at the solid walls, the radiant temperature T_{rad} is equal to the temperature of solid. The radiation flux at solid body walls is not only a function of the T_{rad} gradient, but also depends on the solid surface emissivity [96].

The assumption that the radiation heat flux does not depend on the wavelength is not precise enough. In order to improve the model, the assumption about a gray medium was introduced. The relation for gray medium can be obtained using two limits for “optically thick” and “optically thin medium. The IMMERSOL radiation model is valid both for and between those limits [96]. Both of these extremes are used in practice. Optically thick medium is considered to appear in a large coal-fired furnace, where the products of combustion are considered as optically thick. Second example stands for the room air which can be considered as an optically thin medium. The equation for radiation flux for the optically thick medium is given in form:

$$q_i = -\frac{4}{3} \frac{1}{\varepsilon' + s'} \sigma \frac{\partial \left(T^4 \right)}{\partial x_i}, \tag{50}$$

where T stands for a medium temperature.

If the medium is considered as optically thin, the expression for radiation flux is given as [28]:

$$q = \left(1 + \frac{1-\varepsilon_h}{\varepsilon_h} + \frac{1-\varepsilon_c}{\varepsilon_c} \right)^{-1} \cdot \sigma \cdot \left(T_h^4 - T_c^4 \right), \tag{51}$$

where subscripts “c” and “h” stand for cold and hot wall. From the equations (50) and (51) it is possible to obtain the expressions for the effective conductivities for optically thick and thin mediums.

By setting the equation (48) it is possible to express the effective thermal conductivity for optically thick medium in a form as follows [28]:

$$\lambda_{eff} = \frac{16}{3} \frac{\sigma T^3}{\left(\varepsilon' + s'\right)} . \tag{52}$$

Analogous, if the emissive coefficients of walls are equal to one, the equation (51) becomes:

$$q = 4\sigma T^3 \left(T_h - T_c\right) . \tag{53}$$

Since temperature gradient of walls is equal $\left(T_h - T_c\right) / L_{GAP}$, the effective conductivity is:

$$\lambda_{eff} = 4\, L_{GAP}\, \sigma T^3 , \tag{54}$$

where L_{GAP} stands for the difference between the solid surfaces and the conductivity increase is directly proportional to inter-wall difference.

By combining the expressions (48) and (52) it is possible to assume that for the case between the extremes the equation for the conductivity becomes [28]:

$$\lambda_{eff}^{-1} = \frac{\left(\frac{3}{4}\left(\varepsilon' + s'\right) + \frac{1}{L_{GAP}} \right)}{4\sigma T^3} , \tag{55}$$

Having in mind the fact that the air in the classroom during the classes is contaminated with high concentration of triatomic molecules, such as CO_2 and water vapor, the air can be considerate as a non-transparent medium. The relative humidity can be assumed as constant, and the concentration of ozone can be neglected, so it can be assumed that the emissivity and scattering coefficients are function just from CO_2 concentration. These functions are considered to be linear as follows [28]:

$$\begin{aligned} \varepsilon' &= A + B \cdot C_{CO2} , \\ s' &= 0.2 \cdot \varepsilon' . \end{aligned} \tag{56}$$

where constants A and B have the values [28]:

$$\begin{aligned} A &= 0.31 , \\ B &= 1.852 \cdot 10^{-4} . \end{aligned} \tag{57}$$

6.2. Phoenics FLAIR software descriptions and results

Phoenics FLAIR is commercial software for HVAC systems and building simulations which can provide information of thermal comfort, IEQ, productivity loss, contamination, smoke movement and fire risk and many other possibilities for airflow analysis. This software was used in this thesis in order to determine airflow, velocities, temperature distribution, radiant temperature, CO_2 concentrations, PMV, PPD and PLOS in every spot of the observed classroom. The measured values were used as the initial and boundary input parameters for CFD simulations for each from the four described scenarios. The idea was to compare measured and simulated values in the same spots of the classroom in order to evaluate the CFD model and its accuracy. Then, it is possible to obtain the values in every spot, and to use them with certainty for local thermal comfort prediction.

The program has three main features: problem definition (in pre-processor), simulations using solver and presentation of results (in post-processor).

The problem definition starts with geometry and shapes creation directly in a Virtual Reality Graphical Interface, or it can be imported as a CAD file. The created geometries for all four characteristic scenarios are shown on Figure 36.

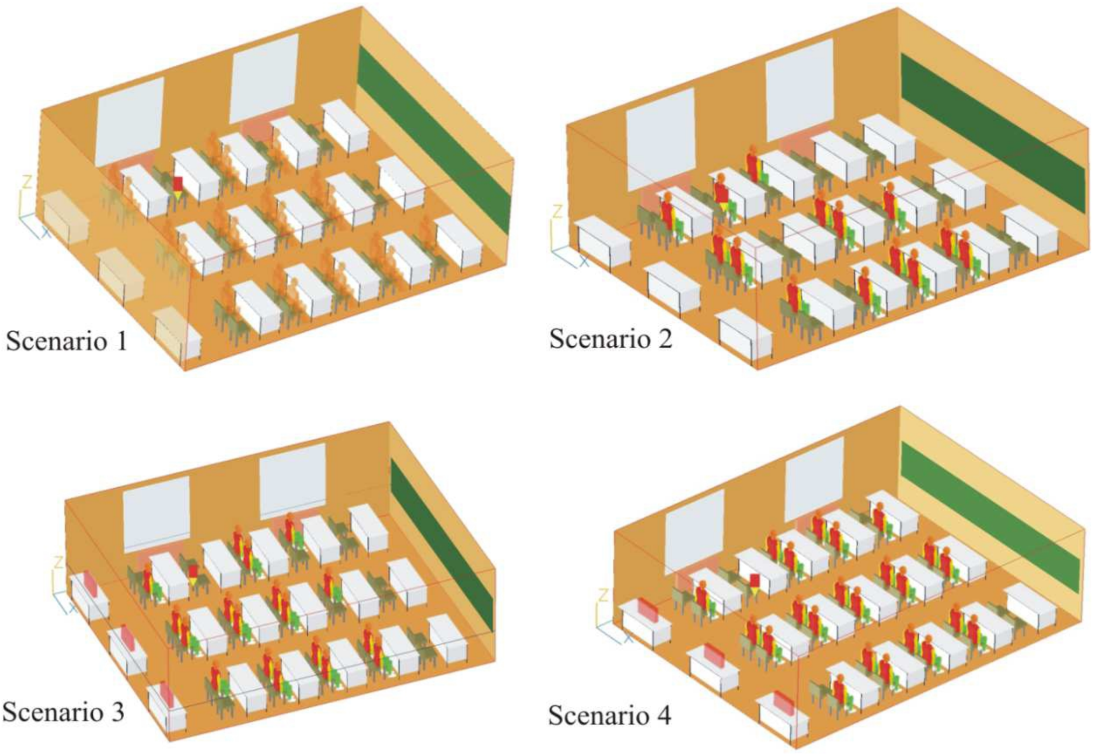

Figure 36 . Geometry of the observed classroom for each scenario

The less important surfaces, such as internal walls, doors and ceiling are hidden in order to have a good overview of the classroom inside.

After the geometry creation, it is necessary to define the materials, thermodynamic characteristics, solvers, domain-boundary conditions and computational grid. The number of cells can be set in Grid Mesh settings menu. The thickness of the grid was set manually around every solid and near the surfaces which are subject to a change of the observed variables. The cells were ordered thicker near the critical spots, where the transition between the materials or elements was important regarding the results (Fig.37).

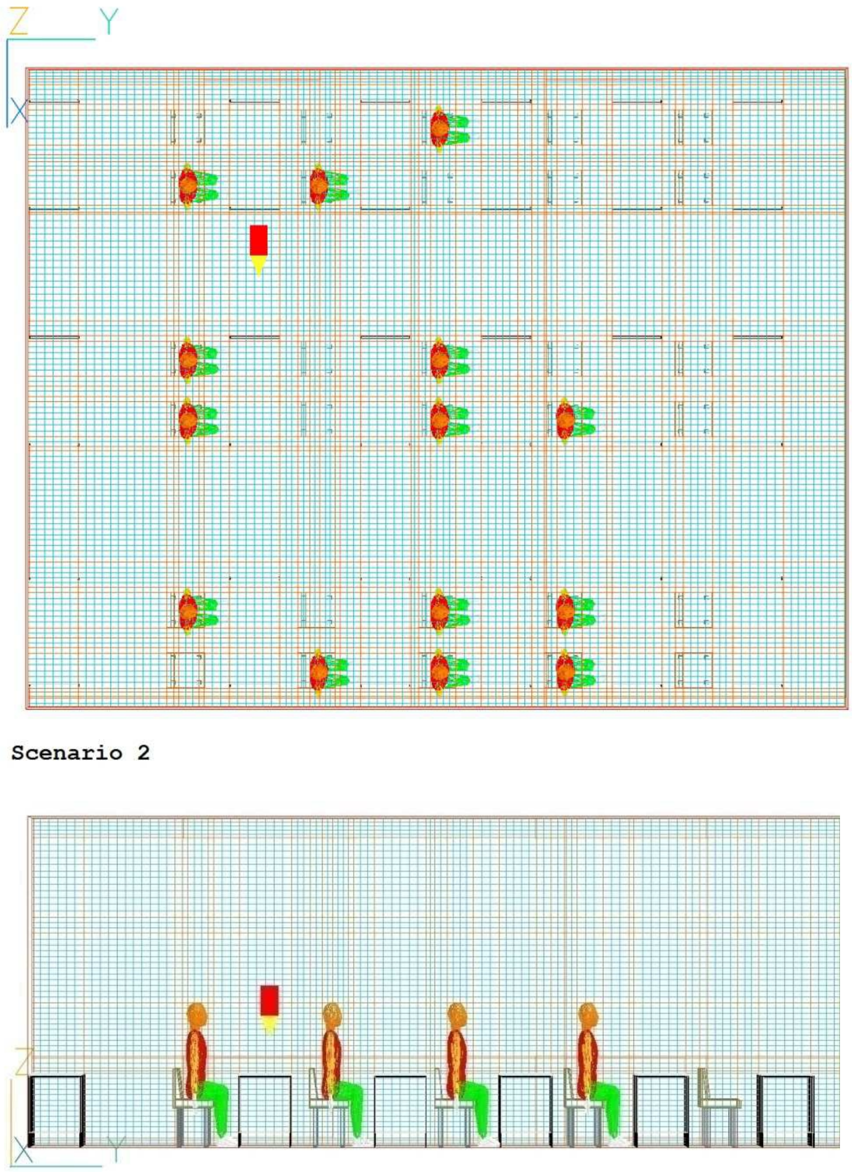

Figure 37. The mesh example shown for Scenario 2

Pre-settings can be defined in Domain Settings menu. After the settings part, the solver EARTH starts with a main program. The time for solving the problem depends from the complexity of the task and the wanted number of iteration. The number of iteration was checked in range from 100 to 500, and it is concluded that the optimal number of iterations in these cases is 300, having in mind the long period of time for each simulation. The results are very close to the measured values already for 200 iterations.

The EARTH solver with the converged solutions for four scenarios is shown on figure 38. It can be seen that the curves on the right side of each graph (the error values) have decreased steadily, which indicates the convergence of solutions. The left side of each graph shows the variations of the variables in setting spot. The right part, with the error values is more important as a parameter of the solutions accuracy.

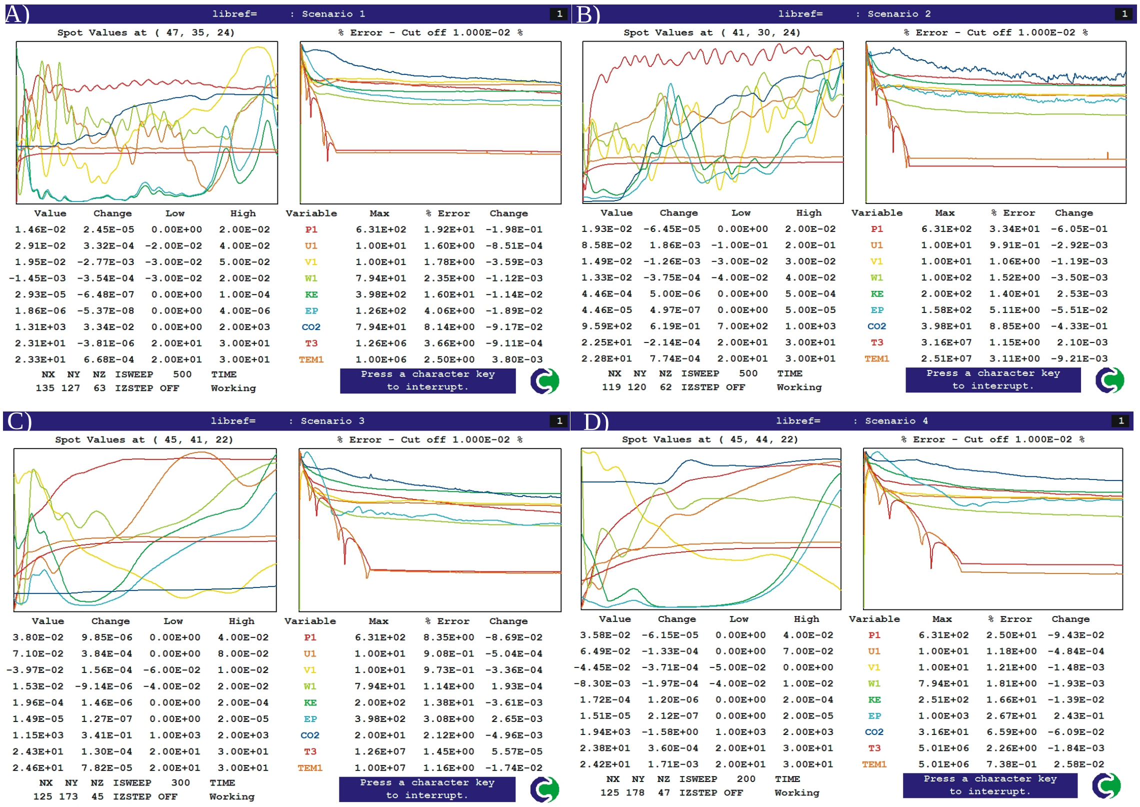

Figure 38. Solution convergence for A) Scenario 1, B) Scenario 2, C) Scenario 3, D) Scenario 4

The results of simulations can be viewed using “GUI post processor” (VR viewer), where the desirable point or plane or section can be adjusted and exported as a picture. The results for all four scenarios are numerous, and for different heights: z=0.1 m, 0.6 m, 1.1 m, 1.3 m and 1.6 m above the floor level. Due to the cumbersome display of all of these numerous results, the values are divided into tables instead of the figures and shown in the Appendix 5. The results are shown and discussed in next chapter. Some of the results are presented in figures 39 – 67 just as an example of the obtained results. The part of the results had been published in paper [98] discussing the impact of local thermal comfort conditions on students' productivity loss.

The results presented in further were chosen in order to obtain the values on students' heads level (1.3 m). The measurements were possible only in the limited number of spots. The simulations give decent results in every spot of the classroom volume and according to model validation (7.3. Models validation and Appendix 5), they can be used with a good certainty.

