DIPLOMARBEIT

Thermal Performance assessment of an existing School Building in Kyiv

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eingereicht an der

Technische Universität Wien

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Wien, April 2018

ABSTRACT

Nowadays, various systems are used in buildings to maintain a comfortable living and work environment. These building technologies can increase the building energy consumption significantly and could lead to unnecessary greenhouse gas emissions together with a considerable contribution to the global climate change. However, the construction sector has a great potential to decrease the energy usage and significantly reduce carbon dioxide emission. For this aim, Ukraine, as a member of the European Energy Community, is obliged to bring its legislation in the sphere of energy efficiency, in line with European directives and has to implement building energy consumption optimization measures.

This Master's Thesis focuses on the evaluation of thermal comfort and indoor air quality in a typical School (No 317) in Kyiv (Kiev), Ukraine. Thermal comfort is assessed by applying different scientific methods including the PMV/PPD model. Results of a monitoring campaign are presented together with a comparison of the objective and subjective evaluation based on a user survey. In a second part, energy efficiency is evaluated, and different thermal performance improvement measures are analysed via simulation. Finally, the values obtained from the simulation are compared with the values presented in the school Energy Certificate and the real measured energy consumption.

Keywords

Thermal comfort, energy efficiency, energy simulation, indoor air quality, PMV, PPD, thermal performance, heating degree days, energy certificate, retrofit scenarios.

KURZFASSUNG

In unserer heutigen Zeit verwenden wir eine Vielzahl an gebäudetechnischen Systemen um ein komfortables Wohn- und Arbeitsumfeld zu schaffen. Die Systeme der Haustechnik können den Energieverbrauch eines Gebäudes erheblich erhöhen und so mit den verbundenen Treibhausgasemissionen zum globalen Klimawandel signifikant beitragen. Allerdings hat die Baubranche auch ein sehr großes Potenzial den Energieverbrauch zu senken und somit die Kohlendioxidemissionen deutlich zu reduzieren. Um diese Ziele zu erreichen versucht die Ukraine, als ein Mitglied der europäischen Energiegemeinschaft, ihre Gesetze im Bereich der Energieeffizienz in Einklang mit den europäischen Direktiven zu bringen und Maßnahmen zur Optimierung von Gebäude zu fördern.

Diese Masterarbeit beschäftigt sich mit der Evaluierung des thermischen Komforts und der Raumluftqualität in einer typischen Schule (No 317) in Kiew, Ukraine. Der thermische Komfort wird auf Basis von gesammelten Messdaten und der Anwendung verschiedener wissenschaftlicher Methoden, wie z.B. dem PMV/PPD Model bewertet. Ein Vergleich der objektiven und subjektiven Beurteilung des thermischen Komforts wird mittels der Daten aus einer Nutzerbefragung gemacht. In einem weiteren Teil der Arbeit wird die Energieeffizienz des Gebäudes untersucht und durch Simulationen werden unterschiedliche Maßnahmen zur thermischen Sanierung beurteilt. Abschließend werden die Energiewerte aus der Simulation mit denen aus dem Energieausweis und dem real gemessenen Verbrauch des Gebäudes verglichen.

Schlüsselwörter

Thermischer Komfort, Energieeffizienz, Energiesimulation, Raumluftqualität, PMV, PPD, thermische Performance, Heizgradtage, Energieausweis, Sanierungskonzept

ACKNOWLEDGEMENTS

This Master Thesis becomes a reality with the kind support and help of many individuals. I would like to extend my sincere thanks to all of them.

I would like to express my special gratitude and thanks to my supervisor Univ.Prof. DI Dr. Ardeshir Mahdavi for the support and imparting his knowledge in this study.

Many thanks and appreciations also go to the members of the Department of Building Physics and Building Ecology, especially to Ass. Prof Dr. Matthias Schuß.

I would like to express my gratitude to the School No 317 administration, teachers and students for their cooperation and response to all the questions solicited in this study.

I owe a deep sense of gratitude to Univ.Prof. DI Oleg Sergeichuk, Department of the architectural constructions, Kyiv National University of construction and architecture, for providing of the necessary information regarding Ukrainian Thermal Comfort Norms.

Above all, I would like to express my gratitude towards my family, especially to my parents for the encouragement and faith in me that helped in the completion of this Master Thesis.

Last, but not least, I would like to use this possibility to thank my beloved and supportive husband who is always by my side in times when I need him most.

Dedicated to my parents.

CONTENTS

1 INTRODUCTION

1.1 Motivation

The construction sector is responsible for the substantial world energy consumption that in its turn influences on the climate change and global warming. According to the UNEP 2015 buildings produce one-third of global greenhouse gas emissions in the atmosphere. Furthermore, the global contribution from buildings towards energy consumption, both residential and commercial, has steadily increased reaching figures between 20% and 40% in developed countries, and has exceeded the other major sectors: industrial and transportation (Pérez-Lombard et al. 2007). The upward trend of population, living standards and level of wealth, will contribute to substantial growth in building energy consumption, provoking more, catastrophic consequences of the climate change. However, the building sector has a high potential for energy demand reduction that makes the building energy efficiency, the key objective for every government at every level.

In Ukraine the majority of the commercial and residential buildings were designed and constructed in the twentieth century, when cheap energy resources were available. Hence, the concept of those buildings did not pay attention to energy consumption and its optimization. Due to the depletion of fossil energy resources, Ukraine, as a member of the European Energy Community (EEC) is obliged to reduce the non-renewable energy usage. The country must adapt its energy efficiency legislation to the EEC directives and implement the energy efficiency potentials. Among all the types of commercial buildings schools are very substantial energy users. Over the day children spend a significant amount of time in schools. Therefore, thermal comfort and indoor air quality are crucial for the children's health and study performance. Comfortable indoor conditions are achieved by the use of various building systems. Heating, cooling and ventilation systems are considered as the substantial tools to sustain and improve thermal comfort levels demanded by occupants. At the same time these indoor technologies are the major energy consumers in buildings.

This study provides a comprehensive evaluation with focus on energy efficiency, thermal comfort, and indoor air quality in a typical school building located in Kyiv (Kiev), Ukraine. Based on the received data, the energy efficiency and thermal comfort improvement options are proposed. These measures can be implemented in the Case Study School, as well as in other schools which are faced with similar problems.

1.2 Objective

This Master Thesis focuses on a typical Ukrainian school building - School No 317. Main objective of this work is the evaluation of the thermal comfort, indoor air quality, energy efficiency and possible retrofitting scenarios.

The Master Thesis should give answers to the below research questions:

- What is the thermal comfort and indoor air quality in this typical school building?
- What is the typical energy consumption in the school building and how does it correlate with the real Energy Certificate?
- What kind of energy efficiency measures are needed to decrease heating energy demand of the school building?

2 BACKGROUND

The background chapter presents information about the Energy Efficiency Directives in European Union. It gives a brief explanation of the Ukrainian Energy Certificate and Ukrainian Education System. Finally, it provides a brief introduction to the Thermal Comfort and Indoor air quality conditions.

2.1 Thesis Structure

The Master Thesis is structured in eight chapters. The first chapter describes the motivation and objective of the current research work. The second chapter presents theoretical background of the chosen topic. The methodology applied in the Master Thesis is described in the third chapter. The fourth chapter represents the results and discussion of the research and the fifth provides conclusions drawn based on the results of the Master Thesis. Index, literature and appendix are included in chapters six, seven and eight respectively.

2.2 Energy efficiency of buildings and related directives.

The European Commission states that about 35% of the European Union's buildings are over 50 years old. By improving the energy efficiency of buildings, we could reduce total European Union energy consumption by 5-6% and lower CO_2 emissions by about 5%. Efficient energy use, sometimes simply called energy efficiency, is the goal to reduce the amount of energy required to provide products and services (Gardoni and La Fave 2016). Energy consumption of buildings depends significantly on the criteria used for the indoor environment (temperature, ventilation and lighting) and building (including systems) design and operation (EN 15251, 2007). Every part of the building, its location and appliances are strongly influencing its energy usage. Compact building design, energy efficient doors and windows, insulation of the walls, slabs and roof can significantly reduce heat loss over the building envelope. Also, as declared by Environmental and Energy Study Institute (2006), thermal comfort improvement of the building's inhabitants and energy consumption reduction can be achieved by the installation of advanced heating and cooling systems.

There are two main EU directives that are designed to reduce energy consumption of the buildings in Europe: 2010 Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive.

The 2012 Energy Efficiency Directive establishes a common framework of measures for the promotion of energy efficiency within the Union in order to ensure the achievement of the Union's 2020 20 % headline target on energy efficiency and to pave the way for further energy efficiency improvements beyond that date. (Directive 2012/27/EU)

Under the Energy Efficiency Directive:

- Every Member State shall establish long-term national renovation strategies for the residential and commercial buildings that have to be included in its National Energy Efficiency Action Plans.
- Every Member State shall make energy efficient renovations to at least 3% of the total floor area of heated and/or cooled buildings owned and occupied by its central government.
- EU countries should only purchase buildings which are highly energy efficient.

The 2010 Energy Performance of Buildings Directive promotes the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness (Directive 2010/31/EU) .

Under the Energy Efficiency Directive:

- Every Member State must set minimum energy performance requirements for new buildings, buildings undergoing major renovation and for the replacement or retrofit of building elements.
- EU countries shall to issue an energy performance certificate for the buildings which are constructed, sold or rented and for the buildings with a total useful area of more than 250m^2 is occupied by the public authorities or visited by the public.
- Energy performance certificates should be included in all advertisements for the sale or rental of buildings.
- Member States shall ensure that all new buildings must be nearly zero energy buildings by 31 December 2020 and public buildings by 31 December 2018.
- Energy performance certificates of buildings and inspection of heating and air conditioning systems are carried out by qualified, accredited experts which are self-employed or employed by public and private enterprises.

2.3 Ukrainian Energy Efficiency Certificate

In Ukraine, energy performance certification appeared in 2007, but for some time, it was optional. The Energy Certificate became a mandatory part of the project documentation for all new and renovated residential and public buildings in January 2009. Despite the fact Ukraine ratified the Treaty of the European Energy Community, for a long time there was no law that would regulate energy certification of buildings and would establish the validity of the certificates. The state law No 4941”. About energy efficiency of the buildings was adopted in July 2017. This law defines legal and organizational basis of the activities in the field of the building energy efficiency and is aimed to create conditions for reducing energy consumption in buildings (No 4941, 2017).

Ukrainian Building Energy Efficiency Certificate is mandatory for the new buildings, building under refurbishment, building enlargement and reconstruction. It’s also mandatory for the public buildings with the area of more than 250 m^2. An Energy Certificate must be issued if the energy efficiency measures are carried out with the help of the state financial support and in the case of sale, renting and leasing. The Energy Certification is not required for: the industrial buildings and agricultural buildings with a low level of the energy usage; worship and religious buildings; cultural heritage buildings; temporary buildings with a period of use of up to 2 years and detached buildings with the conditioned net floor area less than 50m^2. For the existing buildings, Energy Certificates should be issued on demand by the owners or supervising organizations. Energy Certification of the new building is carried out on request and at the expense of the customer. Development and issue of Energy Certificate can be done just by the licensed organizations during the construction of the new building, reconstruction and capital repairs.

Ukrainian Energy Certificate is valid for 10 years. A Building Energy Certificate before the expiration of the established term is considered invalid after the completion of the reconstruction, capital refurbishment or technical reequipment of the building.

The Energy Certificate has seven main indicators which define energy efficiency of the building:

- $g_{буд}$ (specific heat loss for heating of building over heating period)
- $K_{буд}$ (overall heat transfer coefficient of the building insulation envelope)
- $K_{\Sigma пр}$, (adjusted heat transfer coefficient of the building insulation envelope)
- $K_{інф}$ (conventional heat transfer coefficient of the building envelope that includes heat loss from the infiltration and ventilation)
- $n_{об}$, (air exchange rate)

- $m_{ск}$, (facade glazing factor)
- $\Lambda_{к\ буд}$, (compactness of the building).

The class of the building's energy efficiency is defined by the client during the project's stage and it cannot be lower than class "C". For an existing building, the energy efficiency class must be defined based on the energy audit. When an existing building receives an energy efficiency classification under "C", measures must be developed that increase energy performance to at least this level. Developed measures have to be established by the licensed organization with the agreed terms of its implementation.

There are several main guidelines and norms which issue, regulate and develop the Energy Certificates in Ukraine (Table 1).

Table 1: Ukrainian Norms necessary for the Energy Certificate

Number of the Norm	**Title of the Norm**
ДБН В.2.6-31:2006	Thermal insulation of the buildings
ДСТУ-Н Б А.2.2-5:2007	Guidelines for the development and assembly of energy passports for buildings under construction and reconstruction
ДСТУ Б.2.2-8:2010	Designing. Section "Energy Efficiency" as part of the project documentation of the building objects.

Ukrainian Energy Certificate consists out of six main parts. The first part gives an information about type, location and year of the building construction. It also presents information about the project developer and project code.

In the second part, climate data including information about the heating period is presented. Information about the base temperature and designed outside air temperature are taken from the ДБН В.2.6-31:2006. Base temperature ($t_в$) depends on the building type and for a school building, this is 18 °C. Designed outside air temperature ($t_з$) depends on the temperature zone map, presented in Figure 1. Kyiv is located in the first temperature zone, where designed outside air temperature is -22°C.

Figure 1: Map of the Ukrainian temperature zones. Source: steklo-plast.com.ua

Unlike Austria or other countries where the beginning and end of the heating period is determined by the daily, monthly average outside air temperature prescribed in the standards, in Ukraine a fixed value for the duration of the heating period ($z_{оп}$) for the HDD calculation is used (Formula 1).

$$HDD = (t_{в} + t_{оп\ з}) * z_{оп} \qquad (1)$$

HDD Heating Degree Days, [°Cd]

$t_{в}$ Base temperature, [°C]

$t_{оп\ з}$ Average outside temperature over the heating period, [°C]

$z_{оп}$ Duration of the heating period, [d]

The duration of the heating period and average outside air temperature over the heating period ($t_{оп\ з}$) is defined by the State Building Climatology Guidelines (ДСТУ-НБВ. 1.1-27: 2010).

Part number three presents the data about geometrical characteristics and areas of the building envelope: total area of the building envelope, heated and useful area, heated volume, glazing factor and indicator of the house compactness.

The fourth part is called thermo-technical values. It presents the given thermal resistance of the building envelope. For outer enclosure of the heated buildings and internal structures that separate the rooms, which temperature differs in 3°C and more are bound by the terms (ДБН В.2.6-31:2006).

$$R_{\Sigma пр} \geq R_{g\ min}$$

Where:

Given thermal resistance $R_{\Sigma пр}$ [$m^2.K.W^{-1}$]

- is the area - weighted average thermal resistance of the thermally inhomogeneous enclosure, which considers two-dimensional in cross-section heat transfer and which is determined based on the calculations or test results of the construction.

Minimum acceptable thermal resistance $R_{g\ min}$ [$m^2.K.W^{-1}$]

- is the minimum acceptable thermal resistance value of the opaque or translucent enclosure or opaque part of the enclosure.

Minimum acceptable thermal resistance of the opaque and translucent enclosure of the residential and public buildings is determined by the ДБН В.2.6-31:2006 and depends on the temperature zone, in which the building is located. Every Energy Certificate presents the data about min. acceptable thermal resistance and designed given thermal resistance for every type of construction: walls, doors, windows, slabs etc.

In the fifth part, energy indicators and energy class of the building are presented. There are three main indicators, on which the energy class definitions of the building are based: normative, designed and actual specific heat losses. Due to the ДБН В.2.6-31:2006, designed and actual specific heat loss must be lower or equal to normative one:

$$g_{буд} \leq E_{max}$$

Where:

Designed or actual specific heat loss $g_{буд}$ [$kWh.m^{-2}$] or [$kWh.m^{-3}$]

Maximum allowable specific heat loss E_{max} [$kWh.m^{-2}$] or [$kWh.m^{-3}$]

- is the maximum allowable value of the specific heat loss for the building heating over the heating period, that is defined by the type of the building, its height and temperature zone of the building operation after the ДБН В.2.6-31:2006.

Unlike to the Austria energy classification where the designed values are directly compared with the prescribed indicators (Table 2), the Ukrainian building energy efficiency classification is based on the level of relative deviation between designed or actual value from the normative value of the specific heat loss for heating (Formula 2).

$$[(g_{буд} - E_{max}) / E_{max}]\ 100\ \% \quad (2)$$

Table 2: Building Energy Classification (OIB 6, 2015)

Class	$HWB_{Ref,SK}$ [$kWh.m^{-2}.a^{-1}$]	PEB_{SK} [$kWh.m^{-2}.a^{-1}$]	$CO_{2\ SK}$ [$kg.m^{-2}.a^{-1}$]	fGEE [-]
A++	10	60	8	0.55
A+	15	70	10	0.70
A	25	80	15	0.85
B	50	160	30	1.00
C	100	220	40	1.75
D	150	280	50	2.50
E	200	340	60	3.25
F	250	400	70	4.00
G	>250	>400	>70	>4.00

Table 3 represents the classes of the energy performance classification based on Ukrainian Norms and Standards. In this classification, the letter "A" represents buildings with the best energy performance and the letter "F" – buildings with the worst, respectively.

Table 3: Building energy classification in Ukraine, (ДБН В.2.6-31:2006)

Building Energy Efficiency Class	Difference in %, between designed or actual values of the specific heat loss $g_{буд}$, from the maximum allowed value E_{max} $[(g_{буд} - E_{max}) / E_{max}]\ 100\ \%$
A	Minus 50 and less
B	From minus 49 to minus 10
C	From minus 9 to 0
D	From 1 to 25
E	From 26 to 75
F	76 and more

In the final part of the Energy Certificate, conclusions, instructions and recommendations for the building energy performance improvement are presented.

2.4 Ukrainian Education System

There are two types of school in Ukraine: Elementary and High school. Children aged 6 to 11 years old attend the Elementary school, and the High school from 11 to 17 years old. Typically, the two schools are in the same building but on different floors and sometimes with separate entrances.

One lesson lasts for 45 minutes with a break of 15 minutes. The school building is opened from 08:00 till 18:00. Lessons last from 08:30 till 15:00.

Elementary school has 3-4 lessons per day, during which the students sit in the same classroom, except for music and physical education. Every other day, children remain at daycare till 18:00.

High school has 5-7 lessons per day and students change classrooms for each new lesson. After class, depending on the needs, students can attend a variety of activities held at school: dancing, tennis, karate, basketball etc.

2.5 Thermal Comfort

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE 55:2010). Thermal Comfort is a complex meaning, since different people can have large variations of their own physiological and psychological satisfaction. Thermal comfort preferences vary significantly between the people. What is a comfortable zone for one, is the zone of discomfort for another. There are six key factors that affect thermal comfort: air temperature, humidity, air speed, mean radiant temperature, metabolic rate and clothing insulation.

Air temperature is one of the most important factors which affect thermal comfort. Air temperature is defined as an average temperature of the air that surrounds the occupant, considering location and time.

EN 15251:2007 represents four categories of indoor environment and description of the applicability of the categories used.

I: High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.

II: Normal level of expectation and should be used for the new buildings and renovations.

III: An acceptable, moderate level of expectation and may be used for existing buildings.

IV: Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

Another factor that influences on the thermal comfort is humidity. It defined as the amount of water vapour contained in the air. There is a direct relation between temperature and humidity. The higher the temperature is, the more vapour can be hold by the air. The ratio of actual amount of water vapour in the air compared to the max. water vapour that can be present in the air at that temperature is called relative humidity. The moisture content or specific humidity is the ratio of the mass of water vapour to the total mass of the moist air parcel. The recommended limit for the absolute humidity in a building is 12 $g.kg^{-1}$. Humidity has only a small effect on thermal sensation and perceived air quality in the rooms of sedentary occupancy, however, long term high humidity indoors will cause microbial growth, and very low humidity, (<15-20%) causes dryness and irritation of eyes and air ways. (EN 15251:2007). Table 4 shows the example of recommended design criteria for the humidity in occupied spaces if humidification or dehumidification systems are installed.

Table 4: Example of recommended design criteria for the humidity in occupied spaces if humidification or dehumidification systems are installed (EN 15251:2007)

Type of building/space	Category	Design relative humidity for dehumidification, %	Design relative humidity for humidification, %
Spaces where humidity criteria are set by human occupancy. Special spaces (museums, churches etc) may require other limits	I	50	30
	II	60	25
	III	70	20
	IV	>70	<20

The mean radiant temperature is the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure (ISO 7726:1998). The mean radiant temperature refers to the shape of the human body and for this reason alone, is the factor which is difficult to measure precisely (Fanger 1970). Thereby, the mean radiant temperature should have the same value as air temperature, with the acceptable deviation not more than 2 °C.

The air velocity in a space influences the convective heat exchange between a person and the environment. There is no minimum air velocity that is necessary for thermal comfort. However, increased air velocity can be used to offset the warmth sensation caused by increased temperature. Large individual differences exist between people with regards to the preferred air velocity. Therefore, the elevated air velocity must be under the direct control of the affected occupants and adjustable in steps no greater than 0.15 $m.s^{-1}$ (ISO 7730:2005).

Metabolism is measured in Met (1 Met=58.15 $W.m^{-2}$ of body surface). The amount of energy released by the metabolism depends on the body activity. A few examples of the metabolic rates for the different body activities are revealed in Table 5.

Table 5: Example of the Metabolic rates (ISO 7730:2005)

Activity	Metabolic rate	
	$W.m^{-2}$	met
Reclining	46	0.8
Seated, relaxed	58	1.0
Sedentary activity	70	1.2
Standing, light activity	93	1.6
Standing, medium activity	116	2.0
Walking, 5km.h^{-1}	200	3.4

Clothing plays a very important role in the body's heat balance. There is a special clothing classification according to its insulation value. The clothing insulation is defined as Clo units (1 Clo = 0.155 $m^2.K.W^{-1}$). A nude person has a Clo value of 0. The Clo value of the dressed person can be calculated by the simple adding of individual Clo values. Table 6 shows the example of the Clo values for different clothing.

Table 6: Example of the Clo values for different clothing (ISO 7730:2005)

Garment	Clo	$m^2.K.W^{-1}$
Panties	0.03	0.005
T-shirt	0.09	0.014
Shirts/Blouses. Normal, long sleeves.	0.25	0.039
Trousers, normal	0.25	0.039
Sweater	0.28	0.043
Coats	0.6	0.093

The PMV and PPD model was initially presented by Danish scientist, Povl Ole Fanger. This model determines the thermal comfort based on the heat balance equations and experimental studies on skin temperature.

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 (Table 7), based on the heat balance of the human body (ISO 7730:2005). Thermal balance can be obtained only in cases where the human body generates the same amount of internal heat, as it loses in the surrounding environment. The PMV is affected by metabolic rate (Met value), clothing insulation (Clo value), air temperature, mean radiant temperature, air velocity and air humidity.