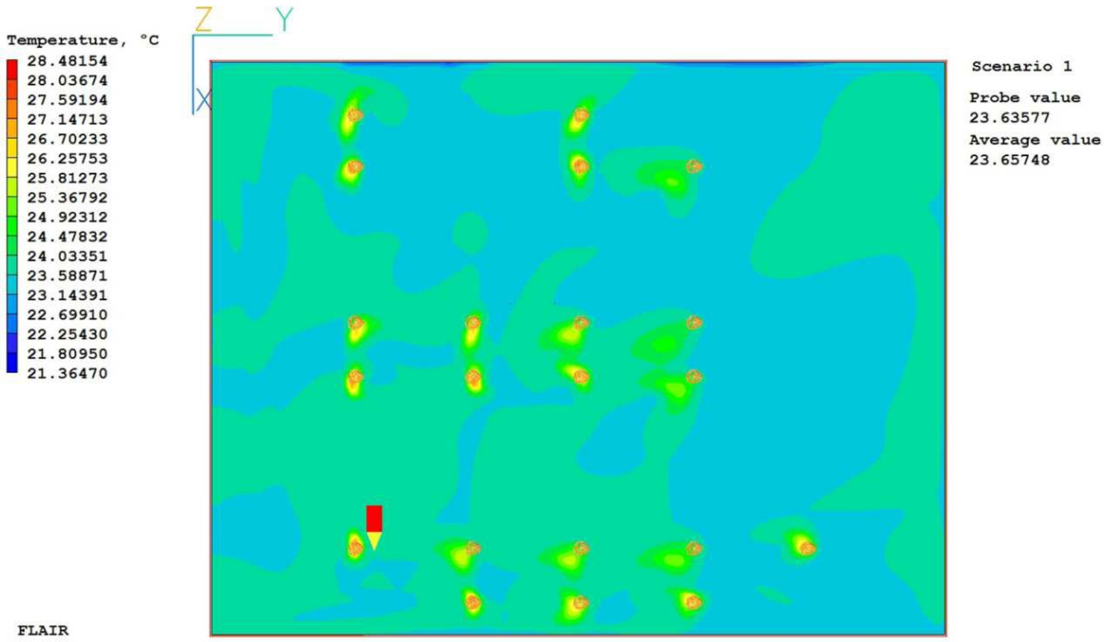

Figure 39. Temperature field at 1.3 m height for Scenario 1

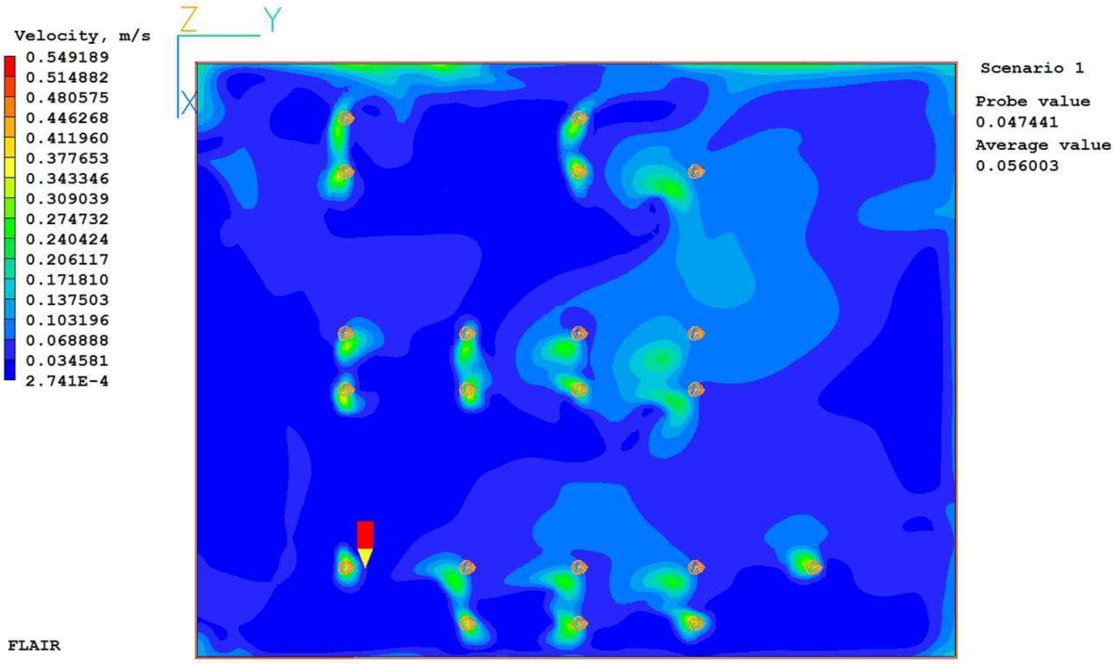

Figure 40. Velocity field at 1.3 m height for Scenario 1

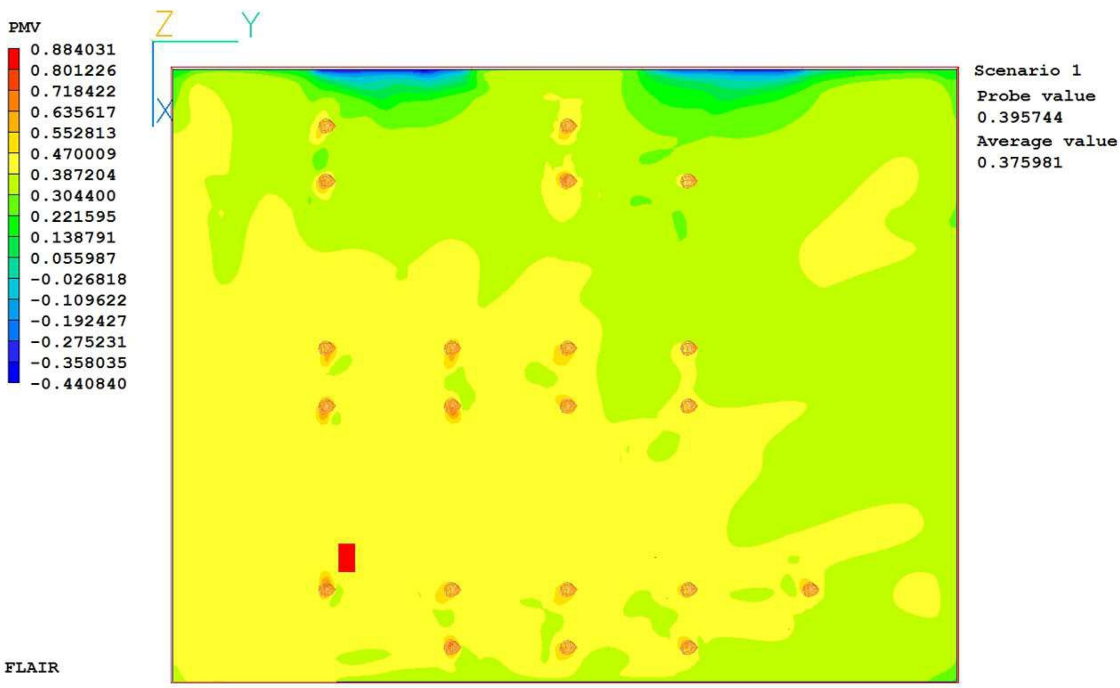

Figure 41. PMV index at 1.3 m height for Scenario 1

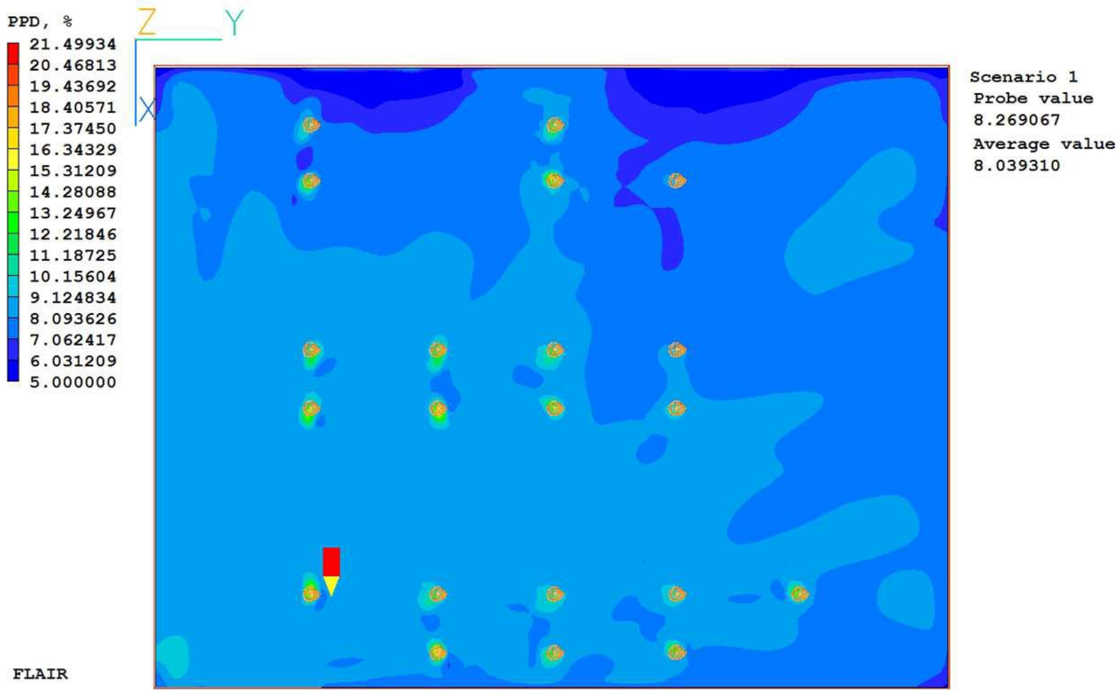

Figure 42. PPD index at 1.3 m height for Scenario 1

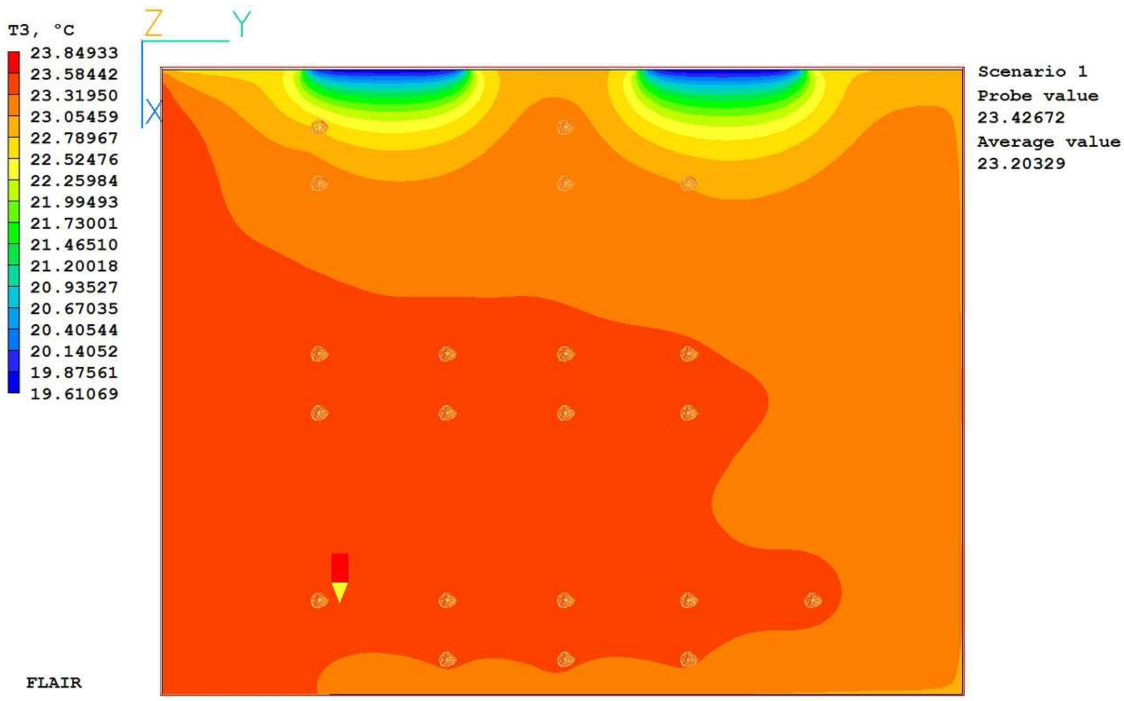

Figure 43. Radiant temperature at 1.3 m height for Scenario 1

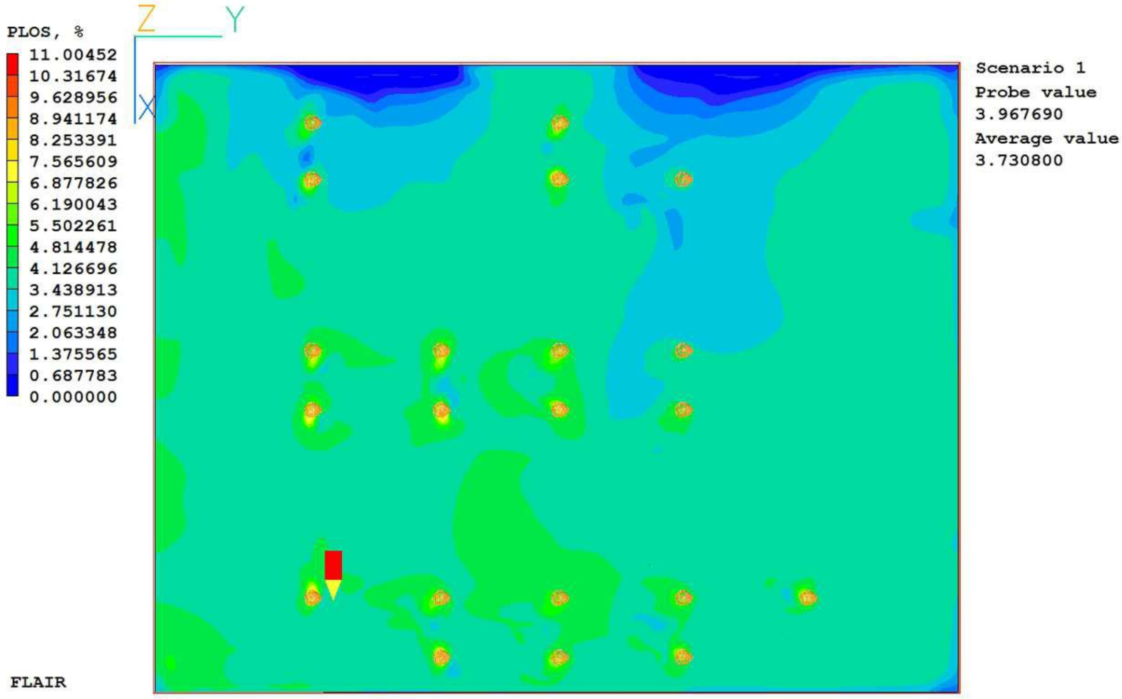

Figure 44. Productivity loss at 1.3 m height for Scenario 1

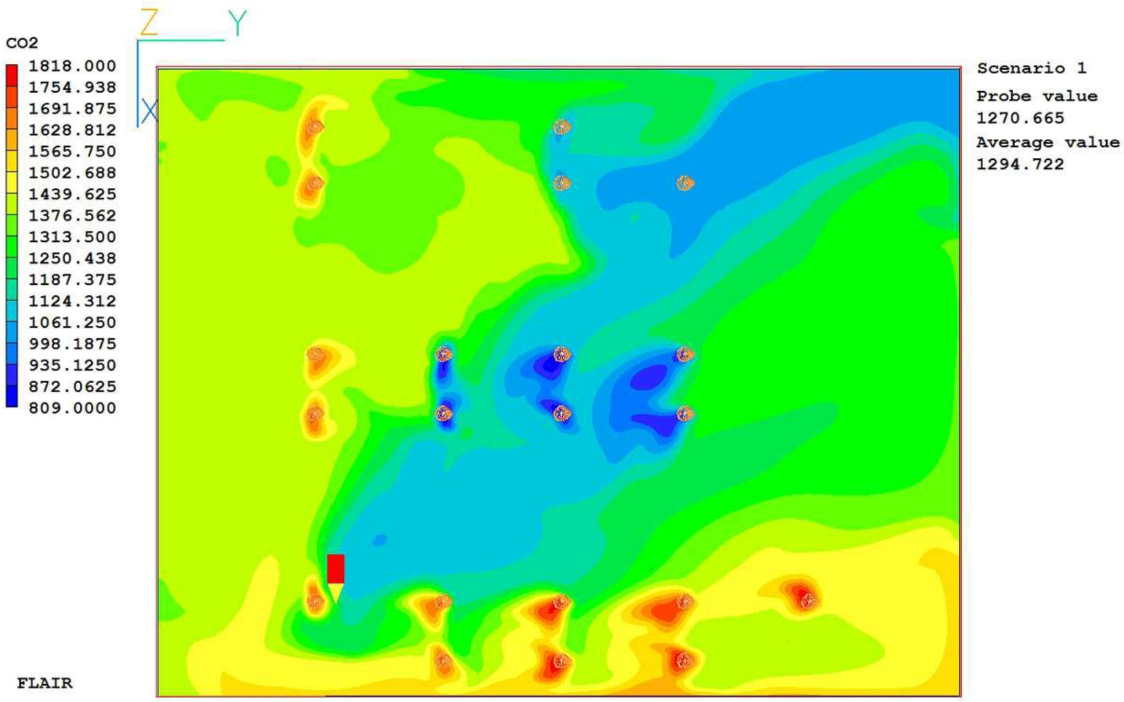

Figure 45. CO_2 concentration at 1.3 m height for Scenario 1

Figure 46. Temperature field at 1.3 m height for Scenario 2

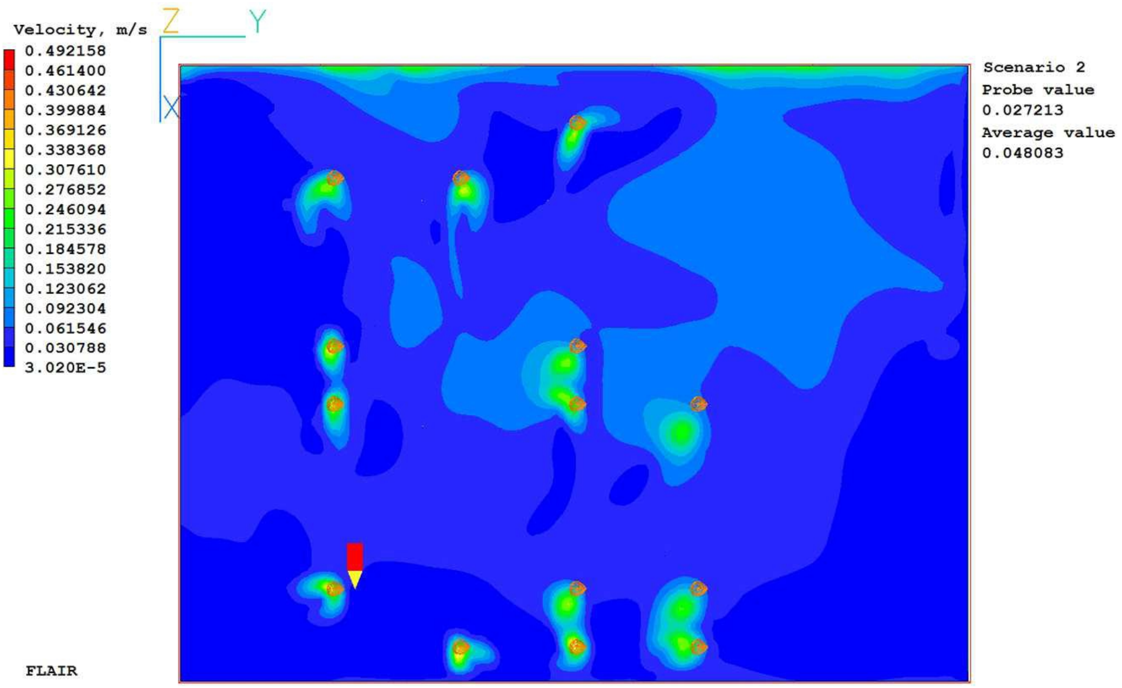

Figure 47. Velocity field at 1.3 m height for Scenario 2

Figure 48. PMV index at 1.3 m height for Scenario 2

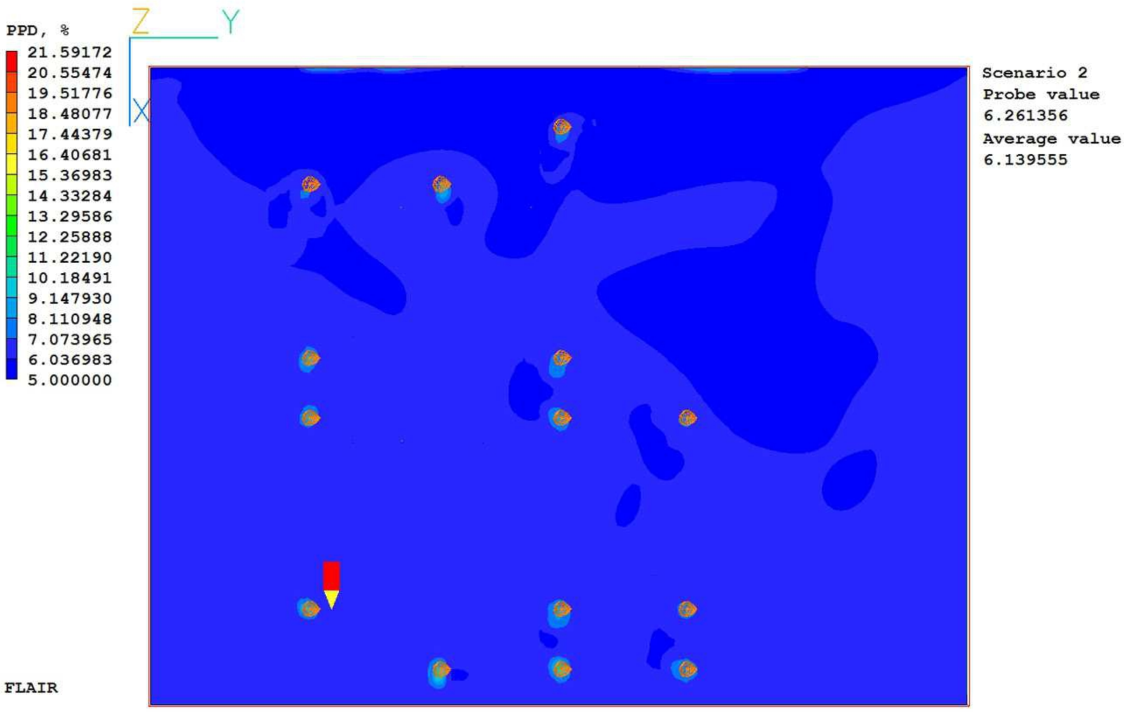

Figure 49. PPD index at 1.3 m height for Scenario 2

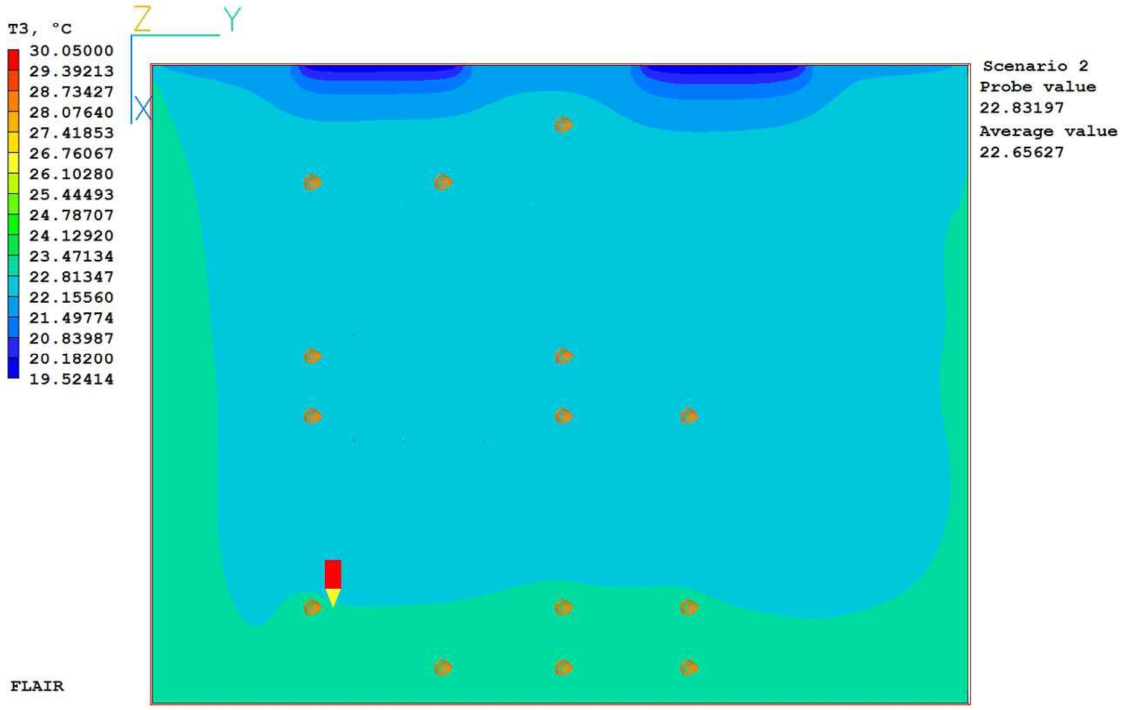

Figure 50. Radiant temperature at 1.3 m height for Scenario 2

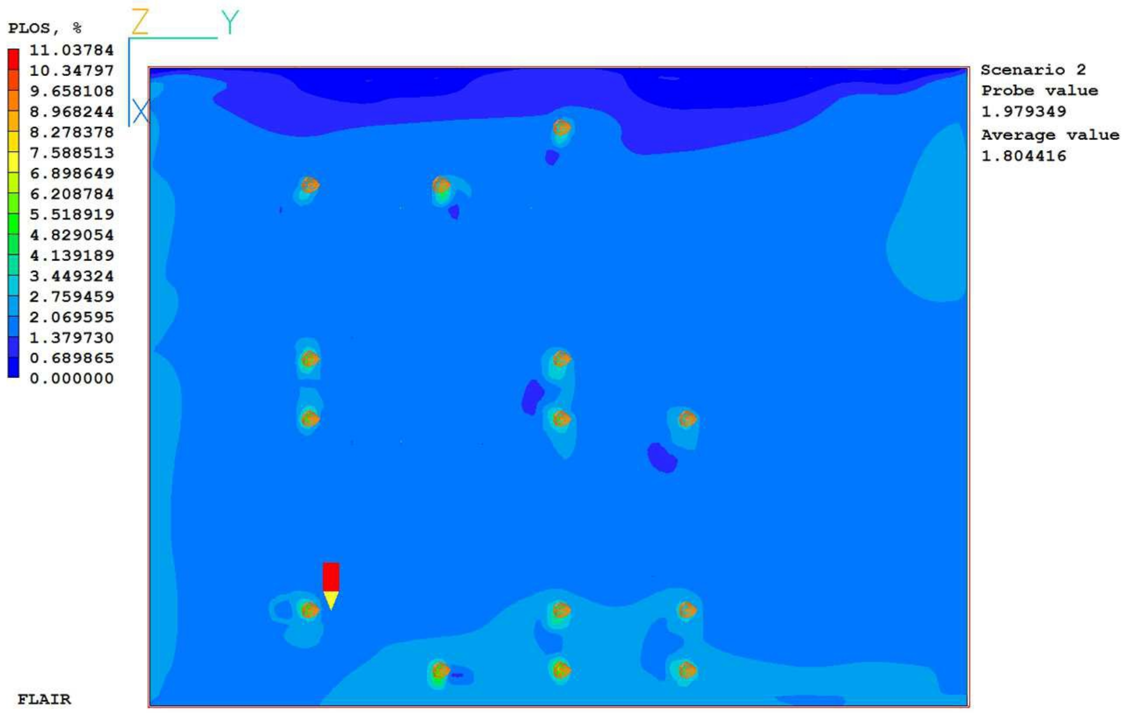

Figure 51. Productivity loss at 1.3 m height for Scenario 2

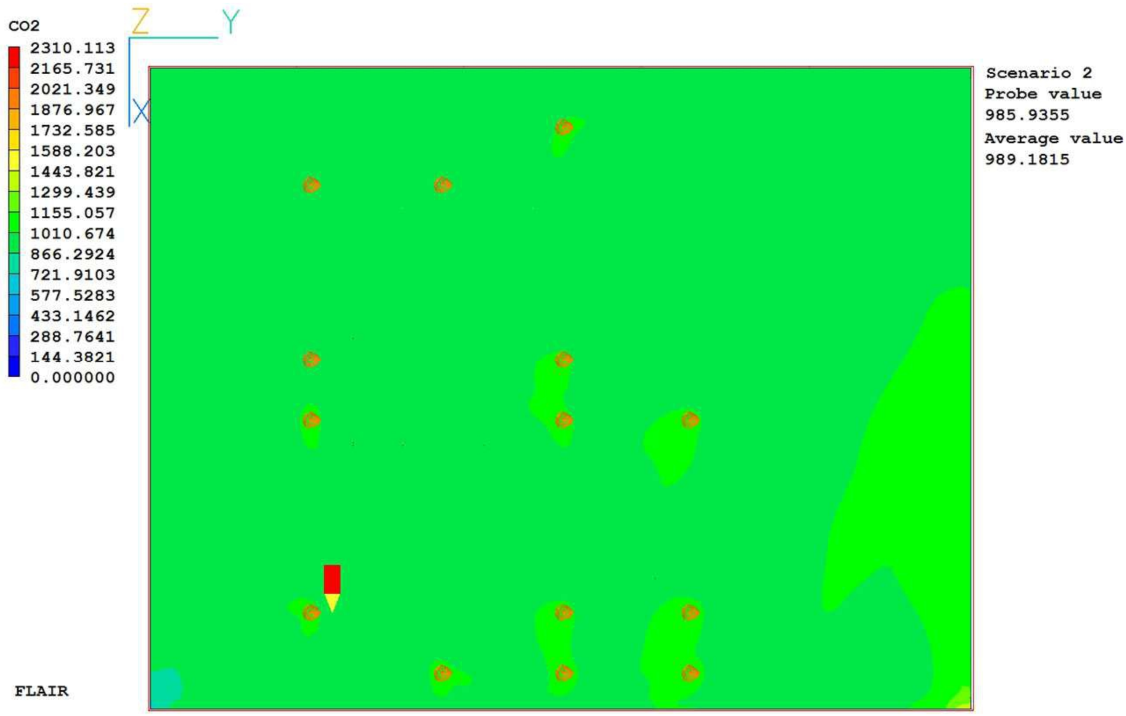

Figure 52. CO_2 concentration at 1.3 m height for Scenario 2

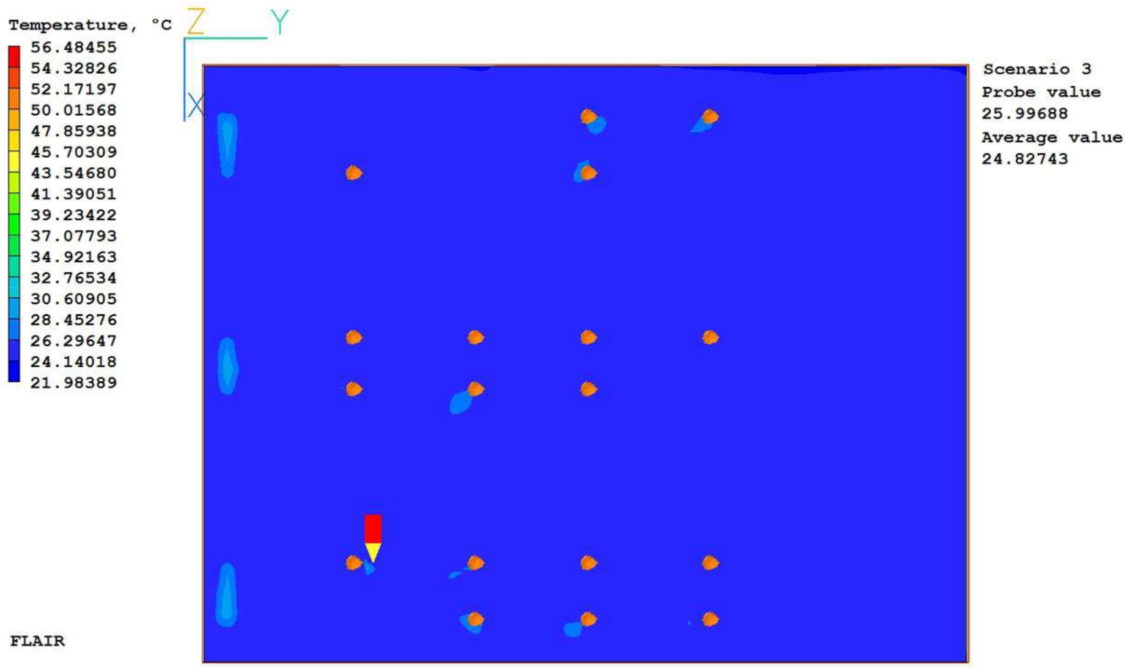

Figure 53. Temperature field at 1.3 m height for Scenario 3

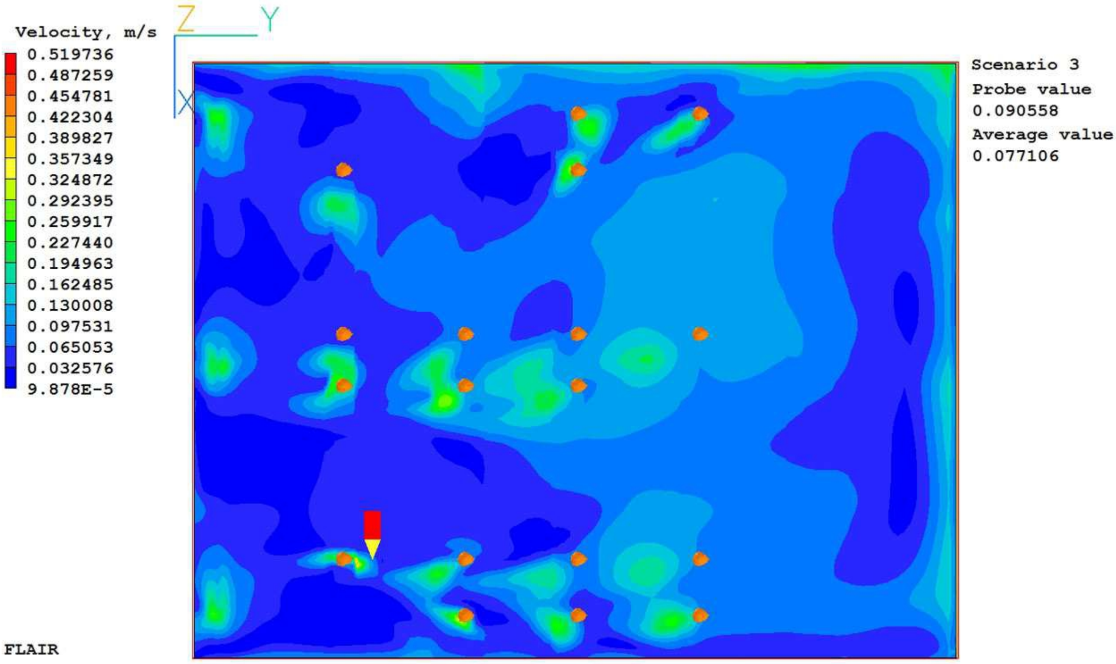

Figure 54. Velocity field at 1.3 m height for Scenario 3

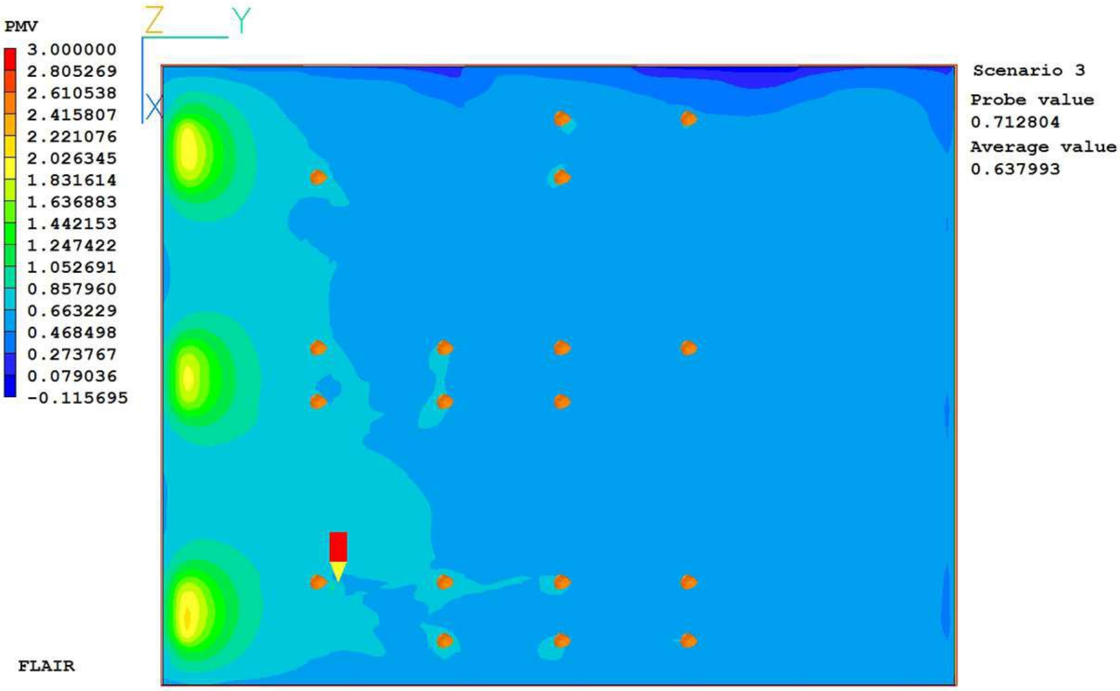

Figure 55. PMV index at 1.3 m height for Scenario 3

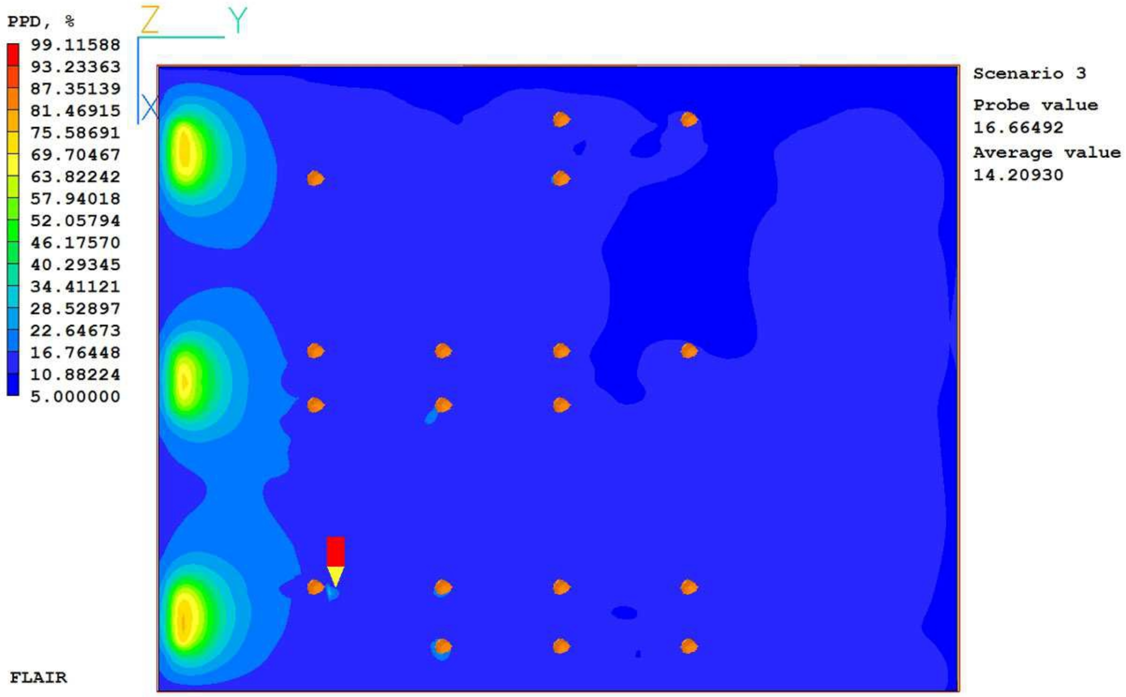

Figure 56. PPD index at 1.3 m height for Scenario 3

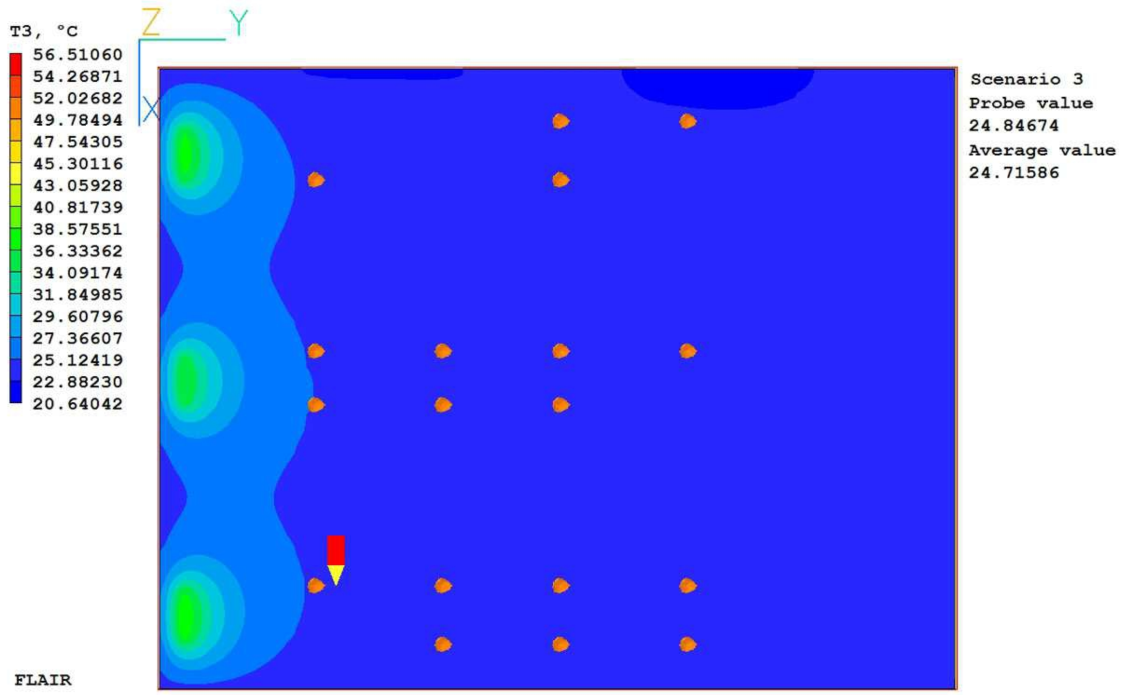

Figure 57. Radiant temperature at 1.3 m height for Scenario 3

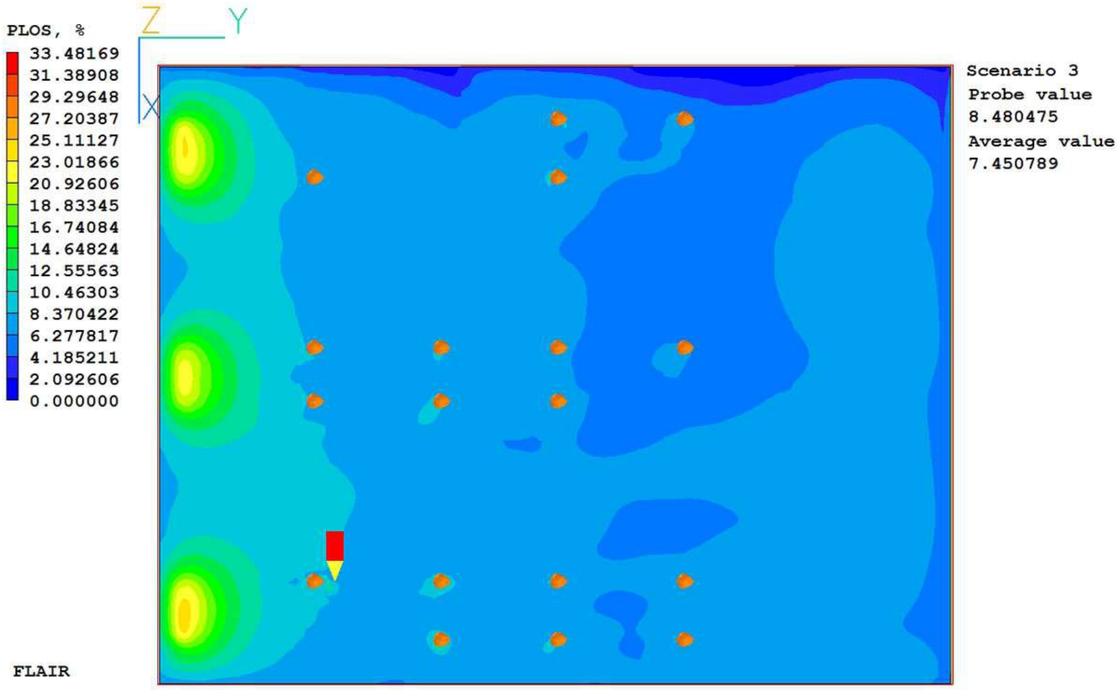

Figure 58. Productivity loss at 1.3 m height for Scenario 3

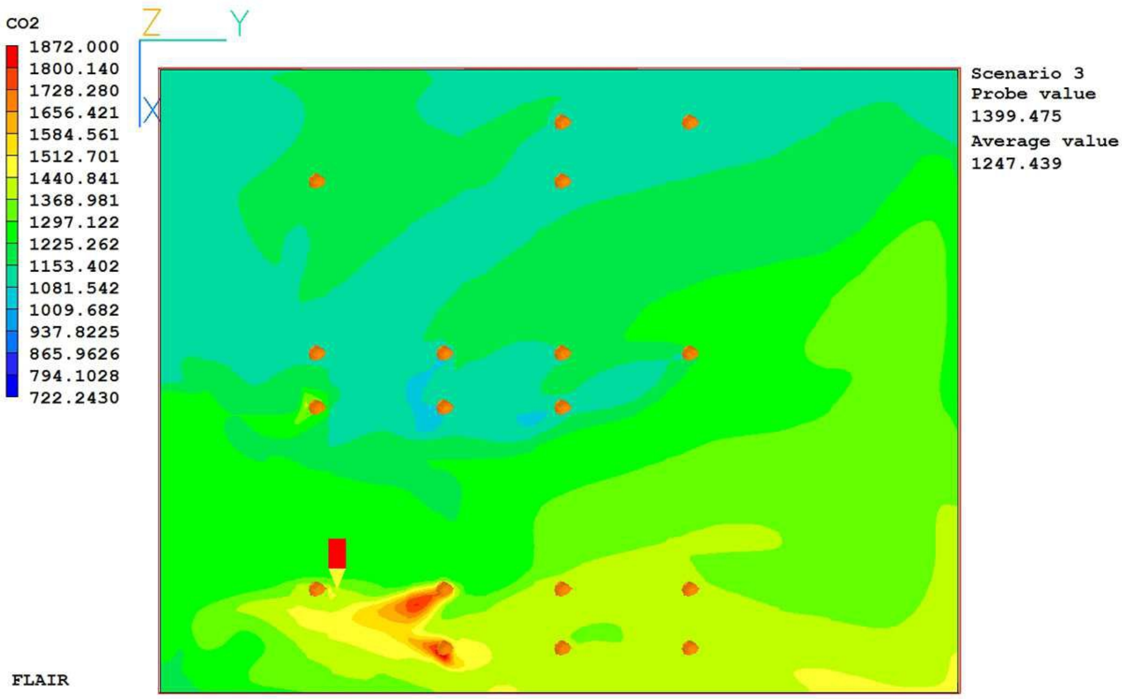

Figure 59. CO_2 concentration at 1.3 m height for Scenario 3

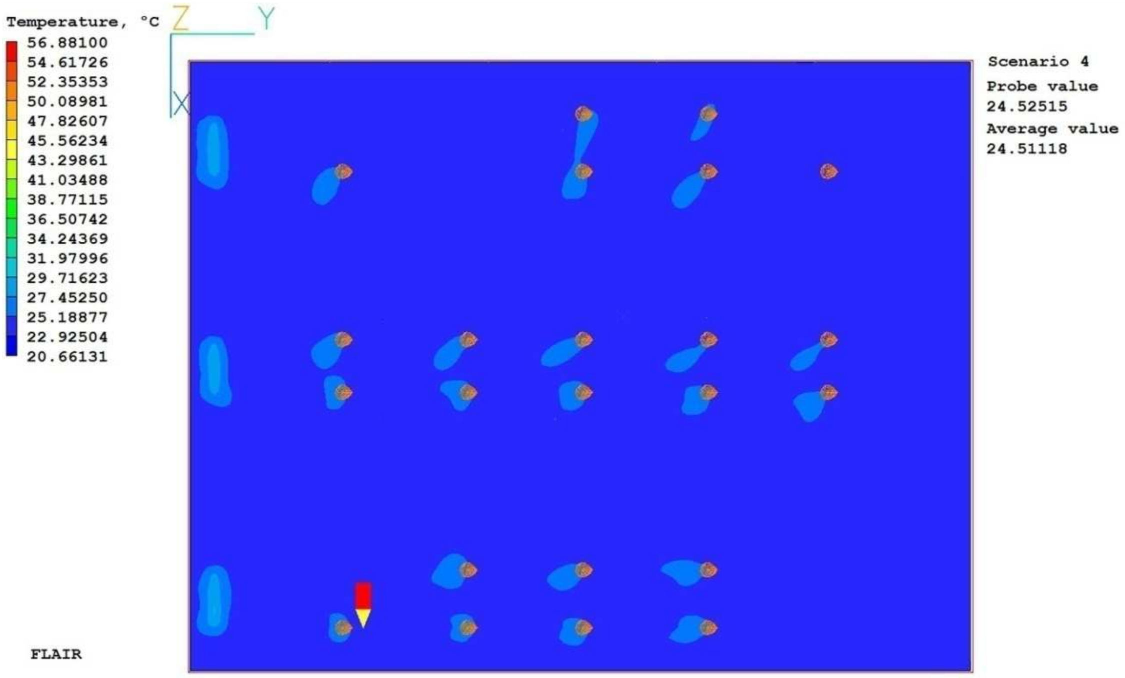

Figure 60. Air temperature at 1.3 m height for Scenario 4

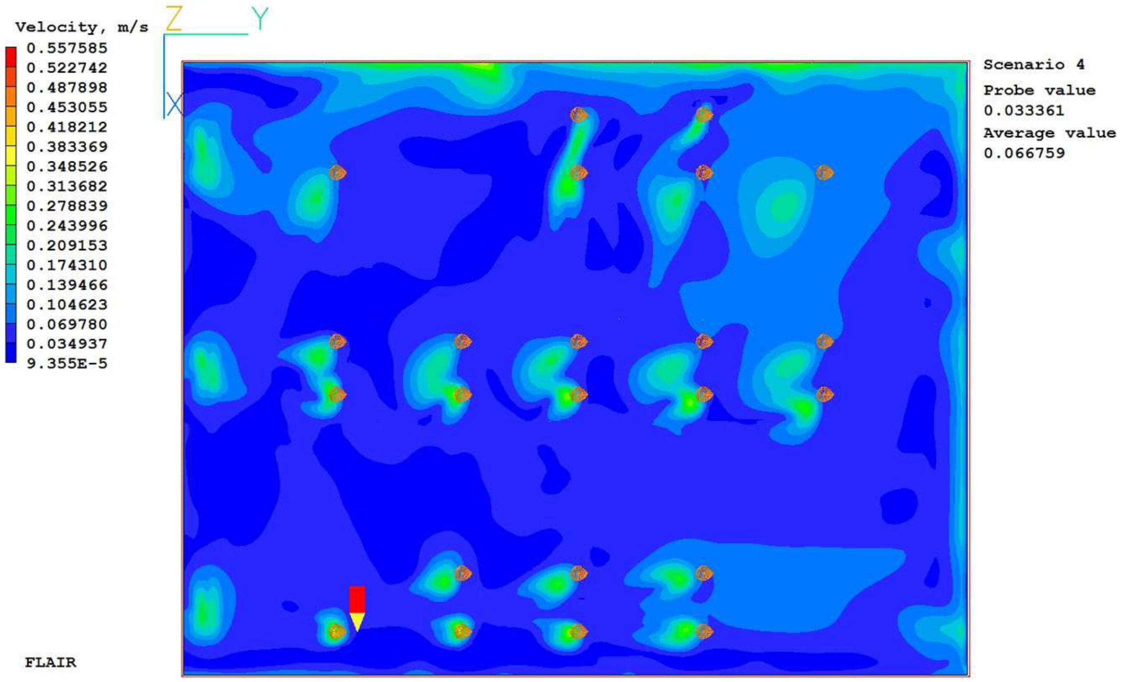

Figure 61. Velocity field at 1.3 m height for Scenario 4

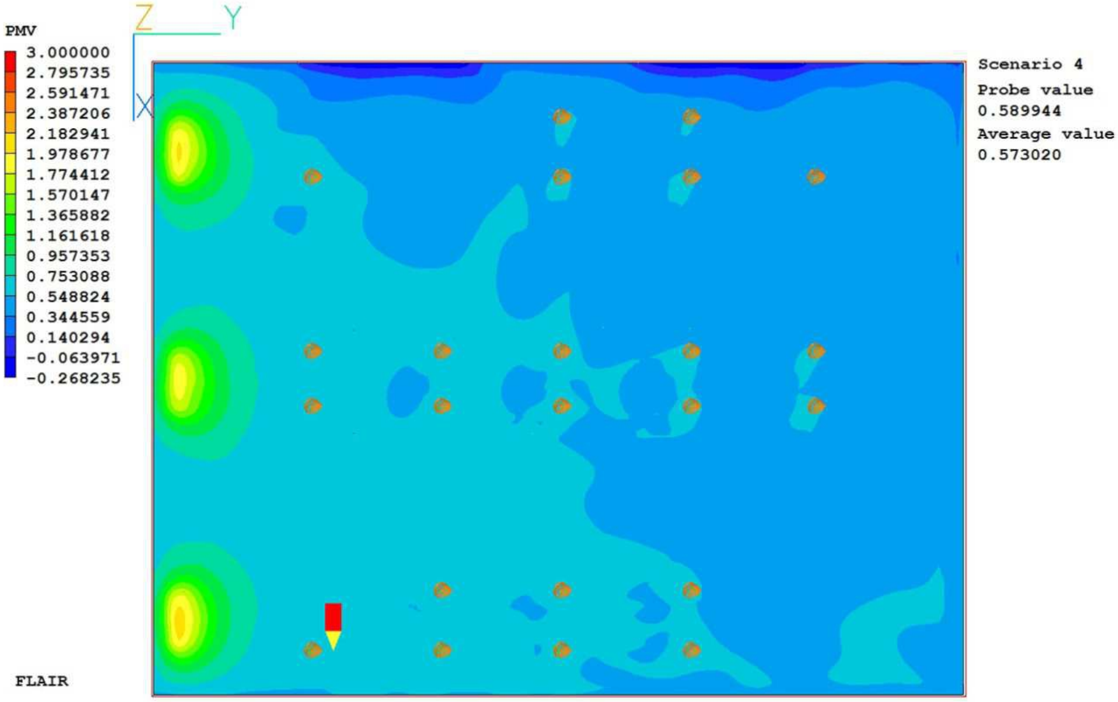

Figure 62. PMV index at 1.3 m height for Scenario 4

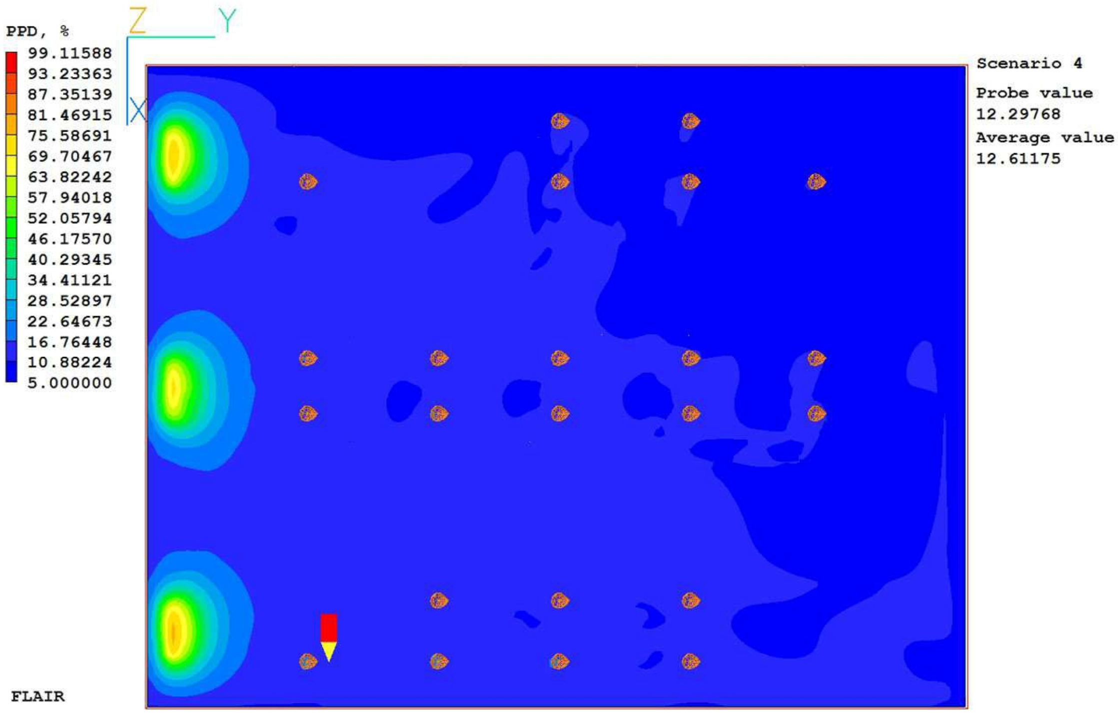

Figure 63. PPD index at 1.3 m height for Scenario 4

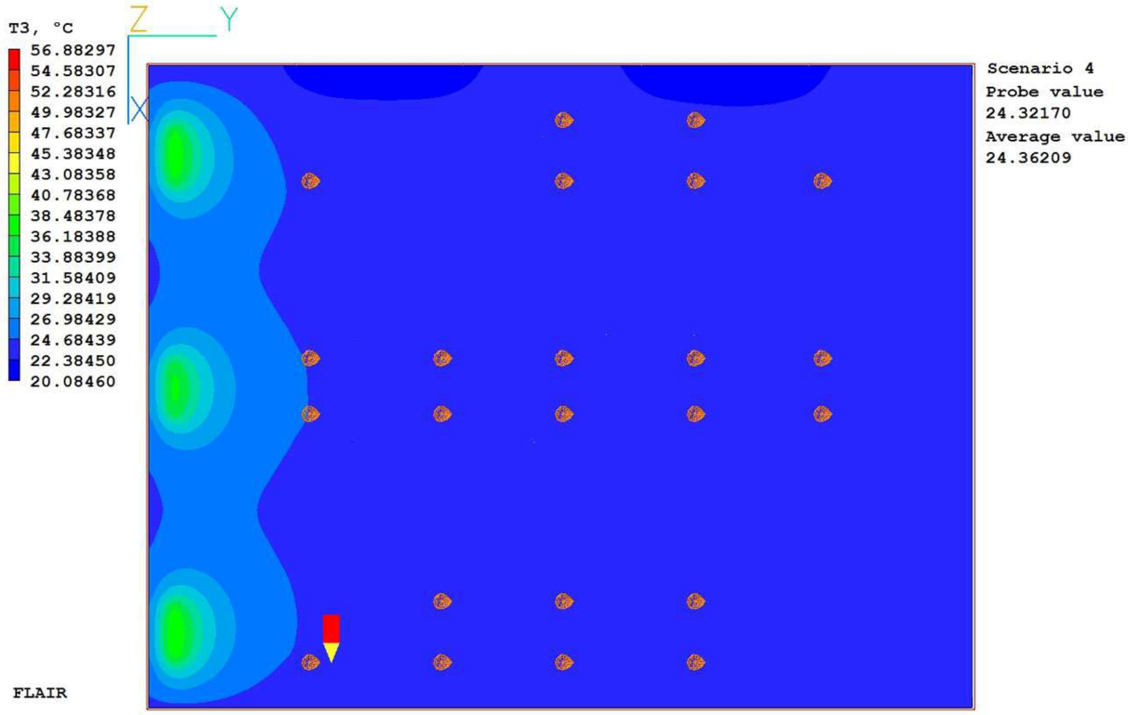

Figure 64. Radiant temperature at 1.3 m height for Scenario 4

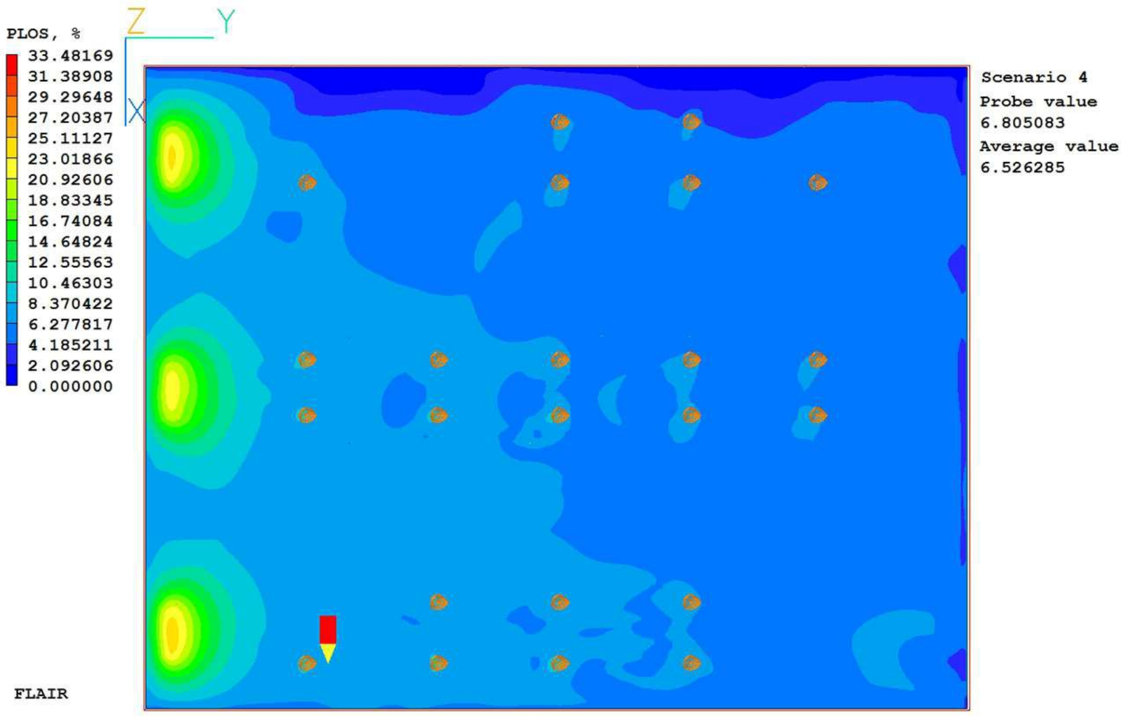

Figure 65. Productivity loss at 1.3 m height for Scenario 4

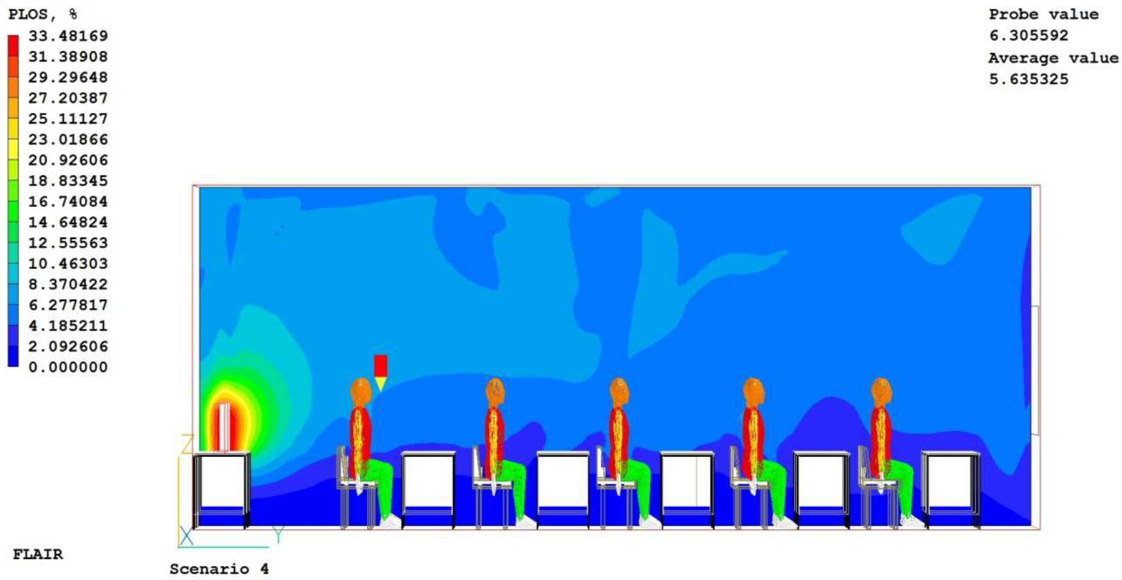

Figure 66. Productivity loss at 1.3m height for Scenario 4 – vertical section across the classroom

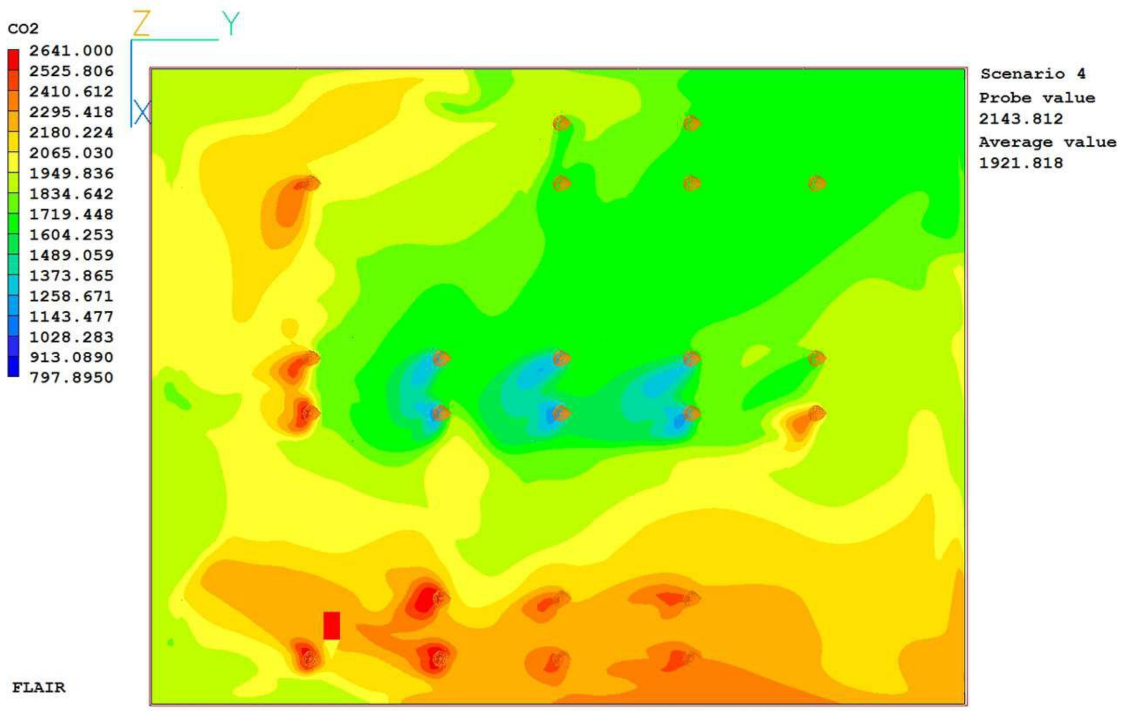

Figure 67. CO_2 concentration at 1.3 m height for Scenario 4

6.3. Models validation

According to Schatzmann et al. [99] the model validation procedure consists of: model and database description, scientific evaluation, code verification, model validation and user-oriented assessment. Model and database description include detail description of characteristics of the model, the range of use, the theoretical background, software and hardware requirements and the explanation about database that had been used. The scientific evaluation covers the mathematical background and the explanation of the chosen numerical model. Code verification includes the error identification in code notation and the validation of the results in comparison with a real physical nature of the problem. The model validation takes into consideration the comparison between numerical and experimental results, quantifying the difference between the results. The deviation between the results describes the quality of the model. The user-oriented assessment describes how the model is applicable in wide range of problems and also the user-friendly interface of the software [99].

The model validation was done using relative error examination between the measured values and the values obtained through the simulations for each of the four scenarios, comparing validation pairs. A lot of simulations were done for four scenarios, but as the appropriate ones only the models with relative error lower than 5% for physical parameters and lower than 50% for thermal comfort indices (in comparison to the measured values) were selected.

The relative error is expressed through the following formula [100]:

$$Error = \frac{x - x_0}{x_0} \cdot 100 \, , \tag{58}$$

where x is a measured value and x_0 is a simulated value.

The total number of validated pairs in Scenario 1 was 23. The comparison between the measured and values obtained in simulations for Scenario 1 is given in Table 44 and 45. The comparisons for other Scenarios are given in the Appendix 5.

Table 44. Measured and simulated air temperatures at different levels of height – Sc.1

Position index	Meas. Ta1 (0.1m) ºC	Flair Ta1 (0.1m) ºC	Rel.error %	Meas. Ta2 (0.6m) ºC	Flair Ta2 (0.6m) ºC	Rel.error %	Meas. Ta3 (1.1m) ºC	Flair Ta3 (1.1m) ºC	Rel.error %	Meas. Ta5 (1.6m) ºC	Flair Ta5 (1.6m) ºC	Rel.error %
P1.1	22.48			22.72			24.03			22.97		
P1.2	22.48			22.72			24.03			22.97		
P1.3	23.01			23.11			24.03			23.20		
P1.4	23.01			23.11			24.46			23.20		
P1.5	22.75	22.10	2.46	22.99	23.45	1.97	24.46	23.62	3.55	23.23	24.42	4.88
P1.6	22.75			22.99			24.46			23.23		
P2.1	22.29			22.93			24.03			23.57		
P2.2	22.29	22.83	0.77	22.93	23.38	1.92	24.03	23.55	2.02	23.57	24.01	1.81
P2.3	23.10	22.13	4.96	23.66	23.17	2.11	22.94	23.50	2.39	24.21	24.05	0.69
P2.4	23.10	22.07	4.82	23.66	23.44	0.91	22.94	23.48	2.30	24.21	24.76	2.21
P2.5	22.91	21.92	4.02	23.71	23.42	1.26	24.46	23.50	4.08	24.51	24.02	2.05
P2.6	22.91	22.13	3.91	23.71	23.60	0.50	24.46	24.01	1.86	24.51	25.16	2.57
P3.1	22.49	22.13	1.83	23.43	23.21	0.95	24.03	23.41	2.63	24.37	25.28	3.61
P3.2	22.49	22.08	2.04	23.43	23.40	0.12	24.03	24.06	0.12	24.37	25.54	4.59
P3.3	23.18	22.02	4.97	23.87	23.17	3.05	22.94	23.69	3.18	24.57	25.00	1.71
P3.4	23.18	22.09	4.02	23.87	23.67	0.83	22.94	24.03	4.54	24.57	24.19	1.56
P3.5	23.01	22.05	4.33	23.26	23.45	0.83	24.46	23.61	3.60	23.50	24.46	3.91