Table 7: Seven-point thermal sensation scale

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

For the prediction of the amount of people who are dissatisfied with the given thermal environment, the PPD index (Prediction Percentage of Dissatisfied) has been introduced. The PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm (ISO 7730:2005). The PPD is directly related to the PMV. In the PPD index, those who vote -3,-2,+2,+3 on the PMV sensation scale are known as thermally dissatisfied people. As presented in Figure 2, the PMV values between -0.5 and +0.5 are considered as comfortable and acceptable. This range indicates that 10% of the occupant that are not satisfied with the given thermal climate. The relation between PMV and PPD never comes below 5% of people who are, supposedly, dissatisfied with the thermal climate in the room.

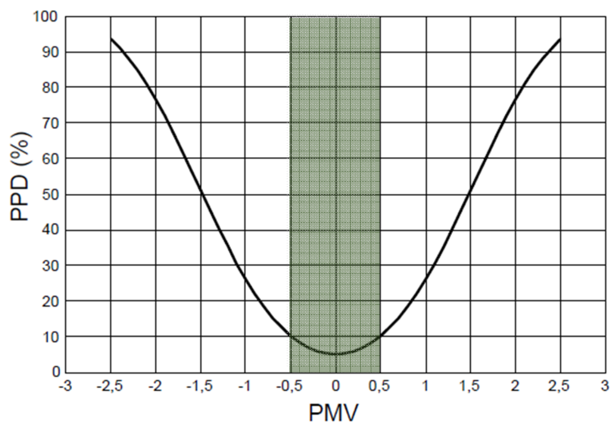

Figure 2: Relation between PMV and PPD index. Source: eneor.com

Desired thermal environment for a space (Table 8) may be selected from the three categories, A, B and C. Example design criteria for spaces in various types of building is presented in the Table 9.

Table 8: Categories of thermal environment (ISO 7730:2005)

Category	Thermal state of the body as a whole		Local discomfort			
				PD, % caused by		
	PPD %	PMV	DR, %	vertical air temp. difference	warm or cool floor	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

Table 9: Example design criteria for spaces in various types of building (ISO 7730:2005)

Type of building/space	Activity $W.m^{-2}$	Category	Operative temperature °C		Max. mean air velocity[a], $m.s^{-1}$	
			Summer (cooling season)	Winter (heating season)	Summer (cooling season)	Winter (heating season)
Single office Landscape office Conference room Auditorium Cafeteria/restaurant Classroom	70	A	24.5 ± 1.0	22.0 ± 1.0	0.12	0.10
		B	24.5 ± 1.5	22.0 ± 2.0	0.19	0.16
		C	24.5 ± 2.5	22.0 ± 3.0	0.24	0.21[b]
Kindergarten	81	A	23.5 ± 1.0	20.0 ± 1.0	0.11	0.10[b]
		B	23.5 ± 1.5	22.0 ± 2.5	0.18	0.15[b]
		C	23.5 ± 2.5	22.0 ± 3.5	0.23	0.19[b]
Department store	93	A	23.0 ± 1.0	19.0 ± 1.5	0.16	0.13[b]
		B	23.0 ± 2.0	19.0 ± 3.0	0.20	0.15[b]
		C	23.0 ± 3.0	19.0 ± 4.0	0.23	0.18[b]

[a] The maximum mean air velocity is based on a turbulence intensity of 40% and air temperature equal to the operative temperature according to 6.2 and Figure A.2. A relative humidity of 60% and 40% is used for summer and winter, respectively. For both summer and winter a lower temperature in the range is used to determine the maximum mean air velocity.

[b] Below 20 °C limit (see Figure A.2).

2.6 Indoor Air Quality

Air quality at classrooms is of special concern since children are susceptible to poor air quality, and indoor air problems can be subtle and do not always produce easily recognizable impacts on health and wellbeing (USEPA 1996). Unfortunately, quite often, classrooms are significantly under-ventilated, which leads to the high level of CO_2 concentration. Bad indoor air quality can multiply the chance of long-term and short-term health problems for students and reduce their academic successes.

Carbon dioxide (CO_2) is a colourless, odourless, non-flammable gas that is a product of cellular respiration and burning of fossil fuels (Longhurst and Brebbia 2012). It is present in the atmosphere at 0.035%. CO_2 is an indicator of human metabolic activity that decrease or increase in relation to it. Defined outside CO_2 value is 400 ppm. According to ASHRAE, recommended indoor air concentration, so-called Pattenkoffer-value, is equal to 1000 ppm. Higher CO_2 value can cause respiratory health problems and causes tiredness, followed by depression. Concentration below 1000 ppm cannot lead to the health problems but can influence on the poor perception of comfort and indoor air quality in the room. Table 10 and Table 11 show basic classification of indoor air quality (IDA) and CO_2 level concentration in rooms presented in EN 13779:2008. For the CO_2 and other pollutants' removal from non-smoking offices, the minimum outdoor air supply requirement is 0.00944 $m^3.s^{-1}$/person or 34 $m^3.h^{-1}$/person (ASHRAE 62-2001).

Table 10: Basic classification of indoor air quality (IDA) (EN 13779:2008)

Category	**Description**
IDA 1	High indoor air quality
IDA 2	Medium indoor air quality
IDA 3	Moderate indoor air quality
IDA 4	Low indoor air quality

Table 11: CO_2 - level in rooms (EN 13779:2008)

Category	CO_2 - level above level of outdoor air in ppm	
	Typical range	**Default value**
IDA 1	≤ 400	350
IDA 2	400-600	500
IDA 3	600-1000	800
IDA 4	>1000	1200

3 METHOD

3.1 Overview

In Ukraine, most of the schools were built 20-30 years ago without any optimization of the energy consumption. The Case Study building, School No 317 in Kyiv with advance study of foreign languages and fine art, is among them. There are three other schools: No 291, No 297 and No 298 constructed after the same project, as the Case Study School. All of them are also located in Kyiv and since construction, haven't had any significant energy efficiency improvements. In Figure 3 and Figure 4, the Schools No 297 and No 291 are depicted.

Figure 3: School No 297. Source: rosvuz.com.ua

Figure 4: School No 291. Source: wikimapia.org

In order to conduct the study about School No 317 thermal comfort and indoor air quality, five classrooms were monitored in Spring 2014. At the end of the measurement period, children with lessons in the monitored classrooms were surveyed to determine subjective perception of the thermal comfort and indoor air quality. For the analyses of the school building energy consumption and its comparison with the existing Energy Certificate, the information about heating and electricity energy usage for the period of 2012-2016 was obtained. To improve energy demand and thermal performance of the building, a Base Case will be compared with three retrofitting options.

In the year 2014, the heating period lasted from 15th November till the 15th April. The Figure 5 shows daily outside temperature during the measurement period from March to May 2014.

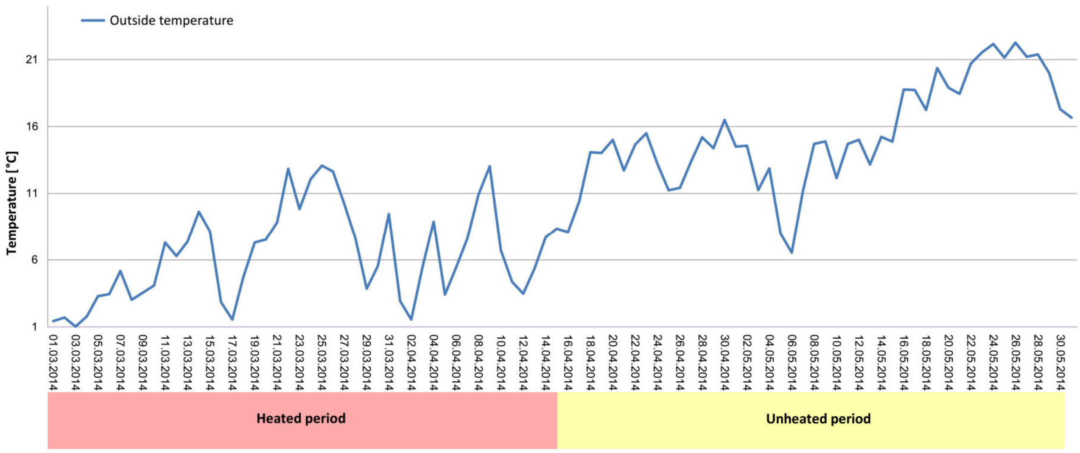

Figure 5: Daily outside temperature over the measurement period. Source: Own

3.2 The Case Study Building

The school project was designed in USSR, based on the USSR indoor climate conditions, building requirements and guidelines. Due to the country's rich energy resources, it was not foreseen that implementing effective energy saving measures in this school project, as well as in others school projects, would be necessary. School construction started in 1986 and eventually, due to the heavy political events in the country, was suspended until 1995. When the construction was resumed, the biggest part of the mechanical engineering systems developed and calculated in 1986 had been already built. During the construction, financing in young Ukraine was not always stable, which led to unforeseen changes in the original building project, resulting in non-working, mechanical ventilation from the beginning of the building operation. Several refurbishments have been made to the school since 1996, focusing on the partial replacement of the old timber-aluminium windows with the new plastic windows.

The school building is a typical example of the construction style of the 1980s. It situated in Kyiv, Ukraine, is in the south-western part of the city in the Svyatoshynskyi district (Figure 6).

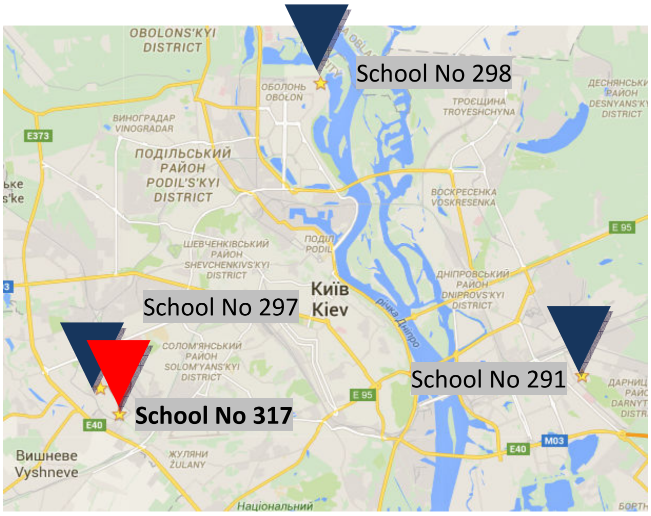

Figure 6: Geographical location of School No 317 and alike schools. Source: maps.google.com

School No 317 (Figure 7, Figure 8) is a four-storey building that includes Elementary and High schools. Regarding the shape, the school is a terraced building, where every next floor is smaller than the previous one. In the original design, almost every class had to have a balcony but during the construction, this idea was abandoned. The total area of the building measures 13584.4 m^2. The Elementary school is located on the ground floor and south-west side of the second floor. The rest of the building belongs to the High school. Elementary and High schools have a common entrance group on the south-east side.

Figure 7 : *School No 317. South-north view.*
Source: http://317school.kiev.ua

Figure 8 : *School No 317. South-west.*
Source: wikimapia.org

The ground floor also contains the big lunch hall and kitchen. Two gyms are located on the first floor, whilst the basement is mostly used as a storage area and is not heated. The school has a central heating and natural ventilation. The outer walls of the school constructed out of full brick and have no additional thermal insulation. From the side of the facade, all the walls are tiled with ceramic unglazed facade tiles. School mostly have double-glazed timber-aluminium windows, but in recent years, some of these windows were changed to double-glazed PVC windows. More information about the Case Study Building is available in the Appendix 8.1.

3.2.1 Heating system

Since the construction of the building in 1995, the school has been connected to the district heating system. In 2004 the old substation was replaced by a modern Individual Heating Substation (IHS) to increase the efficiency of the district heating network. Nowadays, the school heating system has a direct connection to the district heating system with a more efficient hot water heating.

IHS is a set of devices, consisting of components that connect a heating system and the hot water supply system of the building with the district heating network. The district heating network delivers a heat-carrying medium to the building heating system. Over the reverse pipeline, cooled heat-carrying medium returns to the centralized boiler station. IHS is used to regulate the temperature of the heating agent in the heating system of the building and adjust heating supply temperature according to the outside air temperature.

In the school building, a 2-stage water heating system is used (Figure 9). In this 2-stage system, the waste heat energy from the return flow is used to reduce the consumption of the network heat agent. Over the winter, the cold tap water is preheated in the first stage by the return flow of the room heating (approx. from 5°C to 30°C). In the second stage, it heats to the necessary temperature (approx. 60°C). For this purpose, the network water from the supply pipeline of the heating network is used. At the end of the heating period in the school, a single-stage water heating system is used.

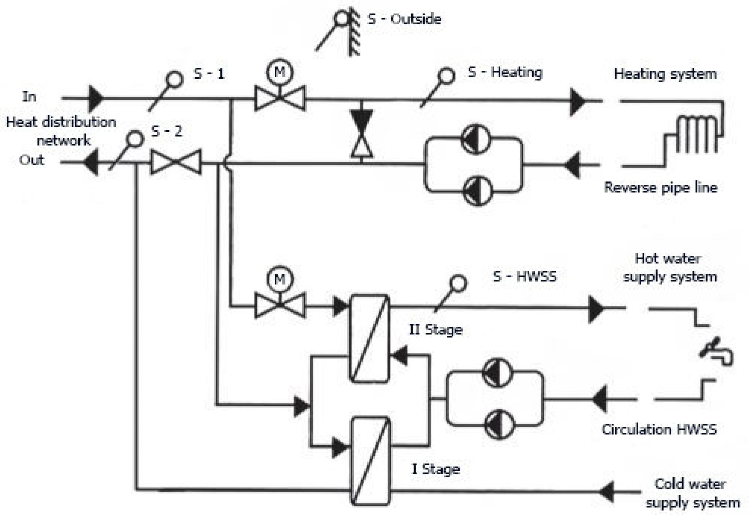

Figure 9: Schema of the IHS in School No 317. Direct connection of the internal heating system to the district heating system with the 2-stage water heating. Source: http://aw-therm.com.ua

The IHS, as shown in Figure 10, is equipped with the automatically regulated devices, controlled by the digital controller DHC 23 from Honeywell.

Figure 10: Individual Heating substations in School No 317. Source: Own

There is only one heat meter (SA-94/1) for the complete heat energy usage of the whole school. It provides information about: energy consumption (Gcal), amount of heat transfer agent (ton), outlet temperature (°C), inlet temperature (°C) and time of the system work (h).

In the school classrooms, old fashioned metal wall convectors were installed (Figure 11, Figure 12). Initially, this type of convectors appeared in the post-Soviet Union, in the 1980s. This convector is the three-quarter turns of the tube with the attached ring fins, covered by the metal plate. Temperature of the convectors cannot be operated directly in the classrooms. It can be adjusted just for the whole school building in the IHS.

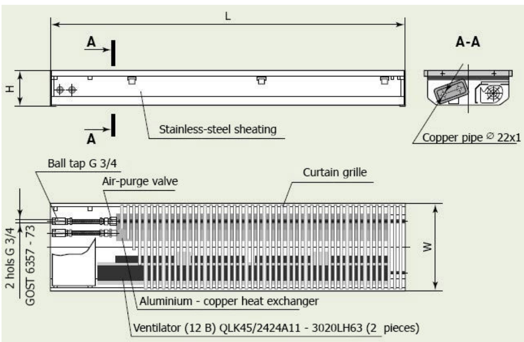

Figure 11: Classrooms convectors.
Source: otoplenie-gid.ru

Figure 12: Classrooms convectors.
Source: Own

3.2.2 Electricity distribution

The school has a big electricity load thus they are divided into four meters: two for the dining room, including kitchen, and two for classrooms including corridors (Figure 13). There is no submetering for the different areas.

Figure 13: Electricity distribution Source: Own

There are two main electricity consumers in the school building: lighting system and electrical equipment (computers, interactive boards, printers, fridges, kitchen boiler, etc.). The main light sources of the electrical lighting system at school are fluorescent lamps that are dominant in all classrooms and corridors.

3.2.3 Energy Consumption and Energy Certificate

Monthly heat energy consumption in 2012-2016 is presented in Appendix 8.2. Monthly electricity energy consumption in 2012-2016 documented in Appendix 8.3 and division between two main electricity meters in the monitored year 2014 depicted in the Appendix 8.4.

The School No 317 Energy Certificate (Appendix 8.5) was issued on the 04.04.2016 and was provided by the Municipal Enterprise "Implementation of the project on energy saving in administrative and public buildings". In the certificate, designed indoor air temperature (base temperature) is 18°C. Average outside air temperature over the heating period is -0.1°C. HDD (in Ukraine Dd) is 3185.6 °Cd and duration of the heated period is 176 days. According to the ДБН В.2.6-31:2006, max. allowable value of the specific heat loss for the school building's heating is 131.66 $kWh.m^{-2}$; the energy efficiency class is C. According to the Energy Certificate, designed max. allowable value of the specific heat loss is 178.4 $kWh.m^{-2}$ with energy efficiency class E. Actual specific heat loss is 76.45 $kWh.m^{-2}$ and is energy efficiency class B.

3.3 Monitoring of indoor conditions

In School No 317, five different classrooms were selected and monitored from the beginning of March till the end of May 2014. All five classrooms are typical for the school building and were chosen because of diverse orientation, floor location and type of the windows. The following dates were selected because of the equal heated (01.03 - 15.04) and unheated (16.04 - 31.05) periods. In the classrooms, the following parameters were measured: temperature, relative humidity and CO_2 concentration. Data was recorded every 5 minutes and read out every 30 days for temperature and relative humidity and every 7 days for CO_2 sensors. All the sensors were placed in an appropriate place without direct sunlight, at a height not accessible by the children. Special care was taken to ensure that all the loggers could not be disturbed by any class activities. Furthermore, the equipment was placed in areas away from heat sources and air currents, such as radiators and IT equipment.

For the data evaluation, only those values that lay within the classrooms' occupancy hours between 08:00-18:00 were considered. The temperature, relative humidity and CO_2 concentration values obtained from the sensors were structured in Excel and later processed in Matlab software.

3.3.1 Measurement equipment

HOBO U12 Data Logger (Figure 14) were used to measure the classrooms indoor temperature and relative humidity. This logger, produced by Onset Inc, has 12-bit resolution and stores 43,000 measurements. HOBO U 12 can be compatible with a broad range of external sensors, has direct USB connectivity for convenient and fast data transfer. Measurements range for the temperature is -20^o to 70^o and 5% to 95% for the relative humidity.

Figure 14: HOBO U12 Data Logger. Source: 4.imimg.com

For the monitoring of the CO_2 indoor air concentration, CDL 210 Datalogger (manufactured by Wöhler) was used. The measurement range of the the Datalogger, displayed in Figure 15, is from 400 to 6000 ppm. It has a comfortable level indicator with adjustable alarm values, automatic calibration function, infrared CO_2 measurement and a non-volatile memory.

Figure 15: Wöhler CDL 210 Datalogger. Source: shkshop24.de

3.3.2 Description of the monitored classrooms

The overview of the monitored classrooms is presented in the Table 12.

Table 12: Overview of the monitored classrooms

Classroom number	Orientation	Floor level	Area [m_2]	Window system	Number of windows
215	south-east	1	59.82	timber-aluminium	7
219	south-east	1	59.82	PVC	9
101	south-west	GF	56.55	timber-aluminium	7
309	south-west	2	58.07	timber-aluminium	7
402	north-west	3	59.82	timber-aluminium	3

Figure 16, shows the location and orientation of the monitored classrooms on the school building plan.

Figure 16: Location and orientation of the monitored classrooms on the plan. Source: maps.google.com

- **Classroom 215**

Classroom 215 is located on the first floor in the south-east wing of the building. It has seven timber-aluminium windows and two outside walls. Due to terraced shape of the building, part of the classroom ceiling, protrudes outwards with the width of 1.2 meter. This classroom belongs to the High school and during the day it is occupied by different groups of students.

As can be seen in Figure 17, a temperature and relative humidity sensor was placed on the wall above the information stands, at the height of 2.7m that is not easily reachable for children. The CO_2 sensor (Figure 18) was placed on the right side of the teachers table. The exact sensors locations are shown on the floor plan in Figure 19.

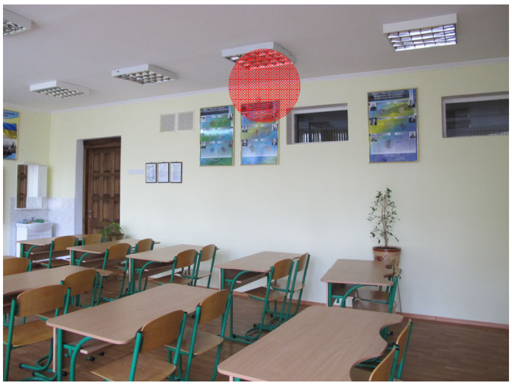

Figure 17: Location of the HOBO sensor in Classroom 215 Source: Own

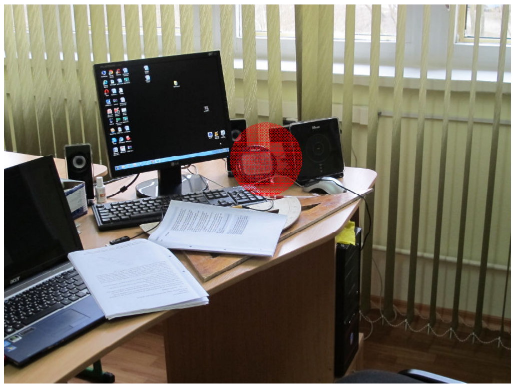

Figure 18: Location of the CO_2 sensor in Classroom 215 Source: Own

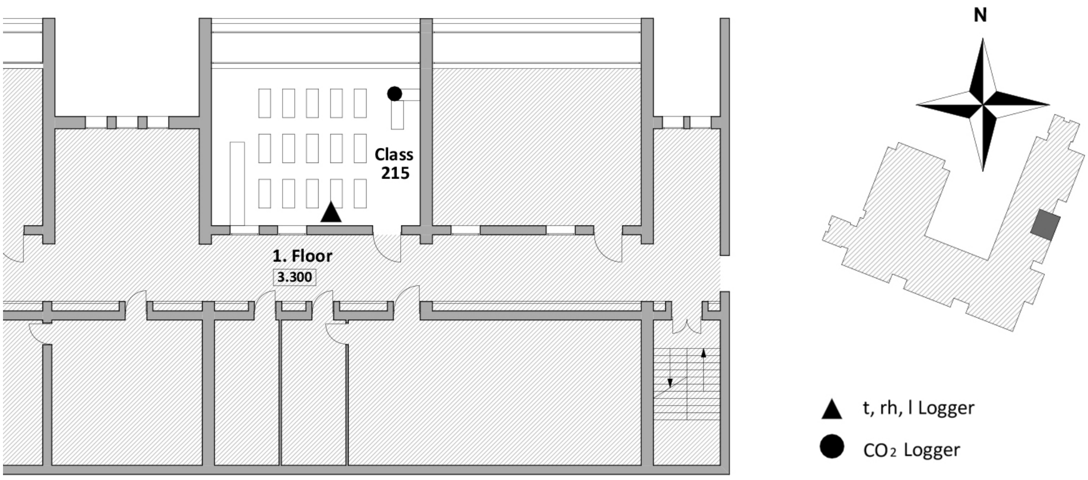

Figure 19: Locations of the sensors in Classroom 215 on the plan. Source: Own

- **Classroom 219**

Classroom 219 is located on the first floor in the south-east wing of the building; it has two outside walls and part of the ceiling that protrudes outwards. However, unlike Classroom 215, new PVC windows were installed here in 2012.

In this classroom, as presented in Figure 20, Figure 21 and Figure 22, the sensors were placed in the same positions, as in the previous classroom.

Figure 20: Location of the CO_2 sensor in Classroom 219. Source: Own

Figure 21: Location of the HOBO sensor in Classroom 219. Source: Own

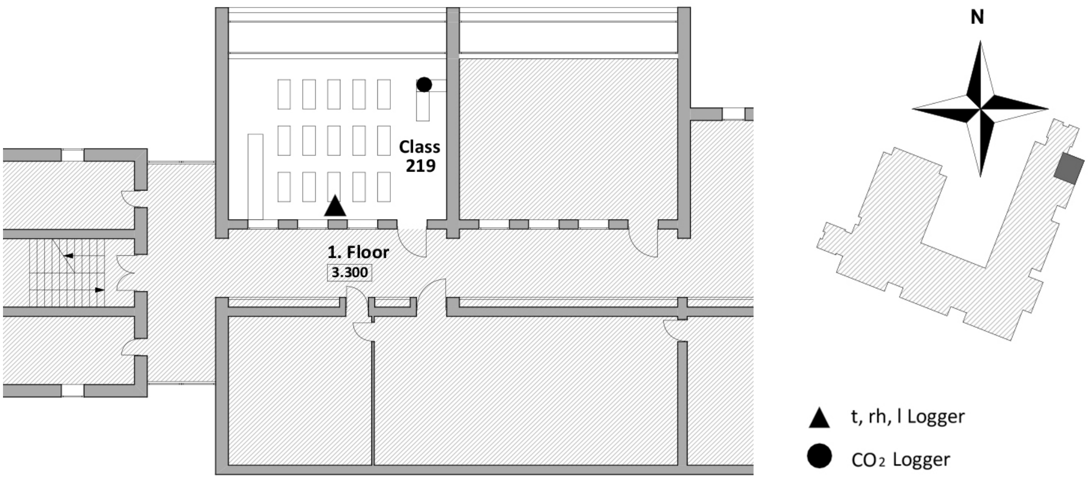

Figure 22: Locations of the sensors in Classroom 219 on the plan. Source: Own

- **Classroom 101**

Classroom 101 is located on the ground floor in the corner of the building and belongs to the Elementary school. This room is constantly described by teachers and students as the cold one. It has seven south-west facing timber-aluminium windows and two outside walls. Just one group of students stays in this classroom during the whole day.

As can be seen from Figure 23, Figure 24 and Figure 25, the temperature and relative humidity sensor was placed on the wall and the CO_2 sensor on the right-hand side of the teacher's table.

Figure 23: Location of the CO_2 sensor in Classroom 101. Source: Own

Figure 24: Location of the HOBO sensor in Classroom 101. Source: Own

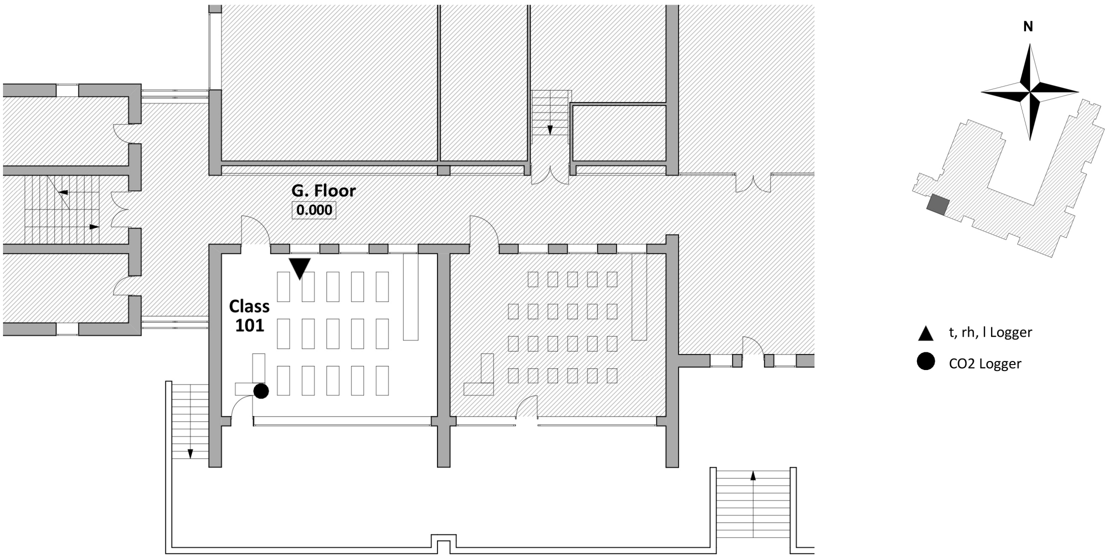

Figure 25: Locations of the sensors in Classroom 101 on the plan. Source: Own

- **Classroom 309**

Classroom 309 is located on the second floor in the south-west wing of the building and has an outwardly exposed part of the ceiling. Its size is 6 x 9m and it has seven timber-aluminium windows. This classroom belongs to the Elementary school, so just one group of students occupies it over the day. As presented in Figure 26 and Figure 27: the temperature, relative humidity and CO_2 sensors are positioned in the same places as in other classrooms. Figure 28 shows the locations of the sensors in Classroom 309 on the plan.

Figure 26: Location of the CO_2 sensor in Classroom 309. Source: Own

Figure 27: Location of the HOBO sensor in Classroom 309. Source: Own

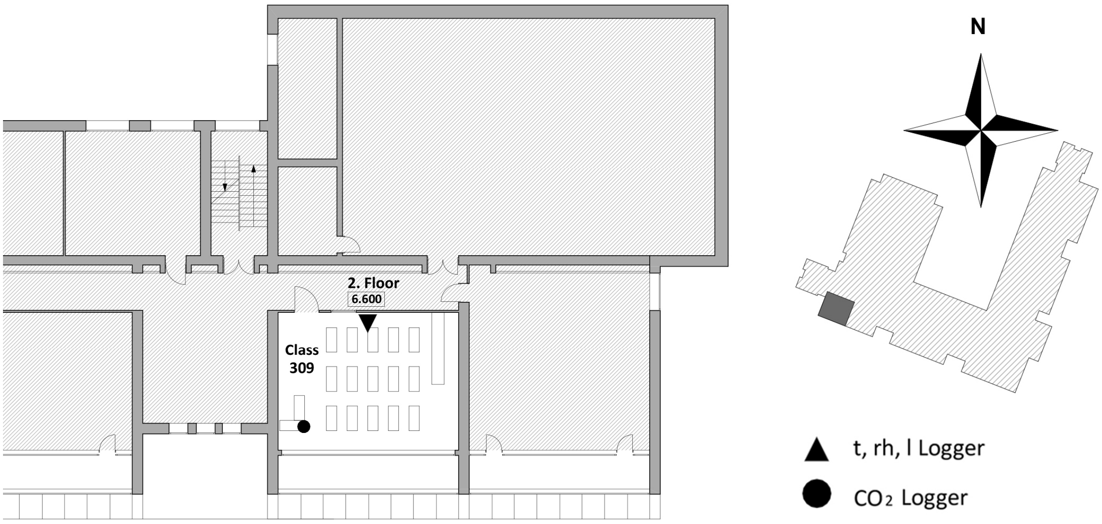

Figure 28: Locations of the sensors in Classroom 309 on the plan. Source: Own

- **Classroom 402**

Classroom 402 is an applied art classroom located on the third/last floor in the High school, so during the day this classroom is occupied by several groups of students. It has three timber-aluminium windows and two outside walls. As presented in Figure 29, like the previous classes, the temperature and relative humidity sensor was placed on the wall, but the CO_2 sensor (Figure 30) was positioned on the shelf behind the teacher's table. Figure 31 shows the location of the sensors in Classroom 402 on the plan.

Figure 29: Location of the HOBO sensor in Classroom 402. Source: Own

Figure 30: Location of the CO_2 sensor in Classroom 402. Source: Own

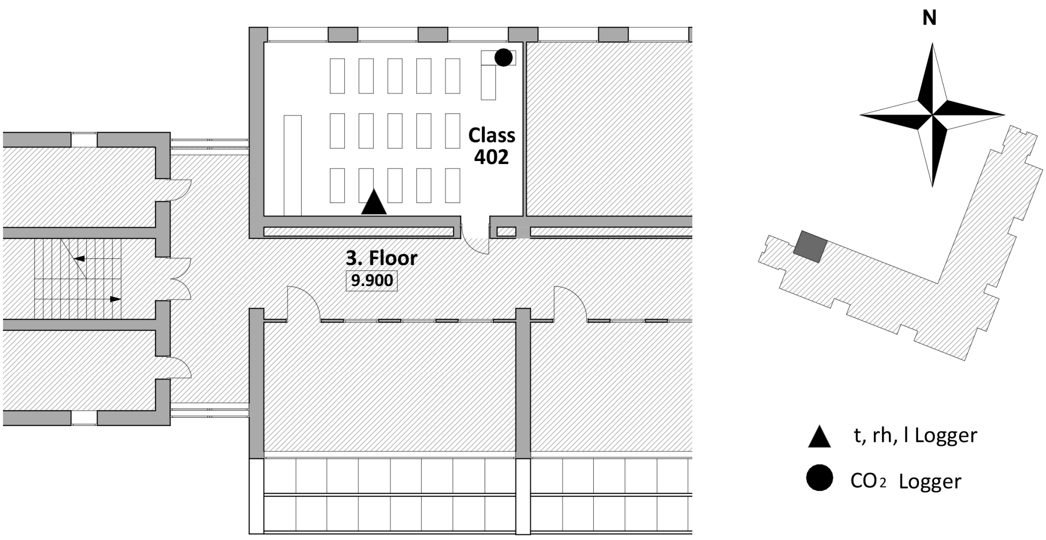

Figure 31: Locations of the sensors in Classroom 402 on the plan. Source: Own

3.4 Interviews

At the end of the measurement period (23.05.2014-29.05.2014), students in Classrooms: 215, 219 and 402 were surveyed, concerning their subjective indoor climate perception in the monitored classes. In the Elementary school classes 101 and 309, students were not interviewed due to their young age (6-9 years old). The age range of the students in the surveyed classrooms was between 11 and 16 years.

All the questions in the paper-based interviews (Appendix 8.6) were designed in a way so that students could understand and answer. In the classes 215, 219 and 402, at least two different groups of students that had lessons in these classes were interviewed. Overall, 165 students in the three monitored classrooms were interviewed.

3.5 Thermal performance simulation and evaluation of retrofitting scenarios

Building energy efficiency and thermal performance improvement measures have been made based on the simulation of the five monitored classrooms. In order to provide an accurate energy simulation, the following information was obtained: Kyiv weather data, building constructions and materials, information about the heating system and monitored classes occupancy schedule.

Base Case and three retrofit scenarios for the monitored classrooms have been simulated in the ArchiPHYSIK program. Base temperature in the classes was defined as 18°C. Air exchange rate was set as $1h^{-1}$. Obtained from the different scenarios, heating demands were compered. Later, based on the classrooms simulation results the Base Case and three retrofit scenarios were used to predict the influence for the whole school building.

3.5.1 Base Case models

For the simulation, the 3D models of the different classrooms were created. They contained the general geometry of the simulated classrooms and building components thickness for the Base Case simulation. The generated models from ArchiCAD were imported to Archiphysik and based on the school building documentation, typical construction materials were defined. The components for the Base Case, as well as, for the three retrofitting scenarios are displayed in the Appendix 8.7.

3.5.2 Retrofit scenarios

- **Base Case**

The Base Case simulation is based on the existing information about the current school building constructions. All the data for the simulation were provided by the school administration and included plans of the building and construction documentation. Table 13, summarizes U-values of the main constructional elements for the Base Case simulation.

Table 13: U-values of the main constructional elements for the Base Case simulation

	Ext. Wall 54 cm	Ext. Wall 28 cm	Floor	Ceiling	Windows	Roof over classroom	Roof
U-value [$W.m^{-2}.K^{-1}$]	1.37	2.17	0,486	0.882	2.5/1.25	0.707	0.278

- **Scenario 1**

In the first retrofit scenario, all the existing window systems in the school were changed with more energy efficient ones. Currently, all the exterior openings have a double-glazing timber-aluminium (U=2.5 [$W.m^{-2}.K^{-1}$]) or PVC (U=1.25 [$W.m^{-2}.K^{-1}$]) frames. The existing windows are proposed to replace with the more efficient UPVC windows with triple glazing (U=0.63 [$W.m^{-2}.K^{-1}$]). Table 14 summarizes U-values of the main constructional elements for the first scenario simulation.

Table 14: U-values of the main constructional elements for first scenario simulation

	Ext. Wall 54 cm	Ext. Wall 28 cm	Floor	Ceiling	**Windows**	Roof over classroom	Roof
U-value [$W.m^{-2}.K^{-1}$]	1.37	2,17	0.486	0.882	**0.63**	0.707	0.278

- **Scenario 2**

As it was mentioned before, the outside walls of the building are made of full brick and have no thermal insulation. In order to increase energy efficiency of the building, thermal insulation of external walls and exchanging of the old windows with energy efficient ones in the second scenario is proposed. Table 15 summarizes U-values of the main constructional elements for the second scenario simulation.

Table 15: U-values of the main constructional elements for second scenario simulation

	Ext. Wall 63 cm	**Ext. Wall 37 cm**	Floor	Ceiling	**Windows**	Roof over classroom	Roof
U-value [$W.m^{-2}.K^{-1}$]	**0.3**	**0.33**	0.486	0.882	**0.63**	0.707	0.278

- **Scenario 3**

The third scenario is the combination of the second scenario with the several new retrofits. The first measure is the thermal refurbishment of the existing roof (U=0.278 [$W.m^{-2}.K^{-1}$]) and roof over the classroom (U=0.707 [$W.m^{-2}.K^{-1}$]). The other measure applied within the third scenario is the thermal insulation of the basement slab (U=0.486 [$W.m^{-2}.K^{-1}$]). Table 16 summarizes U-values of the main constructional elements for the first scenario simulation.

Table 16: U-values of the main constructional elements for third scenario simulation

	Ext. Wall 63 cm	Ext. Wall 37 cm	Floor	Ceiling	Windows	Roof over classroom	Roof
U-value [W.m^{-2}.K^{-1}]	**0.3**	**0.33**	**0.168**	0.882	**0.63**	**0.253**	**0.1**

3.5.3 Weather Data

The Weather File for Kyiv was generated based on the data from the Meteonorm programme. For the file creation, the temperature, relative humidity and global radiation for period of 10 years, from 1991-2010 were used. Available Weather data from the Ukrainian Hydrometeorological Centre for the year 2014, couldn't be used for the simulation, due to the lack of detailed information for solar radiation. For validation of the generated Weather File a comparison with the provided data, the year 2014 was performed.

As can be seen in Figure 32, the biggest difference between the average outside temperature in 2014 and 1991-2010 can be seen in February and March. In the summer months, the temperature almost doesn't vary. In October and November, temperature slightly differs but not significantly.

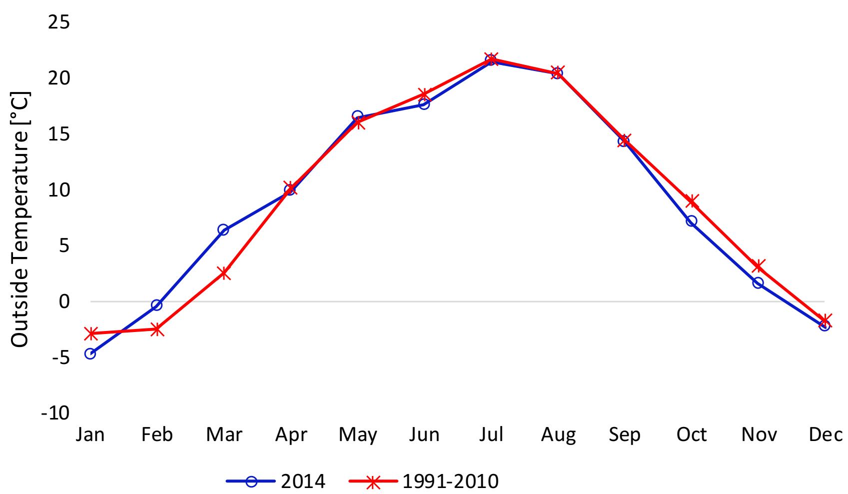

Figure 32: Comparison of the mean outside air temperature in the periods of 2014 and 1991-2010

From the Figure 33, we can see that the mean outside relative humidity has a bigger difference between the observed periods, especially in April and May. In these months, it varies by 10 - 15%.

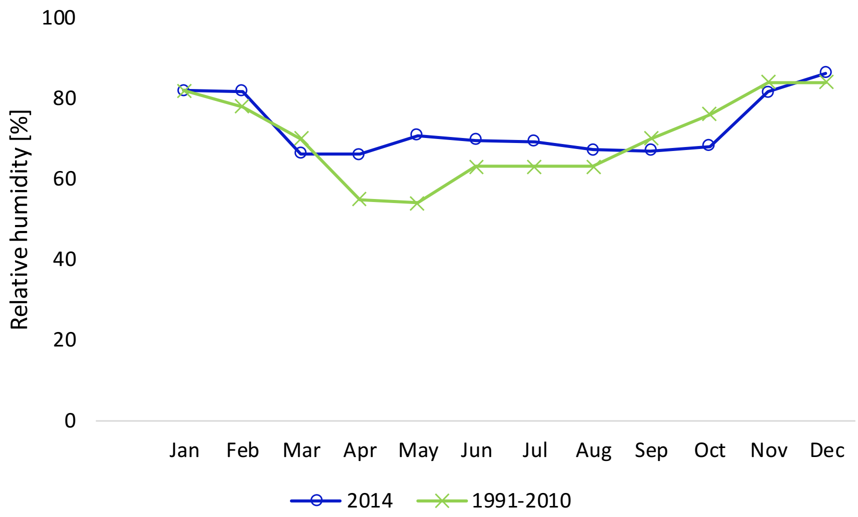

Figure 33: Comparison of the mean outside relative humidity in the periods of 2014 and 1991-2010

Comparison of the global horizontal radiation between the periods of 2014 and 1991-2010 (Figure 34), shows the small difference between the data between April and October. The largest deviation is 22%, observed in April.

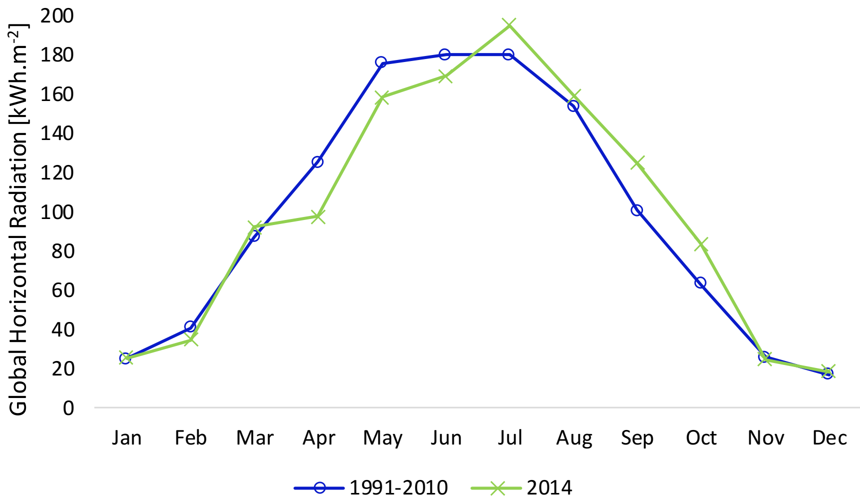

Figure 34: Comparison of the mean global horizontal radiation in the periods of 2014 and 1991-2010

4 RESULTS AND DISCUSSION

4.1 Overview

The Results and Discussion chapter is divided into five main sections. Firstly, the evaluation of the thermal comfort and indoor air quality in the monitored classrooms is presented. This includes data visualizations of temperature, humidity, and CO_2, concentration as well as Psychrometric charts and distributions of PMV and PPD. In the following section results from the subjective evaluation of the indoor climate are discussed. A comparison of the real measured energy consumption, result from the Base Case simulation and the Energy Certificate was performed and differences are considered. Finally, simulation results from three retrofit scenarios (1SC, 2SC, 3SC) are compared with the Base Case (BC) scenario to illustrate the potential of those options.

4.2 Thermal comfort

4.2.1 Temperature, Relative and Specific humidity

As presented in the Figure 35 the temperature in all five classrooms during the heated period mainly stays between 18 and 25 °C. Three classrooms (215, 219 and 309) didn't show significant difference in the temperature range. At the same time, Classrooms 101 and 402 demonstrate much lower temperature diapason. The lowest temperature can be observed in Classroom 402, showing that, for 90% of time, it stays in the range of 18 and 20 °C.

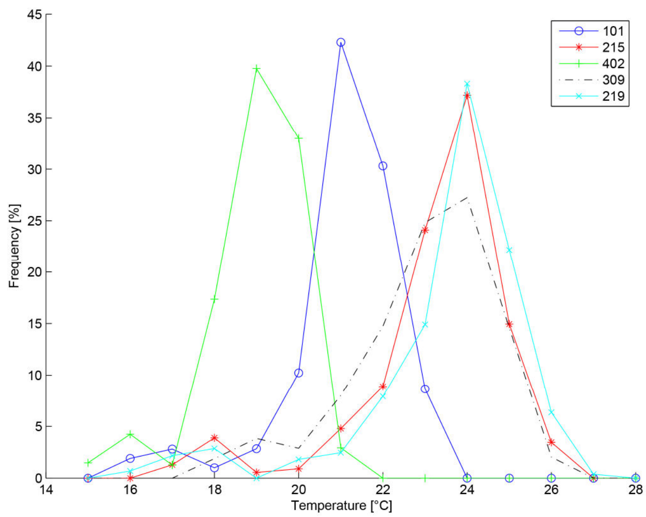

Figure 35: Frequency distribution of the temperature during occupancy hours in heated period

As shown in the Figure 36, temperature in Classrooms 215 and 219 during the unheated period is widely distributed and primarily lie between 21 and 25 °C in the thermal comfort zone. Classroom 309 shows the average result, with its temperature range lying between 19 and 23°C for more than 50% of time. Classrooms 101 and 402 show the lowest temperature range between 18 and 23 °C.

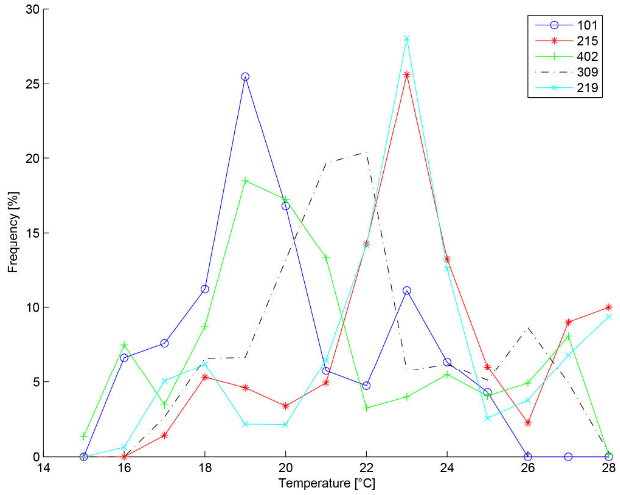

Figure 36: Frequency distribution of the temperature during occupancy hours in unheated period

April can be called - “transition month”, therefore it includes both heated and unheated periods. In this month, the coldest temperature can be observed in Classroom 402 (Figure 37). It has a temperature range of 15 to 21°C that lies under the temperature comfort zone (19-27°C).