P3.6	23.01	22.06	4.01	23.26	23.74	2.02	24.46	23.70	3.20	23.50	24.62	4.57
P4.1	22.48			23.26			24.69			24.03		
P4.2	22.48			23.26			24.69			24.03		
P4.3	23.12	22.09	5.09	23.84	23.51	1.40	22.94	23.64	2.96	24.56	25.67	4.33
P4.4	23.12	22.06	5.04	23.84	23.41	1.85	22.94	24.23	5.32	24.56	24.54	0.08
P4.5	22.88	22.00	4.13	24.13	23.12	4.36	24.85	23.48	5.83	25.37	24.72	2.62
P4.6	22.88	22.06	3.95	24.13	23.60	2.23	24.85	24.28	2.36	25.37	24.80	2.31
P5.1	22.37	22.90	2.20	23.26	23.38	0.50	24.69	23.57	4.76	24.15	25.29	4.50
P5.2	22.37	22.51	1.35	23.26	23.21	0.23	24.69	23.57	4.77	24.15	26.04	7.27
P5.3	23.08	22.12	4.18	23.68	23.26	1.78	24.69	24.55	0.58	24.28	25.51	4.83
P5.4	23.08	22.21	4.42	23.68	23.39	1.24	24.85	23.66	5.03	24.28	25.38	4.35
P5.5	23.20	22.12	4.43	23.60	23.01	2.56	24.85	24.10	3.13	24.00	25.01	4.01
P5.6	23.20			23.60			24.85			24.00		
Average	22.82	22.17	2.92	23.43	23.38	0.21	24.16	23.77	1.62	24.04	24.88	3.39
q			0.90			1.00			0.86			0.95

Table 45. Measured and simulated radiant temperatures at 1.1 m height - Scenario 1

Position index	Measured T_{rad} (1.1) [°C]	Flair T_{rad} (1.1) [°C]	Rel. error [%]
P1.1	22.88		
P1.2	22.88		
P1.3	22.88		
P1.4	24.26		
P1.5	24.26	23.27	4.26

Position index	Measured T_{rad} (1.1) [^{o}C]	Flair T_{rad} (1.1) [^{o}C]	Rel. error [%]
P1.6	24.26		
P2.1	22.88		
P2.2	22.88	23.20	1.38
P2.3	23.42	23.24	0.76
P2.4	23.42	23.27	0.64
P2.5	24.26	23.31	4.06
P2.6	24.26	23.28	4.21
P3.1	22.88	23.10	0.94
P3.2	22.88	23.19	1.33
P3.3	23.42	23.32	0.45
P3.4	23.42	23.33	0.38
P3.5	24.26	23.37	3.83
P3.6	24.26	23.31	4.10
P4.1	24.45		
P4.2	24.45		
P4.3	23.42	23.32	0.42
P4.4	23.42	23.35	0.31
P4.5	24.82	23.35	6.32
P4.6	24.82	23.31	6.50
P5.1	24.45	22.73	7.58
P5.2	24.45	23.09	5.87
P5.3	24.45	23.33	4.81
P5.4	24.82	23.33	6.38
P5.5	24.82	23.33	6.38
P5.6	24.82		
Average	23.90	23.25	2.11
q			0.71

The other significant parameter for model validation is the hit rate. According to the definition from the literature [99]: “The hit rate specifies the fraction of model results that differ within an allowed range D or W from the comparison data. D accounts for the relative uncertainty of the comparison data. W describes the repeatability of the comparison data.” The hit rate q can be described using the equation [99]:

$$q = \frac{N}{n} = \frac{1}{n}\sum_{i=1}^{n} N_i, \; N_i = \begin{cases} 1 \text{ for } \left|\frac{P_i - O_i}{O_i}\right| \leq D \text{ or } \left|P_i - O_i\right| \leq W \\ 0 \text{ else} \end{cases}, \qquad (59)$$

where P_i is normalized model result and O_i is normalized comparison data. The allowed D value is up to 25% for physical parameters according to VDI2005, and W depends on experimental uncertainty and it is different for each variable [99]. For this investigation, the allowed relative difference for physical parameters is 5%, and for PMV, PPD and PLOS indexes the allowed D value is considered to be 50% on a local level, having in mind the complex nature of these indexes, as a function of several parameters and the deviation from ideal conditions. The hit rate value has to be q≥0.66.