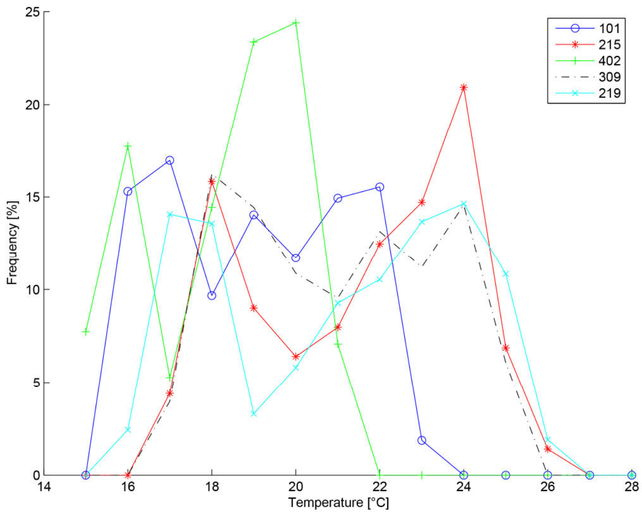

Figure 37: Frequency distribution of the temperature during occupancy hours in April

As presented in the Figure 38, the relative humidity in all classrooms during the heated period, except the Classroom 402, typically stays between 30 and 50 %. In Classroom 402 it lies between 40 and 60 %.

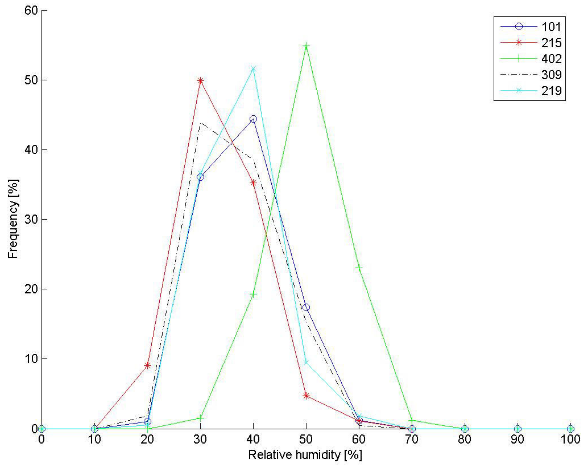

Figure 38: Frequency distribution of the relative humidity during occupancy hours in heated period

In the Figure 39, we can see that during the unheated period, the relative humidity in Classrooms 215, 219 and 309 is distributed between 40 and 60%. In Classes 402 and 101, relative humidity is higher and predominantly distributed between 50 and 70 %.

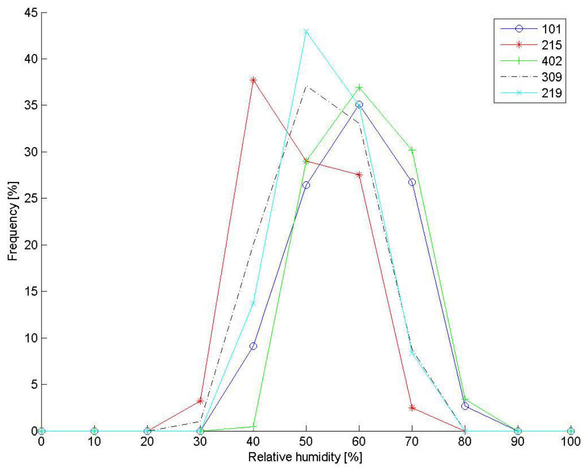

Figure 39: Frequency distribution of the relative humidity during occupancy hours in unheated period

In April, as shown in Figure 40, all five classrooms stay in the interval of 20-70%, as suggested by EN 15251:2007. Class 402 has a higher relative humidity compared to the rest of the classrooms.

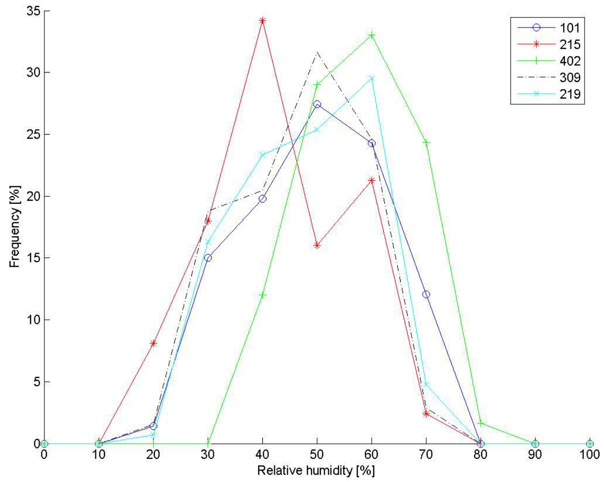

Figure 40: Frequency distribution of the relative humidity during occupancy hours in April

Figure 41 demonstrates that, over the heated period, all five classrooms have almost the same moisture content: approximately between 5 and 8 $g.kg^{-1}$. In Classrooms 101 and 402, the amount of moisture in the air is slightly higher than in the other classrooms.

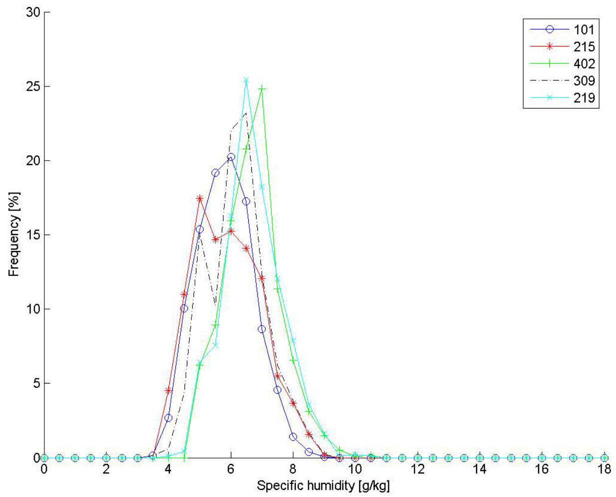

Figure 41: Frequency distribution of the specific humidity during occupancy hours in heated period

As can be seen from the Figure 42, over the unheated period, all the classrooms have similar distribution of the moisture in the air. The amount of vapour in the air lays between 6 and 12 $g.kg^{-1}$; that is higher than during the heated period.

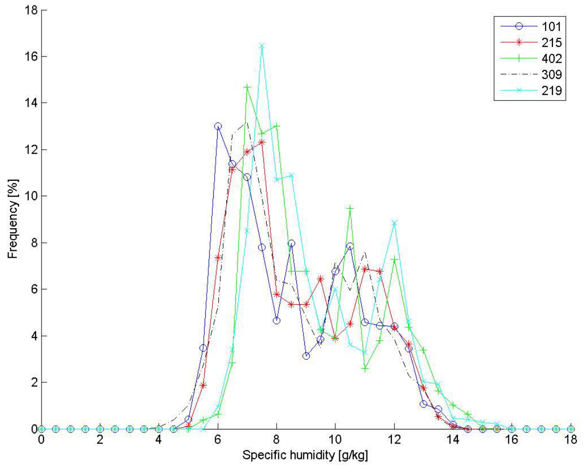

Figure 42: Frequency distribution of the specific humidity during occupancy hours in unheated period

In April (Figure 43), Classrooms 402 and 101 still demonstrate slightly higher specific humidity compared to the rest of the classes. All the classrooms have a moisture content that stays under the prescribed limit of 12 $g.kg^{-1}$.

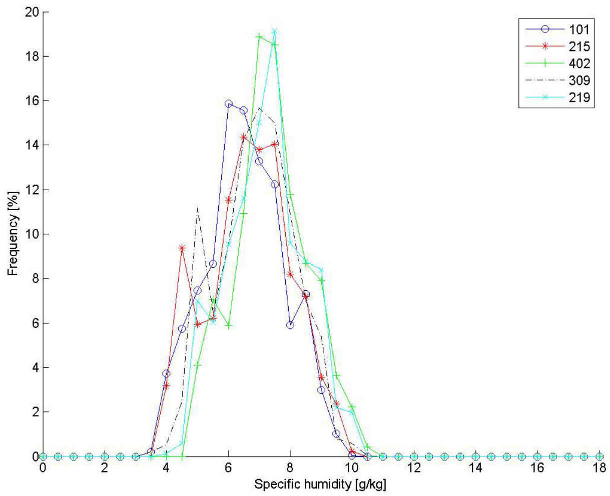

Figure 43: Frequency distribution of the specific humidity during occupancy hours in April

The rest of the temperature, relative and specific frequency distribution histograms can be observed in Appendix 8.8.

4.2.2 Psychrometric Charts

In this subsection, graphical representation of the relationship between air temperature and humidity, known as Psychrometric Chart is shown. Table 17 lists the data percentage of time that was outside the comfort zone in all classrooms during the heated, unheated periods and in the monitored spring months.

Table 17: Percentage of out-of-range data points [%]

Classroom	Heated period	Unheated period	Average	March	April	May	Average
101	6.19	47.84	30.11	0	51.02	31.7	41.36
215	5.74	25.12	15.43	0	29.01	19.38	24.20
219	5.71	25.98	15.85	0	33.97	15.93	25.00
309	3.98	17.92	10.95	0	31.22	4.69	18.00
402	39.57	47.46	43.52	52.34	54.84	31.33	46.17

Comparing the results from all five classrooms over the heated period, it can be seen that Classroom 402 has the biggest percentage of values outside the comfort zone. Among the others, Classroom 309 performs the best, with just 3.98% of the results outside the thermal comfort zone.

Over the unheated period, Classrooms 402 and 101 have the biggest percent of values outside of the comfort zone. The best performance is seen again in Classroom 309. It has just 18 % of values outside of the thermal comfort zone.

In March, Classroom 402 has a 52 % of data points lying outside of the comfort zone. The rest of the classrooms display values that lay in the comfort zone over the considered period. In April, the best values belong to Classroom 215 and the worst to Classroom 101. In May, the best performance is shown in Classroom 309, which has 4.69% of data points laying outside the comfort zone. Classrooms 101 and 402, as usual, have the biggest amount of data points outside the comfort zone, with values of 31.7% and 31.33% respectively.

As can be seen from the Figure 44, over the whole measurement period, the maximum temperature can be found in Classroom 215, with a value of 29.52°C. The lowest temperature over the measurement period is in Classroom 101 (Figure 45) and it is equal to 15.68°C. The rest of Psychrometric Chart can be seen in (Appendix 8.9).

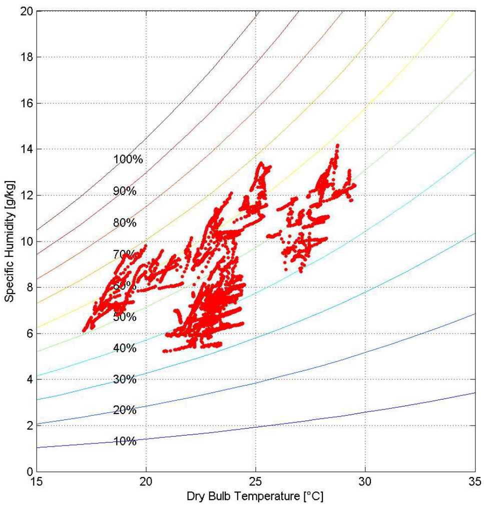

Figure 44: Psychometric chart of Classroom 215 during occupancy hours in unheated period

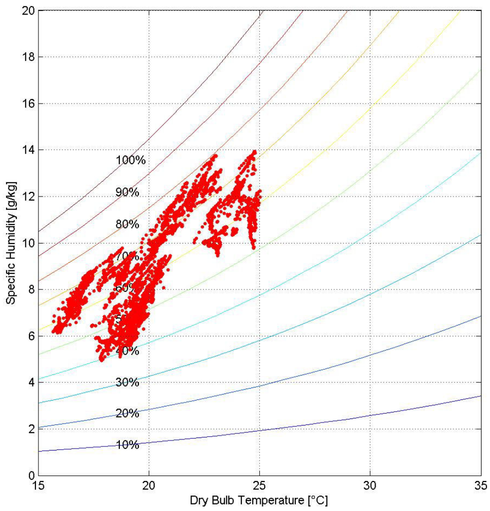

Figure 45: Psychometric chart of Classroom 101 during occupancy hours in unheated period

4.2.3 PMV and PPD

For the PMV and PPD evaluation in the five monitored classes the values listed in Table 18, were assumed.

Table 18: Values for the PMV and PPD calculation

Clo	Met	Air velocity [m/s]	External work
1	1.2	0.15	0

Figure 46 reveals that nearly all the measured data points for Classes 215, 219 and 309 over the heating period lie within the comfortable values -0.5 and 0.5. Class 101 has a PMV range between -1 and 0. The lowest values occur in Class 402, where students feel rather cool.

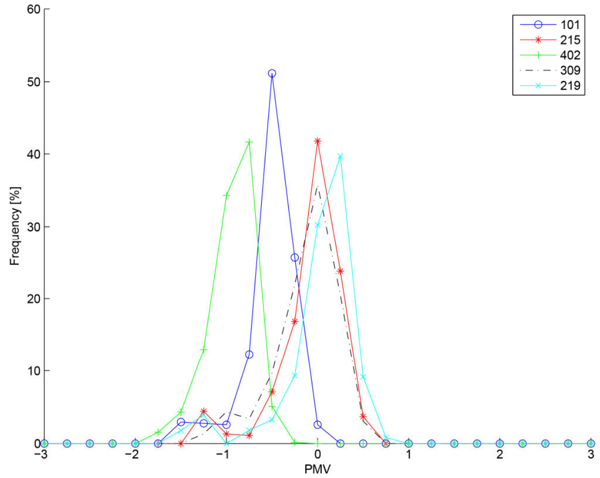

Figure 46: Frequency distribution of the PMVs during occupancy hours in heated period

As presented in Figure 47, over the unheated period, PMV in Classes 215,219 and 309 lies most of the time inside the comfortable area between -0.5 and 0.5. Class 101 and 402 have the PMV range between -1.5 and 0, where the temperature is defined as slightly cool.

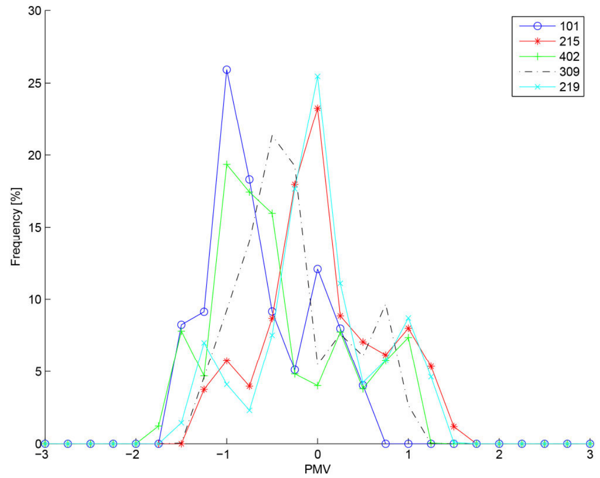

Figure 47: Frequency distribution of the PMVs during occupancy hours in unheated period

In April (Figure 48), PMV in Classrooms 215, 219 and 309 has a range between -1.5 and 0.5. The lowest PMV values occur in Classes 402 and 101. Their values are located on the sensation scale between - 1.5 and - 0.5.

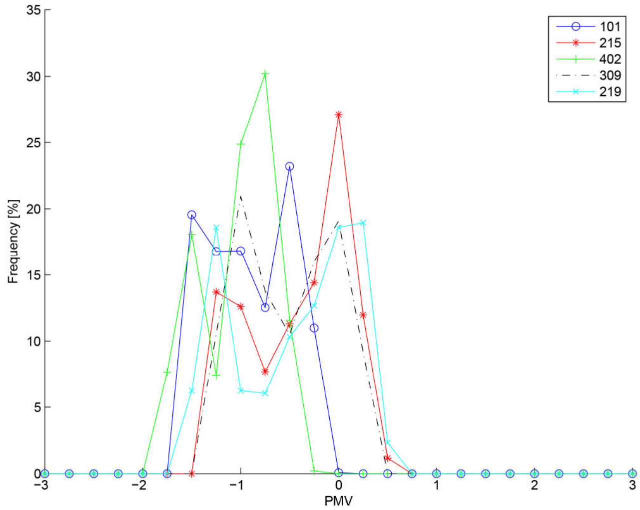

Figure 48: Frequency distribution of the PMVs during occupancy hours in April

In the Appendix 8.10, frequency distributions of the PMVs in the classrooms during the May and March are presented.

Table 19 presents the results of PPD calculated averaged values in all five monitored classrooms during the heated and unheated period and every monitored month separately.

Table 19: Predicted Percentage of Dissatisfied PPD [%]

Classroom	Heated period	Unheated period	Average	March	April	May	Average
215	9.56	14.2	11.88	9.56	17.49	11.65	12.90
219	9.97	14.94	12.46	9.97	20.23	11.16	13.79
101	16.63	22.70	19.66	16.63	30.47	15.88	20.99
309	9.82	14.96	12.39	9.82	18.28	11.42	13.18
402	28.82	21.98	25.40	28.82	34.83	15.47	16.37

As can be seen from this section, thermal comfort in the five monitored classrooms vary and depends on the floor location. Classrooms 101 and 402 which are located on the ground and top floors, perform less good regarding thermal comfort than the rest of the classrooms.

Classrooms 215, 219 and 309 have a good thermal comfort, with PMV values for the heated and unheated periods, within the comfort zone. The temperature in these three classrooms over the whole measurement period can be evaluated as neutral. Classrooms 402 and 101 are displaying the lowest PMVs. Air temperature in these classes was rather cool. Over the heated period, Classroom 402 has the lowest temperature compared to rest of the classrooms. This could be because of insufficient heating, north-west orientation and heat loss through the roof. During the unheated period, the lowest temperature was observed in Classroom 101. This can be explained by the high thermal storage mass of the basement which decreases air temperature in the class. In April, air temperature dropped in every classroom, which caused by the transition period between the heated and unheated seasons. In all classrooms over the heating period, besides Class 402, relative humidity is quite low (~35%). In the unheated period, all the classrooms demonstrate higher relative humidity and was in the thermal comfort range of 20-70%. Specific humidity in the monitored classrooms over the whole measurement period shows similar behavior and is less than the recommended minimum of $12 g.kg^{-1}$. In April, the moisture content during the heated and unheated periods in Classes 402 and 101 was slightly higher than in the rest of the classes. The small differences of specific humidity in all five classrooms shows that the higher relative humidity in Classroom 402 was caused by the lower temperature.

4.3 Indoor Air Quality

Data of indoor air CO_2 concentration was measured in five naturally ventilated classrooms. Figure 49, shows the cumulative distribution of the data for the heated period. It illustrates that CO_2 concentration in 80% below 1000 ppm. Only in Classroom 402, the carbon dioxide concentration exceeds 1000 ppm in 50% of time.

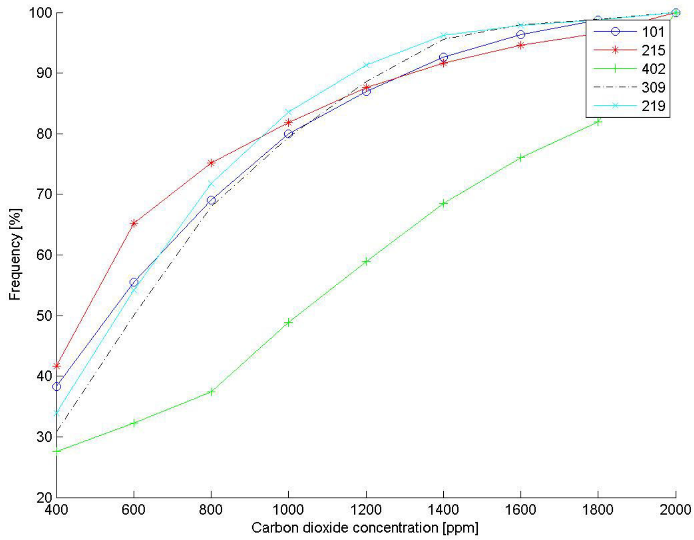

Figure 49: Cumulative distribution of the CO2 concentration during occupancy hours in heated period

As presented in Figure 50, over the unheated period, CO_2 concentration in Classes 215, 219 and 309 for the large number of hours under 1000 ppm. Classes 101 and 402 show lowest performance. In Class 402, carbon dioxide concentration stays over 1000 ppm for 40% of time. In Class 101, it exceeds the Pettenkoffer value in 45% of the time.

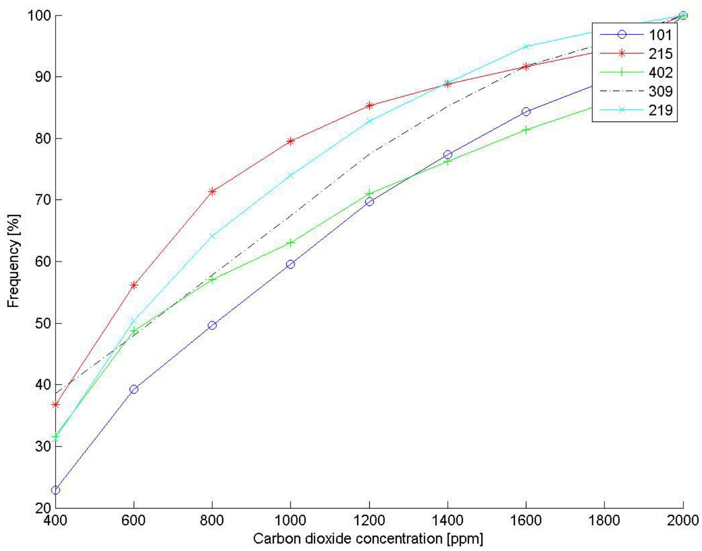

Figure 50: Cumulative distribution of the CO_2 concentration during occupancy hours in unheated period

In April, (Figure 51) the CO_2 concentration in Classroom 402 was significantly higher than in the other classrooms and for 68% of the time, exceeds the Pettenkoffer value. Classroom 101 showed better results; with CO_2 concentration below 1000 ppm in 55% of the time. The rest of the classrooms show carbon dioxide concentrations that significantly remain under the Pettenkofer threshold.

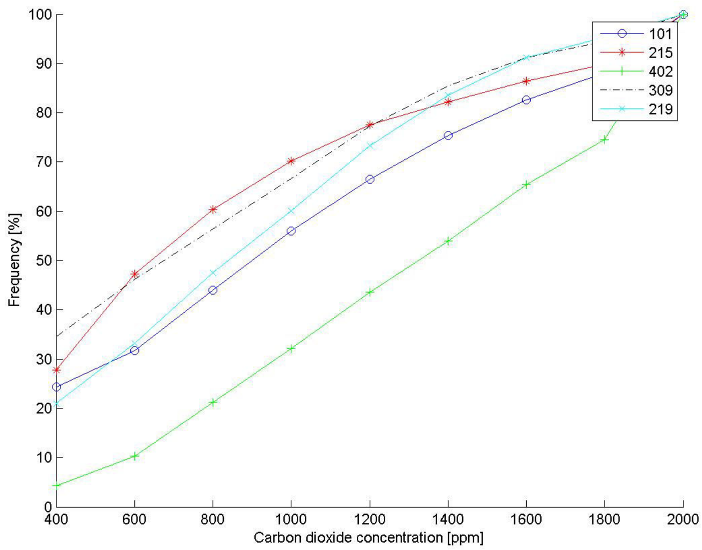

Figure 51: Cumulative distribution of the CO_2 concentration during occupancy hours in April

Appendix 8.11, includes cumulative frequency distributions of the CO_2 in the classrooms during May and March.

As can be seen from the figures over the heated and unheated periods, most of the classrooms showed good air quality. Most of the time, CO_2 stays under the Pattenkofer value of 1000 ppm. Over the heated period, Classrooms 101, 309, 215 and 219 show good results with a low CO_2 concentration, more than 80% of time. In April, CO_2 increases in all classrooms. The same situation is apparent over the unheated period in all classrooms, besides 402. This CO_2 growth in the unheated period could be explained by the lower air exchange due to the small difference between inside and outside temperature. Significant growth of the carbon dioxide concentration in Class 101 over the unheated period was the result of the poor and insufficient class ventilation.

Over the whole measurement period, Classroom 402 demonstrates the worst air quality. As it was concluded in the previous section, Class 402 has insufficient ventilation and a constant occupancy.

4.4 Subjective Evaluation of the indoor climate

The results of the students' interviews, provide a subjective assessment of the thermal comfort and indoor air quality in the three monitored classrooms. Table 20 gives an overview about the number of students that were interviewed at the end of the spring. All interviewed students over the whole measurement period constantly had the lectures in the selected classrooms.

Table 20: Amount of the students interviewed in the monitored classrooms

Classroom	**215**	**219**	**101**	**309**	**402**
Classroom	52	44	0	0	69
Total			165		

- How do you assess classroom air temperature?

The Figure 52 displays that in Classrooms 215 and 219, the students defined the air temperature halfway as neutral or slightly warm. In Classroom 402, 64% of children determined the air temperature as neutral.

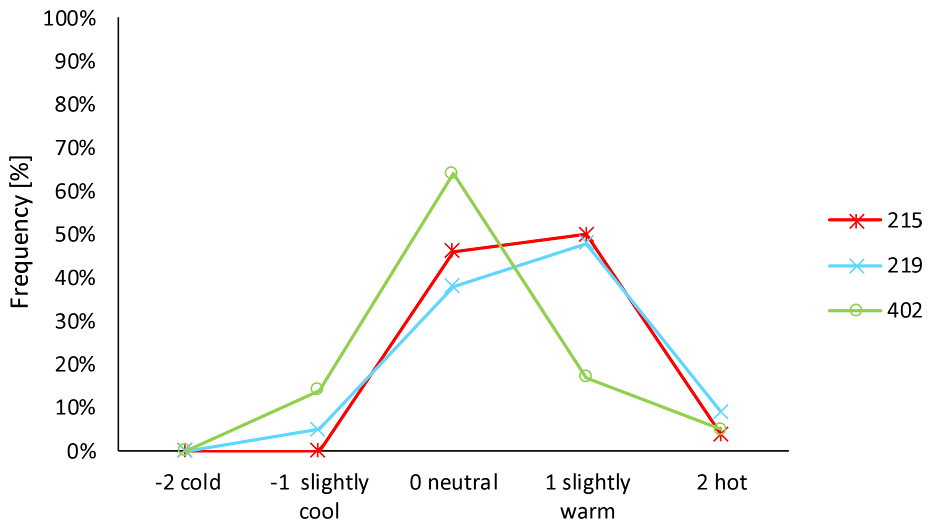

Figure 52: Temperature in the classrooms

- How do you find air quality in this classroom?

The satisfaction with the classrooms' air quality is displayed below in Figure 53. In Classes 215 and 219, students defined the air quality as normal and good. In Classroom 402, most of the students answered that air quality is bad and normal.

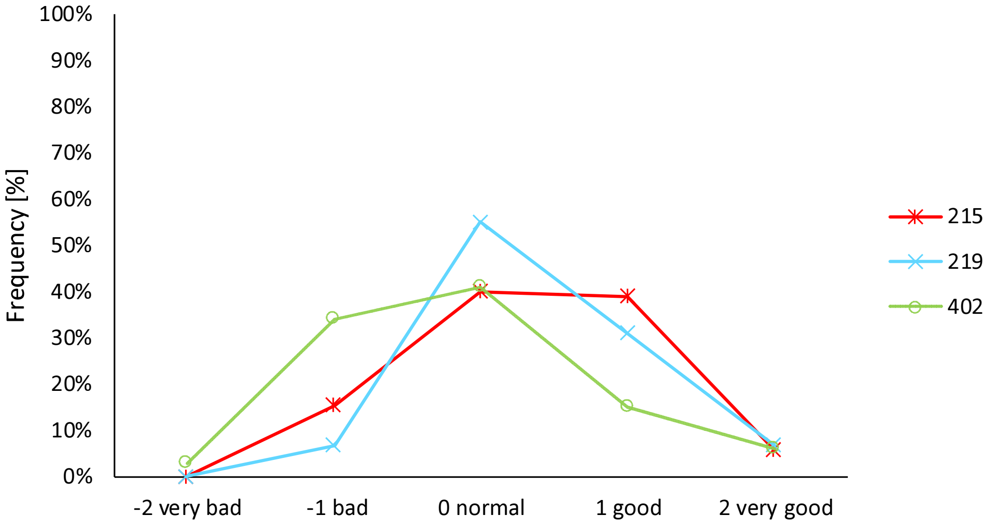

Figure 53: Satisfaction with air quality in the classrooms

- Are you satisfied with the classroom's ventilation possibilities?

Figure 54 presents satisfaction with the classrooms' ventilation possibilities. In Classroom 215 and 219, around 50% of pupils defined the ventilation possibilities as neutral. At the same time, in Classroom 402 the ventilation possibility was determined as less than satisfactory by 45% of students.

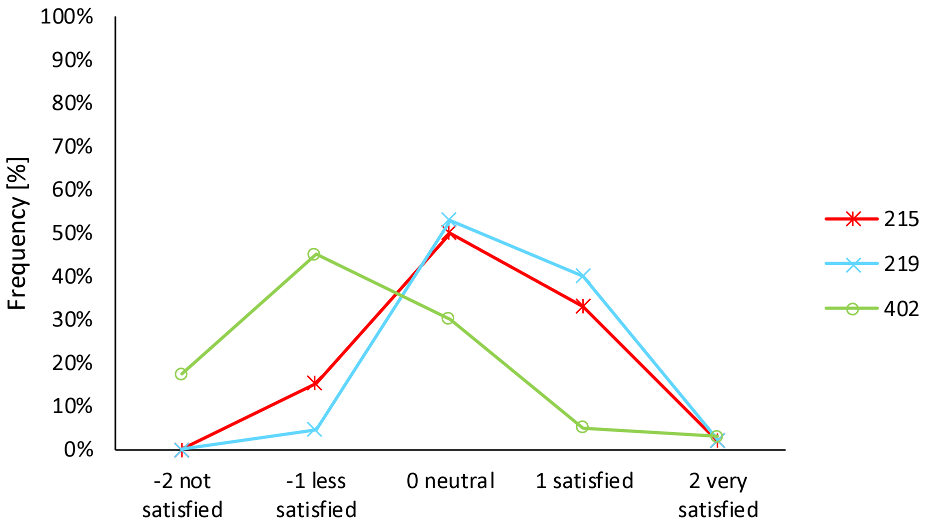

Figure 54: Satisfaction with the classroom's ventilation

- Are you satisfied with the heating system in the classroom?

As can be seen in Figure 55, the satisfaction with the classroom heating system in Class 402 is defined as less satisfactory by 48% of students. Class 219 has 49% and 44% of students that are "okay" and satisfied with the heating system. Classroom 215 shows 27% of students are less than satisfied and 70% of students that evaluated the heating system, as ok and satisfactory.

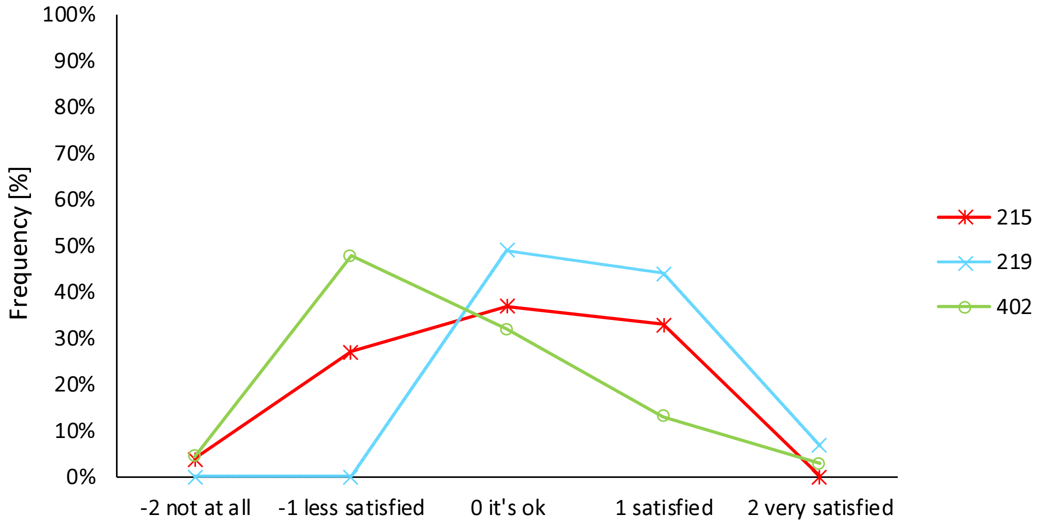

Figure 55: Satisfaction with the classroom's heating system

- Are you feeling tired?

Figure 56 displays that 42% of the pupils feel tiredness in Class 402. In Classes 215 and 219, students mostly don't have feeling of tiredness.

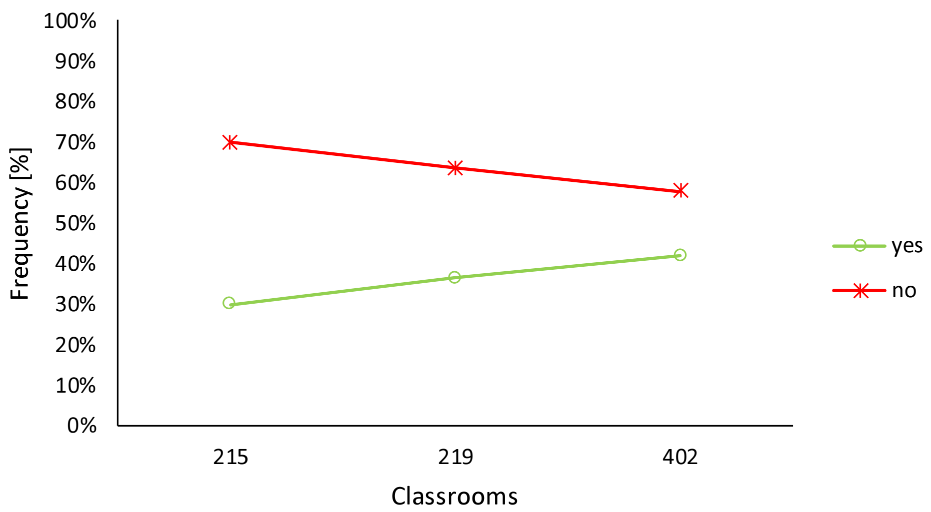

Figure 56: Level of expressed tiredness in the monitored classrooms

In the questionnaire, it can be observed that temperature in Classroom 402 is mostly defined as neutral. At the same time, objective temperature estimation defines 402 as a slightly cool class. In the interview, just 17% of students gave “slightly cool” as an answer. In the objective and subjective evaluation in Classes 215 and 219, air temperature is mostly defined as neutral or slightly warm.

Evaluation of the heating system in Classroom 402 shows that children were mostly less satisfied with it. This answer confirms the results from the objective evaluation with low temperature in the heated and unheated period. In the Classroom 215, around 30% of students expressed their dissatisfaction with the classroom heating system, despite that objective evaluation shows comfortable air temperature over the whole measurement period. Classroom 219, performs satisfaction with the heating system in the subjective evaluation and shows similar result to the objective evaluation.

Subjective assessment of the CO_2 concentration in Classrooms 402 looks mostly similar to the measurement results. Students defined the air quality in Class 402 mostly as normal or bad. Ventilation possibility in this classroom was defined as less than satisfactory or not satisfactory. Finally, 58% of students expressed their filing of tiredness in this class.

Air quality in Classrooms 215 and 219 was defined as normal and good. The biggest number of students answered that they have no feeling of tiredness in this classes. Results obtained from these questions are similar to the CO_2 concentration histograms and show that Classes 215 and 219 have good air quality.

Comparing objective and subjective evaluation of thermal comfort and indoor air quality, it can be seen that results correlate with each other rather well.

4.5 Energy Consumption

In order to analyses how good, the existing Energy Certificate reflects the real energy consumption of the school building, the values from the Energy Certificate and simulation values were compared. This section is divided into four parts. The first one makes a comparison of the Heating Degree Days displayed in the Energy Certificate with the Heating Degree Days' value for the monitored year 2014. The second, shows the difference between transmittance coefficients in the Energy Certificate and thermal transmittance coefficients calculated for the simulation. The third part presents electric energy consumption of the school between 2012-2016. The last part represents comparison of the real and simulated school heating energy consumption with the values displayed in Energy Certificate.

4.5.1 Heating Degree Days comparison

In the Energy Certificate, HDD value is calculated with the method that uses constant outside air temperature and duration of the heating period. For the calculation of the Heating Degree Days in the monitored year 2014, detailed outdoor temperature records, such as half-hourly readings, were used.

From Table 21, it can be observed that the difference between the HDD value in the Energy Certificate and monitored year 2014 doesn't differentiate significantly and has a deviation of less than 3%.

Table 21: Comparison of the HDD values between Energy Certificate and monitored year 2014

	Energy Certificate	**2014**
HDD [°C.d^{-1}]	3185.6	3097.2

4.5.2 Thermal transmittance comparison

The Energy Certificate of the building presents five thermal resistance values for the walls, windows / balcony doors, entrance doors, roof, attic slabs (cold attics) and slabs above unheated basements or underground. Unlike to the thermal simulation which contains U-Value for every single construction, the Energy Certificate includes only this basic values about the building construction. In order to provide accurate comparison of the thermal values, the given thermal resistance for all parts of the building's construction for simulation were defined properly based on the avaliable data from plans and descriptions of the building.

There are three types of outside walls' thickness in the school building: 51, 38 and 25cm. The school building documentation defines that 80% of the walls have a thickness of 51cm, 15% are 38cm thick and 10% are 25cm. As mentioned in the method section, there are two types of windows in the school: with timber-aluminium or PVC frames. The ratio of the timber-aluminium windows to PVC windows in the building is 95% to 5% respectively.

As shown in the Table 22, the U-values for the walls and window/balcony doors from the Energy Certificate and Energy Simulation do not vary significantly. Values have a deviation of 12.5 % for walls and 7.3 % for windows/balcony doors. U-value of the slabs above unheated basements in the Energy Certificate and simulation have a deviation of 17.3%. There is a signifficant difference of 68.61 % between the Energy Certificate and simulation for the roof values. This difference may appear, due to the use of different roof constructions in the Energy Certificate and the simulation.

Table 22: Comparison of the thermal values in Energy Certificate with the simulation values

Thermal transmittance, U [$W.m^{-2}.K^{-1}$]	**Energy Certificate**	**Simulation**
walls	1.25	1.40
windows / balcony doors	2.63	2.44
roof, attic slabs (cold attics)	0.84	0.28
slabs above unheated basements or underground	0.40	0.49

4.5.3 Electricity consumption

School annual electricity consumption was provided with measured monthly values. Figure 57 displays monthly electricity consumption from 2012 till 2016, including the monitored year 2014. In this figure, it can be observed that over the winter period, electricity consumption is significant higher. Over the summer period, the school consumes less electricity due to the brighter and warmer days and due to the fact, that from the beginning of June till the end of August, students have a summer holidays.

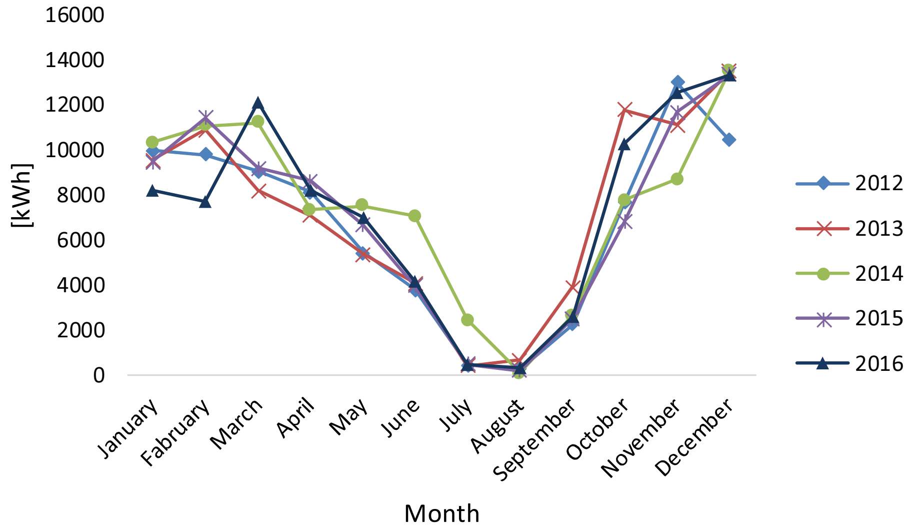

Figure 57: Monthly electricity energy consumption

In the monitored year 2014, electricity usage mostly shows a similar tendency to the rest of the observed years. However, it has a significant energy growth from May till July. The cause of this jump is the repair work of the building facade conducted during the school summer vacation period from May to July 2014.

4.5.4 Heating Demand

In the Figure 58, the actual monthly heat energy consumption from 2012 until 2016 is presented. As can be observed from this figure, in the years 2012 and 2013 the highest annual heating demands of 94,6 kWh.m^{-2}and 115,79 kWh.m^{-2} were recorded. Over the next three years the heat energy consumption decreased significantly. This reduction is observed especially in autumn and partially in the winter months in 2014 and 2015. In the year 2016, the heating energy consumption was low during the whole heating period, except in November and December. This fact couldn't be explained but may be caused by wrong data records. The lowest annual heat energy consumption is 72.25 kWh.m^{-2}, seen in 2014.

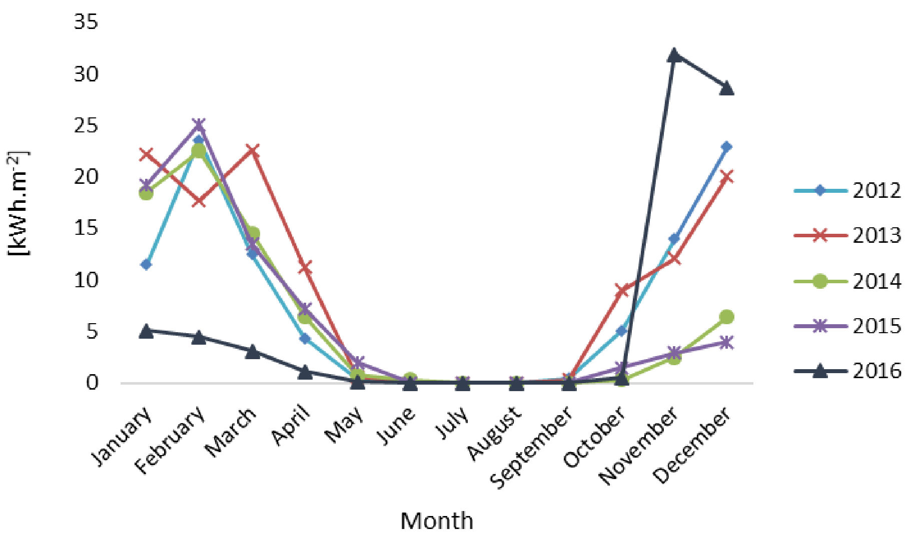

Figure 58: Monthly heat energy consumption in 2012-2016

Table 23 demonstrates the annual heat energy consumption over the heating period 2012 to 2016.

Table 23: Annual heat energy consumption [kWh.m^{-2}] over the heating period 2012-2016

	2012	2013	2014	2015	2016
Heating Demand [kWh.m^{-2}]	94.66	115.79	72.25	75.38	74.93

In the official Energy Certificate issued for School No 317, that design value for the annual specific heat loss is stated as 178.4 kWh.m^{-2}; that is significantly higher than the normative value of 131.66 kWh.m^{-2}. Due to the ДБН В.2.6-31:2006, design and actual values must be lower or equal to the normative one. Table 24 shows that in the monitored year 2014, real annual school heat usage is 72.25 kWh.m^{-2}; that is significantly lower than the maximum normative value, prescribed for school buildings in Ukrainian building standards. Similar to that, the design specific heat loss from the Energy Certificate with 178.4 kWh.m^{-2}, is 60% higher than the actual consumption of 72.25 kWh.m^{-2} in 2014 and any other year from 2012 to 2016. According to the Base Case simulation, school energy demand for heating is 133.46 kWh.m^{-2}, which is much closer to the design value in the Energy Certificate but is 45% higher than the real consumption recorded in 2014.

Table 24: Comparison of the annual heating demand [kWh.m^{-2}] between the monitored year 2014, simulation and Energy Certificate

	2014 (actual)	**Energy Certificate (design)**	**Simulation (simulated)**
Heating Demand [kWh.m^{-2}]	72.25	178.4	133.46

Discrepancy of 25 % between the designed and simulated school heating demand in 2014 can be caused by two factors. The first factor is the usage of two different roof U-values for the simulation and Energy Certificate. As mentioned before, in the Energy Certificate the higher U-value of 0.84 W.m^{-2}.K^{-1} and in the simulation much lower U-value of 0.28 W.m^{-2}.K^{-1} for the calculation were applied. The second factor is the different approaches for the annual heating demand calculation. In the simulation, the heat energy consumption was calculated for the 5 monitored classrooms and used to predict the consumption for the whole school. In the real Energy Certificate, the heat energy consumption was calculated for the whole building.

The difference between the actual, simulated and designed annual heating demand is notably big. The real heat energy consumptions, of the years 2012-2016 are too low and cannot be considered as appropriate for the building due to the fact that since its construction in 1995 it did not have any significant thermal refurbishment. There is no clear explanation of such low actual heating demands, but as assumptions can be called the defect functioning of the heat energy meter, misalignment of the hydraulic mode and incorrect manual intervention to the heating system.