The model validation using hit rate parameter is shown in Table 46-49. for the air temperatures at 0.1, 0.6, 1.1 and 1.6 m height and in Table 50. for radiant temperature at 1.1 m height above the floor.

Table 46. Model validation for air temperatures at 0.1 m height

	Measured	Simulated				
Scenario	**$T_{a1,av}$ (0.1m)**	**$T_{a1,av}$ (0.1m)**	**Error [%]**	**q**	Validated	Valid pairs < 5% error
1	22.82	22.17	2.92	0.90	21	19
2	21.47	21.52	0.23	1.00	14	14
3	22.57	23.01	2.09	0.94	18	17
4	22.16	22.00	0.80	1.00	23	23

Table 47. Model validation for air temperatures at 0.6 m height

	Measured	Simulated				
Scenario	**$T_{a2,av}$ (0.6m)**	**$T_{a2,av}$ (0.6m)**	**Error [%]**	**q**	Validated	Valid pairs < 5% error
1	23.43	23.38	0.21	1.00	21	21
2	21.70	22.32	2.80	1.00	14	14
3	23.39	24.40	3.64	0.94	18	17
4	23.07	23.68	2.57	1.00	23	23

Table 48. Model validation for air temperatures at 1.1 m height

	Measured	Simulated				
Scenario	**$T_{a3,av}$ (1.1m)**	**$T_{a3,av}$ (1.1m)**	**Error [%]**	**q**	Validated	Valid pairs < 5% error
1	24.16	23.77	1.62	0.86	21	18
2	23.10	23.15	0.25	1.00	14	14
3	25.15	24.95	0.78	0.83	18	15
4	24.70	24.28	2.57	0.91	23	21

Table 49. Model validation for air temperatures at 1.6 m height

	Measured	Simulated				
Scenario	**$T_{a5,av}$ (1.6m)**	**$T_{a5,av}$ (1.6m)**	**Error [%]**	**q**	Validated	Valid pairs < 5% error
1	24.04	24.88	3.39	0.95	21	20
2	22.39	23.55	4.94	0.86	14	12
3	24.63	25.14	1.97	0.94	18	17
4	24.31	24.94	2.49	0.96	23	22

Table 50. Model validation for radiant temperatures at 1.1m height

	Measured	Simulated				
Scenario	**Trad,av**	**Trad,av**	**Error [%]**	**q**	Validated	Valid pairs < 5% error
1	23.90	23.25	2.11	0.71	21	15
2	23.00	22.71	1.26	1.00	14	14
3	24.91	24.36	2.28	0.83	18	15
4	24.47	23.93	1.26	0.91	23	21

The hit values for both air and radiant temperatures show very good agreement between the measured values and the simulations, so the accepted models for scenarios 1 to 4 can be considered satisfying, looking at the physical parameters: air and radiant temperatures at different levels of height.

The model validation for thermal comfort indices and PLOS are presented in Tables 51-54. The hit rate is validated for the valid pairs for each scenario.

Table 51. Model validation for thermal comfort indexes and productivity loss for Scenario 1

Scenario 1	Meas.	Sim.	Error [%]	q	Validated	Valid pairs < 50% error
PMV_{av}	0.56	0.39	32.80	0.86	21	18
PPD_{av}	12.90	8.18	38.01	0.71	21	15
$PLOSS_{av}$	6.37	3.88	40.50	0.67	21	14

Table 52. Model validation for thermal comfort indexes and productivity loss for Scenario 2

Scenario 2	Meas.	Sim.	Error [%]	q	Validated	Valid pairs < 50% error
PMV_{av}	0.29	0.24	19.22	1.00	14	14
PPD_{av}	9.20	6.18	32.78	1.00	14	14
$PLOSS_{av}$	2.57	1.87	27.51	0.79	14	11

Table 53. Model validation for thermal comfort indexes and productivity loss for Scenario 3

Scenario 3	Meas.	Sim.	Error [%]	q	Validated	Valid pairs < 50% error
PMV_{av}	0.74	0.63	17.22	0.94	18	17
PPD_{av}	21.13	13.85	37.84	0.83	18	15
$PLOSS_{av}$	8.97	7.47	22.27	0.94	18	17

Table 54. Model validation for thermal comfort indexes and productivity loss for Scenario 4

Scenario 4	Meas.	Sim.	Error [%]	q	Validated	Valid pairs < 50% error
PMV_{av}	0.68	0.55	24.26	1.00	23	23
PPD_{av}	16.05	11.32	34.09	1.00	23	23
$PLOSS_{av}$	8.11	6.19	29.68	1.00	23	23

According to the results shown in Table 51 to 54, the models used for Scenarios 1 to 4 showed a good agreement with the measured values. The relative error is lower than predicted 50% for thermal comfort indexes and productivity loss, as well as a hit rate, which is higher than allowed 0.66.

Looking at both physical parameters and thermal comfort indices, the used models have a decent agreement with the experimental results, and can be used as a valuable prediction tool when the experiments are difficult or impossible to perform.

CHAPTER 7

“The cave you afraid to enter holds the treasure you seek.”

Joseph Campbell

„Пећина у коју се плашиш да уђеш скрива благо које тражиш.“

Џозеф Кемпбел

7. SYNTHESIS OF MEASUREMENTS, STATISTICAL AND NUMERICAL RESULTS

In this chapter the combined results obtained through experiment, statistical analysis and the use of numerical simulation (Figure 68) are presented and discussed.

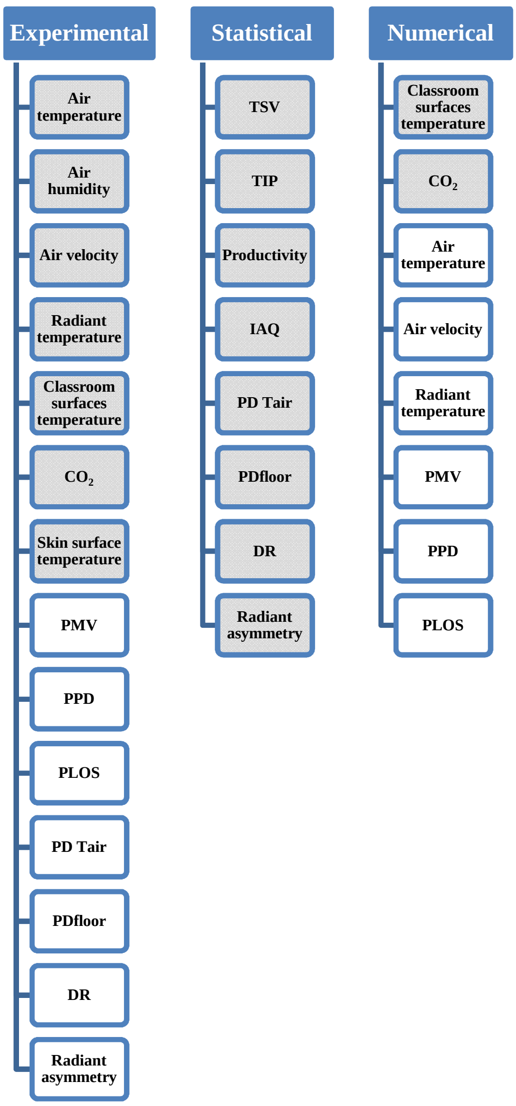

Figure 68. The synthesis of the measured, surveyed and simulated values

The measured and surveyed values are shown in grey fields, the same as the values used as an input for the numerical simulations. The indirectly deduced values, using calculations and simulations, are presented in white rectangles.

7.1. Comparison between the measurements and questionnaires

The differences between the students' personal sensations about thermal environment and its impact on students' productivity and the measured values are presented in this chapter, correlating the data collected, processed and concluded through this research into a final conclusions and suggestions for the future work.

The comparison between the measured PMV and PPD and TSV and TIP collected through the questionnaires and its impact on students' performances are averaged for each position and presented in tables 55 to 58.

Table 55. PMV, PPD and TIP indices in correlation with an ability to work, compared for measurement and questionnaires for Scenario 1

Position index	PMV	TSV	PPD [%]	TIP [%]	Productivity [%]
P1.1	0.42		9.87		
P1.2	0.42		9.87		
P1.3	0.42		9.87		
P1.4	0.68	0.0	15.47		90.0
P1.5	0.68	1.0	15.47	10.0	
P1.6	0.68		15.47		20.0
P2.1	0.42	2.0	9.87	5.0	80.0
P2.2	0.42	1.3	9.87	15.0	50.0
P2.3	0.33	1.3	8.06	19.3	65.0
P2.4	0.33	1.3	8.06		62.5
P2.5	0.68	1.0	15.47	11.3	67.5
P2.6	0.68	0.8	15.47	6.5	62.5
P3.1	0.42	1.0	9.87	18.3	42.0
P3.2	0.42	1.0	9.87	20.0	57.5
P3.3	0.33	2.0	8.06	72.5	67.5
P3.4	0.33	0.0	8.06		63.3
P3.5	0.68		15.47		55.0
P3.6	0.68	1.0	15.47	35.0	72.5
P4.1	0.7		15.96		
P4.2	0.7		15.96		
P4.3	0.33	1.0	8.06	10.0	44.0
P4.4	0.33	1.0	8.06	15.0	43.3

Position index	PMV	TSV	PPD [%]	TIP [%]	Productivity [%]
P4.5	0.72	0.7	16.32	2.5	73.3
P4.6	0.72	1.3	16.32	10.0	80.0
P5.1	0.7	1.5	15.96	45.0	50.0
P5.2	0.7	1.0	15.96	5.0	53.3
P5.3	0.7	1.7	15.96	25.0	66.7
P5.4	0.72	1.7	16.32	45.0	41.3
P5.5	0.72	0.0	16.32		25.0
P5.6	0.72		16.32		60.0
MAX	0.72	2	16.32	72.5	90
MIN	0.33	0	8.06	2.5	20
Average	0.56	1.07	12.90	20.58	58.5

Table 56. PMV and PPD indices in correlation with an ability to work, compared for measurement and questionnaires for Scenario 2

Position index	PMV	TSV	PPD [%]	TIP [%]	Productivity [%]
P1.1	0.23	1.0	9.08	0.0	0.0
P1.2	0.23		9.08		
P1.3	0.23		9.08		
P1.4	0.24	0.0	8.09		65.0
P1.5	0.24		8.09		
P1.6	0.24		8.09		
P2.1	0.23		9.08		
P2.2	0.23	0.5	9.08	10.0	70.0
P2.3	0.23	0.5	9.08	5.0	80.0
P2.4	0.24	1.0	8.09	3.0	66.7
P2.5	0.24	0.0	8.09		75.0
P2.6	0.24	1.0	8.09	1.0	90.0
P3.1	0.23	1.7	9.08	17.5	90.0
P3.2	0.23	1.5	9.08	5.0	80.0
P3.3	0.23	1.3	9.08	12.5	76.7
P3.4	0.24	1.5	8.09	20.0	32.5
P3.5	0.24		8.09		95.0
P3.6	0.24	1.0	8.09	22.5	55.0
P4.1	0.36		10.47		
P4.2	0.36		10.47		
P4.3	0.36	1.0	10.47	85.0	65.0
P4.4	0.39		9.77		80.0
P4.5	0.39	1.0	9.77	0.0	30.0
P4.6	0.39	1.0	9.77		60.0
P5.1	0.36		10.47		
P5.2	0.36	0.0	10.47		40.0
P5.3	0.36	0.5	10.47	15.0	65.0

Position index	PMV	TSV	PPD [%]	TIP [%]	Productivity [%]
P5.4	0.39	1.0	9.77	0.0	75.0
P5.5	0.39		9.77		
P5.6	0.39		9.77		
MAX	0.39	1.67	10.47	85	95
MIN	0.23	0	8.09	0	0
Average	0.29	0.86	9.20	14.04	68.4

Table 57. PMV, PPD and TIP indices in correlation with an ability to work, compared for measurement and questionnaires for Scenario 3

Position index	PMV	TSV	PPD [%]	TIP [%]	Productivity [%]
P1.1	1.05	0.00	29.69		55.0
P1.2	1.05		29.69		
P1.3	1.05	1.00	29.69	0	40.0
P1.4	0.54	2.00	12.94	22	45.0
P1.5	0.54		12.94		
P1.6	0.54		12.94		
P2.1	1.05	2.00	29.69	20	40.0
P2.2	1.05	1.50	29.69	3	55.0
P2.3	0.70	2.00	20.67	43	53.8
P2.4	0.70	2.00	20.67	58	43.8
P2.5	0.54	1.67	12.94	18	75.0
P2.6	0.54	1.50	12.94	4	70.0
P3.1	1.05	1.67	29.69	20	73.3
P3.2	1.05	2.25	29.69	41	60.0
P3.3	0.70	2.00	20.67	13	77.5
P3.4	0.70	2.00	20.67	30	56.7
P3.5	0.54	2.00	12.94	13	66.7
P3.6	0.54	1.00	12.94	20	65.0
P4.1	0.59		21.25		
P4.2	0.59		21.25		
P4.3	0.70	1.33	20.67	35	60.0
P4.4	0.70	1.33	20.67	23	41.3
P4.5	0.81	2.00	21.05	30	92.5
P4.6	0.81	1.00	21.05	53	40.0
P5.1	0.59		21.25		
P5.2	0.59	1.50	21.25	20	85.0
P5.3	0.59	1.00	21.25	15	32.5
P5.4	0.81	2.50	21.05	55	52.5
P5.5	0.81		21.05		
P5.6	0.81		21.05		
MAX	1.05	2.5	29.69	57.5	92.5
MIN	0.54	0	12.94	0	32.5
Average	0.74	1.60	21.13	25.38	58

Table 58. PMV, PPD and TIP indices in correlation with an ability to work, compared for measurement and questionnaires for Scenario 4

Position index	PMV	TSV	PPD [%]	TIP [%]	Productivity [%]
P1.1	0.51		11.67		
P1.2	0.51		11.67		45.0
P1.3	0.51	0.0	11.67		35.0
P1.4	0.78	1.0	18.57	15.0	55.0
P1.5	0.78		18.57		
P1.6	0.78		18.57		
P2.1	0.51	1.3	11.67	20.0	46.7
P2.2	0.51	0.0	11.67		35.0
P2.3	0.67	0.8	15.22	30.0	29.0
P2.4	0.67	1.8	15.22	49.3	45.0
P2.5	0.78	2.0	18.57	22.5	45.0
P2.6	0.78	1.7	18.57	7.7	71.7
P3.1	0.51	1.4	11.67	11.3	42.0
P3.2	0.51	1.3	11.67	15.0	23.3
P3.3	0.67	1.2	15.22	18.4	49.0
P3.4	0.67	0.5	15.22	20.0	61.7
P3.5	0.78	3.0	18.57	60.0	45.0
P3.6	0.78	3.0	18.57	50.0	85.0
P4.1	0.84		20.4		
P4.2	0.84		20.4		
P4.3	0.67	1.0	15.22	12.5	45.0
P4.4	0.67	1.5	15.22	31.3	45.0
P4.5	0.63	1.0	15.28	10.0	43.3
P4.6	0.63	1.0	15.28	60.0	55.0
P5.1	0.84		20.4		
P5.2	0.84	0.0	20.4		30.0
P5.3	0.84	1.3	20.4	27.5	30.0
P5.4	0.63	1.7	15.28	30.0	53.3
P5.5	0.63	1.5	15.28	30.0	37.5
P5.6	0.63	2.0	15.28	25.0	30.0
MAX	0.84	3	20.4	60	85
MIN	0.51	0	11.67	7.67	23.33
Average	0.68	1.30	16.05	27.27	44.50

Comparing the results above, it is shown that the students' productivity was lowest in Scenario 4, where also their subjective evaluation of thermal comfort, reflected through the TIP index, shown the highest percent of people dissatisfied (around average 27%). The highest productivity is evaluated through tests in Scenario 2, when both measured and evaluated values of PMV, PPD and TIP were lowest. The deviation between measured PPD and subjectively evaluated by students TIP was 35%. Evaluated impact of thermal comfort on PLOS was around 14%, even though the averaged measured PPD was around 9%. The productivity of students averaged for each scenario as a function of students' personal evaluation of thermal comfort impact on PLOS, TIP is shown on figure 69.

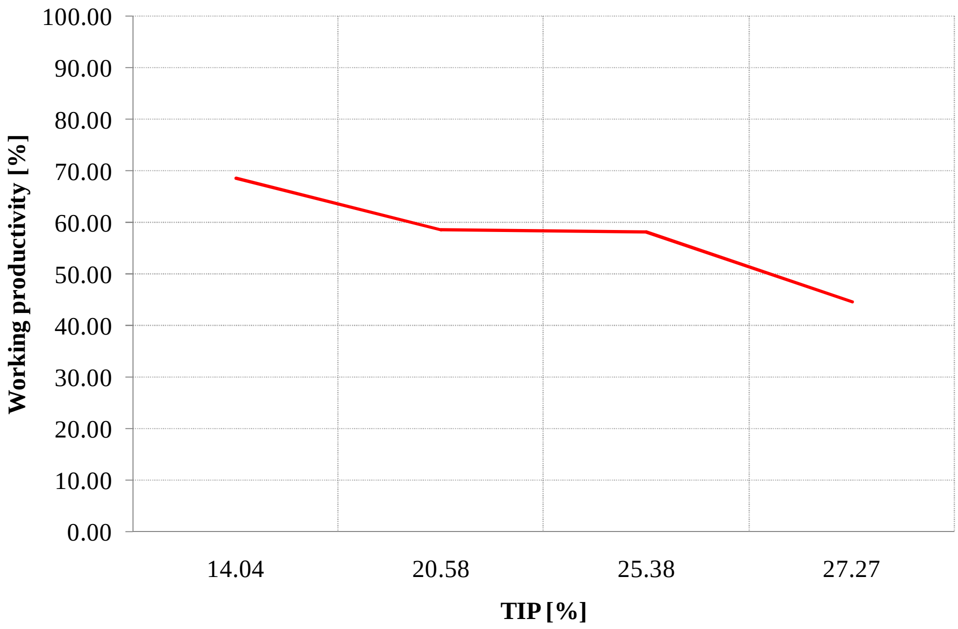

Figure 69. The productivity as a function of personal students' dissatisfaction with thermal environment TIP

According to the results, the productivity loss is proportional to the students' dissatisfaction: the higher dissatisfaction the higher the losses. The collected data is possible to correlate using the new equation, which is derived through this research, using TableCurve 2D v5.01 software for curve fitting:

$$Productivity = a + b \cdot e^{TIP} + c \cdot e^{-TIP}, \qquad (60)$$

where the coefficients have the values: $a = 59.3199, b = -2.1057 \cdot 10^{-11}, c = 1.1364 \cdot 10^{7}$.

This correlation is obtained for averaged data for TIP and productivity evaluated through tests for four scenarios, and can be used as an overall prediction of productivity in the classroom, if the students' dissatisfaction is quantified through the survey. This equation is not valid for individual student's productivity prediction.

Looking at the nature of all obtained results, it is noted that the impact of personal factor is huge. If the results are concerned averaged for the whole section of the classroom, as it was done during the radiant temperature measurements, it is possible to have a more general correlation between the productivity and PMV, which is less influenced personally. It is very difficult to observe productivity of each student locally and derive general conclusions. The results are shown on figure 70.

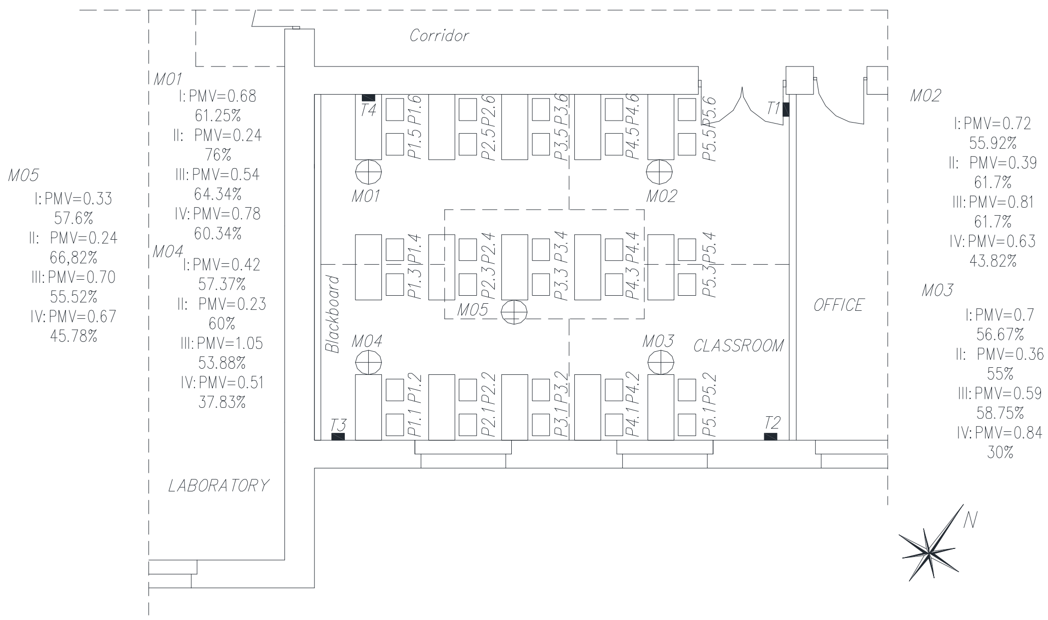

Figure 70. Productivity and measured PMV in five classroom sections

The part of the classroom M01 is depicted as the one with the highest students' productivity results. It is an interesting fact that this was the part of the classroom where the students with the best marks in university subjects were seated. Their productivity was the highest in the Scenario 2: about 76% averaged. The productivity loss of about 16% is noticed comparing to the fourth scenario. Looking at the M03 part of the classroom, personal factor was the most visible: when the PMV was the lowest, in Scenario 2, it was expected that the students would have the highest productivity, but on the contrary: the productivity was about 55% averaged for the students’ results in this section, which was even lower than in the first and the third scenario. These results strongly indicate that the personal factor is dominant, comparing to the PMV impact.

The deviation from an average productivity for each scenario is clearly visible on Figure 71. The impact of personal factors is dominant.