4.6 Retrofit Scenarios evaluation

This section presents the classrooms' annual heating demand simulation results for the Base Case and three thermal refurbishment scenarios for the monitored year 2014. This chapter also shows the annual heating demand for the entire school building, which was defined from the simulation results of the five monitored classrooms.

Base Case (BC) shows the current state of the building and presents the actual thermal quality of the building envelope. Scenario 1 (1SC) represents the first variant of the building thermal refurbishment: exchanging of the existing external doors and windows to the new energy efficient one. The Second Scenario (2SC) represents thermal improvement of the building facade by replacement of the old window systems together with an insulation of the outer walls. Scenario number three (3SC) combines the 2SC with other retrofit measures, such as improved insulation of the roof and the slab between the basement and ground floor.

As can be seen from the Figure 59, in every classroom, all three retrofit scenarios demonstrate significant heating demand reductions compared to the Base Case.

The highest energy consumption can be observed in Classrooms 101 and 402. Despite the fact that Classroom 101 has the south-west orientation, highest energy usage can be explained by the fact that Classroom 101 is on the ground floor with high loses to the unheated basement. Also, this class has old windows, non-insulated outer walls and is positioned on the corner of the building. In comparison with BC, 1SC reduces the energy consumption by 29 % and 2SC by 51%. The best result is achieved by 3SC, where energy consumption can be reduced by the 65%.

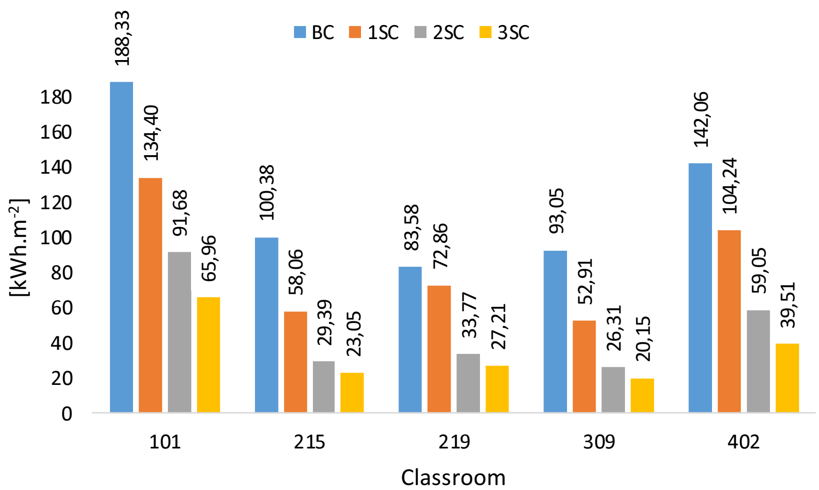

Figure 59: Annual heating demand [kWh.m^{-2}] of the monitored classrooms

Classroom 402 has a north-east orientation, located on the top floor in the building's corner with a flat roof above it. 1SC and 2SC can decrease the classroom heating demand by 27% and 58%. The third scenario results in a 72% energy reduction.

Classes 215 and 219 have the same orientation and floor location. Case 1SC significantly reduces the energy usage by 42% for Classroom 215. Class 219, shows just 13% for this case. This could be explained by the fact that in the Base Case, Class 215 has old and inefficient windows. Class 219 shows less reduction after the window replacements, as the PVC windows of the Base Case are more effective than the old timber-aluminium windows of Class 215. In the 2SC, Classroom 219 has an energy reduction of 60% and of 70% for Class 215. Among the other classrooms, Room 309 has the highest reduction result of 78% in case 3SC. The first scenario performs very good for Classroom 215.

Figure 60, shows that case 1SC reduces the energy demand compared to the BC by 34%. 2SC shows better results and reduces heating energy consumption by 60%. Scenario 3 presents the biggest energy reduction of 71 %, compared to the BC.

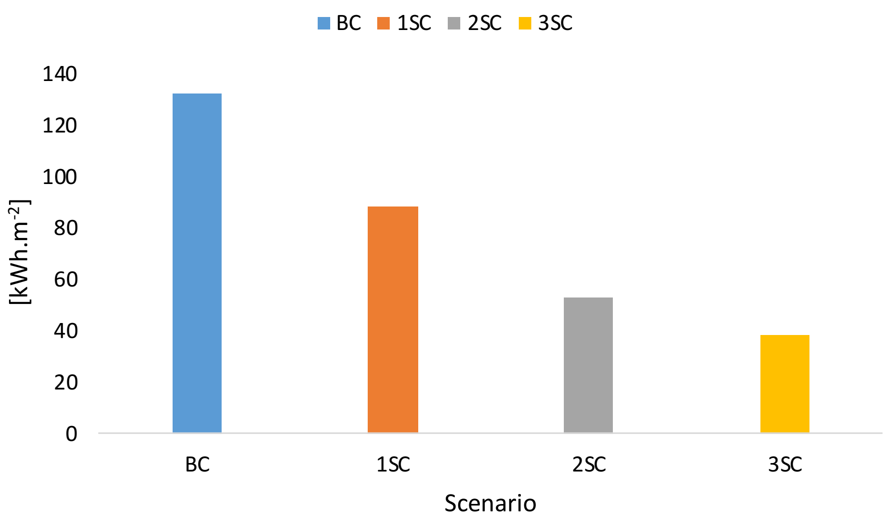

Figure 60: Annual heating demand [kWh.m^{-2}] of the School 317

Table 25, shows the comparison of the three thermal refurbishment scenarios with the Base Case according to the kWh.m^{-2} of heating demand.

Table 25: School Heating demand [kWh.m^{-2}] for the base and three thermal refurbishment scenarios.

	BC	1SC	2SC	3SC
Heating Demand [kWh.m^{-2}]	133.46	88.41	52.77	38.15

5 CONCLUSION

The thermal comfort in the school building varies significantly depending on the classroom location within the school. Classrooms which are not located on the last or ground floor, achieve better thermal comfort than the rest. The CO_2 concentration mostly lies within acceptable limits, but classrooms with constant occupancy are showing notably higher values, which indicates the need for additional ventilation or better window operation during lecture brakes. Over the heated period, relative humidity is mostly low but increases significantly over the unheated period. Specific humidity over the whole measurement period shows similar behaviour in all five classes. In Classes 101 and 402 specific humidity is slightly higher than in the rest and could be explained by the low indoor temperatures and reduced natural ventilation.

Student's subjective evaluation of the thermal comfort and indoor air quality in the school essentially confirmed the conclusions obtained from the objective evaluation.

Annual energy consumption in the monitored year 2014 and the other years was significantly lower than the design value of the Energy Certificate as well as the simulated value. They are 60 % and respectively 45% higher than the values recorded for 2014. The difference between the annual specific heat loss in the Energy Certificate and simulation is significantly lower and differs by 25 %. This difference can be because of the higher roof U-value, used for the calculations in the Energy Certificate than in the simulation. The analyzed, recorded data shows that after the year 2013 the school heat energy consumption reduced and behaved itself differently, especially in the year 2016. There is no clear explanation of this reduced energy consumption. The recorded low values can be caused by a malfunctioning heat meter or incorrect installation within the IHS or wrong settings after the latest adaptations.

Thermal comfort improvement and heating energy demand reduction in the school can be achieved by the replacement of the old transparent building elements with more energy efficient ones and an insulation of the facade. Thermal enhancement of the building facade, together with the replacement of the transparent elements can reduce the school energy consumption by 60%. A combination with additional measures, such as the thermal improvement of the roof and the basement, can reduce heating energy demand by 70%.

6 INDEX

6.1 List of Figures

6.2 List of Tables

6.3 Abbreviations

Acronym	Meaning
Av.	Average
BC	Base case
EEC	European Energy Community
HDD	Heating Degree Days
IHS	Individual Heating Substation
Max	Maximum
Min	Minimum
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
PVC	Polyvinyl chloride
SC	Scenario
UPVC	Unplasticized polyvinyl chloride

Symbol	Meaning	Units
Clo	Clothing insulation	$K.m^{-2}.W^{-1}$
CO_2	Carbon dioxide	ppm
$CO_{2\ SK}$	Carbon dioxide at reference climate	$kg.m^{-2}.a^{-1}$
E_{max}	Max. allowed specific heat loss	$kWh.m^{-2}$ $kWh.m^{-3}$
fGEE	Total energy efficiency factor	[-]
$g_{буд}$	Designed or actual specific heat loss	$kWh.m^{-2}$, $kWh.m^{-3}$
HDD	Heating Degree Days	°C.d
$HWB_{Ref,SK}$	Reference heating demand at reference climate	$kWh.m^{-2}.a^{-1}$
Met	Activity	met, $W.m^{-2}$
PEB_{SK}	Primary energy demand at reference climate	$kWh.m^{-2}.a^{-1}$
$R_{g\ min}$	Min. acceptable thermal resistance	$m^2.K.W^{-1}$
RH	Relative humidity	%
$R_{\Sigma пр}$	Given thermal resistance	$m^2.K.W^{-1}$
t_a	Air temperature	°C
t_B	Basic temperature	°C
T_o	Operative temperature	°C
$t_{оп\ з}$	Av. outside temp. over the heating period	°C
t_r	Mean radiant temperature	°C
U	Thermal transmittance	$W.m^{-2}.K^{-1}$
v_a	Air velocity	$m.s^{-1}$
$z_{оп}$	Duration of the heating period	day

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8 APPENDIX

8.1 Additional information about the Case Study Building

Address	Bulgakova street 12, Kiev, Ukraine, 03134	
Year of construction	1995	
Number of students	626	
Number of school staff	96	
Number of classes	36	
School hours	08:00-18:00	
Number of floors	4	
Useful area	10867.3	
	Total area, m^2	**height, m**
Basement	3854.21	2.5
Ground floor	2809.81	3
First floor	2615	3
Second floor	2298.48	3
Third floor	2006.5	3
Outer walls	Brick: 51cm, 38cm, 25 cm	
Fundament	precast foundation, concrete block foundation	
Floor slabs	prefabricated hollow-core slabs	
Staircase	reinforced concrete	
Roof	flat roof	
Windows	plastic, timber-aluminium	
Doors	wood, timber-aluminium	
Heating	district heating network	
Electric power supply	central electricity supply network	

8.2 Monthly heating energy consumption [kWh] in 2012-2016

Month	2012	2013	2014	2015	2016
January	11.47	22.21	18.50	19.25	5.08
February	23.6	17.69	22.55	25.06	4.45
March	12.5	22.57	14.51	13.46	3.07
April	4.32	11.22	6.44	7.21	1.08
May	0.42	0.63	0.75	2	0.09
June	0	0	0.32	0.01	0.01
July	0	0	0	0	0
August	0	0	0	0	0
September	0.43	0.29	0	0.01	0
October	5.07	9.01	0.31	1.5	0.49
November	13.94	12.09	2.48	2.92	31.93
December	22.92	20.08	6.39	3.96	28.71
Total	94.66	115.79	72.25	75.38	74.93

8.3 Monthly electricity energy consumption [kWh] in 2012-2016

Month	2012	2013	2014	2015	2016
January	9970	9530	10340	9470	8250
February	9790	10890	11060	11430	7720
March	9050	8200	11220	9180	12120
April	8120	7100	7340	8630	8240
May	5440	5360	7520	6660	6990
June	3790	4070	7080	3960	4200
July	450	420	2440	510	450
August	270	660	120	210	350
September	2290	3930	2660	2520	2610
October	7680	11800	7760	6820	10280
November	12990	11120	8680	11690	12580
December	10440	13490	13530	13360	13330
Total	**82292**	**88583**	**91764**	**86455**	**89135**

8.4 Monthly electricity consumption [kWh] in 2014, divided by two meters

Month	Corridors, Classrooms	Dining room	Total
January	7260	3080	10340
February	7620	3440	11060
March	7380	3840	11220
April	4380	2960	7340
May	3600	3920	7520
June	3720	3360	7080
July	720	1720	2440
August	120	0	120
September	1100	1560	2660
October	3840	3920	7760
November	5760	2920	8680
December	9450	4080	13530

8.5 Translated Energy Certificate

General information

Date of completion	**04.04.2016**
Address	**Secondary School No 317**
Project developer	**-**
Address and telephone of the developer	**-**
Code of the building project	**-**
Construction year	**1995**

Estimated parameters

Title of the estimated parameters	Denotation	Units	Value
Base temperature	tв	°C	18,00
Design outside air temperature	tз	°C	-22
Design temperature of the warm attic	tвг	°C	-
Design temperature of the basment utility service space	tц	°C	5
Duration of the heating period	zоп	day	176
Average outside air temperature over the heating period	tоп з	°C	-0,1
Heating degree days	Dd	°Cd	3185,6

Geometrical, thermal and energy values

Values	Denotation, Units	Normative value	Design value	Actual value
Total area of the building envelope	F_{Σ}, m^2	-	13475,56	-
Including:				
- walls	$F_{нп}$, m^2	-	4845	-
- windows and balcony doors	$F_{сп}$, m^2	-	1729,41	-
- stained glass	$F_{сп\ вт}$, m^2	-	-	-
- lanterns	$F_{сп\ л}$, m^2	-	-	-
- entrance doors, gates	$F_{д}$, m^2	-	31,33	-
- coatings (combined)	$F_{пк}$, m^2	-	-	-
- roof, attic slabs (cold attic)	$F_{пк\ хг}$, m^2	-	3435,00	-
- warm attic slabs	$F_{пк\ тг}$, m^2	-	-	-
- slabs above basment utility service	$F_{ц1}$, m^2	-	3435,00	-
- slabs above unheated basements and basment utility service space	$F_{ц2}$, m^2	-	-	-
- slabs above the passages and under the bow windows	$F_{ц3}$, m^2	-	-	-
- floor above the earth	$F_{ц}$, m^2	-	-	-
Heated area	F_{h}, m^2	-	10867	-
Useful area (for public buildings)	F_{lK}, m^2	-	13384	-
Area of the living spaces and kitchen	$F_{lж}$, m^2	-	-	-
Estimated area (for public buildings)	F_{lp}, m^2	-	13384	-
Heated volume	V_{h}, m^3	-	46153	-
Glazing Factor	$m_{ск}$	-	0,26	-
Indicator of the house compactness	$\Lambda_{к\ буд}$, m^{-1}	-	0,29	-

Thermo-technical values

Values	Denotation, Units	Normative values	Design value	Actual value
Given thermal resistance of the building envelope:	$R_{\Sigma пр}$, $m^2.K.W^{-1}$	-	1,26	-
- walls	$R_{\Sigma пр\ нп}$	3,3	0,8	-
- windows and balcony doors	$R_{\Sigma пр\ сп\ в}$	0,75	0,38	-
- stained glass	$R_{\Sigma пр\ сп\ вт}$	-	-	-
- lanterns	$R_{\Sigma пр\ сп\ л}$	-	-	-
- entrance doors, gate	$R_{\Sigma пр\ л}$	0,6	0,39	-
- coatings (combined)	$R_{\Sigma пр\ пк}$	-	-	-
- roof, attic slabs (cold attic)	$R_{\Sigma пр\ хг}$	4,95	1,13	-
- warm attics slabs (including coatings)	$R_{\Sigma пр\ тг}$	-	-	-
- slabs above basment utility service space	$R_{\Sigma пр\ ц1}$	3,75	-	-
- slabs above unheated basements and basment utility service space	$R_{\Sigma пр\ ц2}2$	3,75	2,48	-
- slabs above the passages and under the bow windows	$R_{\Sigma пр\ ц3}$	3,5	-	-
- floor above the earth	$R_{\Sigma пр\ ц}$	-	-	-

Energy indicators

Values	Denotation, Units	Normative value	Design value	Actual value
Design-specific heat loss	$q_{буд}$, кWh.m^{-2} [кWh.m^{-3}]		178,4 [42]	76,45 [18]
The maximum allowable value of specific heat loss for the building heating	Emax, кWh.m^{-2} [кWh.m^{-3}]	131,66 [31]		
Energy efficiency class	-	C	E	B
The term of the efficient building envelope exploitation and its elements	-	-	-	-
Relevance of the building projects to the normative requirements	-	-	No	
Need for the project revision	-	-	Yes	

Conclusions :

The actual specific heat losses are on the normative level. The actual consumption of the thermal energy is significantly lower than design consumption, due to the failure of the internal temperature regimes.

Guidelines for building energy efficiency improvement
Recommended:
Individual sub station settings improvement Lighting system improvement Replacement of the old doors to the new energy efficicent ones Replacement of the old windows to the new energy efficicent ones Walls insulation Roof insulation Heating system improvement Installationof the local ventilation systems

Passport completion	04.04.2016

Organization	
Adress and telephone	
Responsible executor	

Energy Certificate

ЕНЕРГЕТИЧНИЙ ПАСПОРТ

Загальна інформація

Дата заповнення	**04.04.2016**
Адреса будинку	**Середня загальноосвітня школа №317**
Розробник проекту	-
Адреса і телефон розробника	-
Шифр проекту будинку	-
Рік будівництва	**1995**

Розрахункові параметри

Найменування розрахункових параметрів	Позначення	Одиниця виміру	Величина
Розрахункова температура внутрішнього повітря	tв	оС	18,00
Розрахункова температура зовнішнього повітря	tз	оС	-22
Розрахункова температура теплого горища	tвг	оС	-
Розрахункова температура техпідпілля	tц	оС	5
Тривалість опалювального періоду	zоп	доба	176
Середня температура зовнішнього повітря за опалювальний період	tоп з	оС	-0,1
Розрахункова кількість градусо-діб опалювального періоду	Dd	оС • доба	3185,6

Геометричні, теплотехнічні та енергетичні показники

Показники	Позначення і розмірність показника	Нормативне значення показника	Розрахункове (проектне значення показника)	Фактичне значення показника
Загальна площа зовнішніх огороджувальних конструкцій будинку	F_{Σ}, м^2	-	13475,56	-
В тому числі:				
- стін	$F_{нп}$, м^2	-	4 845	-
- вікон і балконних дверей	$F_{сп}$ в, м^2	-	1729,41	-
- вітражів	$F_{сп\ вт}$, м^2	-	-	-
- ліхтарів	$F_{сп\ л}$, м2	-	-	-
- вхідних дверей, воріт	$F_{сп\ д}$, м2	-	31,33	
- покриттів (суміщених)	$F_{пк}$, м^2	-	-	-
- горищних перекриттів (холодного горища)	$F_{пк\ хг}$, м^2	-	3435,00	-
- перекриттів теплих горищ	$F_{пк\ тг}$, м^2	-	-	-
- перекриттів над техпідпіллями	$F_{ц1}$, м^2	-	3435,00	-
- перекриттів над неопалювальними підвалами і підпіллями	$F_{ц2}$, м2	-	-	-
- перекриттів над проїздами і під еркерами	$F_{ц3}$, м^2	-	-	-
- підлоги по ґрунту	$F_{ц}$, м2	-	-	-
Площа опалювальних приміщень	F_{h}, м^2	-	10 867	-
Корисна площа (для громадських будинків)	F_{Ik}, м^2	-	13 384	-
Площа житлових приміщень і кухонь	$F_{Iж}$, м^2	-	-	-
Розрахункова площа (для громадських будинків)	F_{Ip}, м^2	-	13 384	-
Опалювальних об'єм	V_{h}, м^3	-	**46 153**	-
Коефіцієнт скління фасадів будинку	$m_{ск}$	-	0,26	-
Показник компактності будинку	$\Lambda_{к\ буд}$, м$^{-1}$	-	0,29	-

Теплотехнічні та енергетичні показники

Теплотехнічні показники

Приведений опір теплопередачі зовнішніх огороджувальних конструкцій:	$R_{\sum пр}$, $м^2 \cdot К/Вт$	-	1,26	-
- стін	$R_{\sum пр}$ НП	3,3	0,80	-
- вікон і балконних дверей	$R_{\sum пр\ сп\ в}$	0,75	0,38	-
- вітражів	$R_{\sum пр\ сп\ вт}$	-	-	-
- ліхтарів	$R_{\sum пр\ сп\ л}$	-	-	-
- вхідних дверей, воріт	$R_{\sum пр\ д}$	0,6	0,39	-
- покриттів суміщених	$R_{\sum пр\ пк}$	-	-	-
- горищних перекриттів (холодних горищ)	$R_{\sum пр\ г}$	4,95	1,13	-
- перекриттів теплих горищ (включаючи покриття)	$R_{\sum пр\ тг}$	-	-	-
- перекриттів над техпідпіллями	$R_{\sum пр\ ц1}$	3,75	-	-
- перекриттів над неопалювальними підвалами або підпіллями	$R_{\sum пр\ ц2}$	3,75	2,48	-
- перекриттів над проїздами й під еркерами	$R_{\sum пр\ ц3}$	3,5	-	-
- підлоги по ґрунту	$R_{\sum пр\ ц}$	-	-	-

Енергетичні показники

Розрахункові питомі тепловитрати	qбуд кВт . год/м2, [кВт . год/м3]		[42]	[18]
Показники	**Позначення і розмірність показника**	**Нормативне значення показника**	**Розрахункове (проектне значення показника)**	**Фактичне значення показника**
Максимальне допустиме значення питомих тепловитрат на опалення будинку	Emax кВт . год/м2, [кВт . год/м3]	[31]		
Клас енергетичної ефективності	-	C	E	B
Термін ефективної експлуатації теплоізоляційної оболонки та її елементів	-	-	-	-
Відповідність проекту будинку нормативним вимогам	-	-	Ні	
Необхідність доопрацювання проекту будинку	-	-	Так	

Висновки за результатами оцінки енергетичних параметрів будинку

Фактичне споживання теплової енергії на рівні нормативного. Фактичне споживання теплової енергії значно менше розрахованого споживання в наслідок недотримання внутрішніх температурних режимів.

Вказівки щодо підвищення енергетичної ефективності будинку
Рекомендовано:
Налаштування МІТП Реконструкція системи освітлення Заміна старих дверей на енергозберігаючі Заміна старих вікон на енергозберігаючі Утеплення стін Утеплення плаского даху Реконструкція системи опалення Встановлення локальних систем вентиляції

Паспорт заповнений:	-	04.04.2016

Організація	КП „ГВП“
Адреса і телефон	Б. Хмельницького, бул. 3А
Відповідальний виконавець	[illegible] С.М.

8.6 Questionnaire

In the following, the paper-based questionnaire is presented.

1. How do you assess classroom air temperature in spring?

☐ cold ☐ slightly cool ☐ neutral ☐ slightly warm ☐ hot

2. How do you find air quality in this classroom?

☐ very bad ☐ bad ☐ normal ☐ good ☐ very good

3. Are you satisfied with the classroom's ventilation possibilities?

☐ not satisfied ☐ less satisfied ☐ neutral ☐ satisfied

☐ very satisfied

4. Are you satisfied with the heating system in the classroom?

☐ not at all ☐ less satisfied ☐ it's ok ☐ satisfied

☐ very satisfied

5. Are you feeling tired?

☐ yes ☐ no

8.7 Building construction components

- **Base Case Scenario 101**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall	Tiles	0.01	1.3	2300	0.84	150	
54 cm	Full Brick	0.51	0.96	2000	0.9	5	1.366
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall	Tiles	0.01	1.3	2300	0.84	150	
41 cm	Full Brick	0.38	0.96	2000	0.9	5	1.675
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Floor	Hollow-core slab	0.22	0.75	1000	1.13	10	0.486
33 cm	Mineral heat insulation panel	0.06	0.044	112	1	0	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	
	Cement screed	0.04	1.33	2000	1.08	50	
	Natural rubber	0.0001	0.13	910	1.1	0	
	Linoleum	0.005	0.17	1000	1.3	1	
Ceiling	Linoleum	0.005	0.17	1000	1.3	1	0.882
31 cm	Natural rubber	0.0001	0.13	910	1.1	0	
	Cement screed	0.04	1.33	2000	1.08	50	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	
	Wood fibre insulation board	0.025	0.06	300	2.5	5	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	1.425
Wall	Full Brick	0.38	0.96	2000	0.9	5	
42 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	1.195
Wall	Full Brick	0.51	0.96	2000	0.9	5	
55 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Entrance door 220x121	Wood	0.05					2.35
Window	Timber/Aluminium	0.06					2.5
720x207	Double laminated clear glass						
Inside Window	Wood	0.06					4
50x122	Single Glass						
Balcony door	Timber/Aluminium	0.06					2.5
290x91	Double laminated clear glass						

- **1 Scenario 101 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Window 720x207	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63
Balcony door 290x91	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.71

- **2 Scenario 101 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall 63 cm	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.303
	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall 50 cm	Silicate plaster (reinforced)	0.005	0,8	1800	0	0	0.316
	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.38	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Window 720x207	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63
Balcony door 290x91	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.71

- **3 Scenario 101 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall 63 cm	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.303
	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall 50 cm	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.316
	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.38	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Floor 49 cm	Rockwool Planrock	0.16	0.041	60	0	1	0.168
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Mineral heat insulation panel	0.06	0.044	112	1	0	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	
	Cement screed	0.04	1.33	2000	1.08	50	
	Natural rubber	0.0001	0.13	910	1.1	1	
	Linoleum	0.005	0.17	1000	1.3	1	
Window 720x207	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63
Balcony door 290x91	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.71

- **Base Case Scenario 215**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall 54 cm	Tiles	0.01	1.3	2300	0.84	150	1.366
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall 28 cm	Tiles	0.01	1.3	2300	0.84	150	2.169
	Full Brick	0.25	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Floor 31 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	0.882
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Wood fibre insulation board	0.025	0.06	300	2.5	5	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	
	Cement screed	0.04	1.33	2000	1.08	50	
	Natural rubber	0.0001	0.13	910	1.1	0	
	Linoleum	0.005	0.17	1000	1.3	1	
Ceiling 31 cm	Linoleum	0.005	0.17	1000	1.3	1	0.882
	Natural rubber	0.0001	0.13	910	1.1	0	
	Cement screed	0.04	1.33	2000	1.08	50	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	
	Wood fibre insulation board	0.025	0.06	300	2.5	5	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Roof over classroom 31,5 cm	Sheet metal covering	0.01	60	7800	1	10^6	0.707
	Shuttering	0.02	0.15	600	1.61	50	
	Wooden baton W: 0,05 A: 0,6 V	0.04	0.15	600	1.61	50	
	Mineral fibre stone wool	0.04	0.043	200	1.03	1	
	PE-Sealing sheets	0.005	0.25	1100	0.79	10^5	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside Wall 55 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	1.195
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside Wall 42 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	1.425
	Full Brick	0.38	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Entrance door220x121	Wood	0.05					2.35
Window 874x207	Timber/Aluminium Double laminated clear glass	0.06					2.5
Inside Window 50x122	Wood Single Glass	0.06					4

- **1 Scenario 215 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Window 874x207	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **2 Scenario 215 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	
63 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	0.303
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	
36,5 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	0.330
	Full Brick	0.25	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Window 874x207	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **3 Scenario 215 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [$W.m^{-1}.K^{-1}$]	Density [$kg.m^{-3}$]	Specific Heat [$kJ.kg^{-1}.K^{-1}$]	Vapour Diff. Factor	U-Value [$W.m^{-2}.K^{-1}$]
Outside Wall 63 cm	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.303
	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.51	0.96	2000	0,9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall 36,5 cm	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.330
	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.25	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Roof over classroom 40 cm	Sheet metal covering	0.01	60	7800	1	10^6	0.253
	PP-Felt with PE-Foil	0	0.35	950	1.9	10^5	
	PE-Sealing sheets	0.003	0.25	1100	0.79	10^5	
	Shuttering	0.02	0.15	600	1.61	50	
	Wooden baton W: 0,03 A: 0,6 V	0.06	0.15	600	1.61	50	
	ROCKWOOL Fixrock 032	0.06	0.032	75	0	1	
	Wooden baton W: 0,03 A: 0,6 H	0.06	0.15	600	1.61	50	
	ROCKWOOL Fixrock 032	0.06	0.032	75	0	1	
	Aluminium vapour barrier	0.005	221	2800	0.9	9999999	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Window 874x207	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **Base Case Scenario 219**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall 54 cm	Tiles	0.01	1.3	2300	0.84	150	1.366
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall 28 cm	Tiles	0.01	1.3	2300	0.84	150	2.169
	Full Brick	0.25	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Floor 31 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	0.882
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Wood fibre insulation board	0.025	0.06	300	2.5	5	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	
	Cement screed	0.04	1.33	2000	1.08	50	
	Natural rubber	0.0001	0.13	910	1.1	0	
	Linoleum	0.005	0.17	1000	1.3	1	
Ceiling indoor 31 cm	Linoleum	0.005	0.17	1000	1.3	1	0.882
	Natural rubber	0.0001	0.13	910	1.1	0	
	Cement screed	0.04	1.33	2000	1.08	50	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	
	Wood fibre insulation board	0.025	0.06	300	2.5	5	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Roof over classroom 31,5 cm	Sheet metal covering	0.01	60	7800	1	10^6	0.707
	Shuttering	0.02	0.15	600	1.61	50	
	Wooden baton W: 0,05 A: 0,6 V	0.04	0.15	600	1.61	50	
	Mineral fibre stone wool	0.04	0.043	200	1.03	1	
	PE-Sealing sheets	0.005	0.25	1100	0.79	100	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside Wall 55 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1,11	15	1.195
	Full Brick	0.51	0.96	2000	0,9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1,11	15	
Inside Wall 42cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	1.425
	Full Brick	0.38	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Entrance door220x121	Wood	0.05					2.35
Window 874x207	PVC 2-panes clear glass	0.06					1.25
Inside Window 50x122	Wood Single Glass	0.06					4

- **1 Scenario 219 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [$W.m^{-1}.K^{-1}$]	Density [$kg.m^{-3}$]	Specific Heat [$kJ.kg^{-1}.K^{-1}$]	Vapour Diff. Factor	U-Value [$W.m^{-2}.K^{-1}$]
Window 874x207	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **2 Scenario 219 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [$W.m^{-1}.K^{-1}$]	Density [$kg.m^{-3}$]	Specific Heat [$kJ.kg^{-1}.K^{-1}$]	Vapour Diff. Factor	U-Value [$W.m^{-2}.K^{-1}$]
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.303
63 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.330
36,5 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.25	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Window 874x207	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **3 Scenario 219 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	
63 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	0.303
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	
36,5 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	0.330
	Full Brick	0.25	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Roof over classroom	Sheet metal covering	0.01	60	7800	1	10^6	
	PP-Felt with PE-Foil	0	0.35	950	1.9	10^5	
40 cm	PE-Sealing sheets	0.003	0.25	1100	0.79	10^5	
	Shuttering	0.02	0.15	600	1.61	50	
	Wooden baton W: 0,03 A: 0,6 V	0.06	0.15	600	1.61	50	
	ROCKWOOL Fixrock 032	0.06	0.032	75	0	1	0.253
	Wooden baton W: 0,03 A: 0,6 H	0.06	0.15	600	1.61	50	
	ROCKWOOL Fixrock 032	0.06	0.032	75	0	1	
	Aluminium vapour barrier	0.005	221	2800	0.9	9999999	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Window	Internorm, UPVC KF410	0.093					0.63
874x207	3-panes insulating glass						

- **Base Case Scenario 309**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall 54 cm	Tiles	0.01	1.3	2300	0.84	150	1.366
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall 28 cm	Tiles	0.01	1.3	2300	0.84	150	2.169
	Full Brick	0.25	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Floor 31 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	0.882
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Wood fibre insulation board	0.025	0.06	300	2.5	5	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	
	Cement screed	0.04	1.33	2000	1.08	50	
	Natural rubber	0.0001	0.13	910	1.1	0	
	Linoleum	0.005	0.17	1000	1.3	1	
Ceiling indoor 31 cm	Linoleum	0.005	0.17	1000	1.3	1	0.882
	Natural rubber	0.0001	0.13	910	1.1	0	
	Cement screed	0.04	1.33	2000	1.08	50	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	
	Wood fibre insulation board	0.025	0.06	300	2.5	5	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0,02	0.87	1800	1.11	15	
Roof over classroom 31,5 cm	Sheet metal covering	0.01	60	7800	1	10^6	0.707
	Shuttering	0.02	0.15	600	1.61	50	
	Wooden baton W: 0,05 A: 0,6 V	0.04	0.15	600	1.61	50	
	Mineral fibre stone wool	0.04	0.043	200	1.03	1	
	PE-Sealing sheets	0.005	0.25	1100	0.79	100	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside Wall 55 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	1.195
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside Wall 14 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	2.439
	Full Brick	0.10	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Entrance door220x121	Wood	0.05					2.35
Window 840x200	Timber/Aluminium Double laminated clear glass	0.06					2.5
Inside Window 50x122	Wood Single Glass	0.06					4

- **1 Scenario 309 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Window 840x200	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **2 Scenario 309 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.303
63 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.330
36,5 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.25	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Window 840x200	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **3 Scenario 309 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall 63 cm	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.303
	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Outside Wall 36,5 cm	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.330
	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.25	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Roof over classroom 40 cm	Sheet metal covering	0.01	60	7800	1	$1*10^6$	0.253
	PP-Felt with PE-Foil	0	0.35	950	1.9	$1*10^5$	
	PE-Sealing sheets	0.003	0.25	1100	0.79	$1*10^5$	
	Shuttering	0.02	0.15	600	1.61	50	
	Wooden baton W: 0,03 A: 0,6 V	0.06	0.15	600	1.61	50	
	ROCKWOOL Fixrock 032	0.06	0.032	75	0	1	
	Wooden baton W: 0,03 A: 0,6 H	0.06	0.15	600	1.61	50	
	ROCKWOOL Fixrock 032	0.06	0.032	75	0	1	
	Aluminium vapour barrier	0.005	221	2800	0.9	9999999	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Window 840x200	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **Base Case Scenario 402**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall	Tiles	0.01	1.3	2300	0.84	150	
54 cm	Full Brick	0.51	0.96	2000	0.9	5	1.366
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Floor	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
31 cm	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Wood fibre insulation board	0.025	0.06	300	2.5	5	
	Bitumen cardboard	0.0002	0.23	1100	1.26	36000	0.882
	Cement screed	0.04	1.33	2000	1.08	50	
	Natural rubber	0.0001	0.13	910	1.1	0	
	Linoleum	0.005	0.17	1000	1.3	1	
Roof	Gravel	0.05	0.7	1800	1	2	
53,5 cm	Bitumen cardboard	0.004	0.17	1200	1.26	40000	
	Concrete	0.04	1.4	2000	1.08	100	
	EPS	0.12	0.041	15	1.45	50	
	Gravel	0.04	0.7	1800	1	2	0.278
	Aluminium vapour barrier	0.001	21	2800	0.9	9999999	
	Concrete	0.04	1.4	2000	1.08	100	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Wall	Full Brick	0.51	0.96	2000	0,9	5	1.195
55 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Wall	Full Brick	0.125	0.96	2000	0,9	5	2.294
16,5 cm	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Inside	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Wall	Full Brick	0.065	0.96	2000	0.9	5	
79 cm	Air	0.31	0.025	1	1	0	0.076
	Brick	0.38	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Entrance door220x121	Wood	0.05					2.35
Window 210x200 209x200	Timber/Aluminium Double laminated clear glass	0.06					2.5

- **1 Scenario 402 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Window 210x200 209x200	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **2 Scenario 402 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.303
63 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Window 210x200 209x200	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

- **3 Scenario 402 (Improved constructions)**

Construction	Description	Width [m]	Conduct. [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [kJ.kg^{-1}.K^{-1}]	Vapour Diff. Factor	U-Value [W.m^{-2}.K^{-1}]
Outside Wall	Silicate plaster (reinforced)	0.005	0.8	1800	0	0	0.303
63 cm	Rockwool Coverrock 035	0.09	0.035	122	1.03	1	
	Full Brick	0.51	0.96	2000	0.9	5	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Roof	Gravel	0.06	0.7	1800	1	0	0.1
75,3 cm	Polym. bitum. waterpr. memb.	0.008	0.23	1100	1.26	36000	
	Vapour control layer	0.0016	0.17	1060	0	0	
	EPS-W 20 (19,5 kg/m^2)	0.36	0.038	19	1.45	0	
	Aluminium vapour barrier	0.0014	0.23	1100	1.26	36000	
	Vapour control layer	0.0018	0.17	1060	0	0	
	Slope concrete	0.08	1.4	2000	1.08	100	
	Hollow-core slab	0.22	0.75	1000	1.13	10	
	Plastering mortar (lime cement)	0.02	0.87	1800	1.11	15	
Window 210x200 209x200	Internorm, UPVC KF410 3-panes insulating glass	0.093					0.63

8.8 Thermal Comfort Histograms

Below, the frequency distribution of the temperature, relative and specific humidity during occupancy hours in March and May are presented.

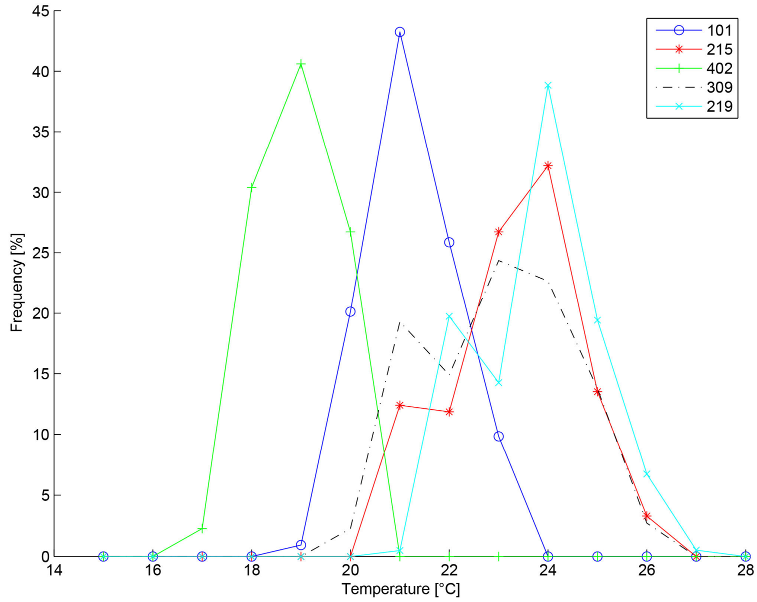

Figure 61: Frequency distribution of the temperature during occupancy hours in March

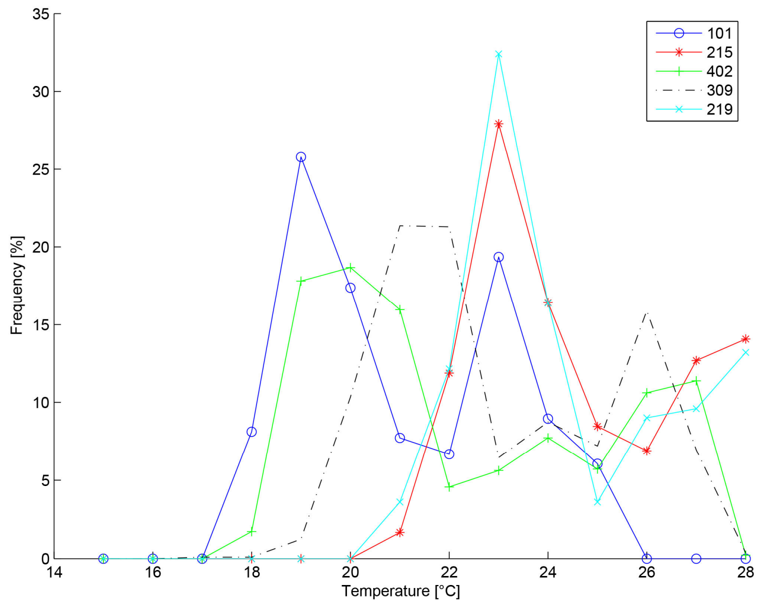

Figure 62: Frequency distribution of the temperature during occupancy hours in May

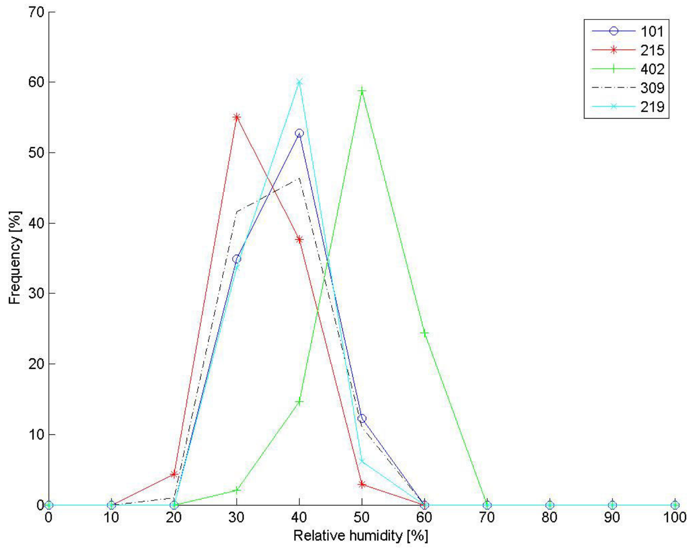

Figure 63: Frequency distribution of the relative humidity during occupancy hours in March

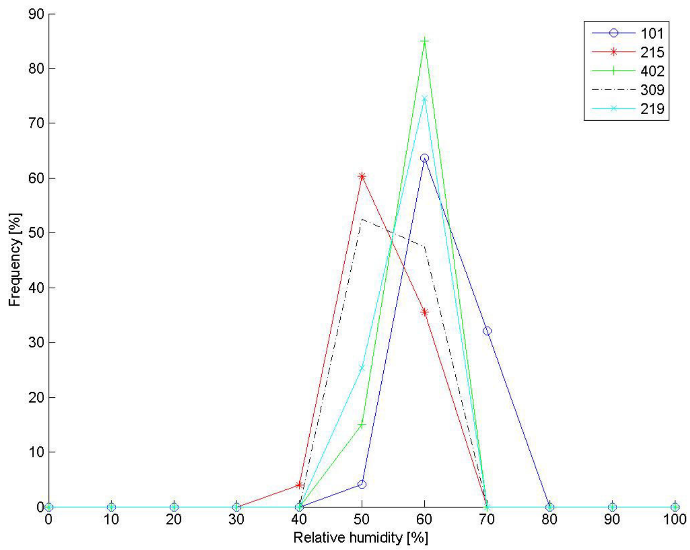

Figure 64: Frequency distribution of the relative humidity during occupancy hours in May

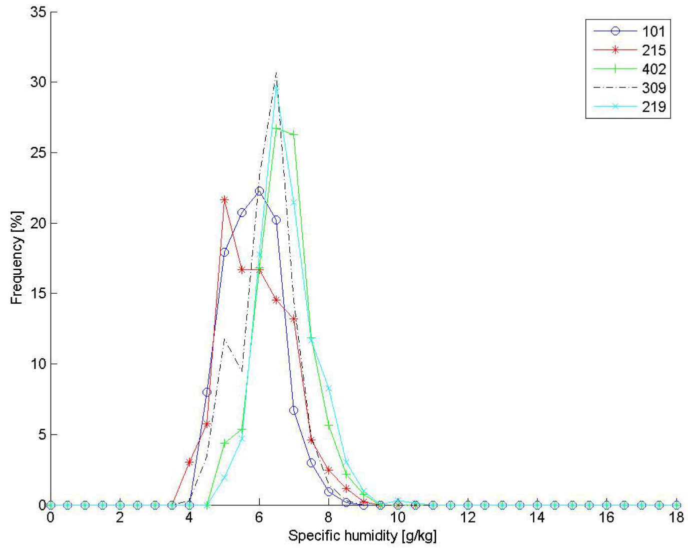

Figure 65: Frequency distribution of the specific humidity during occupancy hours in March

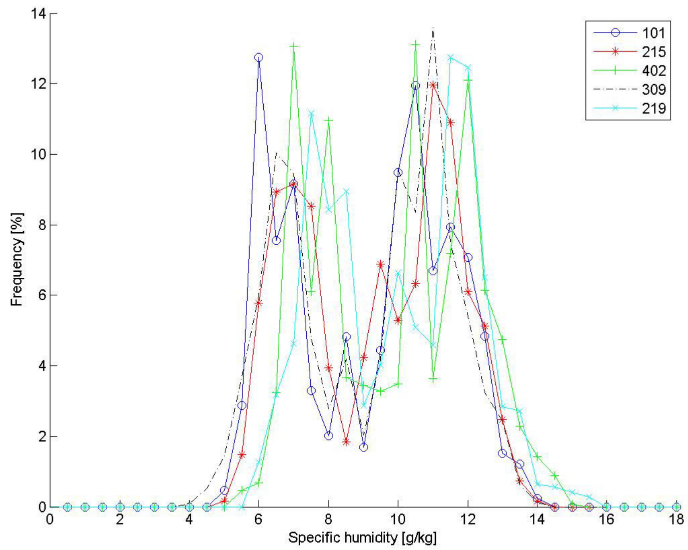

Figure 66: Frequency distribution of the specific humidity during occupancy hours in May

8.9 Psychrometric Charts

In the following, the Psychometric charts of monitored classrooms during occupancy hours are presented.