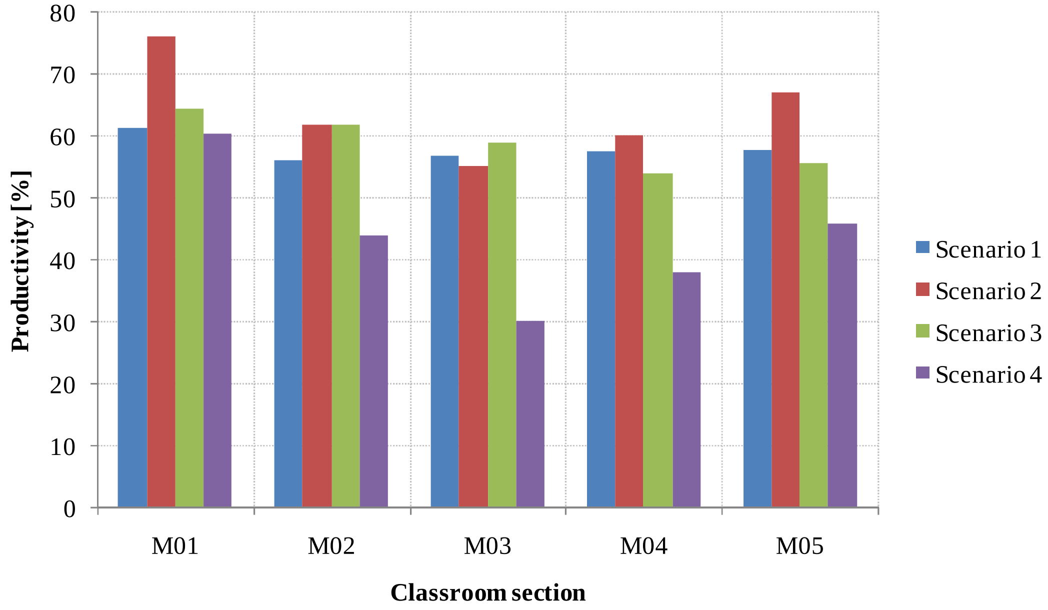

Figure 71. Students' productivity in five sections of classroom for all scenarios

The impact of the personal factor and its correlation with thermal sensation votes is possible to distinguish through the much detailed analysis of human physical and psychological condition. This attempt was made through the skin temperature measurement, presented in Chapter 4. The cheek temperature is correlated with TSV and TIP. The personal evaluation of the impact of the environment on students' performances and PLOS in relation with the left cheek temperature of the participants is shown on Figure 72-75.

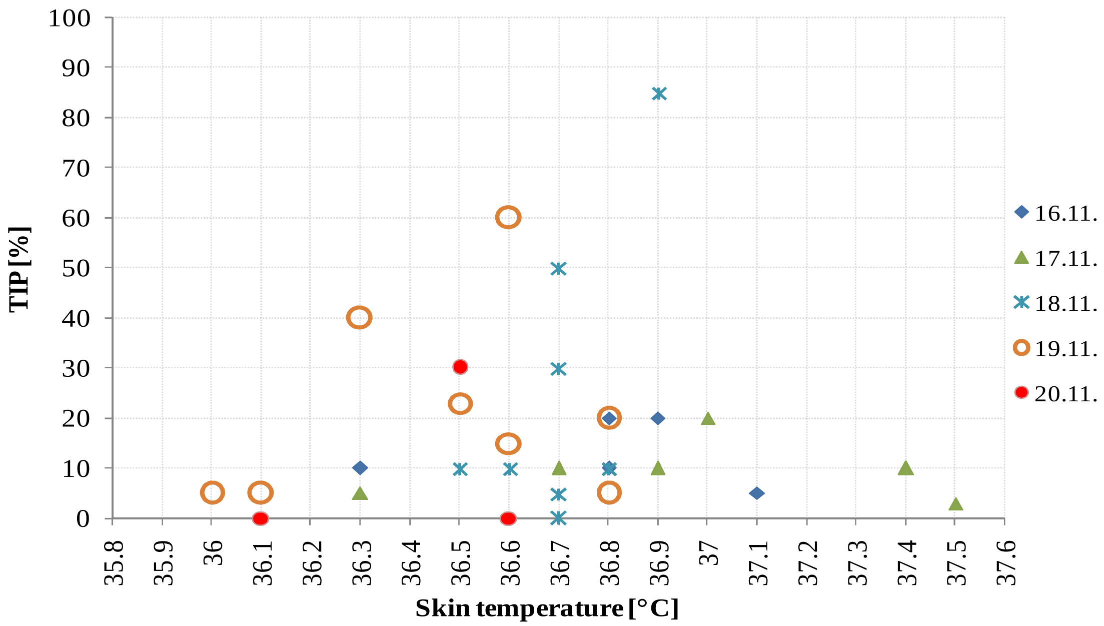

Figure 72. TIP in correlation with students' cheek temperature for Scenario 1

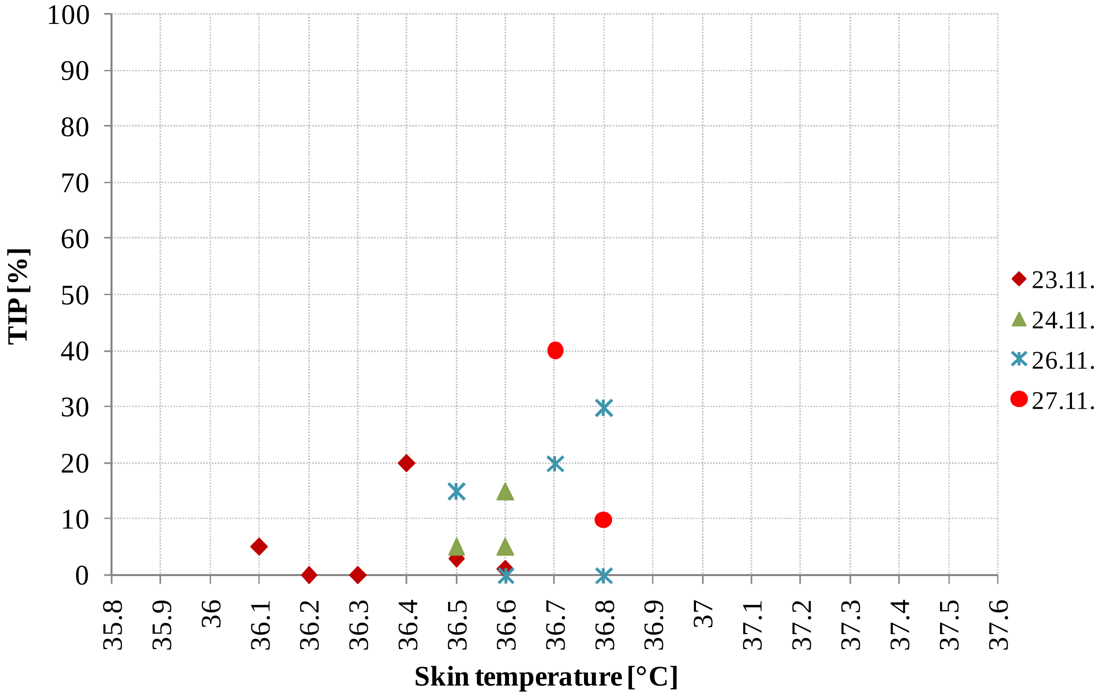

Figure 73. TIP in correlation with students' cheek temperature for Scenario 2

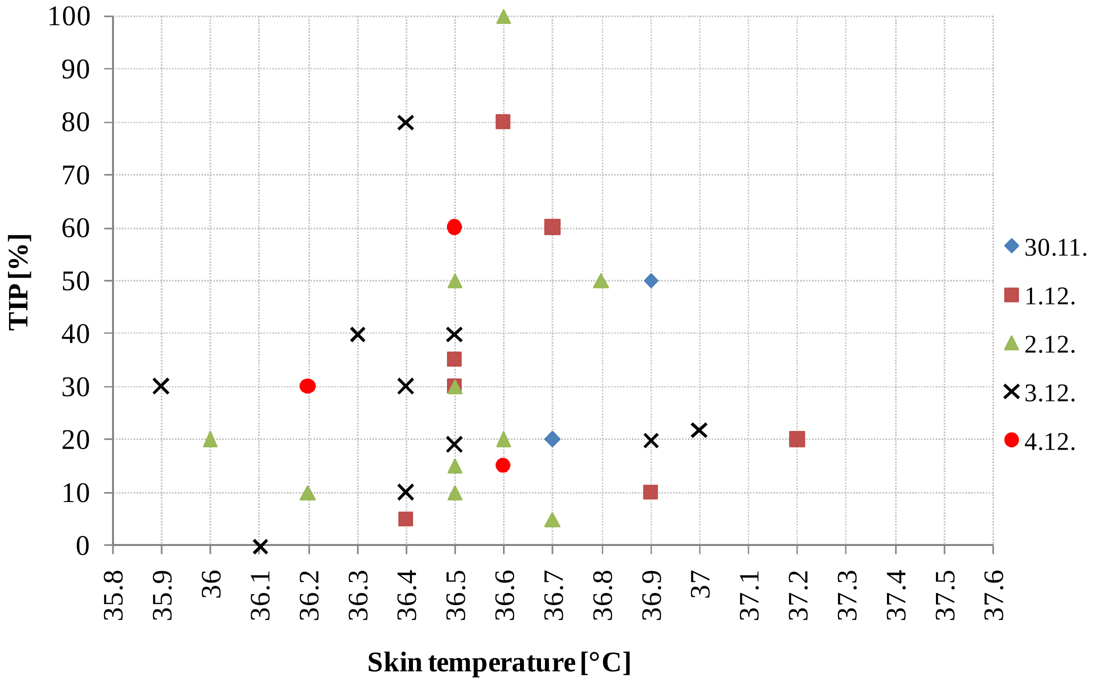

Figure 74. TIP in correlation with students' cheek temperature for Scenario 3

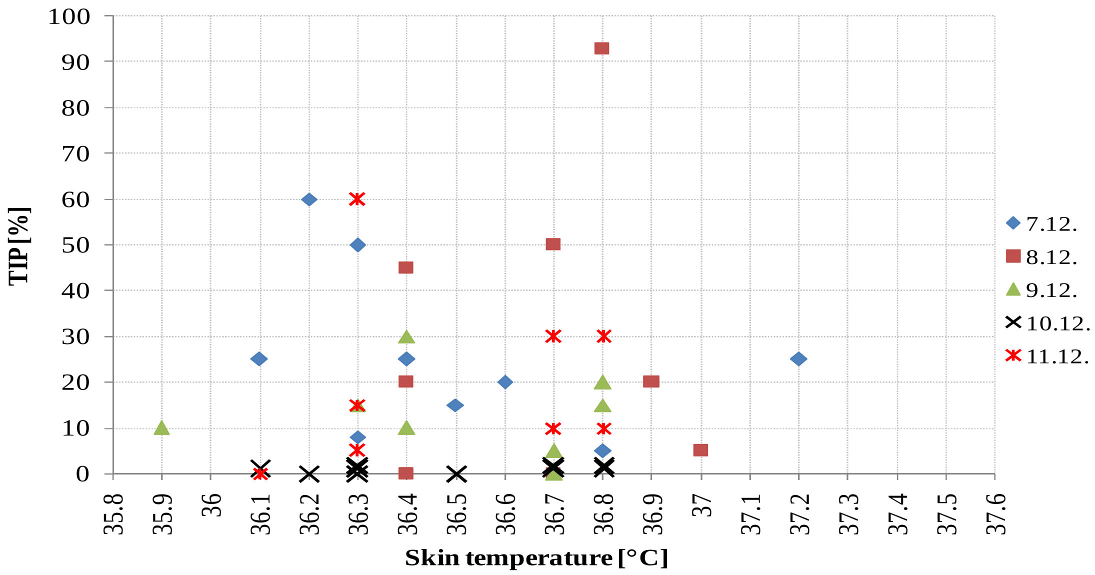

Figure 75. TIP in correlation with students' cheek temperature for Scenario 4

The students' evaluation of thermal comfort impact on concentration and productivity loss, presented above was, as expected, in direct correlation with thermal environment conditions, suggesting the highest impact on students' performances in third and fourth scenario. The highest average students' skin temperature was noticed in first scenario. The biggest deviation between left and right cheek temperature is noticed in fourth scenario, on students seated close to the electrical heater. The deviations between the temperatures from Scenario 1 to 4 were slight, just within in the 0.5°C. Significant deviations were not noticed. As suggested by the numbers of researchers, the normal adult human body temperature is in between 35.7 to 37.7°C [101, 102]. For defining the more precise correlations, more detailed investigations are necessary. The cheek temperature measurements are insufficient for describing the physical and psychological state of human body and metabolism in non-uniform environments. More detailed investigation, with measurements of other body parts, sweat secretion and neuro-behavioral tests is necessary for drawing the more precise conclusions, which is very difficult to accomplish in real classroom, during the regular semester.

Productivity loss equations known so far are function of PMV index only [8, 103], or thermal sensation votes [58]. The available data in literature regarding the possible methods for productivity loss calculations are limited and based on assumptions and researches performed in experimental conditions on a relatively small number of volunteers. This investigation demonstrated that the productivity and productivity loss are not just a function of PMV index. The obvious prove is shown on Figure 76.

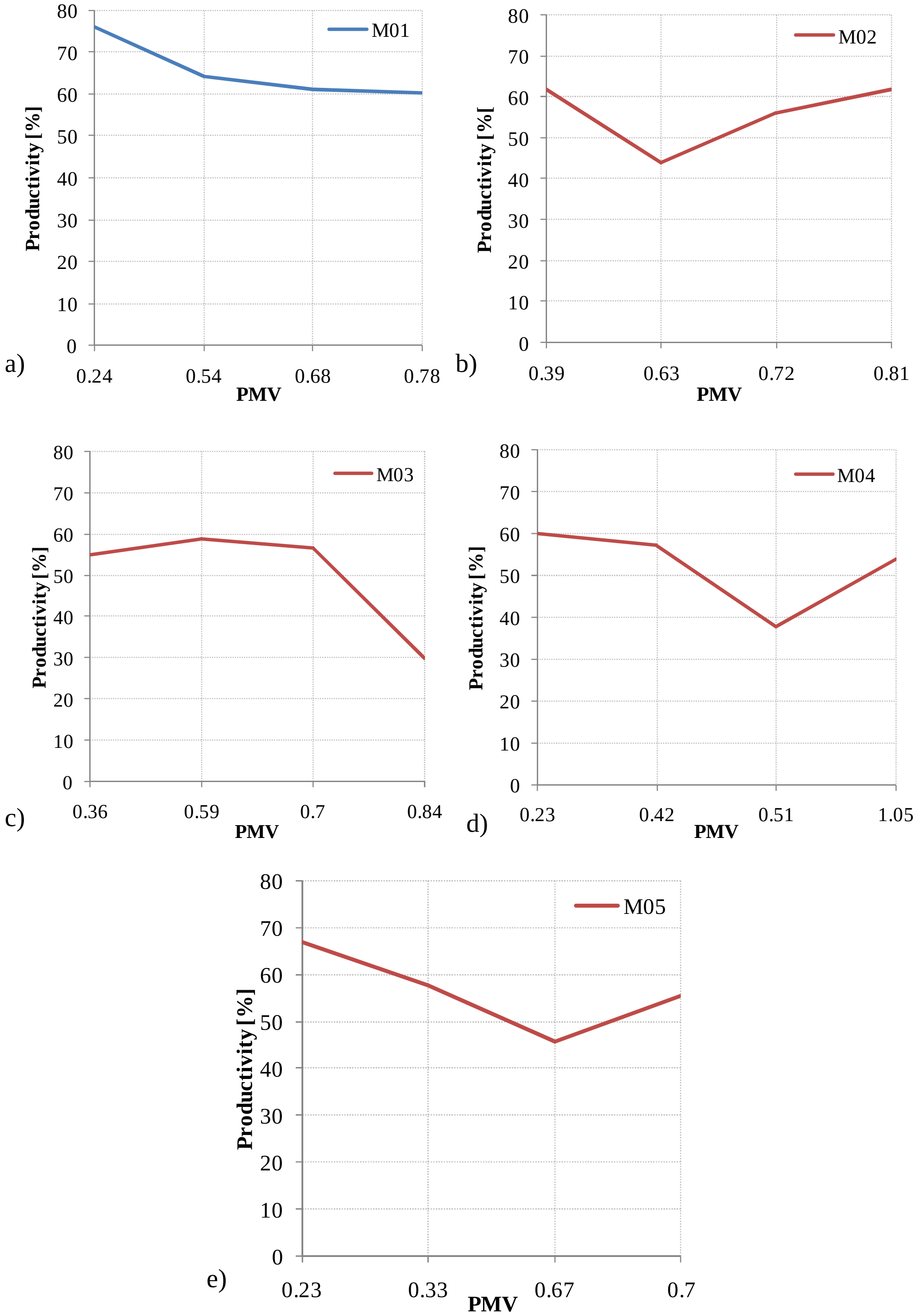

Figure 76. Productivity as a function of PMV index in different classroom sections for four scenarios a) Section M01 b) Section M02 c) Section M03 d) Section M04 and e) Section M05

There is no simple relation in real conditions that can link productivity with a PMV index only. The obtained results were conducted for 19 days in different conditions of thermal environment, in real classroom, during lectures, on a sample of 73 for scenario 1, 37 for scenario 2, 62 for scenario 3 and 68 samples for scenario 4, which is in total 240 results of productivity tests. These results represent a valuable contribution obtained through this research.

The results shown on Figure 76 clearly emphasizes that the productivity is not a simple function of a PMV. During the interview with students, they stated that the impact of thermal environment on their performance was noticeable, but significantly lower than their personal state. Also, analyzing all important factors conducted through this research, it is noted that the worst results regarding students' performance occurred during the fourth scenario, even though the PMV index was lower than in third scenario. Looking at the physical parameters in Tables 11 to 14 it is clear that the CO_2 concentration was significantly higher exactly in Scenario 4, with an average value of 2050 ppm. Scenario 2 had satisfactory results with an average value of 1052 ppm. The Scenario 1 and 3 had almost equal concentration: 1390 and 1322 ppm respectively. Knowing the negative influence of high CO_2 concentration on human health and performance, this factor can be observed as an important one for searching the causes of higher productivity loss in fourth scenario.

7.2. Local thermal discomfort impact on productivity loss

The results obtained comparing the calculations using formulas given in Standard ISO 7730:2005 and gathered through the students' survey in situ showed a valuable mismatching and confirmed one of the hypothesis of this research that there is no reason to believe that there are always 5% of people dissatisfied in moderate thermal environments. This is an original contribution obtained through this thesis. This observation is derived from the results regarding the floor temperature, as one of the local discomfort parameters. The comparisons for PD caused by floor temperature are given in table 59.

Table 59. Percentage of people dissatisfied calculated by ISO 7730:2005 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

Comparing the results from Table 59. it can be concluded that even though the floor temperatures in Scenario 2 and 4 were almost equal (only 0.09°C difference), the subjective evaluation was almost 10% different. This was definitely the consequence of students' dissatisfaction with overall thermal comfort conditions in the classroom, which they also reflected on dissatisfaction with floor temperature. From this point, it can be concluded that personal factor and subjective feelings have a huge impact on results. The personal factor is very difficult to evaluate in precise boundaries of values.

Looking at the similarity of the measured floor temperatures in all scenarios, it can be pointed out that their impact on students' productivity loss can be neglected as non dominant.

The parameters for local thermal discomfort impact, such as floor temperature, draught, and radiant asymmetry measured and calculated in this dissertation showed no significant impact on productivity loss. Only the percentage of people dissatisfied with a vertical air temperature difference was about average 7% in third and fourth scenario, which can have an impact on productivity loss. This parameter is considered through the local PMV index, calculated for every position. The percentage of students dissatisfied with draught was about 7.6% in Scenario 2, for the seats next to the windows, but in this scenario, not a single person (from 31 answers) felt an air movement neither the draught, and 39% of students stated that they were sensitive to draught, as it was shown in Table 30. This parameter is also considered as non-significant for productivity loss in this research. Air movement is also included indirectly in PMV index calculation for each segment of the classroom through the air velocity.

The significant parameters for this research are PMV index, personal factors and CO_2 concentration. These so far known relations are dependent only from PMV index in a form:

$$PLOS = f(PMV), \tag{61}$$

The results for productivity loss, obtained using the polynomial correlation suggested by Kosonen and Tan [8], take into a consideration only thermal environment impact through the PMV index, measured in the observed classroom (Table 17). The values obtained using the equation suggested by Kosonen and Tan for thinking activity are pretty uniform, as expected in ideal conditions, and because of that, inappropriate for real conditions, in the actual classroom. Exactly this original conclusion, influenced on the need to form more realistic model, which takes into consideration the influence of CO_2 concentration and the most influenced personal parameter expressed through the variable C_{pers} .

Through this research, the novel, original relation is suggested in form:

$$PLOS = f(PMV, CO_2, C_{pers}), \tag{62}$$

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

$$z = a + bx + cx^2 + dx^3 + ex^4 + fx^5 + gy + hy^2 + iy^3 + jy^4 + ky^5 \tag{63}$$

where z stands for productivity, x for PMV and y 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, d = -64808.8852, g = 5.747102797, j = $-1.51 \cdot 10^{-9}$,
b = -10929.1291, e = 51070.70669, h = -0.00788315, k = $1.72 \cdot 10^{-13}$.
c = 38910.35993, f = -15370.0523, i = $5.04 \cdot 10^{-6}$,

The personal factor of each student is strongly visible through the test results, but very difficult to quantify precisely and express mathematically, due to that, it is excluded from the equation.

The suggestion for future work would be to consider the personal factor through the variable C_{pers} which could be possible to derive through the input tests, used as an etalon for measuring personal availabilities of each person, together with a medical research.

The novel equation, suggested in form (63), more realistically approaches the problem, considering also the high CO_2 concentration in the classroom, which is also marked as one of the key, environmental parameters of productivity loss. A lack of this model is a difficulty of a personal factor prediction, and generalization of it in a global model equation for overall productivity loss.

This is a novel and an original contribution obtained through this thesis and it can be implemented in the existing thermal comfort standards as an additional tool for productivity evaluation in thermal environments such as classrooms, lecture halls, open spaces offices with a large number of occupants and natural ventilation. This research is done for hot scenarios in winter season, so the equation is applicable for this period. In order to examine the applicability and reliability of this equation for the summer season in air-conditioned spaces, more detailed researches in the future are necessary.

In this research, with much effort the physical parameters of local thermal discomfort have been correlated with the students' productivity loss. The most important conclusions are: a personal factor is much more dominant then thermal environment parameters, there are the impacts of the local thermal discomfort which are not possible to strictly separated from personal factors (thus mathematically quantify); for personal factor quantification it is necessary to perform neuro-behavioral tests, along with other medical researches on each person, as it is also necessary to perform the initial tests in "ideal" conditions, in which is possible to evaluate the maximal personal performance, and then to use it as an etalon for comparison with other cases. These are some of the suggestions for future work.