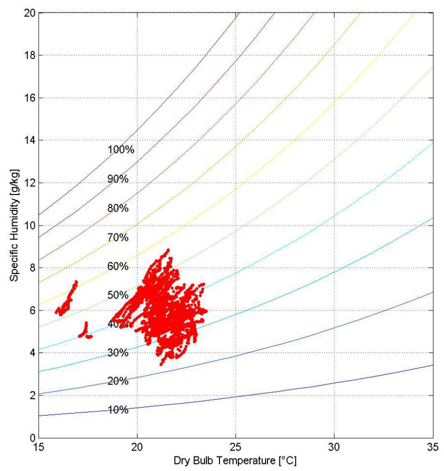

Figure 67: Psychometric chart of Classroom 101 during occupancy hours in heated period

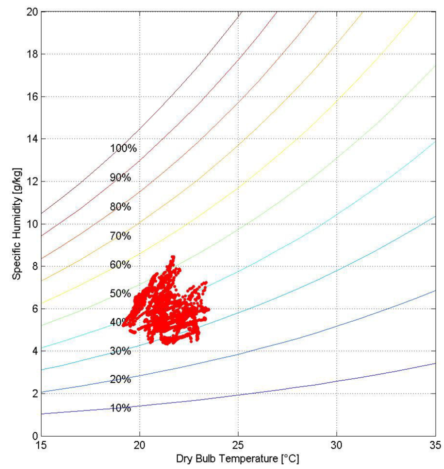

Figure 68: Psychometric chart of Classroom 101 during occupancy hours in March

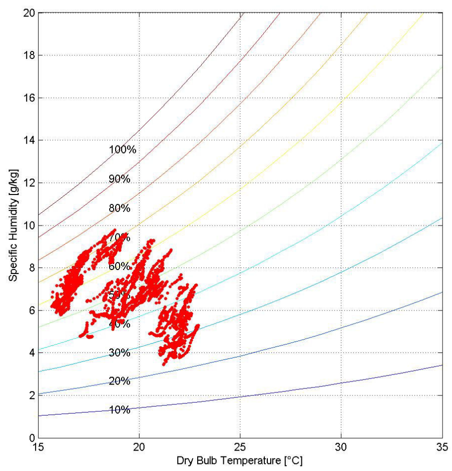

Figure 69: Psychometric chart of Classroom 101 during occupancy hours in April

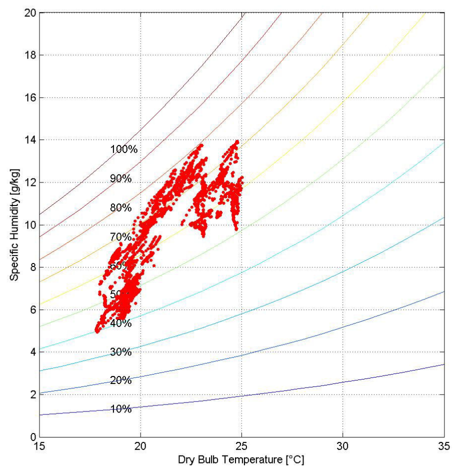

Figure 70: Psychometric chart of Classroom 101, during occupancy hours in May

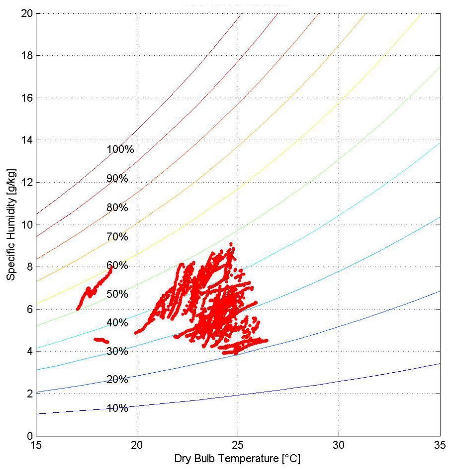

Figure 71: Psychometric chart of Classroom 215 during occupancy hours in heated period

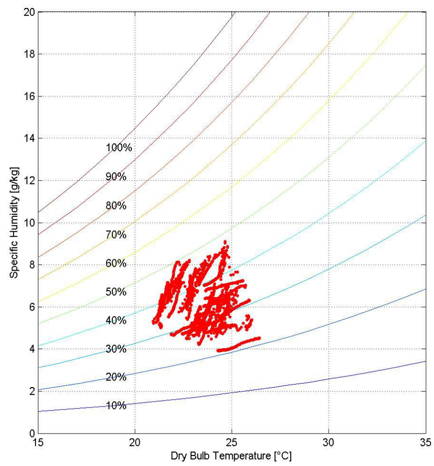

Figure 72: Psychometric chart of Classroom 215 during occupancy hours in March

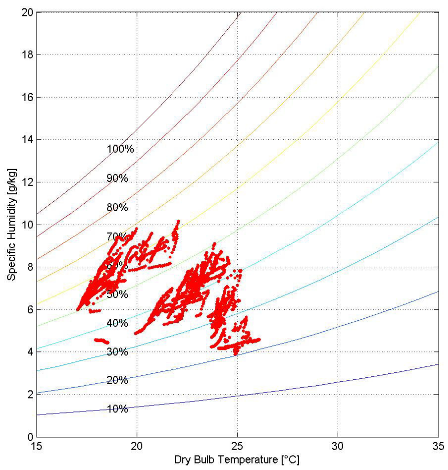

Figure 73: Psychometric chart of Classroom 215 during occupancy hours in April

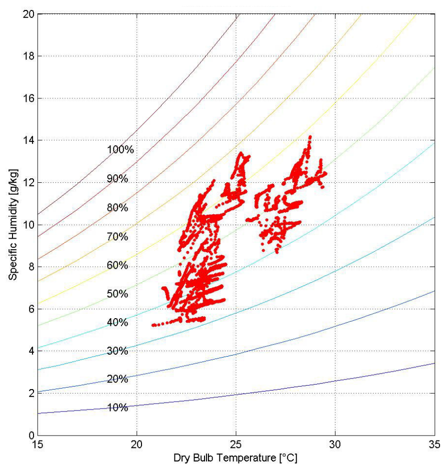

Figure 74: Psychometric chart of Classroom 215 during occupancy hours in May

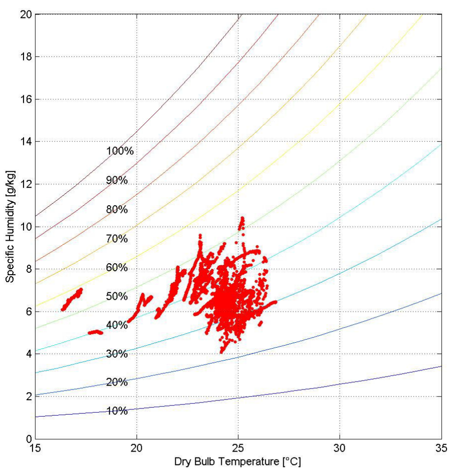

Figure 75: Psychometric chart of Classroom 219 during occupancy hours in heated period

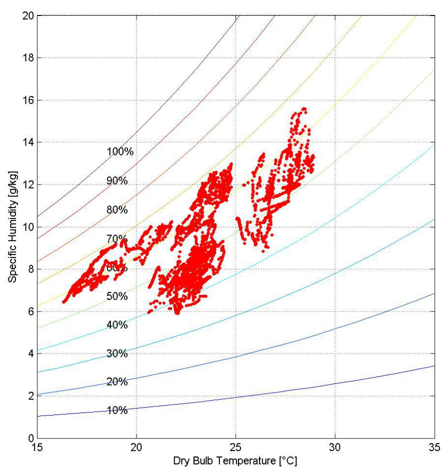

Figure 76: Psychometric chart of Classroom 219 during occupancy hours in unheated period

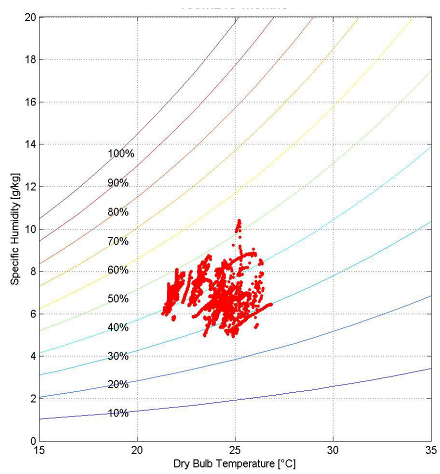

Figure 77: Psychometric chart of Classroom 219 during occupancy hours in March

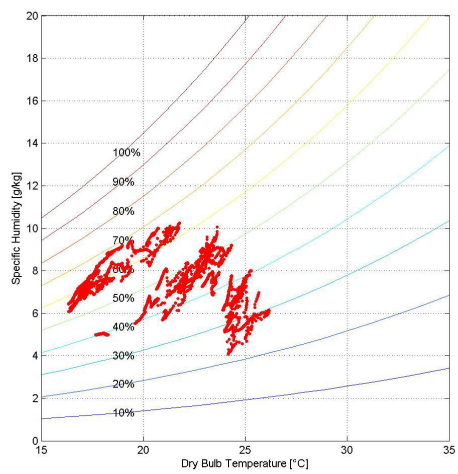

Figure 78: Psychometric chart of Classroom 219 during occupancy hours in April

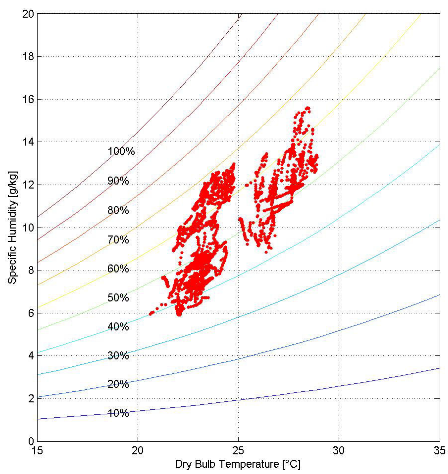

Figure 79: Psychometric chart of Classroom 219 during occupancy hours in May

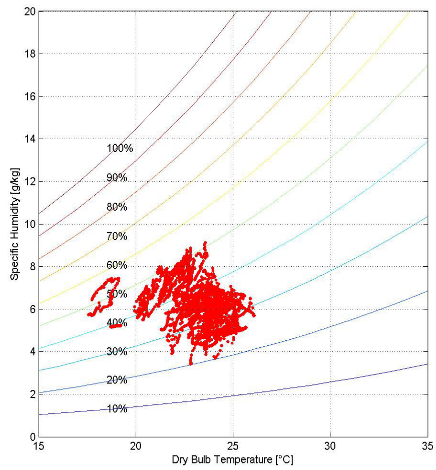

Figure 80: Psychometric chart of Classroom 309 during occupancy hours in heated period

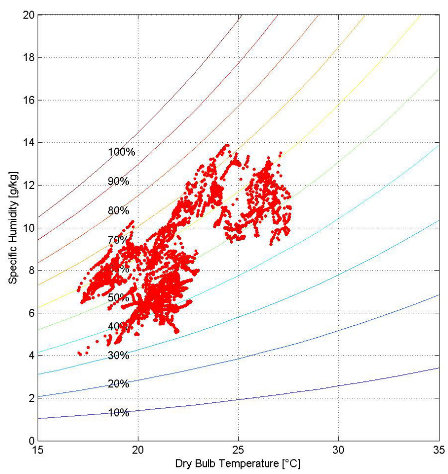

Figure 81: Psychometric chart of Classroom 309 during occupancy hours in unheated period

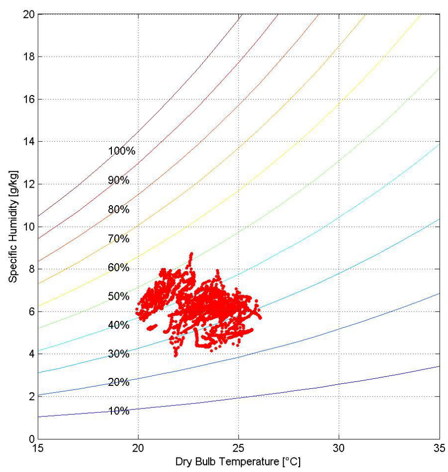

Figure 82: Psychometric chart of Classroom 309 during occupancy hours in March

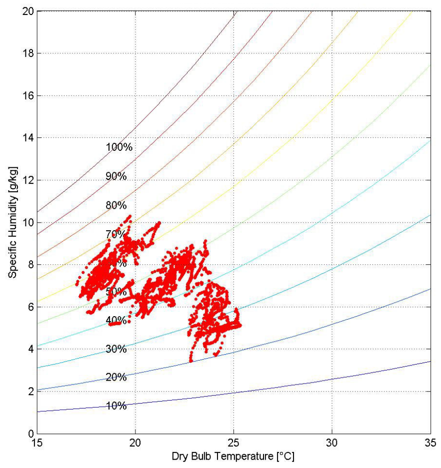

Figure 83: *Psychometric chart of Classroom 309 during occupancy hours in April*

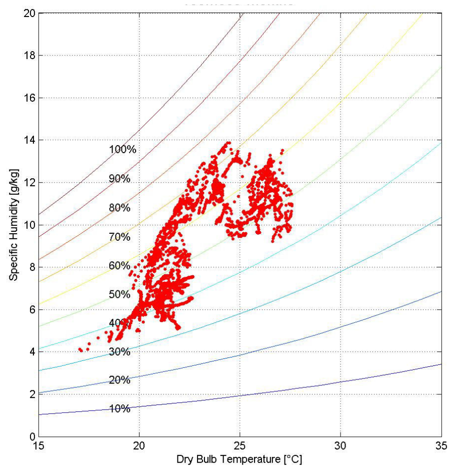

Figure 84: *Psychometric chart of Classroom 309 during occupancy hours in May*

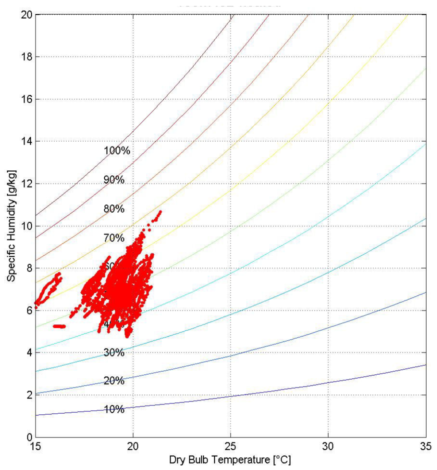

Figure 85: Psychometric chart of Classroom 402 during occupancy hours in heated period

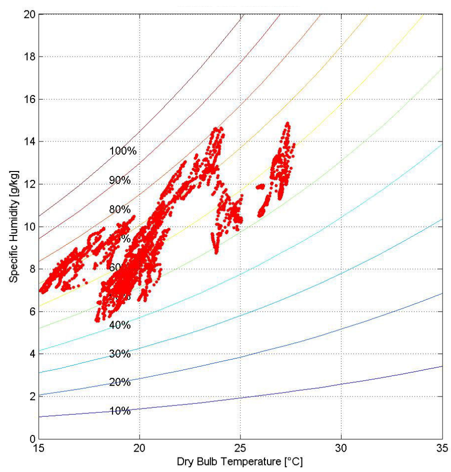

Figure 86: Psychometric chart of Classroom 402 during occupancy hours in unheated period

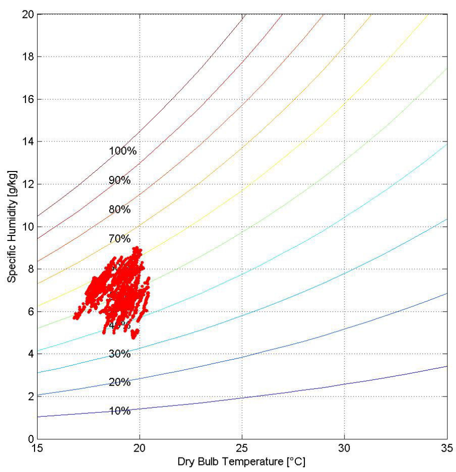

Figure 87: Psychometric chart of Classroom 402 during occupancy hours in March

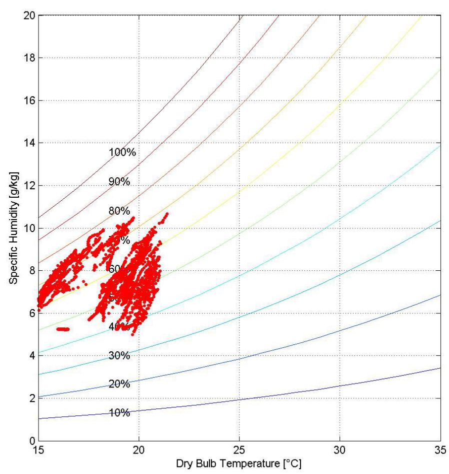

Figure 88: Psychometric chart of Classroom 402 during occupancy hours in April

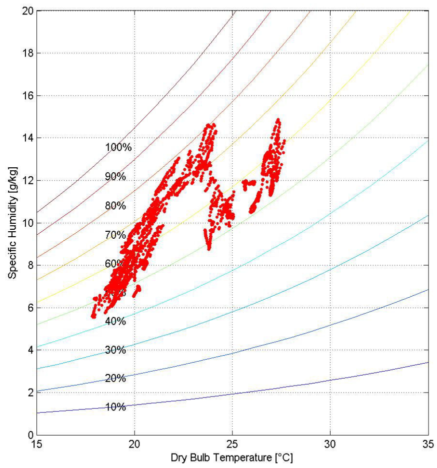

Figure 89: Psychometric chart of Classroom 402 during occupancy hours in May

8.10 PMV Histograms

Below, the frequency distribution of the PMVs during occupancy hours in March and May are displayed.

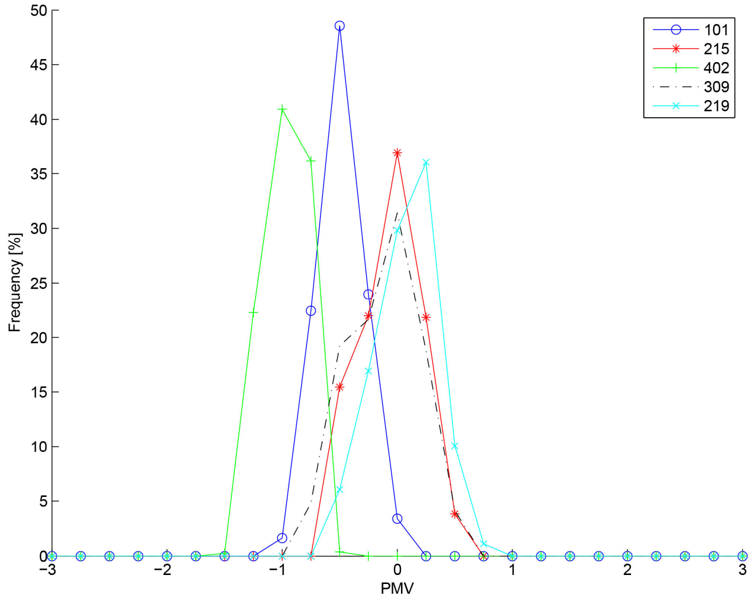

Figure 90: Frequency distribution of the PMVs during occupancy hours in March

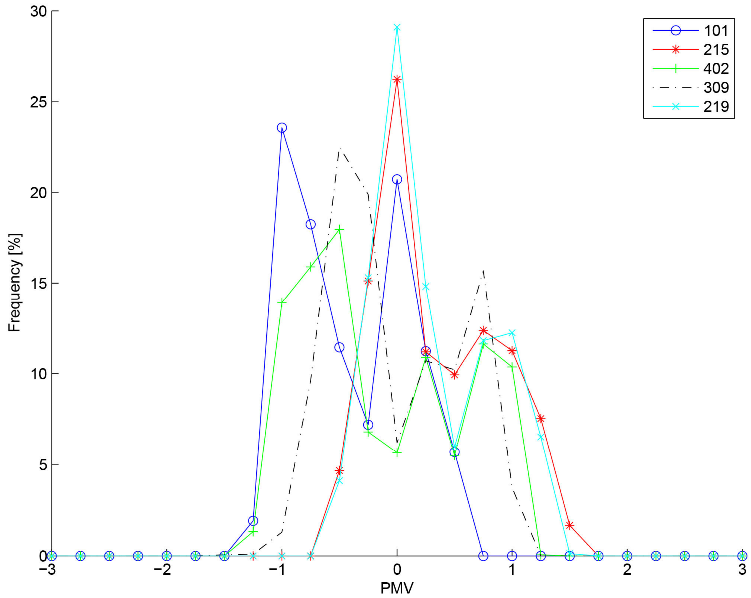

Figure 91: Frequency distribution of the PMVs during occupancy hours in May

8.11 Indoor Air Quality Histograms

Below, the cumulative distribution of the CO_2 concentration during occupancy hours in March and May are displayed.

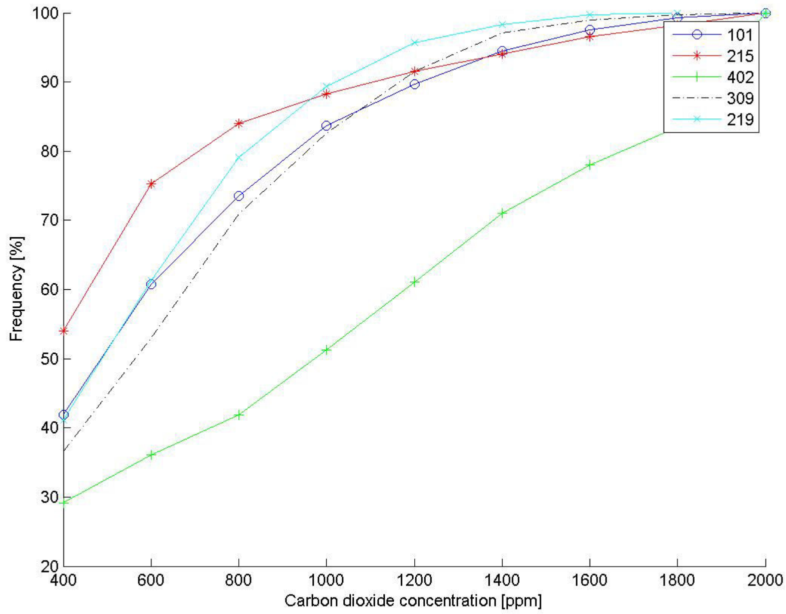

Figure 92: Cumulative distribution of the CO2 concentration during occupancy hours in March

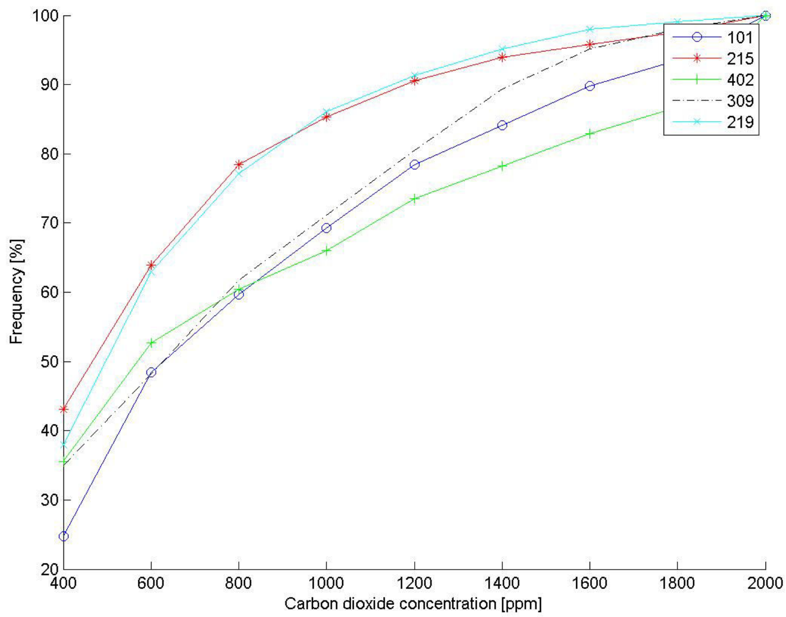

Figure 93 Cumulative distribution of the CO2 concentration during occupancy hours in May