8. FINAL CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

A new approach implemented in this research gives a comprehensive data on local and overall thermal comfort indicators in the observed classroom, and together with a subjective evaluation and numerical simulations helps researching the reasons of students' productivity loss. The local approach, instead of overall, gives an opportunity to distinguish the reasons for higher productivity loss locally, in a part of the classroom with more unfavorable thermal comfort conditions. The comprehensive research done through this thesis is the first of this type done "live", in real classroom with university level students, for moderate climate conditions. The improved methodology for measuring the physical parameters of the environment in real conditions introducing detailed, continuous measurement across a large number of locations within the volume was implemented. Valuable data was collected during the ongoing winter semester, for adult occupants between the ages of 20 and 25. The results published so far in literature are mainly based on research conducted in laboratory conditions, but the research conducted for this dissertation represents a significant contribution to the understanding of the correlation between local thermal comfort and working productivity loss in real conditions, in non-residential buildings. The need for this analysis came from the fact that it is quite difficult to predict productivity loss in non-residential buildings in real conditions, and that the correlation between the thermal comfort obtained in laboratory conditions substantially differs from the results in real classrooms and buildings of a similar sort, with large number of users. The research also analyzed the impacts of air velocity, radiant temperature, vertical air temperature differences, floor temperature and the concentration of carbon dioxide on occupants’ productivity loss. Analyses have shown that the local value of the indicator of thermal comfort conditions differs significantly from the averaged values, and that this deviation is one of the causes of the occupants’ productivity loss. The second significant factor is carbon dioxide concentration which, when increased above the prescribed limits, leads to concentration loss, drowsiness and reduced productivity loss. The third and also dominant factor is the sum of complex personal parameters which are very difficult to quantify precisely, and therefore complex to separate and analyze individually. The original questionnaires were developed and used during the research. The first kind collected general data related to age, sex, physical condition and clothing of the population that was surveyed, then the part with an evaluation of the thermal comfort conditions; as well as the local parameters which can affect thermal discomfort and evaluation of parameters regarding the indoor environmental quality, as well as the subjective feeling of the users about the impact of these parameters on working productivity loss, concentration and overall health of the user. The second kind was a more specific questionnaire, which included a concentration test. A significant number of concentration tests were performed during the four-week period. Tests were carried out every day and the level of productivity, thus productivity loss, was determined using these results. Through this research, a new index TIP was developed, describing the students' subjective evaluation of thermal environment impact on working productivity and concentration loss.

It was found that the users' subjective feelings about the indoor air quality generally correspond to the results of measurements. It has been shown that the occupants were most sensitive to higher temperatures in the space (radiant and air temperature), the vertical temperature difference, a high concentration of carbon dioxide and poor ventilation. A negative impact of indoor environmental conditions on users' health was noted, because in Scenario 3 and Scenario 4, users complained of headaches, the productivity loss and a decrease in concentration caused by staying in the classroom. A novel index for the quantitative subjective evaluation of the percentage of thermal comfort impact on the concentration and productivity loss (TIP) was developed in the research. The "TIP" index is expressed as a percentage (from 0 to 100%) and represents a quantitative subjective evaluation of the impact of thermal comfort on the concentration and productivity loss of users. By using this index in the collection and analysis of questionnaire data, it is possible to detect the existence of factors that decrease levels of thermal comfort in buildings, based on which these causes can be eliminated, thereby contributing to the development and promotion of the concept of healthy buildings.

The results of the statistical survey showed that Scenario 2 was rated as the scenario with the best working conditions, with influence on loss of working productivity at an average of 14%, while Scenario 4 was rated as the worst, with a TIP index value of almost 30%. Respondents also rated the local thermal comfort indicators and based on what is shown, all users in Scenario 2 declared that the intensity of the draught in the classroom was 0%, the percentage of those dissatisfied with the floor temperature was also 0% (proven for overall PMV=0.29 on percent dissatisfied with a floor temperature). According to these results, the adopted recommendation of 5% of people dissatisfied in neutral conditions is not always suitable. The lowest percentage of those dissatisfied with the radiant asymmetry and the vertical air temperature difference was also observed during Scenario 2, in comparison with all four scenarios.

Using a total number of 240 productivity test results, the complex nature of productivity loss was determined, which, as highlighted, does not only depend on the thermal comfort index, but also on the concentration of carbon-dioxide in space, as well as on a variety of personal parameters, which are very complex in nature. Based on this analysis, a unique correlation equation between thermal comfort, the concentration of carbon dioxide in a space and productivity was established.

The most important conclusions are: personal factor is more dominant then thermal environment parameters; there are certainly the impacts of the local thermal discomfort which are not possible to be strictly separated from personal factors, and thus mathematically precisely quantified in that manner. For personal factor quantification it is necessary to perform neurobehavioral tests together with other medical researches on each person.

Creating models and combining this with numerical methods, further validated by experimental results, highlights the importance and potential of using numerical simulation during the planning and design phase of a building, as well as to make decisions on new systems of heating, cooling and air conditioning implementation, which significantly affect the optimal conditions for users' comfort and productivity.

The obtained results give the novel guidelines for existing standards in order to improve a thermal comfort in educational buildings. The results can also be researched for office buildings, with a large number of occupants, and a future work could follow this direction.

The suggestions for future work could follow the direction of researching the personal factors more exactly. The impact of personal factors is of tremendous importance for a more comprehensive analysis and during the thermal comfort measurements in buildings, the medical and psychological research should also be carried out simultaneously. Moreover, it is necessary to perform the initial tests in "ideal" conditions in which it is possible to evaluate (but never mathematically precise) the maximal personal performance, which would then be possible to use as an etalon for comparison with other cases. In this manner, it would be possible to deduce a relation regarding the productivity loss caused by personal factors and implement it into a complex correlation with local thermal comfort parameters.

Correlations between the local thermal comfort state and indoor environmental quality impact on occupants' productivity loss can rarely be found in the existing literature. Most of the available studies in this field are related to general models of thermal comfort, and the results are obtained mainly in the laboratory, using a small sample size. In the dissertation, the novel results were obtained using a variety of experimental, numerical and statistical analysis methods, from which novel correlations of local thermal comfort conditions and user productivity were developed, obtained in real conditions, using a large sample group of respondents.

The scientific contributions achieved in the doctoral dissertation are as follows:

- improved methodology for measuring the physical parameters of the environment in real conditions introducing detailed, continuous measurement across a large number of locations within the volume.
- quantification of the impact of local physical parameters of air non-homogeneity in indoor environments on the general and local thermal comfort indicators, using experimental methods.
- models for the complex numerical analysis of local thermal comfort parameters in all points of the observed space.
- original questionnaires for statistical data collection and a subjective evaluation of the parameters of general and local thermal comfort.
- novel tests for the evaluation of user productivity levels.

- a new TIP index for the quantification of the subjective impact of general and local thermal comfort on occupants' productivity.
- new correlation relations between local thermal comfort indicators and the level of occupants' productivity.
- new correlations between productivity and TIP index.
- recommendations and guidelines for the interdisciplinary design of new, healthy buildings during the earliest stages of design, as well as the inclusion of the concept of healthy buildings in the process of upgrading existing buildings and HVAC systems.
- increased levels of knowledge and consideration of the complex impacts of general and local thermal comfort conditions, and the quality of the indoor environment on the health and productivity of occupants in high-capacity non-residential buildings.

The scientific contributions of the research can be verified by the publications:

1. **Bajc, T.**, Todorović, M., Svorcan, J., *CFD analyses for passive house with Trombe wall and impact to energy demand,* Energy and Buildings, 2015, VOL.98, ISSN0378-7788, doi:10.1016/j.enbuild.2014.11.018, Elsevier, pp. 39-44. (M21, IF 2014 (2015): 2.884)
2. **Bajc, T.**,Todorović M., Papadopoulos, A., *Indoor Environmental Quality in Non-residential Buildings – experimental investigation*, Thermal science, 2016, VOL.20, Supplement 5, ISSN 0354-9836, doi: 10.2298/TSCI16S5521B, Vinča Institute of Nuclear Sciences, pp. S1521-S1529 (M23, IF 2015: 0.939)
3. Todorović, M., Ristanović, M., Lazić, D., Galić, R.,**Bajc, T.**, *A novel laboratory set-up for the investigation of intelligent automatic control in complex HVAC systems*, FME Transactions, 2015/3, VOL.43, ISSN 1451-2092, Faculty of Mechanical Engineering University of Belgrade, pp. 243-248. (M24)
4. **Bajc, T.**, Todorović M., Papadopoulos, A., *Indoor Air Quality in Office Buildings – experimental investigation*, 17th International symposium on Thermal science and engineering of Serbia, 20-23.10.2015, Sokobanja, Serbia, ISBN 978-86-6055-077-6, University of Niš, Faculty of Mechanical Engineering in Niš, Proceedings on http://simterm.masfak.ni.ac.rs. (M33)

5. **Bajc, T.**, Todorović M., Stevanović, Žarko, Stevanović, Žana, Banjac, M., *Local thermal comfort indices impact on productivity loss in classrooms*, The 1st international conference on buildings, energy, systems and technology, 2.-4.11.2016, Belgrade, Serbia, Society of thermal engineers of Serbia, Proceedings on http://www.best2016-conference.com/papers-presentations.php. (M33)

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APPENDIX

APPENDIX 1

Table A1. 1. Average surfaces temperature for four scenarios

Surface	Glass 1	Glass 2	Wall 1.1	Wall 1.2	Wall 1.3	Wall 2	Wall 3	Wall 4	Floor	Ceiling	Radiator 1	Radiator 2	Blackboard	Door
Scenario 1														
16.11	21.2	21	22.7	22.9	22.6	23.6	23.8	23.2	22.4	23.9	22.4	22.5	23.5	23.3
17.11	22.2	22	22.6	22.7	22.7	23.4	23.5	23.4	22.7	23.8	23.1	23.2	23.6	23.5
18.11	22.9	22.9	23.1	22.8	22.3	23.5	23.6	23.1	22.6	24.1	23	23.4	24	23.5
19.11	26.1	27.7	22.6	22.7	22.9	23.3	23.4	22.3	22	23.5	22.2	22.7	23.1	23.1
20.11	26.8	26.1	22.7	23.1	22.6	23.6	23.4	23	22.1	24	22.3	22.3	23.3	23.3
Aver.	**23.8**	**23.9**	**22.7**	**22.8**	**22.6**	**23.5**	**23.5**	**23.0**	**22.4**	**23.9**	**22.6**	**22.8**	**23.5**	**23.3**
Scenario 2														
23.11	19.2	19.1	21.8	21.3	21.6	22.7	22.6	22.6	21.4	24.3	32.6	38.8	22.7	22.7
24.11	18.8	19	21.9	22.2	22	23.2	23.4	23.2	21.5	24.7	24.6	24.2	23.5	22.9
26.11	18	18.3	22.4	22	22.2	23.6	23.3	23.3	22.2	24	25.6	29.4	23.6	23.1
27.11	19.8	19.6	21.7	21.6	21.5	22.9	23.3	22.8	21.1	24.7	28.6	27.8	23.6	22.7
Aver.	**18.9**	**19.0**	**21.9**	**21.8**	**21.8**	**23.1**	**23.1**	**23.0**	**21.5**	**24.4**	**27.8**	**30.0**	**23.3**	**22.8**
Scenario 3														
30.11	20.9	21.5	22.1	22.8	22.4	24.2	23.8	23.4	21.8	24.8	22.4	26.6	23.4	23.2
1.12	21.1	21.3	22.8	22.6	22.6	24	24	23.7	21.7	24.1	25.9	25.4	23.8	23.9
2.12	21.5	21.7	23.4	23.3	23.2	24.3	24.2	23.8	21.8	25.3	26.5	27.1	24.6	24.2
3.12	23.1	23.6	23.1	22.8	23.1	24.1	23.8	23.7	22.3	25.1	24.4	28.1	24.6	23.8
4.12	24.8	25.3	23.6	23.4	23.6	25	24.6	24.3	22.3	26.4	24.7	24.3	25.4	24.8
Aver.	**22.3**	**22.7**	**23.0**	**23.0**	**23.0**	**24.3**	**24.1**	**23.8**	**22**	**25.1**	**24.8**	**26.3**	**24.4**	**24.0**
Scenario 4														
7.12	18.8	18.5	22.3	22.1	22.5	24	24.4	23.3	21.8	25.7	22.3	25.9	23.4	23.2
8.12	18	18	21.7	21.9	21.9	23.2	23.4	23.3	21.9	24.1	22.6	21.8	23.1	23.7
9.12	19	19.4	21.9	22.1	22.1	23.4	23.5	22.6	21.3	25.6	23.9	23	23.5	23.3
10.12	20.9	20.9	23.2	23.2	23.2	24.3	24.5	23.9	21.8	26.5	22.9	22.6	25	24.2
11.12	20.3	20.3	22.5	22.2	22	23.7	23.9	23.2	21.4	25.3	22.9	21.7	23.9	23.4
Aver.	**19.4**	**19.4**	**22.3**	**22.3**	**22.3**	**23.7**	**23.9**	**23.3**	**21.6**	**25.4**	**22.9**	**23.0**	**23.8**	**23.6**

APPENDIX 2

Table A2. 1. Average measured concentration of CO_2 in outdoor air

Date	$CO_{2\ out}$ [ppm]	Date	$CO_{2\ out}$ [ppm]
16.11.	450	30.11.	434
17.11.	447	01.12.	439
18.11.	436	02.12.	444
19.11.	450	03.12.	477
20.11.	484	04.12.	501
Scenario 1 aver.	**453**	**Scenario 3 aver.**	**459**
23.11.	461	07.12.	406
24.11.	457	08.12.	390
26.11.	450	09.12.	482
27.11.	481	10.12.	483
Scenario 2 aver.	**460**	11.12.	487
		Scenario 4 aver.	**450**

APPENDIX 3

Table A3. 1. The local mean air velocity measured for four scenarios according to ISO 7730:2005

Scenario	1	2	3	4
Position index	**$V_{a,l}$ [m/s]**	**$V_{a,l}$ [m/s]**	**$V_{a,l}$ [m/s]**	**$V_{a,l}$ [m/s]**
P1.1	0.04	0.16	0.03	0.03
P1.2	0.04	0.16	0.03	0.03
P1.3	0.04	0.16	0.03	0.03
P1.4	0.04	0.03	0.03	0.03
P1.5	0.04	0.03	0.03	0.03
P1.6	0.04	0.03	0.03	0.03
P2.1	0.04	0.16	0.03	0.03
P2.2	0.04	0.16	0.03	0.03
P2.3	0.03	0.16	0.03	0.03
P2.4	0.03	0.03	0.03	0.03
P2.5	0.04	0.03	0.03	0.03
P2.6	0.04	0.03	0.03	0.03
P3.1	0.04	0.16	0.03	0.03
P3.2	0.04	0.16	0.03	0.03
P3.3	0.03	0.16	0.03	0.03
P3.4	0.03	0.03	0.03	0.03
P3.5	0.04	0.03	0.03	0.03
P3.6	0.04	0.03	0.03	0.03
P4.1	0.05	0.19	0.04	0.06
P4.2	0.05	0.19	0.04	0.06
P4.3	0.03	0.19	0.03	0.03
P4.4	0.03	0.03	0.03	0.03
P4.5	0.03	0.03	0.04	0.03
P4.6	0.03	0.03	0.04	0.03
P5.1	0.05	0.19	0.04	0.06
P5.2	0.05	0.19	0.04	0.06
P5.3	0.05	0.19	0.04	0.06
P5.4	0.03	0.03	0.04	0.03
P5.5	0.03	0.03	0.04	0.03
P5.6	0.03	0.03	0.04	0.03
Average	0.04	0.10	0.03	0.04

Table A3. 2. Turbulent intensity calculated for four scenarios according to ISO 7730:2005

Scenario	1	2	3	4
Position index	**T_u [%]**	**T_u [%]**	**T_u [%]**	**T_u [%]**
P1.1	44.10	29.97	0.00	0.00
P1.2	44.10	29.97	0.00	0.00
P1.3	44.10	29.97	0.00	0.00
P1.4	43.89	0.00	0.00	0.00
P1.5	43.89	0.00	0.00	0.00
P1.6	43.89	0.00	0.00	0.00
P2.1	44.10	29.97	0.00	0.00
P2.2	44.10	29.97	0.00	0.00
P2.3	0.00	29.97	0.00	0.00
P2.4	0.00	0.00	0.00	0.00
P2.5	43.89	0.00	0.00	0.00
P2.6	43.89	0.00	0.00	0.00
P3.1	44.10	29.97	0.00	0.00
P3.2	44.10	29.97	0.00	0.00
P3.3	0.00	29.97	0.00	0.00
P3.4	0.00	0.00	0.00	0.00
P3.5	43.89	0.00	0.00	0.00
P3.6	43.89	0.00	0.00	0.00
P4.1	44.44	21.47	28.97	26.87
P4.2	44.44	21.47	28.97	26.87
P4.3	0.00	21.47	0.00	0.00
P4.4	0.00	0.00	0.00	0.00
P4.5	0.00	0.00	35.27	0.00
P4.6	0.00	0.00	35.27	0.00
P5.1	44.44	21.47	28.97	26.87
P5.2	44.44	21.47	28.97	26.87
P5.3	55.33	21.47	28.97	26.87
P5.4	0.00	0.00	35.27	0.00
P5.5	0.00	0.00	35.27	0.00
P5.6	0.00	0.00	35.27	0.00
Average	**28.30**	**13.28**	**10.71**	**4.48**

APPENDIX 4 - Questionnaire form

Questionnaire

DATE: ______________________

TIME: ______________________

INSTRUCTIONS:

1. The aim of the questionnaire is to establish the correlation between the subjective thermal comfort sensations and IEQ with measured physical data and productivity loss.
2. Please read carefully and give an honest, independent response without the suggestions from other students.
3. The survey is anonymous and has no negative implications.
4. Please circle the answer which best describes your subjective feeling.
5. Please circle just one answer if not indicated otherwise.

STUDENT'S POSITION INDEX: ☐

GENERAL DATA ABOUT RESPONDENT

1. Gender: **male female**
2. Year of birth: __________
3. Body height [cm]: ___________
4. Body weight [kg]: ____________

GENERAL DATA ABOUT PHYSICAL CONDITION

1. Have you had a breakfast/lunch? **YES NO**
2. Do you have a headache, sniffle, fever, toothache or sore throat? **YES NO**
3. Are you in a good physical shape? **YES NO**
4. Do you exercise? **YES NO**
5. For how many hours have you slept last night? ____________________

GENERAL DATA ABOUT CLOTHING

1. Please describe the clothes you are wearing (for example: shoes or boots, sneakers, underwear (standard or long), trousers, skirt, scoop-neck blouse, T-shirt, shirt, sweater, jacket, etc.)

   ____

   ____

   ____

GENERAL THERMAL COMFORT

1. Please circle just one answer in accordance with your subjective feelings:
   A. Hot (*sweating*)
   B. Warm (*need to remove the clothes or move to another place*)
   C. Slightly warm (*nicely warm – you don't mind*)
   D. Neutral (*can't decide*)
   E. Slightly cool (*nicely cool – you don't mind*)
   F. Cool (*need to add the clothes or move to another place*)
   G. Cold (*shivering, reduced breathing, cower*)
2. If your answer is different from "D", please give your subjective evaluation, in percentage, of how much has the thermal comfort in classroom impacted your productivity loss and a possibility to remember new information.

   Answer: ______ %

LOCAL THERMAL COMFORT

1. Do you feel the impact of floor temperature (cold or not)? **YES NO**
2. If your answer is "yes", are you satisfied with a floor temperature: **YES NO**
3. If you are NOT satisfied, please give your evaluation how many percent the floor temperature has influenced your productivity loss.

   Answer: ______ %

4. Do you feel the impact of the temperature of the surfaces around you (radiator, wall, window, etc.)?

   YES NO

5. If you feel the impact, please answer whether you are satisfied with **temperature asymmetry** around you.

   YES NO

6. If you are NOT satisfied, please give your evaluation of how many percent the **temperature asymmetry** has influenced your productivity loss.

   Answer: ______ %

7. Do you feel the impact of the air temperature in the classroom on your ankles, legs, belly, hands or head?

   YES NO

8. If your answer is “yes”, are you satisfied with the vertical air temperature difference?

   YES NO

7. If you are NOT satisfied, please give your evaluation of how many percent the vertical air temperature difference has influenced your productivity loss.

   Answer: ______ %

10. Are you sensitive to draft (***draft is an air flow around your body that you can feel***)?

   YES NO

11. If you are sensitive, please answer is the intensity of draft in the classroom bothers you.

   YES NO

8. If you are NOT satisfied, please give your evaluation of how many percent the draft intensity has influenced your productivity loss.

   Answer: ______ %

GENERAL AIR QUALITY

1. Please evaluate the air quality in the classroom:

A. Very bad
B. Bad
C. I can't judge
D. Good
E. Very good

2. If your answer is "**A" or "B**", please circle the symptoms that you feel (**<u>you can circle more than one answer</u>**):
   A. stuffiness
   B. hard breathing
   C. poor concentration
   D. sleepiness

3. If your answer is "**A" or "B**", please give your evaluation of how many percent the air quality has influenced your productivity loss.

   Answer: ______ %

Thank you!

APPENDIX 5

Table A5. 1. Measured and simulated air temperatures at different levels of height for Scenario 2

Position index	Meas. T_{a1} (0.1m) [°C]	Flair T_{a1} (0.1m) [°C]	Rel.er. [%]	Meas. T_{a2} (0.6m) [°C]	Flair T_{a2} (0.6m) [°C]	Rel.er. [%]	Meas. T_{a3} (1.1m) [°C]	Flair T_{a3} (1.1m) [°C]	Rel.er. [%]	Meas. T_{a5} (1.6m) [°C]	Flair T_{a5} (1.6m) [°C]	Rel.er. [%]
P1.1	21.06			21.52			22.81			22.01		
P1.2	21.06			21.52			22.81			22.01		
P1.3	21.68			21.67			22.81			22.01		
P1.4	21.68			21.67			22.77			22.69		
P1.5	21.57			21.73			22.77			22.69		
P1.6	21.57			21.73			22.77			22.69		
P2.1	21.72			21.89			22.81			22.01		
P2.2	21.72			21.89			22.81			22.01		
P2.3	21.60			21.92			22.81			22.01		
P2.4	21.60	21.30	1.05	21.92	22.68	2.30	22.77	22.98	0.92	22.69	23.72	4.32
P2.5	21.64	21.42	0.41	21.93	22.68	2.31	22.77	22.98	0.92	22.69	23.85	4.84
P2.6	21.64	21.56	0.84	21.93	22.59	1.87	22.77	22.96	0.82	22.69	23.87	4.92
P3.1	21.44	21.45	1.10	21.74	22.57	3.36	22.81	23.49	2.89	22.01	23.12	4.79
P3.2	21.44			21.74			22.81			22.01		
P3.3	21.68	21.41	0.82	21.92	22.65	1.54	22.81	22.98	0.75	22.01	23.36	5.76
P3.4	21.68	21.48	0.76	21.92	22.56	1.79	22.77	23.01	1.03	22.69	23.51	3.47
P3.5	21.69	21.41	0.96	21.63	22.46	3.43	22.77	22.99	0.97	22.69	23.59	3.79
P3.6	21.69	21.79	1.02	21.63	22.66	2.82	22.77	23.36	2.51	22.69	23.85	4.84
P4.1	20.90			21.45			23.59			22.20		
P4.2	20.90	21.83	4.42	21.45	22.53	4.49	23.59	24.10	2.11	22.20	23.33	4.84
P4.3	21.35			21.53			23.59			22.20		
P4.4	21.35			21.53			23.52			22.67		
P4.5	21.48			21.77			23.52			22.67		
P4.6	21.48	21.43	1.04	21.77	22.65	2.34	23.52	23.42	0.44	22.67	23.87	5.05
P5.1	21.73			21.52			23.59			22.20		
P5.2	21.73	21.62	0.67	21.52	22.44	1.86	23.59	23.03	2.42	22.20	23.27	4.60
P5.3	21.37	21.56	0.22	21.74	22.56	2.38	23.59	23.03	2.41	22.20	23.23	4.43
P5.4	21.37	21.51	1.60	21.74	22.71	2.08	23.52	22.99	2.31	22.67	23.40	3.14
P5.5	21.16	21.69	1.29	21.53	22.87	4.02	23.52	22.85	2.94	22.67	23.70	4.36
P5.6	21.16			21.53			23.52			22.67		
Average	21.47	21.53	0.23	21.70	22.62	2.80	23.10	23.15	0.25	22.39	23.55	4.94
q			1.00			1.00			1.00			0.86

Table A5. 2. Measured and simulated radiant temperatures at different levels of height for Scenario 2

Position index	$T_{rad, meas.}$ [°C]	$T_{rad, flair. (1.1)}$ [°C]	Rel. error [%]
P1.1	22.90		
P1.2	22.90		
P1.3	22.90		
P1.4	22.73		
P1.5	22.73		
P1.6	22.73		
P2.1	22.90		
P2.2	22.90		
P2.3	22.90		
P2.4	22.73	22.60	0.57
P2.5	22.73	22.78	0.22
P2.6	22.73	23.00	1.16
P3.1	22.90	22.39	2.29
P3.2	22.90		
P3.3	22.90	22.64	1.15
P3.4	22.73	22.66	0.33
P3.5	22.73	22.82	0.39
P3.6	22.73	23.03	1.31
P4.1	22.96		
P4.2	22.96	22.56	1.78
P4.3	22.96		
P4.4	23.58		
P4.5	23.58		
P4.6	23.58	23.00	2.53
P5.1	22.96		
P5.2	22.96	22.53	1.93
P5.3	22.96	22.63	1.47
P5.4	23.58	22.63	4.20
P5.5	23.58	22.72	3.79
P5.6	23.58		
Average	23.00	22.71	1.26
q			1.00

Table A5. 3. Measured and simulated air temperatures at different levels of height for Scenario 3

Position index	Meas. T_{a1} (0.1m) [°C]	Flair T_{a1} (0.1m) [°C]	Rel.er. [%]	Meas. T_{a2} (0.6m) [°C]	Flair T_{a2} (0.6m) [°C]	Rel.er. [%]	Meas. T_{a3} (1.1m) [°C]	Flair T_{a3} (1.1m) [°C]	Rel.er. [%]	Meas. T_{a5} (1.6m) [°C]	Flair T_{a5} (1.6m) [°C]	Rel.er. [%]
P1.1	21.98			22.84			26.67			24.36		
P1.2	21.98			22.84			26.67			24.36		
P1.3	22.93			23.35			26.67			24.36		
P1.4	22.93			23.35			24.20			24.92		
P1.5	22.39			22.82			24.20			24.92		
P1.6	22.39			22.82			24.20			24.92		
P2.1	22.45	24.07	7.80	23.30	24.24	4.72	26.67	24.67	7.51	24.36	25.36	3.93
P2.2	22.45			23.30			26.67			24.36		
P2.3	22.95	23.37	2.65	23.71	23.97	2.86	24.99	24.49	2.00	24.36	24.70	1.36
P2.4	22.95			23.71			24.99			24.92		
P2.5	22.55	23.25	2.89	23.48	24.08	4.88	24.20	24.73	2.18	24.92	24.65	1.09
P2.6	22.55	23.24	2.91	23.48	24.35	3.12	24.20	24.65	1.85	24.92	24.69	0.91
P3.1	22.37	23.23	3.74	23.78	24.36	0.57	26.67	26.30	1.37	24.36	25.01	2.60
P3.2	22.37	23.29	2.73	23.78	23.92	3.15	26.67	24.64	7.62	24.36	25.67	5.10
P3.3	22.99	22.92	0.21	23.94	24.22	3.59	24.99	24.67	1.28	24.36	24.77	1.64
P3.4	22.99	22.95	0.31	23.94	24.53	3.11	24.99	24.56	1.70	24.92	24.79	0.51
P3.5	22.71	22.97	1.37	23.38	24.13	4.39	24.20	24.75	2.29	24.92	25.07	0.60
P3.6	22.71	23.17	1.53	23.38	24.60	4.47	24.20	24.53	1.35	24.92	24.76	0.65
P4.1	21.72			23.08			24.39			24.41		
P4.2	21.72			23.08			24.39			24.41		
P4.3	22.77	22.63	0.46	23.65	24.16	2.75	24.99	24.63	1.44	24.41	24.82	1.64
P4.4	22.77	22.67	0.34	23.65	24.37	3.02	24.99	24.96	0.12	24.83	25.25	1.65
P4.5	22.47	22.81	1.60	23.70	23.97	2.92	25.31	24.77	2.14	24.83	25.29	1.81
P4.6	22.47	22.84	1.54	23.70	24.24	2.24	25.31	24.68	2.49	24.83	25.92	4.18
P5.1	23.10			23.06			24.39			24.41		
P5.2	23.10	23.03	2.49	23.06	24.20	5.04	24.39	24.82	1.75	24.41	24.88	1.86
P5.3	22.85	22.75	0.75	23.66	24.27	1.81	24.39	24.62	0.96	24.41	24.93	2.05
P5.4	22.85	22.58	1.34	23.66	24.94	3.38	25.31	24.80	2.02	24.83	25.92	4.19
P5.5	22.24	23.10	2.25	23.09	24.37	4.59	25.31	27.90	10.24	24.83	26.10	4.86
P5.6	22.24			23.09			25.31			24.83		
Average	22.57	23.05	2.09	23.39	24.27	3.64	25.15	24.95	0.78	24.63	25.14	1.97
q			0.94			0.94			0.83			0.94

Table A5. 4. Measured and simulated radiant temperatures at different levels of height for Scenario 3

Position index	$T_{rad,\ meas.}$ [°C]	$T_{rad,\ flair.\ (1.1)}$ [°C]	Rel.error [%]
P1.1	26.18		
P1.2	26.18		
P1.3	26.18		
P1.4	24.20		
P1.5	24.20		
P1.6	24.20		
P2.1	26.18	23.48	11.49
P2.2	26.18		
P2.3	24.57	24.18	1.63
P2.4	24.57		
P2.5	24.20	24.27	0.29
P2.6	24.20	24.30	0.40
P3.1	26.18	23.96	9.27
P3.2	26.18	24.14	8.45
P3.3	24.57	24.30	1.13
P3.4	24.57	24.32	1.04
P3.5	24.20	24.37	0.68
P3.6	24.20	24.37	0.69
P4.1	24.36		
P4.2	24.36		
P4.3	24.57	24.39	0.73
P4.4	24.57	24.45	0.49
P4.5	25.11	24.47	2.62
P4.6	25.11	24.45	2.70
P5.1	24.36		
P5.2	24.36	24.61	1.02
P5.3	24.36	24.78	1.71
P5.4	25.11	24.84	1.07
P5.5	25.11	24.81	1.23
P5.6	25.11		
Average	24.91	24.36	2.28
q			0.83

Table A5. 5. Measured and simulated air temperatures at different levels of height for Scenario 4

Position index	Meas. T_{a1} (0.1m) [^oC]	Flair T_{a1} (0.1m) [^oC]	Rel.er. [%]	Meas. T_{a2} (0.6m) [^oC]	Flair T_{a2} (0.6m) [^oC]	Rel.er. [%]	Meas. T_{a3} (1.1m) [^oC]	Flair T_{a3} (1.1m) [^oC]	Rel.er. [%]	Meas. T_{a5} (1.6m) [^oC]	Flair T_{a5} (1.6m) [^oC]	Rel.er. [%]
P1.1	21.61			22.54			24.16			23.98		
P1.2	21.61	22.01	1.78	22.54	23.51	4.14	24.16	24.21	0.21	23.98	24.26	1.16
P1.3	22.52	22.08	2.01	22.95	23.61	2.80	24.16	24.09	0.28	23.98	24.35	1.53
P1.4	22.52	22.07	2.06	22.95	23.90	3.99	24.99	24.11	3.64	24.77	24.31	1.90
P1.5	22.09			22.60			24.99			24.77		
P1.6	22.09			22.60			24.99			24.77		
P2.1	22.06	22.54	2.15	22.77	23.86	4.55	24.16	24.14	0.07	23.98	25.20	4.86
P2.2	22.06	22.12	0.28	22.77	23.80	4.29	24.16	24.17	0.05	23.98	24.25	1.14
P2.3	22.61	21.98	2.86	23.44	24.47	4.23	24.65	24.19	1.91	23.98	24.49	2.11
P2.4	22.61	21.64	4.46	23.44	23.71	1.14	24.65	24.24	1.69	24.77	25.08	1.21
P2.5	22.24	22.09	0.67	23.28	23.98	2.90	24.99	24.21	3.22	24.77	24.49	1.17
P2.6	22.24	22.08	0.74	23.28	23.72	1.87	24.99	24.24	3.12	24.77	25.48	2.78
P3.1	21.91	22.18	1.24	23.03	23.93	3.75	24.16	24.86	2.80	23.98	24.86	3.55
P3.2	21.91	22.02	0.52	23.03	23.35	1.38	24.16	24.33	0.68	23.98	25.05	4.29
P3.3	22.56	21.55	4.68	23.58	23.13	1.95	24.65	24.23	1.72	23.98	24.83	3.45
P3.4	22.56	21.83	3.33	23.58	23.83	1.03	24.65	24.25	1.63	24.77	25.05	1.12
P3.5	22.40	21.63	3.57	23.35	23.78	1.80	24.99	24.33	2.72	24.77	24.69	0.34
P3.6	22.40	21.86	2.49	23.35	23.69	1.41	24.99	24.34	2.66	24.77	25.62	3.32
P4.1	21.35			22.69			25.62			23.92		
P4.2	21.35			22.69			25.62			23.92		
P4.3	22.39	21.87	2.38	23.47	24.03	2.32	24.65	24.24	1.70	23.92	24.66	2.98
P4.4	22.39	21.91	2.18	23.47	23.67	0.82	24.65	24.29	1.48	24.53	24.90	1.51
P4.5	22.24	21.88	1.61	23.20	23.28	0.35	24.21	24.38	0.69	24.53	24.63	0.43
P4.6	22.24	22.07	0.75	23.20	23.57	1.57	24.21	24.38	0.68	24.53	25.49	3.77
P5.1	22.15			22.72			25.62			23.92		
P5.2	22.15	21.99	0.70	22.72	23.46	3.14	25.62	24.31	5.38	23.92	24.65	2.95
P5.3	22.38	22.00	1.73	23.56	23.91	1.46	25.62	24.26	5.62	23.92	25.05	4.50
P5.4	22.38	22.11	1.23	23.56	23.10	1.98	24.21	24.23	0.10	24.53	25.49	3.77
P5.5	21.95			22.88			24.21			24.53		
P5.6	21.95	22.18	1.04	22.88	23.36	2.07	24.21	24.48	1.09	24.53	26.66	7.98
Average	22.16	21.99	0.80	23.07	23.68	2.57	24.70	24.28	1.73	24.31	24.94	2.49
q			1.00			1.00			0.91			0.96

Table A5. 6. Measured and simulated radiant temperatures at different levels of height for Scenario 4

Position index	$T_{rad, meas.}$ [^oC]	$T_{rad, flair. (1.1)}$ [^oC]	Rel.error [%]
P1.1	24.75		
P1.2	24.75	23.63	4.72
P1.3	24.75	23.84	3.80
P1.4	24.87	23.90	4.06
P1.5	24.87		
P1.6	24.87		
P2.1	24.75	23.00	7.59
P2.2	24.75	23.62	4.80
P2.3	24.58	23.88	2.94
P2.4	24.58	23.93	2.73
P2.5	24.87	24.02	3.55
P2.6	24.87	24.10	3.20
P3.1	24.75	23.53	5.17
P3.2	24.75	23.79	4.06
P3.3	24.58	23.93	2.72
P3.4	24.58	23.96	2.60
P3.5	24.87	24.06	3.35
P3.6	24.87	24.14	3.02
P4.1	23.37		
P4.2	23.37		
P4.3	24.58	23.96	2.58
P4.4	24.58	24.00	2.43
P4.5	24.46	24.08	1.56
P4.6	24.46	24.16	1.24
P5.1	23.37		
P5.2	23.37	24.05	2.84
P5.3	23.37	24.30	3.81
P5.4	24.46	24.32	0.58
P5.5	24.46		
P5.6	24.46	24.25	0.86
Average	24.47	23.93	1.26
q			0.91

APPENDIX 6 - Building plans

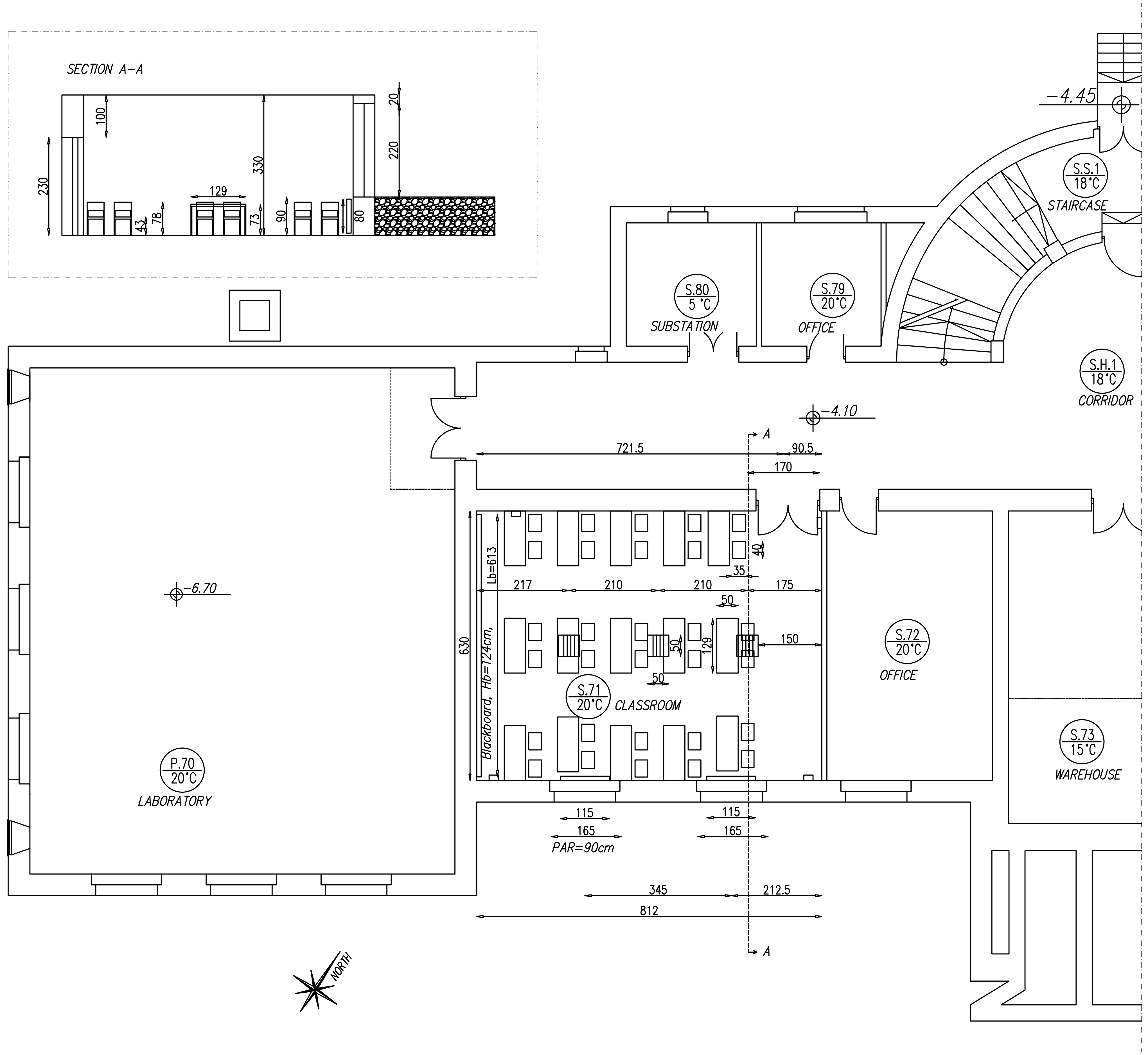
Automatic control Department laboratory - old building
Faculty of Mechanical engineering
University of Belgrade, Ruzveltova Street 1a

LEGEND:

- EXISTING THERMAL SUBSTATION
  Q=404757 W
- GREENERY
- UNDERGROUND LABORATORY
- AUTOMATIC CONTROL DEPARTMENT BUILDING
- OBSERVED CLASSROOM

PROJECT:	DOCTORAL DISSERTATION TAMARA S. BAJC	
BUILDING:	Automatic control Department laboratory - Faculty of Mechanical engineering University of Belgrade Ruzveltova Street 1a, Belgrade	
Drawing scale: 1:500 DATE: 12.2015.	DRAWING: SITUATION PLAN	APPENDIX: 6 P. num.: 173

Automatic control Department laboratory
Faculty of Mechanical engineering
University of Belgrade,
Ruzveltova Street 1a



PROJECT:	DOCTORAL DISSERTATION TAMARA S. BAJC	
BUILDING:	Automatic control Department laboratory - Faculty of Mechanical engineering University of Belgrade Ruzveltova Street 1a, Belgrade	
Drawing scale: 1:100 DATE: 12.2015.	DRAWING: GROUND FLOOR PLAN	APPENDIX: 6 P. num.: 174

Curriculum Vitae
Tamara S. Bajc

Tamara S. Bajc was born in Belgrade, Republic of Serbia, on 12.03.1984. She enrolled at the Faculty of Mechanical Engineering, University of Belgrade in the academic year 2003/2004, and finished on 26.02.2009 with a grade average of 8,72 (out of the maximum 10) at the Department of Thermal science engineering, where she also received a grade of 10,00 for her M.Sc. thesis on air-conditioning, titled: "The energy demands of a passive house with Trombe walls for Belgrade weather data", under the supervision of Dr Maja Todorovic.

She worked for the company "Aerprojekt" as a mechanical engineering designer for HVAC installations from 2009 to 2010.

Tamara enrolled in PhD studies at the Faculty of Mechanical Engineering University of Belgrade in the academic year 2009/2010. In January 2011, she was employed to work as a research and teaching associate on a research project (number TR33047) funded by the Ministry of Education, Science and Technological Development.

In 2012, Tamara S. Bajc participated in the „International ASHRAE student design competition" as leader of the team representing the University of Belgrade. She won third place in this prestigious competition in the "Integrated sustainable building design"category.

In April 2016, she was selected as the teaching assistant for the scientific sub-discipline of Thermal science engineering at the Faculty of Mechanical Engineering, University of Belgrade.

Additionally, she has two licences from the Serbian Chamber of Engineers for HVAC installation design and energy efficiency in buildings.

She is the author or coauthor of 18 published papers in international and national scientific journals, and international conference proceedings.

Tamara speaks fluent English and basic German and Russian.

Прилог 1.

Изјава о ауторству

Потписана Тамара С. Бајц

број индекса D 11/09

Изјављујем

да је докторска дисертација под насловом

"Утицај локалног стања топлотног комфора на смањење радне способности у нестамбеним зградама"

("The local thermal comfort impact on working productivity loss in non-residential buildings")

- резултат сопственог истраживачког рада,
- да предложена дисертација у целини ни у деловима није била предложена за добијање било које дипломе према студијским програмима других високошколских установа,
- да су резултати коректно наведени и
- да нисам кршио/ла ауторска права и користио интелектуалну својину других лица.

Потпис докторанда

У Београду, 22.05.2017.

Прилог 2.

Изјава о истоветности штампане и електронске верзије докторског рада

Име и презиме аутора Тамара С. Бајц

Број индекса D11/09

Студијски програм Докторске студије

Наслов рада **"Утицај локалног стања топлотног комфора на смањење радне способности у нестамбеним зградама" ("The local thermal comfort impact on working productivity loss in non-residential buildings")**

Ментор проф. др Милош Бањац

Потписани/а ______________________

Изјављујем да је штампана верзија мог докторског рада истоветна електронској верзији коју сам предао/ла за објављивање на порталу **Дигиталног репозиторијума Универзитета у Београду.**

Дозвољавам да се објаве моји лични подаци везани за добијање академског звања доктора наука, као што су име и презиме, година и место рођења и датум одбране рада.

Ови лични подаци могу се објавити на мрежним страницама дигиталне библиотеке, у електронском каталогу и у публикацијама Универзитета у Београду.

Потпис докторанда

У Београду, 22.05.2017.

Прилог 3.

Изјава о коришћењу

Овлашћујем Универзитетску библиотеку „Светозар Марковић“ да у Дигитални репозиторијум Универзитета у Београду унесе моју докторску дисертацију под насловом:

"Утицај локалног стања топлотног комфора на смањење радне способности у нестамбеним зградама"("The local thermal comfort impact on working productivity loss in non-residential buildings")

која је моје ауторско дело.

Дисертацију са свим прилозима предао/ла сам у електронском формату погодном за трајно архивирање.

Моју докторску дисертацију похрањену у Дигитални репозиторијум Универзитета у Београду могу да користе сви који поштују одредбе садржане у одабраном типу лиценце Креативне заједнице (Creative Commons) за коју сам се одлучио/ла.

1. Ауторство

2. Ауторство - некомерцијално

3. Ауторство – некомерцијално – без прераде

4. Ауторство – некомерцијално – делити под истим условима

5. Ауторство – без прераде

6. Ауторство – делити под истим условима

(Молимо да заокружите само једну од шест понуђених лиценци, кратак опис лиценци дат је на полеђини листа).

Потпис докторанда

У Београду, 22.05.2017.

1. Ауторство - Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце, чак и у комерцијалне сврхе. Ово је најслободнија од свих лиценци.

2. Ауторство – некомерцијално. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце. Ова лиценца не дозвољава комерцијалну употребу дела.

3. Ауторство - некомерцијално – без прераде. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, без промена, преобликовања или употребе дела у свом делу, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце. Ова лиценца не дозвољава комерцијалну употребу дела. У односу на све остале лиценце, овом лиценцом се ограничава највећи обим права коришћења дела.

4. Ауторство - некомерцијално – делити под истим условима. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце и ако се прерада дистрибуира под истом или сличном лиценцом. Ова лиценца не дозвољава комерцијалну употребу дела и прерада.

5. Ауторство – без прераде. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, без промена, преобликовања или употребе дела у свом делу, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце. Ова лиценца дозвољава комерцијалну употребу дела.

6. Ауторство - делити под истим условима. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце и ако се прерада дистрибуира под истом или сличном лиценцом. Ова лиценца дозвољава комерцијалну употребу дела и прерада. Слична је софтверским лиценцама, односно лиценцама отвореног кода.